Third International Symposium
on

UNMANNED UNTETHERED SUBMERSIBLE TECHNOLOGY

June 6-9, 1983

Marine Systems Engineering Laboratory
University of New Hampshire
Durham, NH 03824

and

UNH/UME Sea Grant College Program

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A special thanks to John B. Gregory and the Minerals Management Service whose research program has fostered the communication brought about by this symposium.

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WELCOME

Robert W. Corell
Marine Systems Engineering Laboratory
University of New Hampshire

Welcome to the Third International Symposium on Unmanned, Untethered Submersible Technology. We are delighted to see so many familiar faces, and new friends of this research community concerned with unmanned vehicle technology.

It is a pleasure to welcome you to Durham on behalf of the University of New Hampshire and bring you greetings from our President and from the University's marine faculty and research staff. For those of you who have been to Durham before, we are glad you are back; for those of you who have not been to Durham before, we hope you enjoy your stay. We hope the weather cooperates for all of us so that we can enjoy these next few days together working, thinking, and exploring various aspects of the unmanned, untethered submersible business. A special welcome to those of you who come from abroad to share your time, talent and interest with us here.

This Symposium is the third in a series, each of which have been separated by roughly eighteen months. This year we have added some new dimensions. The National Sea Grant College Program through the University of New Hampshire and Maine Sea Grant College have become sponsors to this Symposium. Sea Grant is a partnership between industry, government and universities focused on research, education and public service. Many of you, of course, know of the Sea Grant Program. We are delighted that Sea Grant recognizes the importance of this technology. The most important new addition has been the real participation and financial support from industry. This has become a vital part of this particular Symposium. Through industrial participation and financial support, we are able to continue this series of Symposia.

The whole field of unmanned, untethered submersibles is built upon many technologies and applied aspects of science. In many ways it is a marriage of engineering and science that creates the technologies that are the keystone of the unmanned, untethered vehicle. As virtually all of you at this Symposium know, the past several years have seen an explosive interest in the developments and accomplishments in this field. It is almost a truism to note that the keystone of this growth has been microcomputer/microelectronics and the computer sciences and knowledge engineering. But there are other equally important technologies that have converged to make our business what it is today. High energy/density power sources, are such a field. The revolution, in my mind, is driven by work systems essential to offshore development. Early systems were handled extensively by divers, and then increasingly by submersibles. All of you are aware of the tremendous impact that ROV's (Remotely Operated

Vehicle) have had. These systems play a significant and important part in the total work requirements in the offshore. The technology about which we will spend many hours in the next few days will be an additional component of those work systems and vehicle systems that are essential to offshore development. It is the convergence of those needs with the significant technologies that make it possible to discuss what some of us are more frequently calling; underwater robotic system.

For some of us, working with these technologies we are drawn by the needs of products or services for particular applications. For others, we are drawn by the imperatives or the excitement that goes with the science and technology of unmanned, untethered, underwater vehicle systems.

Ours is a problem-driven field of endeavor where we as engineers and applied scientists seek significant advances in this field of underwater vehicles. It is not always clear how that technology is going to emerge and develop. It is not clear how a particular technology is going to fall in place. A good example is the problems of producing a transistor. In its early days, products were driven by germanium as the basic ingredient of the transistors. This was largely because of electron mobility which was high and speeds could be higher in germanium. Evidently, as we now know, this was not the case. Silicon and other factors such as manufacturing and the availability of oxide coats to protect the units played a more dominant role than speed in evolving technology. I think the same sorts of things are happening in our field. The early logic is replaced by seasoned understanding of a broad spectrum of issues critical to a new technology.

Two or three years ago at these Symposia we talked about things that today are not seen as anywhere near as important to the technology. We have forgotten things that are now emerging as critical to the evolution of this business.

Underwater vehicles are coming of age. The untethered ones are still untried, and that is what brings us together. It is the technology that we will talk about these next few days.

The entire business of technology development is an exciting one for all of us here. Let me share with you some comments by the Vice President of Research at IBM. "Technology development is sensitive to detail. It is sensitive to the culture in which it is embedded. It is an activity that is not well understood. Yet we must go forward with it, regardless. Much of our individual and national welfare depends on our capacity for success in technology development." I think that captures much of what is behind this symposium. We are driven by pragmatic needs of complex and, yet-to-be-understood, systems and components. We hope, therefore, that the discussions here today, tomorrow and throughout the entire Symposium will be wide, open, free, and that we will share questions and comments in a relaxed, informal atmosphere. We seek to make the symposium truely a seminar/workshop environment rather than one of simply formal presentations. I think this will be an exciting time. I've seen what has happened in the last 12 to 18 months and it has been dramatic.

So with this excitement of mutual discovery and an opportunity to share together, we are pleased you are here, we are delighted you have elected to share part of your time here in Durham, and at this particular workshop. There is much to learn. This is a field which will benefit, we hope, from the sharing that will come out of this Symposium. We look forward to an exciting three and a half days.

I would like to turn the meeting over to Dick Blidberg who has really been the central leadership behind this Symposium. Dick and his associates in the Marine Systems Engineering Laboratory have worked hard to organize this Symposium. I went abroad for six weeks prior to this meeting, returning home only yesterday. Consequently, you can imagine how little I have done in bringing together the Symposium. I would like to introduce Dick Blidberg, who is the Associate Director of the Marine Systems Engineering Laboratory, and the backbone behind this Symposium.

THIRD UUST SYMPOSIUM

EPAULARD OPERATIONAL UTILISATION DEVELOPMENT OF THE UNMANNED UNTETHERED SUBMERSIBLE SYSTEMS

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(CNEXO) (CNEXO) (GENAVIR)
(CNEXO-GENAVIR : 83500 LA SEYNE SUR MER - FRANCE)

ABSTRACT.

The 6 000 m depth EPAULARD now hade over 100 dives surveying 800 kilometers on the bottom gathering bathymetry and 200 000 sea bottom photographies.

The system has been operated from five different ships ans used from the Mediterranean Sea to the Pacific Ocean.

Further studies of the development of the concept include :

- a preliminary choice in the tasks beetween what we call linear and stationary missions ;

- a development of basic key technologies (acoustic communication, guidance).

I - EPAULARD.

1.1. Problems encountered with the EPAULARD.

Along this operational experience, some problems has been solved as :

In acoustic :

- the electronic noise has been overcome by extensive care in the preamplifier, and preventing interference with all the switching relays ;

- the acoustic interference beetween codes has been avoided using different frequencies and ajusting more largely the tolerance of the pulse position and duration.

In electronic :

Oil compensated relays, some connectors, moldeld solenoid has required adjustements or to be redesigned.

The consequence of the capacity lost of the lead acid battery in low temperature is a dive duration of 6 hours at 2 knots on a flat bottom.

1.2. Operational evaluation of the EPAULARD.

We had gone thru intensive continous operational evaluation of the capabilities of the system in different environment.

1. On the relatively flat bottom of the nodules area in the Pacific Ocean at 5 400 metersdepth we succeded guiding the EPAULARD on a sweeping survey decided before the dive making paths 2 km long with 250 meters beetween each one, using a long baseline.

2. In the Mediterranean Sea we showed the faisability of crossing a pre-determined point within a few meter.

3. Always in Mediterranean Sea the EPAULARD has been used successfully following the 1 000 meters depth line around an old volcano in spite of the relief difficulties.

1.3. EPAULARD improvements.

In spite of those unexpected results in rough area the EPAULARD remains not able to cross ascending steps more than one meter, and avoiding them need for the pilot high attention and initiative while requiring a relatively good knowledge of the surrounding bathymetry.

The first improvement decided for the EPAULARD is to make her able to cross ascending reliefs by introducing a vertical propeller at first acoustically commanded.

This propeller will be optional on the fish and return to the usual configuration will remain possible.

The front part of the EPAULARD will thus be modular with the possibility to put a nose package for either the vertical propeller or other needed instrumentation (image transmission or other sensors).

Of course those options will react upon speed of the vehicle which we will try to keep similar to now.

II - CONCEPT DEVELOPMENTS.

We started in 81 a faisability study on a second generation unmanned free swimming vehicle without guide rope and it has appeared as an architectural needing to make a preferential choice in the mission requirements between the survey type work and the local work.

Further developments will thus be opened in two ways :

- 1. the linear missions (including fine sweeping) as the EPAULARD do, where this concept has his bigger competitivity potential ;

- 2. the stationary missions as the conventional ROV do, where competitivity is more difficult.

2.1. Linear mission : "SUPER EPAULARD" studies.

2.1.1. Operational specifications.

The mission is geomorphological survey.

First specifications were :

- side-scan sonar survey - range ± 500 m - resolution = 1 m
- TV inspection of local areas.

Studies of system design and operational reflexions showed us the need of choice between these two submissions. The first one has priority, and we admitted that "SUPER EPAULARD" carried out a degraded TV inspection mission : observation "on the wing" and not stationary.

2.1.2. General description of system.

We carried out the studies with two french societies :

- ECA for the general design
- SAFARE CROUZET for the acoustical studies.

We have proved feasability of a untethered vehicle for linear mission of geomorphological survey.

General specifications are :

Autonomy : 50 km of travel survey during 14 hours ;

Surface covered during one dive : 50 km² with a side-scan sonar of ± 500 m of total range ;

Operational cycle : one dive/24 hours ;

Speed : 2 knots ;

Altitude : 20 - 50 m during side-scan survey ;

Recording inside the fish of all informations (sonar, bathymetry, positions,...) for post dive treatment ;

Real time transmission of sonar (with small loss of quality or resolution) in order to control the fonctions of the vehicle and to determine interest of the surveyed area ;

Weight : according to technology (lead acide or silver Zinc battery ; carbon fiber or titanium or light alloy pressure resistant container) ;

. for 6 000 m depth : 3 000 to 5 000 kg
. for 1000m depth : 2 500 to 4 000 kg

Guidance : automatic guidance of the vehicle along a pre-determined path or along an ordered by teletransmission path, using a long base line positionning system with direct position computation inside the fish. Precision of guidance during survey : about 10 m ;

Security : automatic guidance procesure in case of :

. beginning and end of mission (wait, initialization,..)

. obstacle avoidance

. loss of transmission

. leak

.....

Altitude/depth control : the choice between propellers or flaps depends on :

. speed and possible variation

. stiffness of control

. description of operational missions

. waiting procedures

. general design of fish

2.1.3. Acoustic links and equipments.

2.1.3.1. Needs.

- high rate transmission for side scan-sonar or TV (not in same time) ;

- very reliable data transmission from surface to the vehicle for control, and from vehicle to surface for telemetry (low rate) ;

- positionning system :
  - . long baseline
  - . or ultra short baseline + gyro-doppler
- side-scan sonar
- vertical echo-sounder
- obstacle detection system.

2.1.3.2. High rate transmission.

We have several solutions :

1) Medium range.

THOMSON CSF SYSTEM.

Range ≃ about 1 000 m (depends on noise)

Frequency = 60 Khz

Bandwith = 20 Khz

Data rate = 20 000 bit/s - PSK4

1 picture 150x200x4 bits of grey/6seconds

2) Long range.

SYSTEM DEVELOPPED AND TRIED BY CNEXO.

Theorical range > 6 000 m

Frequency = about 9 Khz (underwater telephone)

Bandwith : about 2 500 Hz

Analogical frequency modulation

Data rate : 1 picture about
256 x 256 x 6 bits of grey/32 seconds.

Operationnal results : picture transmitted without defects from 2 400 m depth with CYANA submersible. One system willbe installed on board our futur 6 000 m manned submersible.

SYSTEMS IN DEVELOPMENT BY CNEXO.

Frequency : about 26 Khz

Bandwith : about 5 Khz

Data rate : 2 400 - 4 800 bits/s - FSK or PSK

Picture compression :
256 x 256 x 6 ⟶ 256 x 256 x 2 or 3

2.1.3.3. Control and telemetry link.

We have several solutions, depending on operationnal thoughts and frequency compatibility problems.

1) Low frequency link : 4 Khz - data rate < 100 bits/s

2) High frequency link : (DT 122 from OCEANO INSTRUMENT) - 20-24Khz - data rate : 80 to 300 bits/s.

2.1.3.4. Acoustical compatibility problems.

The quantity of acoustical equipments on board the fish, with great level of emissions (pulse or continous) and high sensibility of receptions, set a great problem of compatibility.

Our studies showed us the need and feasability of

- frequency repartition (doppler, positionning system, sounders, teletransmission links)

- time multiplex :
  . positionning - teletransmissions
  . doppler - side-scan sonar - sounders.

2.1.4. Operational studies.

We carried out an operational study with the french society AERO, in order to determine the best system for deep geomorphologic survey in terms of operation.

The study has proved the great interest of the untethered vehicle concept for the systematic survey of an area :

- rate of surface coverage is better than with a tethered fish, in spite of short autonomy of an untethered vehicle : for 4 000 m depth survey with parallel tracks of 20 Km, this rate is 1,5 to 2 higher ;

- untethered system is obligatory for constitution of mosaïcs with a ⩽ 500 m total range sensor ;

- global cost of operation is smaller owing to use of a smaller banalized vessel support (in comparison with a support equiped for deep towing).

2.2. Stationary missions.

This concept is very different of the linear one.

Our studies are focused on a local observation system, with or without guide rope.

Greatest problem is guidance in order to maintain a stable station for observation, in spite of perturbations (essentially variations of current), and to drive the vehicle to his wished stable station position.

Several means of guidance could partially solve this problem :

- transmitted TV picture : problems of resolution, quality, frame rate and delay ;

- transmitted sonar : problems of quality, rate and delay. Usable only for approach phase ;

- internal navigation (gyro-doppler, inertial systems) : problems of drift ;

- external positioning system (long baseline, short baseline) : problems of rate of information knowledge, loss of transmission, précision. This solution is certainly the best one, but involve operational contraints.

This guidance need certainly a redondancy of systems. Intelligency can be differently distributed between fish (artificial intelligency) and surface (man intelligency).

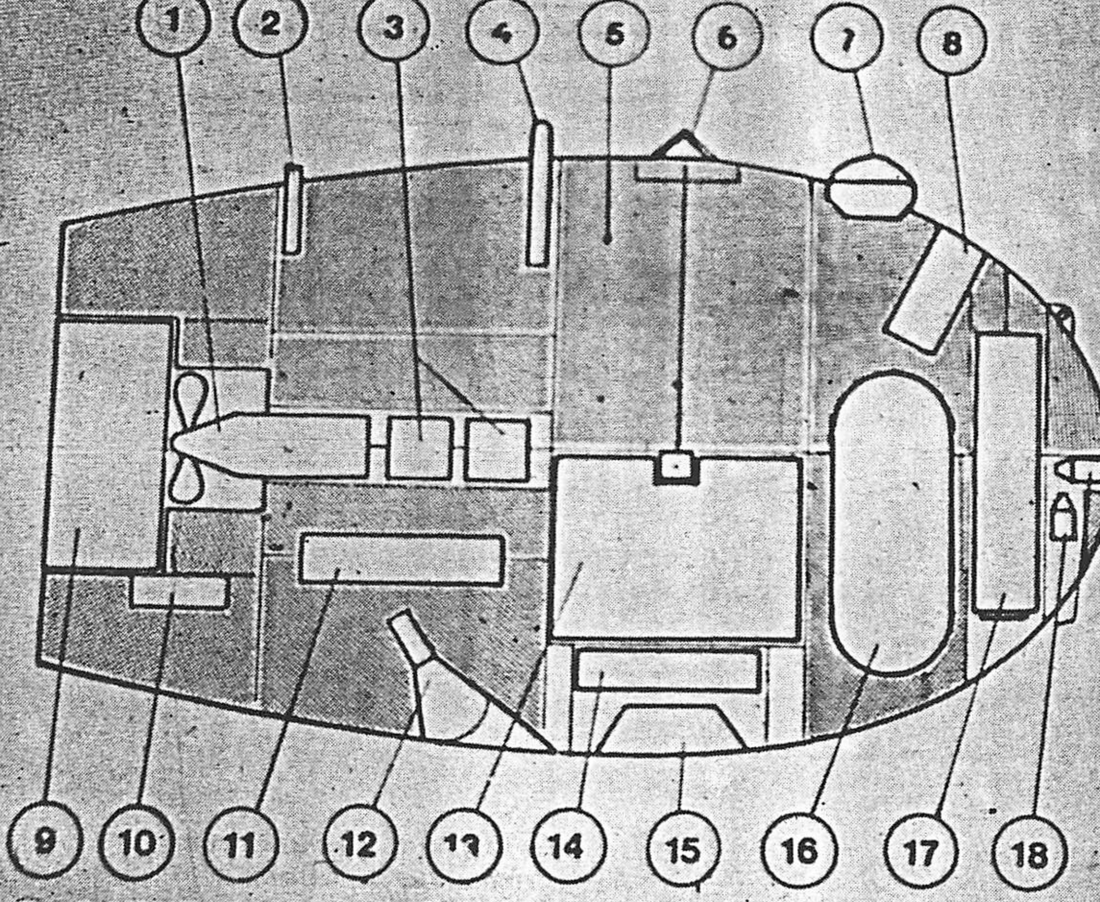
CNEXO now is searching industrial applications of this untethered concept.

III - CONCLUSION.

CNEXO has obtained some operational results with EPAULARD, and has carried out some studies about the unmanned untethered submersible concept.

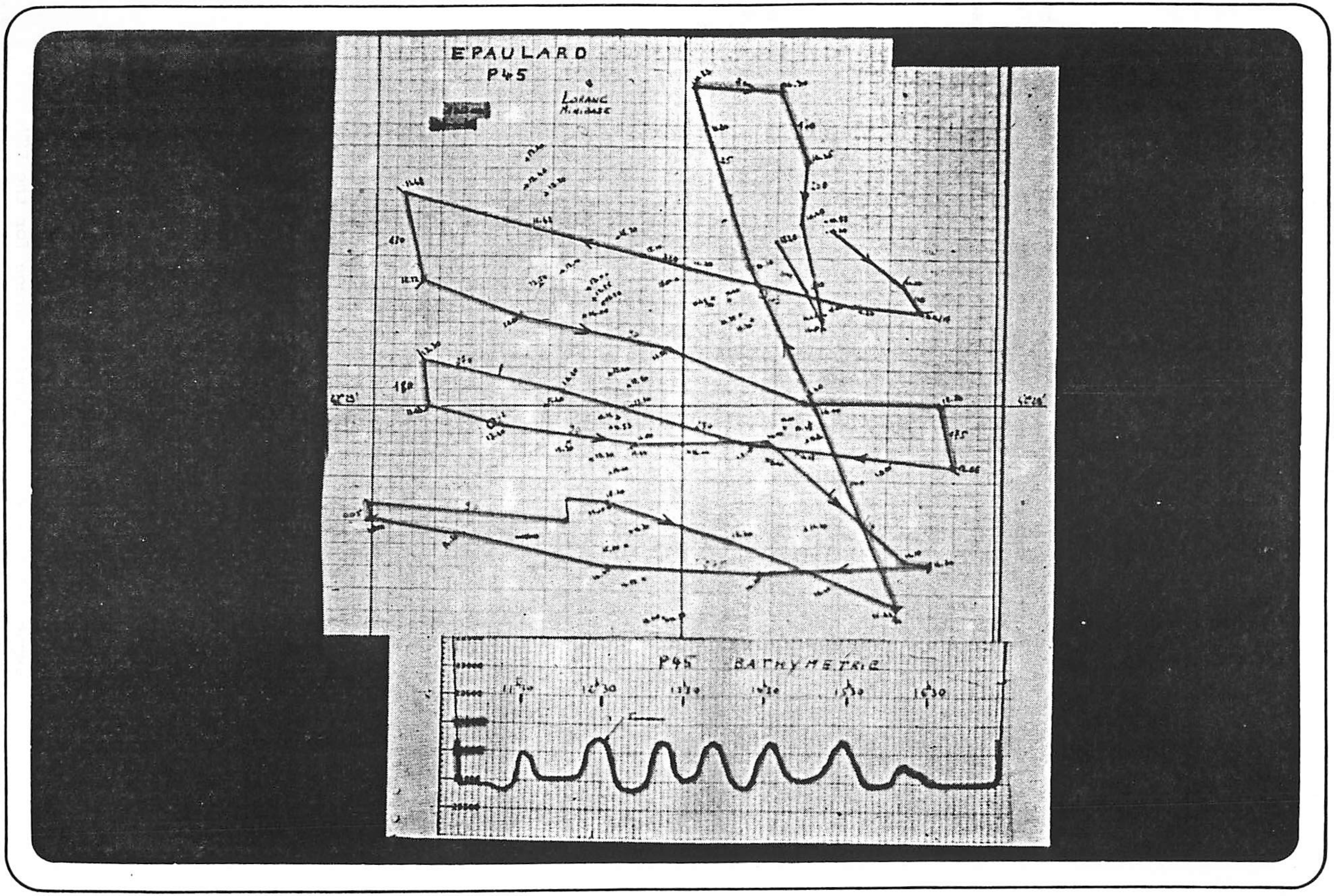
That is why we are convinced that there are other applications of this concept.

But, for these new applications, we need technological progresses, feasability studies and trials.



1	Thruster
2	Pinger
3	Thruster and junction boxes pressure balance
4	Flasher and surface emitter
5	Syntactic foam floats
6	Lifting hook,
7	Acoustic transducer
8	Surface recovery buoy
9	Vertical rudder
10	Rudder actuator
11	Flash electronics
12	Flash probe
13	Battery
14	Junction boxes
15	Rising weight
16	Electronic unit
17	Camera and recorder compartment
18	Vertical echo sounder and obstacle avoidance sonar

Fig. 1 - Description of the submersible


EPAULARD
P45
LORANC
MINIBASE
P45 BATHYMETRIE
11h30
12h30
13h30
14h30
15h30
16h30

A Review of the Free Swimming Submersible research programme 1981/83

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U.K.

Over the last two years the submersible research programme at Heriot-Watt University has gone through the transitory phase from the tethered vehicle, to the system concepts for a free swimming vehicle (FSV). The fundamental problems associated with the free swimming vehicle that have been addressed throughout this phase are:

(i) Guidance and control.

(ii) Information and communication.

The complex interaction between these fundamental objectives is defined by the range and scope of the mission specification. Since it is recognised that a single FSV will not satisfy the requirements for every conceivable mission, a number of overlapping projects have been pursued that attempt to give a general understanding of the basic sub-systems essential to FSV design and operation. The project topics are as follows:

(i) A simulation study to investigate the automatic guidance of an FSV using a forward looking sonar for target identification or obstacle avoidance.

(ii) Three dimensional colour display of sub-sea scene for FSV motion simulation and man/machine interface.

(iii) High data-rate through-water acoustic communication link with adaptive cancellation of multi-path interference.

(iv) Characterisation of short range through-water acoustic path for a number of carrier frequencies.

(v) Slow scan T.V. system utilising the properties of the CCD chip to implement the frame store.

(vi) A general purpose image processing system with real-time colour picture capture and a suite of software modules for bandwidth reduction, restoration, enhancement, edge detection and segmentation.

(vii) Computer vision using a stereo pair of low-light SIT, T.V. cameras and an industrial sub-sea robotic arm.

(viii) Trials and commissioning of the tethered submersible ANGUS 003 to form the tracking garage for the FSV.

This period of the research programme has seen a significant advance in the understanding of some of the fundamental problems related to the autonomous operation of free swimming vehicles that are capable of undertaking tasks associated with the inspection and maintenance of sub-sea equipment. There remains, however, many unknown factors regarding the reliability and efficiency of operating autonomous vehicles, and indeed many alternative approaches to the problem. The research has identified some solutions, provided training for seven young researchers (plus a host of students) and, not surprisingly, raised further problems. This review will briefly discuss each of the project topics to share the experience gained and illustrate some of the new results.

1. THE AUTOMATIC GUIDANCE AND CONTROL OF UNMANNED SUBMERSIBLES

The inspection and maintenance of the huge structures associated with the offshore oil industry present an extremely hazardous and tiresome task. This has led to the development of many unmanned, tethered submersibles designed to carry video and sonar equipment, tools, manipulators and test equipment to aid, or, in some cases replace, the diver in this hostile environment. The search for new oil fields in deeper water and the danger of entanglement of the umbilical cable, has created the need for an untethered or free swimming vehicle possessing robotic skills.

For a submersible system to perform its inspection and maintenance task efficiently it must reflect, to some extent, the human knowledge hierarchy relating the understanding of a sequence of events based upon information collected from the five basic senses. Either the total information collected by the submersible transducers is displayed to the operator for assimilation, or appropriate tasks are performed automatically, by introducing intelligence into the system to reduce the operator load.

If a simple knowledge hierarchy is assumed as follows, then a submersible system structure can be deduced,

Understanding

Intelligence Memory

Vision Hearing Touch Taste Smell

The specific instrumentation and objectives associated with the five basic senses can be itemised for particular missions, so that the submersible vehicle payload can be defined. For example,

Vision;	T.V. camera, low light, colour, CCD, 35 mm or still camera, Appropriate lighting, Used for short range inspection.
Hearing;	Scanning sonar, Acoustic position location, Non-destructive testing, Through water communication link, Used for inspection and surveillance.
Touch;	Temperature, pressure, Manipulator and tools, Instrumentation and remote working mission.
Taste and Smell; (a little more abstract!)	Sand/rock sampling, Pollution, Radioactivity monitor.

In this engineering system, "intelligence" is interpreted as an algorithmic component in the mission control strategy. The implementation being in the form of picture processing, enhancement, edge detection, motion scene analysis, etc., for the vision and sonar inputs. Then for the instrumentation and acoustic positional inputs automatic search, guidance, tracking and target location algorithms are required.

The Memory element is obviously an integral part of the system, not only providing the storage for the operational programs but also providing a data-log facility for the digitised information and perhaps a video record of a particular mission.

The major part of the Understanding element of the structure must reside with the operator, although a few basic decisions, such as "search pattern accomplished", "object detected" etc. can be programmed.

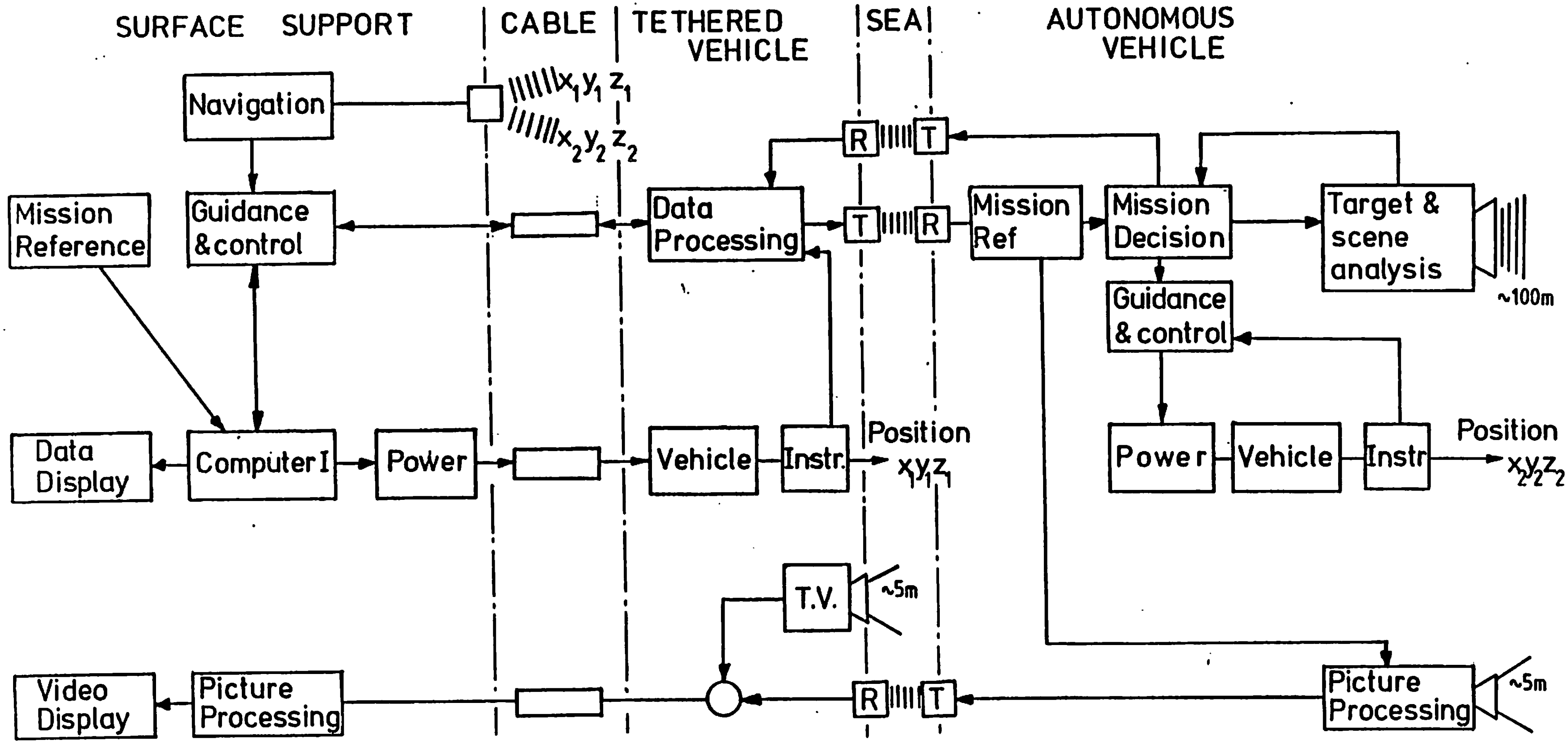
1.1 An Autonomous Under-Sea Vehicle System

The autonomous undersea vehicle system currently under investigation is illustrated in Fig. 1. The mission envisaged is that of conveying a free swimming vehicle (F.S.V.) to a position that is within, say 50-100 m, of the proposed work task, using a tethered submersible as the support vehicle. This minimises the energy required by the F.S.V. to find the work location, as well as minimising the length of the throughwater acoustic data communication path, for information to be transmitted back to the operator on the surface support vessel.

The basic system structure can be considered to be five major interconnected sub-systems, namely, the surface support, the cable, the tethered vehicle, the through-water communication link and the autonomous vehicle. The minor sub-systems such as target and scene analysis, guidance and control, comprise a mixture of hardware and software modules and are interconnected as shown in Fig. 1.

The computer control system can be outlined by considering the major sub-systems in turn. The surface support consists of a diesel generator set, a number of thyristor invertor units to provide the tethered vehicle propulsion, and a launch/retrieval capability for the vehicle and cable. The control computer is a D.E.C. LSI 11/02 supporting graphic and alphanumeric display, operator interface either through the VDU keyboard or a joystick controller. This computer has 28 K words of RAM, a floating point micro code ROM, a dual floppy disc for program or data storage, 16 inputs and 4 outputs for analogue signals. Programs are prepared on a PDP 11/45 computer in a high level language and down-line loaded onto the LSI 11/02 via a serial link using a specially prepared LINK program. The LSI 11/02 runs the user generated software under the control of a low overhead, core resident real-time operating system. This has a multi-task structure, each task representing a separate program with a static software priority assigned when a complete LSI 11/02 load module is BUILT. The real-time tasks can be programmed in the high level language 'C' where intertask communication can be achieved by declaring global variables. The kernel of the real-time executive decides upon the task priority, operating with eight tasks under a three level hierarchy. The communication LINK program between the navigation system and the data processing computer on the tethered vehicle, resides in the kernel. Main software tasks are structured to give heading and depth control, automatic positional guidance, data-logging and operator interface. Also included in this task structure is a six-degree-of-freedom mathematical model of the submersible with a 3-D graphic display for controller design or manoeuvrability simulation.

Positional measurements of range and bearing are generated by the short base line acoustic navigation system (based upon a Zilog Z80A CPU). This data is fed into the guidance and control task that employs an adaptive estimator to achieve the automatic guidance of the submersible.



□ HERIOT-WATT UNIVERSITY

Autonomous Undersea Vehicle System

Fig 1

The autonomous vehicle functions and through-water communication path are the most complex sub-systems and are currently being investigated. Target and scene analysis using scanning sonar is being considered as a means of generating input data for the guidance of the vehicle as shown in Fig. 2. Video picture processing employing slow scan T.V. techniques are to be used to convey a picture through the sea to the tethered vehicle and hence back to the operator. A wide range of picture processing algorithms have been establihsed on a PDP-11/44 computer and an acoustic link using FSK modulation with a 600 kHz carrier frequency has been demonstrated.

1.2 Modelling, Simulation and Control of Submersible Systems

The design of an accurate, reliable and repeatable automatic controller for the position and attitude of an unmanned submersible requires the formulation of a mathematical model of the vehicle hydro-dynamic characteristics. The accuracy and validity required for the particular model depends upon the application envisaged for the model. If it is to be used to give precise definition of vehicle motion for a given power applied to the thruster configuration, then the derivation of the model is extremely difficult and complex. At the other extreme, a very crude model which estimates the major parameters such as mass, added mass and drag would be sufficient to specify demanded thruster power to stem a particular current. A good engineering compromise is to identify the major hydrodynamic characteristics that play a significant role in defining the vehicle motion, using a blend of analysis, experimental investigation and computer simulation. This provides a primitive model that is valid within the bounds of experimental observation. At this stage the closed loop controllers and instrumentation can be designed such that vehicle motion is insensitive to changes in parameters, as the payload is changed, for example, or to the effect of external disturbances and measurement noise. This, being the objective of automatic control, relieves the pilot from the concentrative effort of maintaining position under working conditions.

Since vehicles normally operate in a near neutrally buoyant condition, hydrodynamic forces can have a marked influence upon its motion and hence the control system characteristics. Four different types of force and moment are involved,

(i) Hydrostatic forces; buoyancy.

(ii) Steady-state forces; lift and drag under constant velocity.

(iii) Non-steady state forces; mass of entrained water and a surrounding volume of water must be set in motion during acceleration.

(iv) Propulsion forces; interaction of water flow with the body and other thrusters.

Each type of force can be shown to be significant in different operational situations. The vehicle depends upon a large buoyancy moment for inherent static stability, and steady state forces predominate when the vehicle is either moving forward at speed or when it is stemming a moderate

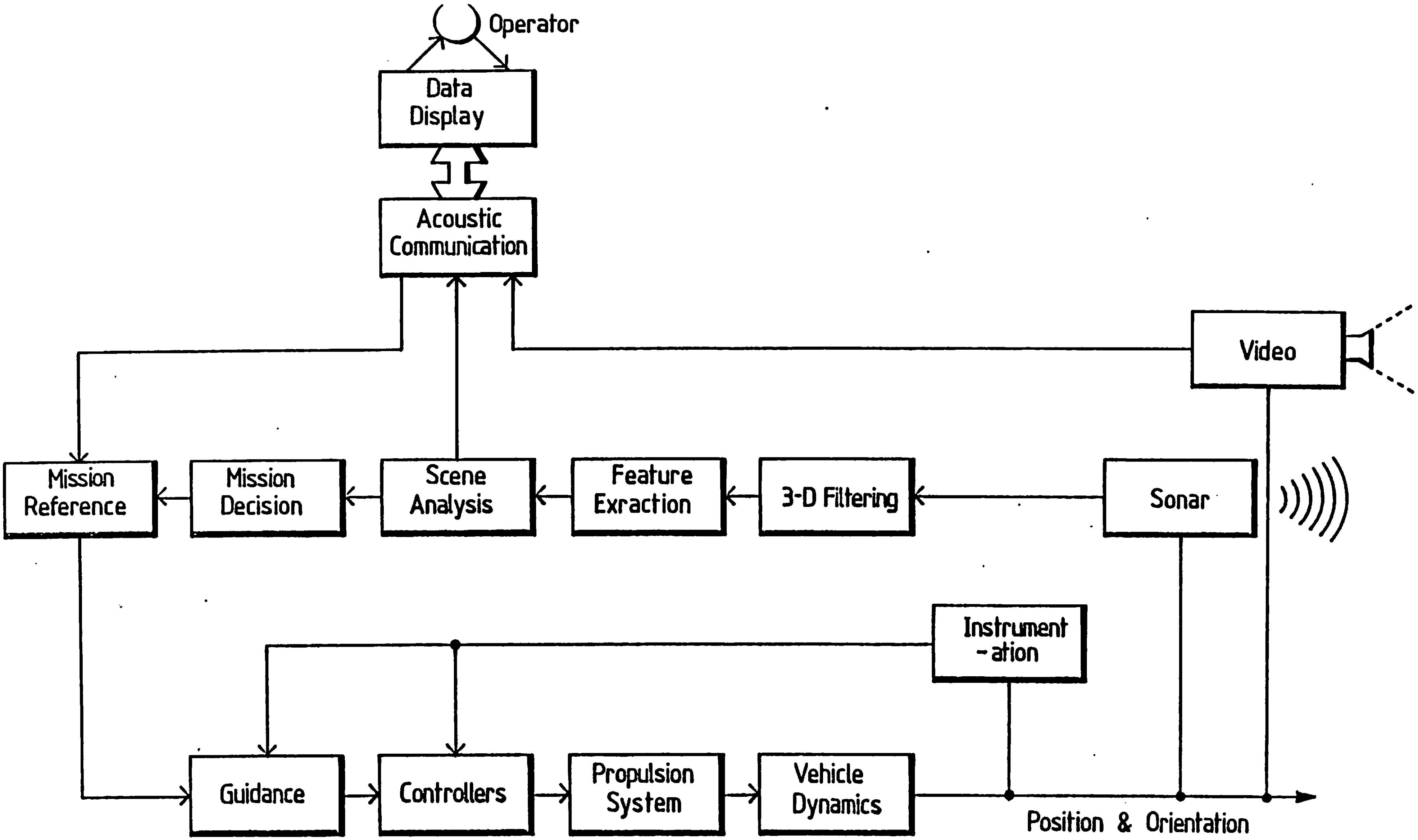

Operator
Data Display
Acoustic Communication
Video
Mission Reference
Mission Decision
Scene Analysis
Feature Exraction
3-D Filtering
Sonar
Instrument -ation
Guidance
Controllers
Propulsion System
Vehicle Dynamics
Position & Orientation

Fig. 2.

current. For a body which is not streamlined the steady-state forces on the vehicle will be comparable with the drag on the cable, but non-steady forces may be expected to play a dominant role, when the vehicle is hovering or manoeuvring around fixed objects. The available propulsion forces set limits to the performance of the vehicle in many instances.

The full six-degree-of-freedom equations of motion of a slow-moving, submerged body are complex. Even for a simple symmetric streamlined shape such as a missile or a submarine, simulation equations with about 20 terms are commonly used for each degree of freedom and a number of terms lead to cross-coupling between the different degrees of freedom. The submersible configuration is neither simple nor streamlined, and, in addition, a number of thrusters are installed in close proximity to give it the required manoeuvrability. Consequently, many cross-coupling interactions can be conceived which could markedly influence the control characteristic. Consideration of Fig. 3, which shows typical stream flow for a vehicle turning in a prevailing current gives an indication of the expected wide variation in forces that can be experienced by a submersible in motion.

The general structure of the equations of motion can be derived from the basic force and moment relationships for a body moving with six-degrees-of-freedom, that is,

$$m\dot{v} = F(u,v,w,r,p,q) - m\omega \times v$$

$$I\dot{\omega} = M(u,v,w,r,p,q) - \omega \times I\omega$$

where

$$v = u\underline{i} + v\underline{j} + w\underline{k}$$

$$\omega = p\underline{i} + q\underline{j} + r\underline{k}$$

are in terms of body axis parameters.

To identify coefficients within these equations that will adequately represent the typical bluff shape of an open frame vehicle configuration is however, extremely difficult. There is no clearly defined analytical calculation to estimate the non-linear hydrodynamic forces or cross-coupling interactions associated with the typical vehicle. The major masses, inertias and hydrodynamic characteristics have been derived experimentally for the ANGUS 002 vehicle, using a planar motion mechanism.

The equations can be expanded into the form,

$$F_x = m(\dot{u} + wq - vr)$$

$$F_y = m(\dot{v} + ur - wp)$$

$$F_z = m(\dot{w} + vp - uq)$$

$$M_x = I_x\dot{p} + I_{xz}(\dot{r} + pq) + (I_z - I_y)qr$$

$$M_y = I_y\dot{q} + (I_x - I_z)pr + I_{xz}(r^2 - p^2)$$

$$M_z = I_{xz}(\dot{p} - qr) + I_z\dot{r} + (I_y - I_x)pq$$

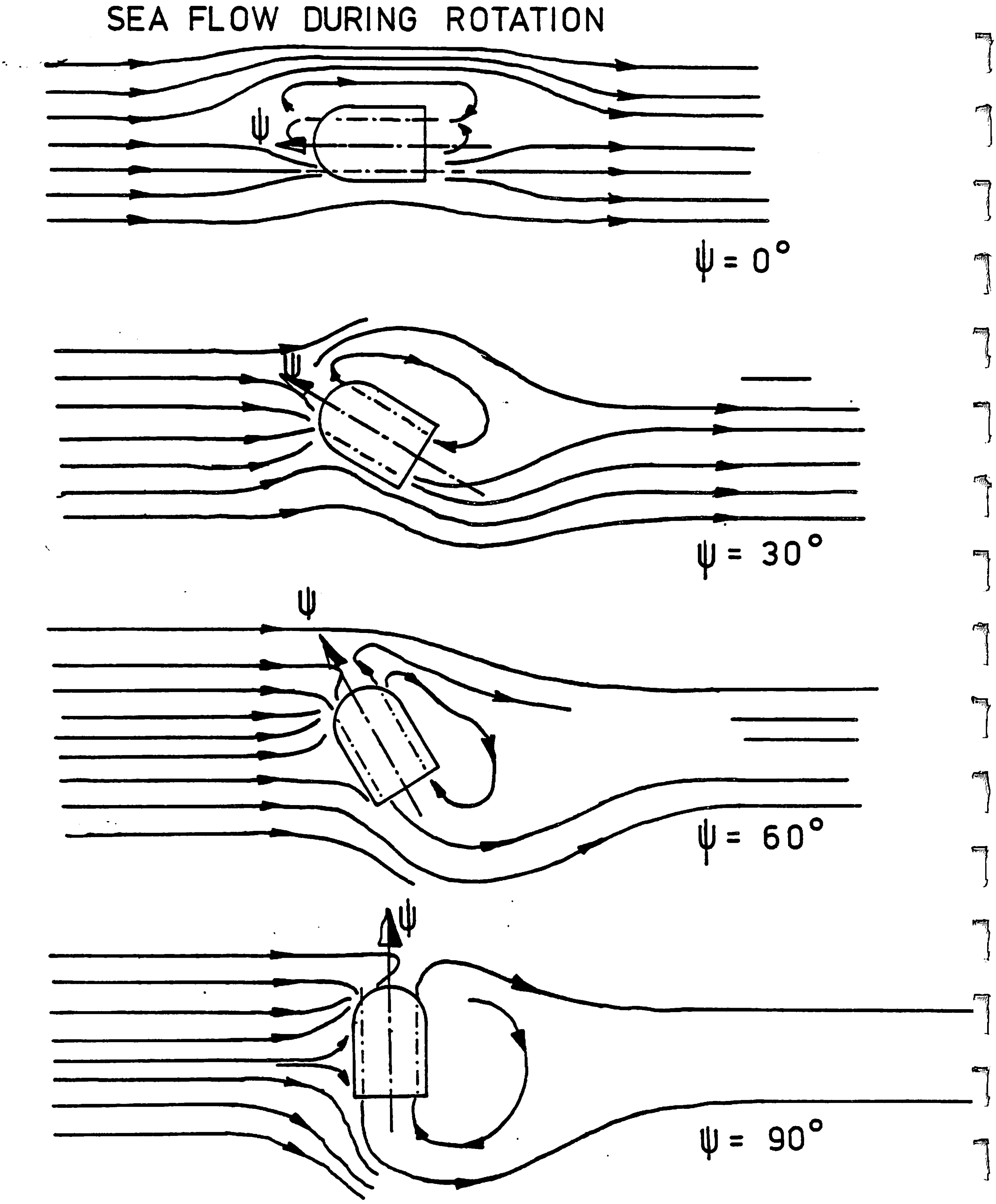


Fig 3

Because the vehicle body axis variables are moving within a fixed coordinate system it is necessary to define the Euler angles ψ, θ and ϕ, such that

$$\dot{\psi} = (q.\sin\phi + r.\cos\phi)/\cos\theta$$

$$\dot{\theta} = q.\cos\phi - r.\sin\phi$$

$$\dot{\phi} = p + (q.\sin\theta + r.\cos\phi)\tan\theta$$

Then if X, Y and Z are the coordinates of the centre of mass of the submersible, in the fixed coordinate system,

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} (\cos\psi.\cos\theta) & (-\sin\psi.\cos\phi + \cos\psi.\sin\theta.\sin\phi) & (\sin\psi.\sin\phi + \cos\psi.\sin\theta.\cos\phi) \\ (-\sin\psi.\cos\theta) & (-\cos\psi.\cos\phi - \sin\psi.\sin\theta.\sin\phi) & (\cos\psi.\sin\phi - \sin\psi.\sin\theta.\cos\phi) \\ \sin\theta & (-\cos\theta.\sin\phi) & (-\cos\theta.\cos\phi) \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

The force and moment vectors can be modelled by the expressions,

$$F = \sum_{n=0}^{5} F_{xn}\underline{i} + \sum_{n=0}^{5} F_{yn}\underline{j} + \sum_{n=0}^{5} F_{zn}\underline{k}$$

and

$$M = \sum_{n=0}^{5} M_{xn}\underline{i} + \sum_{n=0}^{5} M_{yn}\underline{j} + \sum_{n=0}^{5} M_{zn}\underline{k}$$

The above equations provide the essential elements of the primitive mathematical model of the submersible, and can be related to the block diagram shown in Fig. 4.

The motivation behind this simulation study was threefold; firstly it is required to predict the six-degree-of-freedom motion of a general submersible and design appropriate guidance and control algorithms. Then secondly, it is required to efficiently develop and implement real-time control software, and thirdly it will provide a synthetic display for man/machine interface and scene analysis experiments.

The simulation procedure has been implemented as two options, the first on a multi-user DEC PDP-11/44 minicomputer with hardcopy facility for the graphic output and secondly as a real-time process on a DEC LSI-11/23 microcomputer with a graphics terminal. The same high level language is used for both simulations, with program development being carried out on the PDP 11/44 and run on either the host computer or loaded into the LSI-11/23 via a specially designed LINK program. To enhance the interpretation of the simulation results and to provide a pilot display from measured data, a three dimensional perspective representation has been derived to show the vehicle attitude along its trajectory.

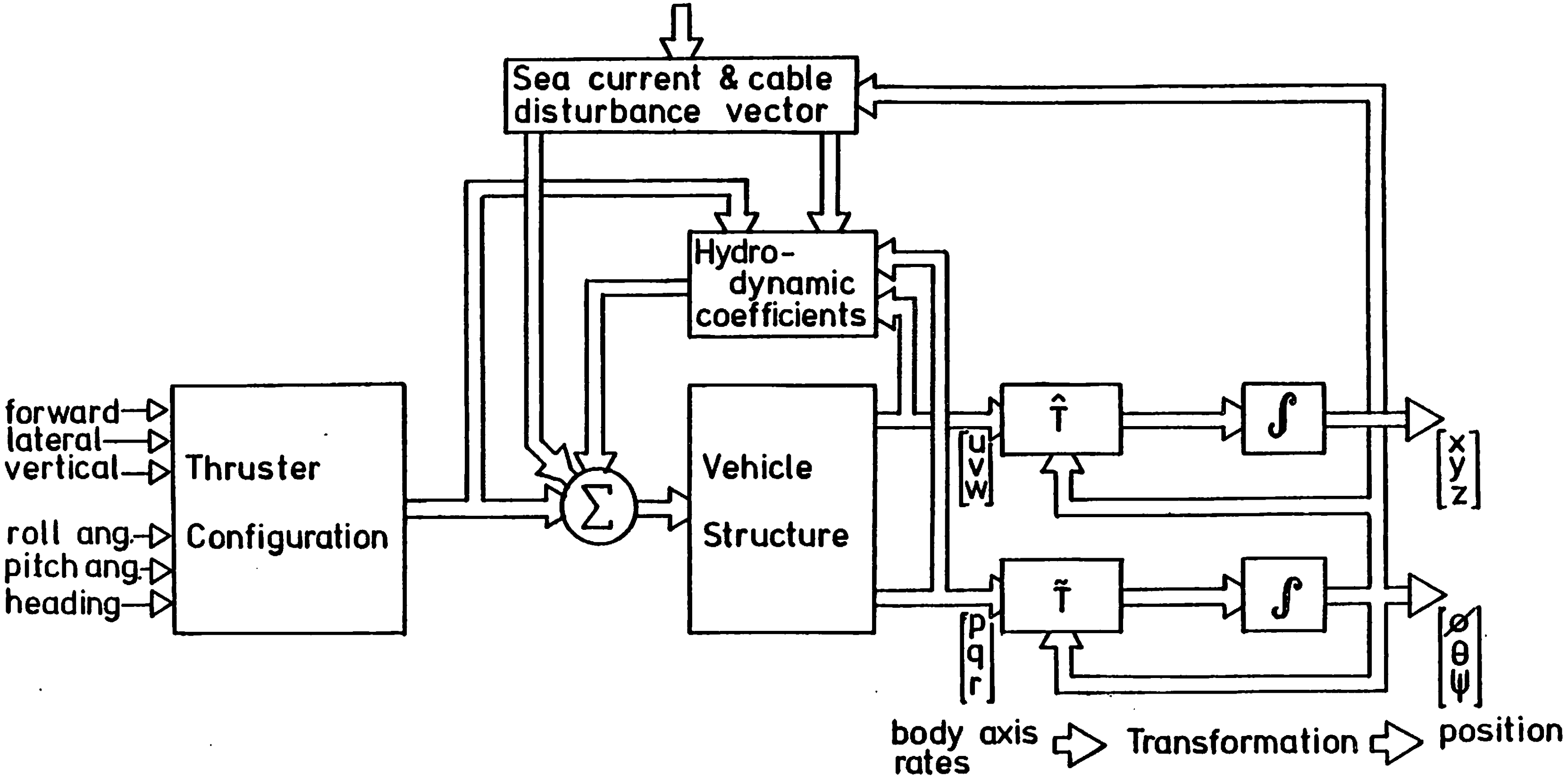


Fig 4 THRUSTER-DISTURBANCE-VEHICLE MOTION INTERACTION

The objectives defined for the simulation procedure can be summarised as follows:

(i) To investigate the manoeuvrability and motion of unmanned submersibles and establish a valid mathematical model.

(ii) To aid the design of automatic guidance and control strategies, with evaluation of the system performance under realistic instrumentation and sea-state disturbances.

(iii) To aid the development of efficient real-time multi-task software for the submersible system.

(iv) To validate the primitive mathematical model with sea trial experiments.

(v) To provide a pilot display under operational conditions as shown in Fig. 5 and a training facility prior to vehicle launch.

There are many alternative control strategies for a vehicle system of this nature, the type and precision of control depending ultimately upon the prescribed mission. It is important then to have a procedure that would enable competing strategies to be easily assessed. It was decided at an early stage in this research project to simulate the vehicle dynamic equations and control structure, and provide interactive software for the control implementation. The instrumentation sub-system must also be considered in the light of the required accuracy, duration and complexity of the operation and the available cost.

For the particular applications envisaged for the vehicle a search and tracking mission was identified and this, coupled with the aim to build a low cost operational system lead to a hierarchical control structure. Obviously, manual control of the thruster demand is the basic level 0, then with minimum instrumentation on the vehicle the heading and height/depth can be measured. This forms the level 1 computer control, in which heading and height can be specified from the computer keyboard and trimmed by the pilot using the joystick on the control console. The level 2 loop, coordinates the geographical range and bearing measurements from the navigation system and estimates the position vector. Because of the limited thrust vector, the position has to be maintained by controlling the forward thrust and rotation in the X-Y plane, and the vertical thrust in the Z-X plane. The man/machine interaction is contained in the level 3 loop, giving the pilot a dynamic status display and a three dimensional graphic display. This shows the actual vehicle position (or simulated position) with a record of the past trajectory over a defined time period. Level 4 of the control structure provides a data-log facility to a floppy disc within the control micro-computer, alarm detection, and vehicle dynamic performance assessment.

The available thrust vector for the submersible contains four components, i.e. forward, lateral, vertical and rotational, and it is through these control devices that the vehicle has to be guided along a prescribed path. The vehicle dynamics are nonlinear, varying with relative velocity, direction of motion and thruster interaction. Instrumentation on the vehicle is serviced

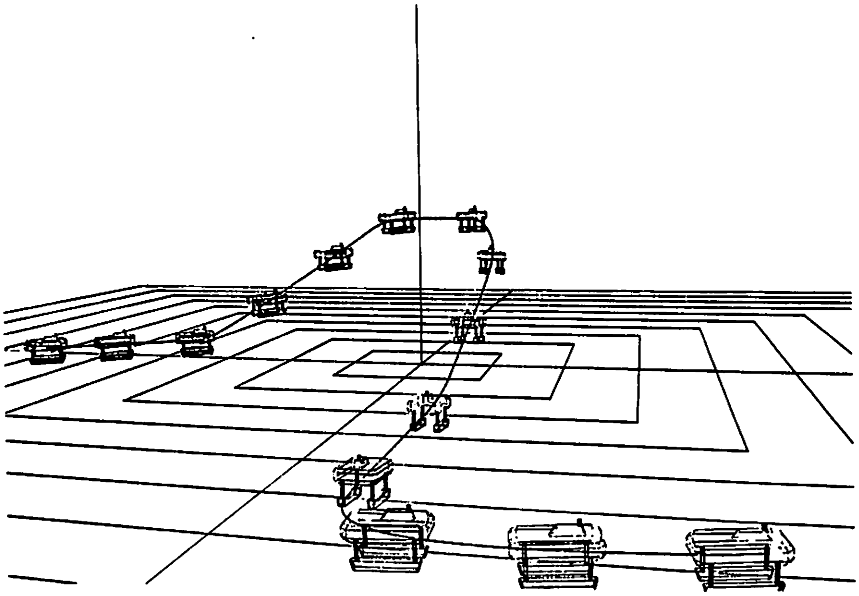


Fig 5

by a microcomputer which formats and transmits a block of data back to the control computer. Conventional sampled-data techniques have been used to obtain a well defined transient response for both heading and height/depth. This first level of feedback control around the body states of the vehicle reduces the effect of the nonlinearities so that a simple model can be adopted to produce an unbiased prediction of the forward and lateral velocities as shown in Fig. 6, i.e.

$$\Delta x_p(n - 1) = \Gamma_1 \Phi_m(n,\psi)\beta(N)$$

The estimated position has three components given by the expression

$$\hat{x}(N) = \hat{x}_p(N) + K_\sigma[x_m(N) - x_p(N)] + \overline{\hat{x}_e(N)}$$

where the first term $\hat{x}_p(N)$ is the predicted position

$$\hat{x}_p(n - 1) = \Delta x_p(n - 1) + \hat{x}(N)$$

The second term is the weighted position correction, and the third term is the bias correction.

The weighting factor K_σ is successively adapted to give the minimum tracking error $X_e(N)$ based on the stochastic properties of the filter residue (difference between the measurement and the predicted position).

$$\hat{x}_e(N) = x_m(N) - \hat{x}_p(n)$$

The prediction is computed at a constant sample rate n and the measurement is presented asynchronously at a much slower sample rate N.

The best estimate of position can be transformed into longitudinal and transverse components with respect to the reference path, giving the positional error to derive the driving vector $\beta(N)$, i.e.

$$\beta(N) = [\mathrm{Sat}\{x_R - \Gamma_2\hat{x}(N)\} - \Delta\Gamma_2\hat{x}(N)]\Phi_{LPI}(N)$$

The series controller $\Phi_{LPI}(N)$ is designed to give the minimum transverse offset with a constant longitudinal velocity, with $\Phi_C(N)$ representing the total cascade controller.

A typical trajectory is shown in Fig. 7 for a sea current running at 0.3 m/s and measurement noise of ± 1 m.

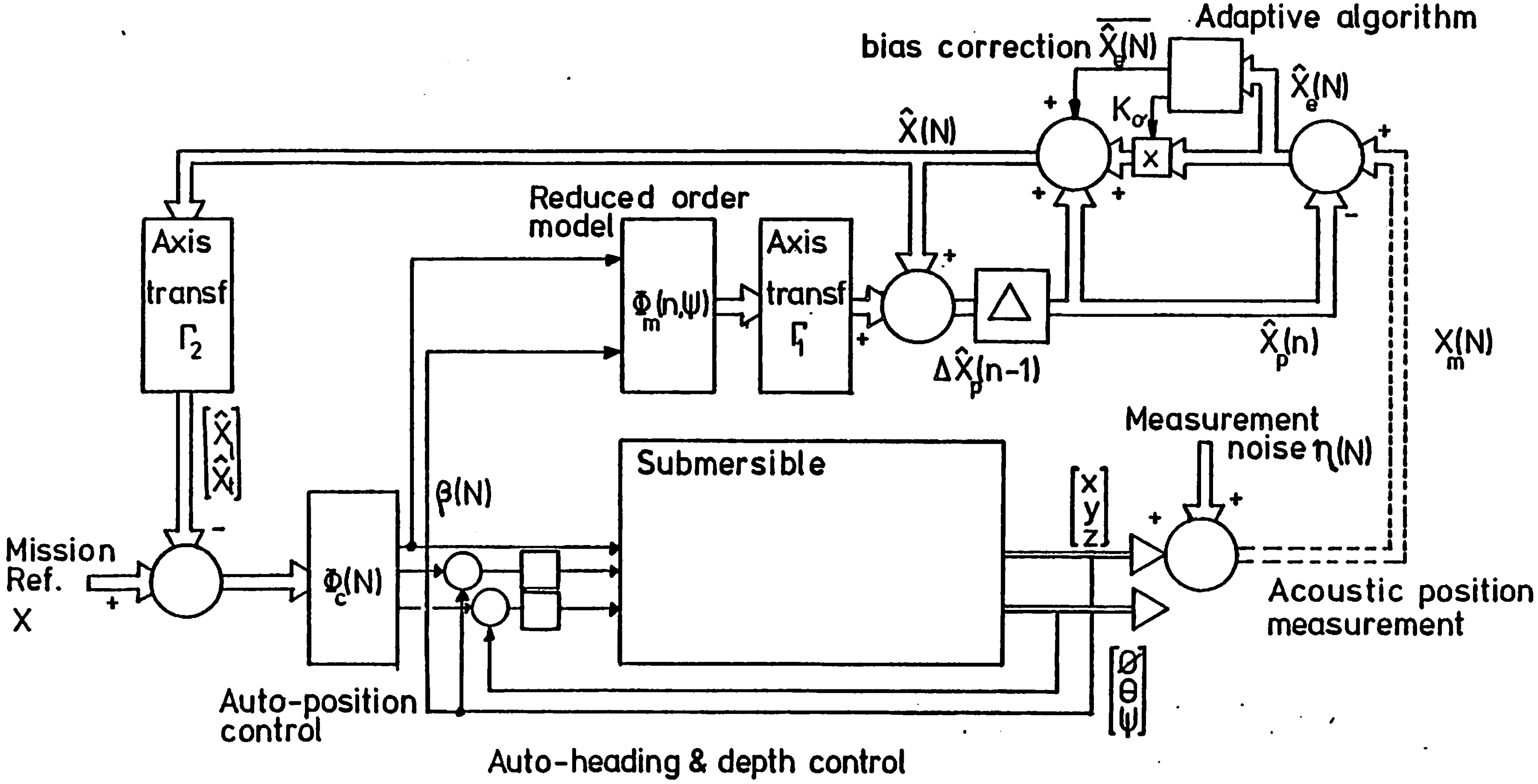

Adaptive algorithm
bias correction $\overline{\hat{X}_e(N)}$
$\hat{X}_e(N)$
K_α
x
$\hat{X}(N)$
Reduced order model
$\Phi_m(n,\psi)$
Axis transf Γ_1
Axis transf Γ_2
$\Delta\hat{X}_p(n-1)$
$\hat{X}_p(n)$
$X_m(N)$
Measurement noise $\eta(N)$
Submersible
$\beta(N)$
$\begin{bmatrix}\hat{X}\\ \hat{X}_t\end{bmatrix}$
Mission Ref. X
$\Phi_c(N)$
$\begin{bmatrix}x\\ y\\ z\end{bmatrix}$
$\begin{bmatrix}\phi\\ \theta\\ \psi\end{bmatrix}$
Acoustic position measurement
Auto-position control
Auto-heading & depth control
+
-

Fig 6

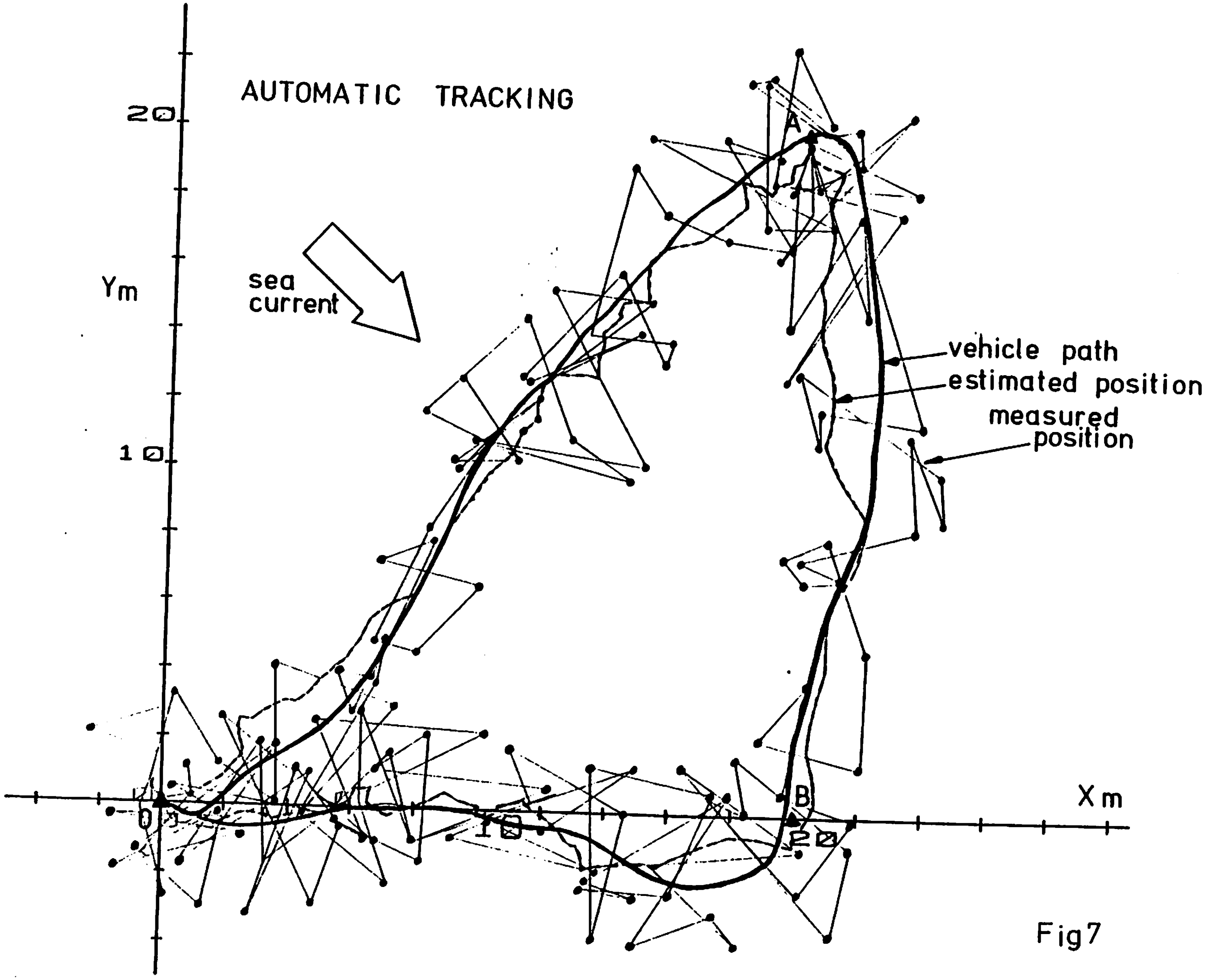

AUTOMATIC TRACKING
sea current
Ym
Xm
20
10
0
10
20
A
B
vehicle path
estimated position
measured position

Fig7

2. ACOUSTIC COMMUNICATIONS

The communication system is required to provide initially, from submersible to surface, a binary digital data link of reasonable accuracy ($Pe = 10^{-3}$) at a rate of at least 10 k bits/sec and preferably much higher. Eventually an additional two way computer data link is required, at slower data rate, but at much higher accuracy. An acoustic carrier is the only practical form of through-water communication for sea water.

The first major decision for an acoustic link is that of carrier frequency. Increasing attenuation with frequency limits the maximum frequency for the operational conditions described to about 600 kHz. A typical path loss for 100 m at 600 kHz is 55 dB, still allowing adequate Signal-to-[thermal] Noise ratio (SNR) at the receiver for only a few watts of transmitter power. It is also important to consider man-made interference at this point. The most significant source of interference will be from other sonar systems, particularly high resolution side-scan sonars which use high frequencies at very large peak powers. A secondary source will be mechanical and cavitation or turbulence noise, although this is more of a problem at lower frequencies.

2.1 Multipath Problems

In most through-water acoustic links, the biggest problem is multipath interference. A ray path study shows that an unwanted reflection differs from the wanted direct signal in three ways, (i) angle of incidence at transducer, (ii) propagation time delay, and (iii) relative attenuation. Difference (iii) tends to be small and insignificant. In any practical system the range of these parameters will be large, but an important correlation exists between them; if the angular difference is small at both transducers of the link then the time delay tends to be short, and relative attenuation is small. However, when using high data rates, even these short delays are long enough to cause the unwanted reflection to be delayed by 10's of data bits. For this reason fast acting agc systems as used on mobile radios will not solve the multipath problem.

Various observers have noted that in many cases the multipath signal is found to consist of just one strong unwanted component and some much lower level reflections which can be classed as noise. To enable one to determine how much the unwanted reflection must be reduced relative to the wanted signal one must investigate the characteristics of the receiver particularly with respect to the modulation performance.

2.2 Modulation Comparisons

The performance of binary modulation systems in the presence of Gaussian noise is well documented. The performance in the conditions of a two path channel as described is considerably different however. To make measurements of the performance, "Echotest", a general purpose communication channel, designed for many applications including use with transducers for trials work, was constructed. Binary data at a choice of 10 k bits/sec or 30 k bits/sec is produced by a pseudo random sequence generator of length 1023 bits, and modulated on the high frequency carrier.

The output of a second identical synchronised generator is compared with the demodulated received signal. If the two are different an error pulse is recorded.

Four basic different modulation types were investigated, ASK, FSK, PSK and DPSK. Results so far point to three main facts: (i) the error performance shows a very pronounced threshold effect, greater than that obtained using Gaussian noise as interference, (ii) the threshold is at 4 dB approximately instead of 12 dB for Gaussian noise, and (iii) AM and PSK performance varies widely depending on the exact delay of the unwanted signal, whereas FSK and DPSK show a much smaller variation. Overall, SNR performance has been measured to be approximately 5 dB better using FSK and DPSK for $Pe = 10^{-5}$.

Further investigation of the effect of modulation index (peak-to-peak frequency deviation divided by the bit rate) shows that the optimal result of 0.7 is very nearly optimal for the two-path channel considered here.

The final choice of modulation to be used in any link is a practical one, and since FSK is easier to implement than DPSK, FSK is the initial choice for this underwater communication link. The performance of FSK on a typical link will therefore give acceptable error rates for signal-to-noise ratios greater than the threshold which in a practical situation will be somewhere between approximately 4 dB and 12 dB depending on the amplitude of the noise, and the small reflections considered as noise. One other important characteristic noted during any practical experiment is that the received SNR changes in a random manner over a period of seconds, or faster.

This leads to the characteristic burst of errors found in underwater communication links. To be safe when designing the communication link under these conditions a general figure of 12 dB SNR plus a safety margin was aimed for. The unwanted reflections must therefore be attenuated. The most obvious way of doing this is to use directional transmit and receive transducers. This will be discussed next.

2.3 Transducers and Arrays

At 600 kHz the wavelength in water is 2.5 mm. This means that any transducer element is going to be physically small in size. The design of the transducer is a compromise between bandwidth and sensitivity, and also beamwidth and power handling. For present experiments using "Echotest" a set of cylindrical tube transducers with approximately 150 kHz bandwidth are in use.

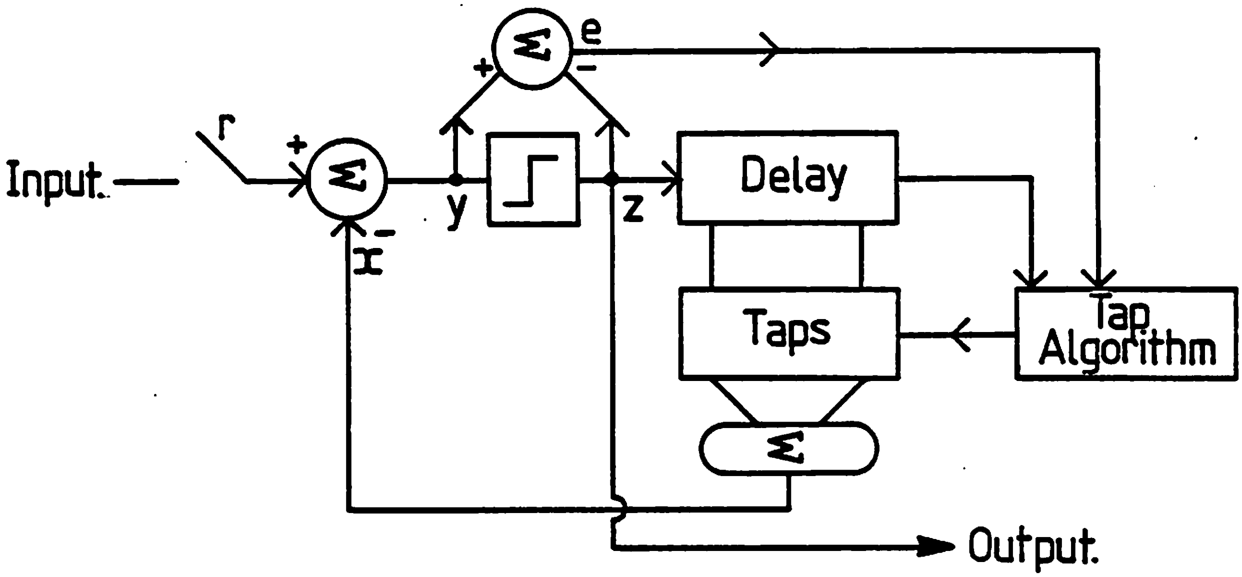
In any situation where directional transducers are used there is the problem of alignment. In a mobile situation this becomes even more severe with the very real problem of losing the desired signal completely. Directional transducer arrays using adaptive algorithms help the situation to some extent but can be costly to implement and with a carrier frequency of 600 kHz the transducer elements themselves need to be spaced closely to avoid aliasing effects. It thus becomes very difficult or costly to construct the alignment mechanism or algorithm necessary to remove multipath using very directional transducers. A relaxed beam width requirement to, say, 40° reduces the alignment problem greatly whilst still attenuating approximately 80% of the unwanted signals.

A further reduction in alignment complexity from two dimensions to one dimension can be obtained by using the ANGUS-ROVER technique of operating the free swimming submersible. This involves positioning ANGUS on the edge of the working area at the same depth as ROVER. The transducers then have only to scan in the horizontal direction. An added bonus is that both transducers are remote from the water surface thus eliminating reflection from it. Since these reflections fluctuate widely in amplitude at a rate of up to 40 Hz their removal considerably eases processing problems described later.

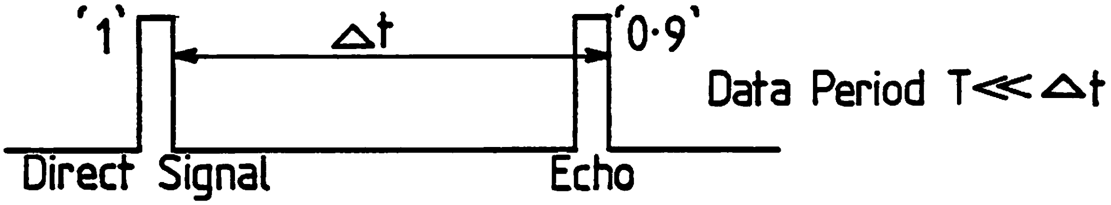
2.4 Signal Processing

There still remains some 20% of reflections for which the FSK decoder will not perform adequately. These cases mainly occur in work where one transducer is near to a reflector. Investigation is currently under way on processing the signal to make use of the time delay between multipaths. This processing is only practicable on the signals from directional transducers, due to the much smaller range of the time delay parameter. To cope with transducer motion this processing must also be adaptive. The other requirement is that the data rate should not be slowed down unacceptably by this processing. Some of the possible methods such as burst transmission or frequency swept carrier systems, do inherently result in very reduced data rates. Other methods show greater promise, particularly one of adaptive equalisation as used on telephone land lines. This method makes use of transversal filters, as shown in Fig. 8. By using different connections and algorithms, various equalisers and echo cancellers can be implemented and made adaptive to enable these filters to track changing conditions. Some simulation work is in progress on a computer and results are encouraging. The problems that evolve generally concern the processing speed of the signal, and the length of the delay line that it is possible to implement for the transversal filter. A new C.C.D. transversal filter promises to enable the implementation of these signal processing methods cheaply and in real time.

DECISION FED BACK ECHO CANCELLER AND TYPICAL ASSOCIATED SIGNALS.



TYPICAL RECEIVED SIGNAL FOR A SHORT TRANSMITTED BURST OF DATA.



RECEIVED BASEBAND SIGNAL.

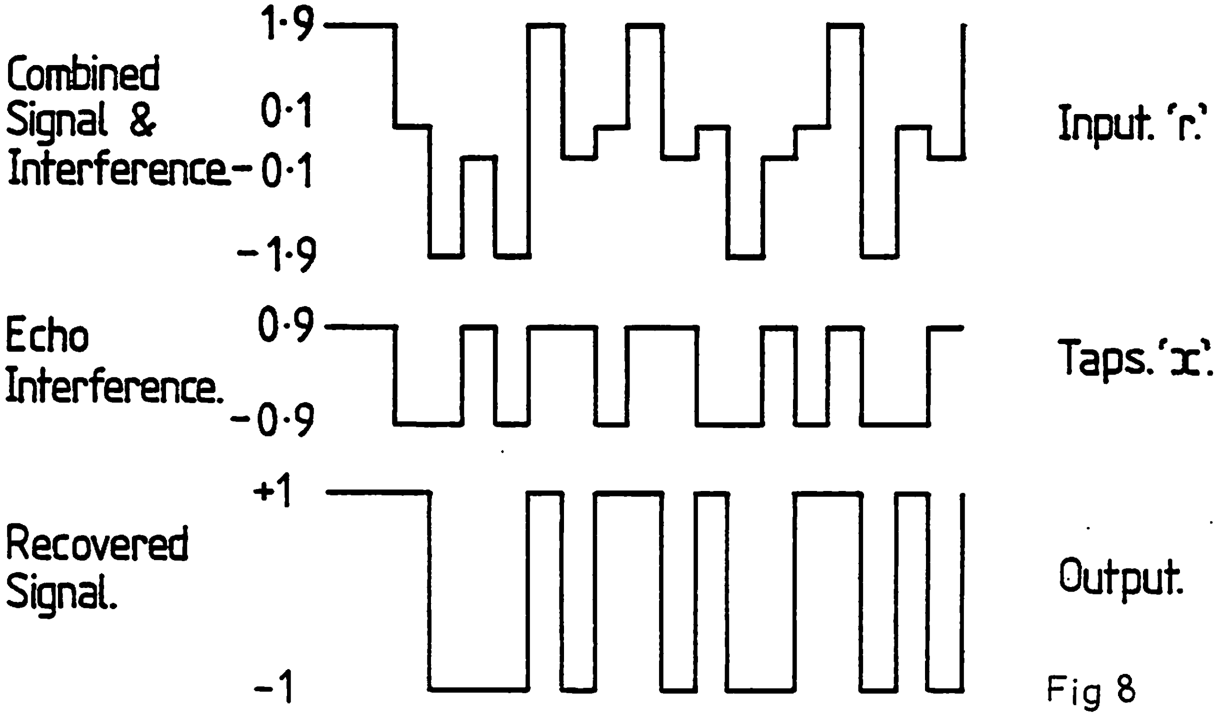


Fig 8

3. IMAGE PROCESSING

3.1 Bandwidth Reduction

The aim of this part of the research programme was to examine various methods of reducing the bandwidth of T.V. images, to permit their transmission across a through-water acoustic communication link. In order to achieve this, a PDP-11/44 computer based image processing system and associated software package have been developed to allow the digitization, display and processing of T.V. images. The results of some initial studies are briefly presented here. An adaptive hybrid coding strategy is also described, as one possible solution to the problem of the restricted bandwidth channel.

The spatial and temporal resolutions of a T.V. system for a free swimming vehicle are to a large extent dictated by the missions such a vehicle would be asked to undertake. In an effort to establish suitable resolution parameters for a system, two possible modes of vehicle operation have been postulated:

(i) Piloting Mode: In this mode the received T.V. images are used by the pilot of the vehicle in and around objects of interest. As the maximum velocity of the vehicle is envisaged at 1 m/s and in view of the fact that the range of viewing in turbid waters may only be a matter of a few metres, a frame rate update time of 4 frames/sec. is desirable. The spatial resolution, however, need only be sufficient to allow the identification of an object and an image of 128 x 128 picture elements (pixels) is thought sufficient. Adaptive resolution is also feasible, related to vehicle speed, and visibility.

(ii) Inspection Mode: In this mode the received images are used to inspect objects of interest, to assess defects and damage in underwater structures for example. This mode then requires higher definition images, but since the objects are in the main stationary, a further reduction in the frame rate is normally acceptable. For this mode an update time of 1 frame every four seconds or more can be tolerated, while a spatial resolution of 512 x 512 pixels/frame is desirable.

Preliminary Trials

In order to establish the suitability of the above resolution parameters, preliminary tests have been carried out using a prototype Slow Scan T.V. System developed by British Telecoms Research Group. The system, which digitizes and transmits single T.V. frames at a rate governed by an external clock generator, has allowed the subjective assessment of various frame rate update times. Using video tapes taken while piloting ANGUS 002, it has been established that for many of the proposed vehicle missions, the resolution parameters above are adequate.

Further tests using the Slow Scan System were carried out across an acoustic link with a through water path length of ten metres and using FSK modulation. The results highlight features of the coding strategy adopted in this system. It was found that in the absence of multipath interference the received image was error free, however, when the effects of multipath interference were introduced, single errors would occur resulting in the rest of the current line becoming erroneous. This effect is a direct result of DPCM coding between adjacent pixels in a line.

Although the slow scan system used can detect errors, it is unable to correct them and simply conceals the error by mapping the previously correct line into the erroneous one. For single errors this technique is satisfactory because of the strong correlation which exists between adjacent pixels in a column, however, when burst errors occur the reconstructed image becomes difficult to interpret. The equipment, however, performs excellently for its designed purpose.

Bandwidth Reduction Techniques

Many different methods have been developed for reducing the bandwidth of a video signal, however, few of these techniques are capable of the high compression factor desired for this application. When selecting a coding strategy here, not only should the strong correlation which exists between adjacent pixels in a line and column be exploited, but also the temporal correlation which exists between adjacent pixels in subsequent frames.

Theoretical studies have shown that three-dimensional transform coding can achieve significant bandwidth reduction, however its implementation requires the simultaneous storage of several T.V. frames making the coder and decoder extremely complex to implement. A suitable compromise, and one which also exploits both the spatial and temporal resolution, is that of adaptive interframe hybrid coding. This technique employs a two-dimensional transform coding method to exploit spatial redundancy within a frame, while using the DPCM between frames to exploit temporal redundancy. Since the temporal redundancy has already been crudely reduced by reducing the frame rate, the hybrid coding technique has been found to achieve large bandwidth reductions comparable with three-dimensional transform coding.

Although a number of different adaptive interframe hybrid coder configurations exist, the particular coder chosen for this application is based on the cosine transform, for two reasons. Firstly, the cosine transform achieves a high energy compaction resulting in a more efficient representation of the image, and secondly, because a fast algorithm exists for its implementation.

In the proposed system for the F.S.V. the digitized image is subdivided into blocks of 16 x 16 pixels and then cosine transformed. The reason a block size of 16 x 16 was selected lies in the results obtained from computer simulation. It has been established that most of the correlation in an image occurs over an area of 20 pixels and accordingly the bandwidth reduction which can be achieved with any transform will rise quite rapidly with an increase in block size up until this value. However, further increases in block size beyond this point will result in little further reduction.

Having transformed the image it remains to distribute the available transmission bits to the frequency components of the image in such a manner that the reconstructed errors at the receiver are minimized. Current adaptive methods of distributing the available transmission bits are based on the amount of a.c. energy contained within a transformed block and it is this method that has been adopted here.

Many problems however, still remain to be solved before the above system will be realized in hardware. For example, consideration must be given to miniaturized implementation of the coder, its power consumption and the computational logic for the cosine transform.

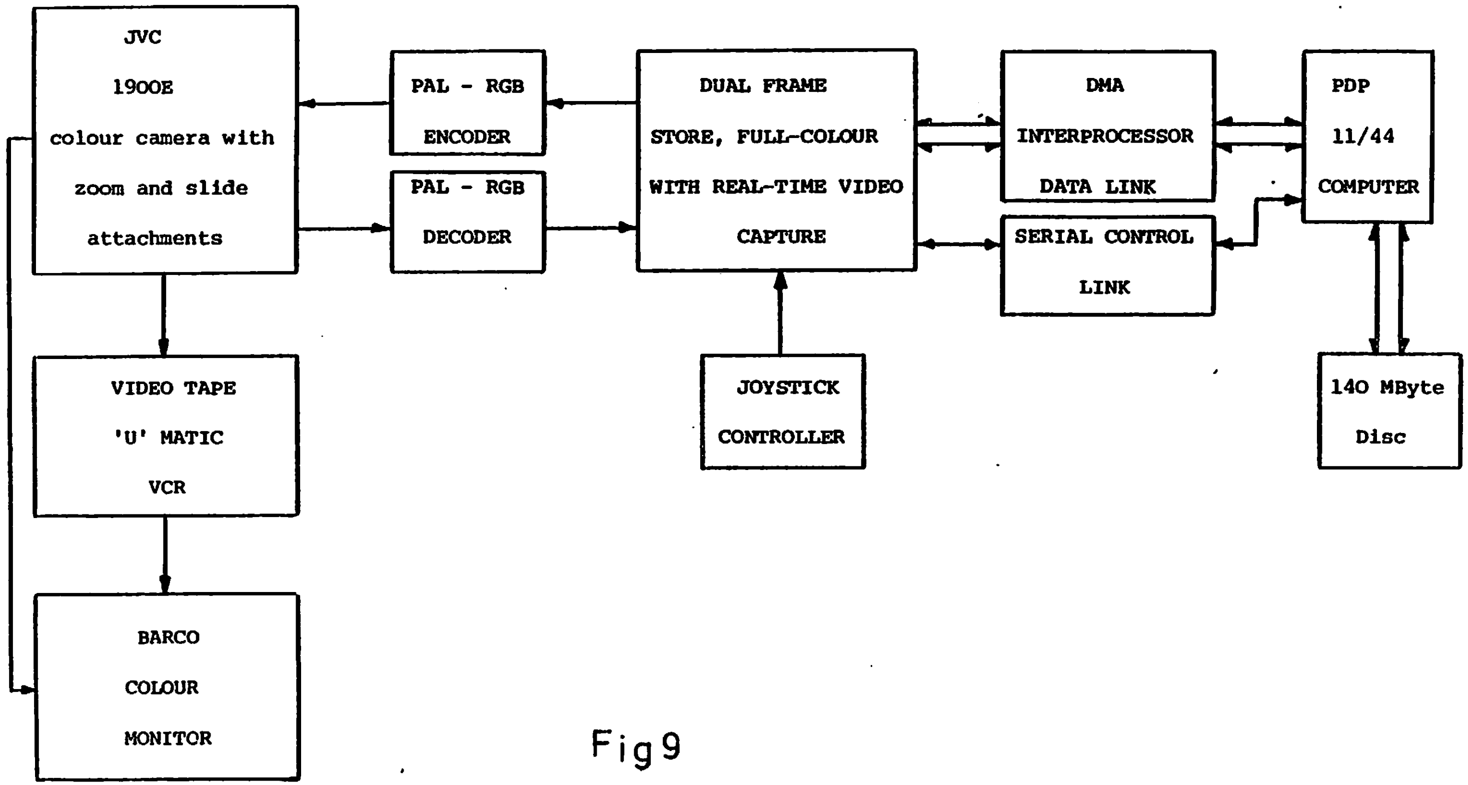

JVC
1900E
colour camera with
zoom and slide
attachments
PAL - RGB
ENCODER
PAL - RGB
DECODER
DUAL FRAME
STORE, FULL-COLOUR
WITH REAL-TIME VIDEO
CAPTURE
DMA
INTERPROCESSOR
DATA LINK
SERIAL CONTROL
LINK
PDP
11/44
COMPUTER
140 MByte
Disc
JOYSTICK
CONTROLLER
VIDEO TAPE
'U' MATIC
VCR
BARCO
COLOUR
MONITOR

Fig 9

3.2 The SPECTACLE Software Package

Spectacle is a software package designed to provide the necessary environment for developing and running image processing algorithms. The package provides the essential programs and routines for the display, capture, manipulation and handling of image data, as well as software modules for the efficient implementation of image processing algorithms. Included in the package are programs for bandwidth reduction, image enhancement, image restoration, feature extraction and image analysis.

Before describing the software package it is necessary to define a number of terms which arise through the course of this specification. These definitions are more easily understood by considering the diagram of Fig. 9. This diagram shows the current hardware configuration used at Heriot-Watt University to run the Spectacle Package. It is apparent that there are two main parts to the image processing facility, the display and capture unit (Supervisor 214) and the DEC PDP 11/44 based computing facility. Programs and routines running on the PDP 11/44 computer are referred to as "Host" software, while software running in the Supervisor 214 unit is referred to as "Satellite" software.

The Spectacle software running on the host machine is written in the high level programming language 'C' and runs under the UNIX operating system, while the satellite software is written in PDP 11 assembly language. The software package can also be viewed in two separate parts. The hardware dependent software which is collectively referred to as "Display" software and that software which for convenience is referred to as the "Processing Software". Specifically, processing programs are those programs which implement some image processing algorithm on a picture file, resulting in a new, modified picture. They make extensive use of the processing routines which handle for the most part, (image data) file input/output. Display programs and routines are concerned mainly with the control of the frame store display and capture facility. They do not modify image files but are concerned mainly with the generation of images on a T.V. screen. These images may be colour, grey-level or graphics images, static images or image sequences. Also included in the package is software for the control of the image capture unit. This software permits the capture of static colour and grey-level images as well as image sequences. The Display software is for use with the Gresham-Lion Supervisor 214 unit only. However, the processing programs and routines are machine independent.

The Supervisor 214 is a modular system consisting of 18 memory planes resolution 1024 x 512 picture elements and a graphics overlay plane of the same resolution. Three video input capture cards are available for real-time digitization of images, as well as three image output cards which can be used to vary the dynamic range of the digitized image before display on a T.V. screen. These cards can also be used to map a monochrome image to colour (pseudo-colour). An LSI 11/02 computer is also present for communication with the host computer and control of the Supervisor 214, and it is upon this that the satellite software runs. Also available with the LSI 11/02 are 2 serial interfaces for communication with the host and a joystick controller, 8K of RAM and a DMA (interlink) interface for image data transfers between the host and satellite.

One of the most powerful features of this display and capture facility is the many ways in which the frame store memory can be configured. Having 1024 x 512 x 18 bits available permits 24 monochrome images at 6 bits/pixel to be stored or 8 colour images at 6 bits/colour. An image of 1024 x 512 x 6 bits/colour can also be stored and displayed. The software residing in the satellite, controlled via commands from the host, can be directed to setup the memory for any of the desired resolutions, with a single command. Once the display and capture facility has been configured, images an be transferred from a bulk storage device on the host and loaded via the DMA link for display. Images can also be captured via the real-time image capture cards and displayed.

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DESIGN AND DEVELOPMENT
OF A DIESEL POWERED SEMI-SUBMERSIBLE ROV

AS COMPILED BY JAMES FERGUSON & ERIC JACKSON
OF
INTERNATIONAL SUBMARINE ENGINEERING LTD.
2601 MURRAY STREET
PORT MOODY, B.C., CANADA

INTRODUCTION

This paper describes the development, design, construction and testing of an unmanned, untethered vehicle whose mission is to gather and transmit hydrographic data on the Canadian Continental Shelf. Because of the requirement to operate at high speeds for extended periods of time, the development of the vehicle has progressed along a path which is dramatically divergent from the one being pursued by developers of other unmanned, untethered submersibles. The need for this divergence can best be appreciated by an understanding of the background leading to the award of the contract and the goals of the project.

Over the past 30 years there has been a steadily growing demand on governments to increase the density of soundings, and therefore, the reliability of navigational charts in the shallow continental shelf margins. At present, the Canadian Hydrographic Service is carrying out this work with 30 foot launches which keep station on a mothership. Normally, five boats are deployed and a sixth is given over to maintenance. Each launch requires a crew of three and is operated in sea state 3 conditions and recovered at sea state 4. Mapping is carried out at a speed of 12 knots and the launches therefore have to be capable of 15 knots for station keeping.

Because of the discomfort imposed on the crew and the consequent limitation on launch endurance and because of the high manpower requirement, studies were conducted in the early 1960's to determine whether the task could be carried out by unmanned or drone vehicles. The conclusion of this effort was that a considerable saving, in terms of cost and survey time, could be realized if a sufficiently high operating speed could be maintained. This saving would be increased further if the mission time of the vehicle could be increased.

In 1965, the Bedford Institute of Oceanography undertook to develop a radio controlled survey vehicle. At this point it was felt that a planing hull would best meet the requirement and a commercially available self-righting 14 foot hull was chosen. It was initially powered by a 68 HP diesel engine. Subsequently a Volvo 110 HP gasoline engine and then a Chrysler 92 HP diesel were fitted and, with the latter, a speed of 22 knots was obtained in still water, although the engine appeared to be greatly overloaded

Sea trials under operational conditions were marginally successful. The launch achieved a speed of 15 knots running into and with the seas in state 4 conditions, at wind speeds of up to 20 knots. Difficulty was experienced in getting the vehicle to plane on any course across the sea however, and further problems were experienced with steering at high speeds and control at low speeds. Finally during the 1971 sea trials off Bermuda the engine repeatedly overheated causing premature shutdown.

In 1972, the radio controlled launch programme was terminated because the growth of multidisciplinary survey requirements coupled with a growth in survey technology caused reactivation of the programme in 1981. In December of that year, International Submarine Engineering Ltd. was awarded a contract to construct a prototype Radio Controlled Survey Vehicle. The vehicle has been given the Acronym DOLPHIN (Deep Ocean Logging Platform Instrumented for Navigation).

THE REQUIREMENT

To be viable, it was decided that the DOLPHIN should be capable of meeting the following parameters.

Speed - 12 knots with 3 knot reserve for station keeping

Endurance - Minimum - 4 hours
- Target - 12 hours

Operating Environment - Operate continuously in 8 to 10 foot breaking seas having a minimum period of 6 seconds.

Control and Data Relay - Real time radio link.

Range of Control - Line of sight (nominally 10 km).

Positionand Control

Navigational Control - To within 10% of lane width (nominally 100 meters).

Positional Accuracy - 1 mm at the scale of survey (nominally ±5.0 meters).

Maximum Weight - 14,000 lbs.

Maximum Dimensions - LOA - 30 feet
- Beam - 10 feet

Operation cycle - 1500 hours between major maintenance periods.

SELECTION OF HULL FORM AND PROPULSION SYSTEM

At the start of the contract ISE Ltd. conducted a survey to determine what hull form would best meet the requirements of the system. At this point, it was also intuitively decided that because the powering requirement could not be satisfied by a battery system and because nuclear and closed cycle power sources were outside the budget of the project, a marine diesel engine would be used for propulsion.

In selection of the hull form it was considered that one which had the following characteristics would probably best meet the requirement:

a) Large BG_Y which is the vertical distance between centres of buoyancy and gravity or in the case of a surfaced craft a large metacentric height.

b) Small waterplane area.

c) Relatively large length - beam ratio.

d) Suitability for integration with an active control system.

The BG or GM of a vessel determines the natural restoring forces that will be present about the roll and pitch axis. Obviously the larger this measure is, the more intrinsic stability it will have.

The smaller the waterplane area of the vehicle is, the less susceptible it will be to the disturbing action of waves. Furthermore, its period of oscillation is long in comparison to larger waterplane forms, and therefore, it is less likely to achieve resonance with normally encountered waves. Thus, small waterplane forms will tend to be stable in the pitch and heave axis.

The length to beam ratio of a vessel is a major factor in determining its natural stability in the yaw axis, and incidentally, its co-efficient of drag. Furthermore, a vessel with a relatively large L/B ratio is suited to active control in the yaw and pitch axis as planes can be located at substantial distance from the centre of gravity.

It was decided that an active control system would be required owing to the small size and high speed requirements of the vehicle. Furthermore, it was felt that such a system could eliminate the requirement to stabilize the echo sounder.

A variety of hull forms were considered in the study and a detailed analysis was made of two, namely:

a) Deep V-type hull; and
b) Subersible with a snorkel mast.

It was decided that while both candidate hull forms would probably meet the requirement, the submersible form had the best chance of exceeding the project goals.

PRELIMINARY DESIGN

Following the decision to construct a submersible, the company compared the static stability in 10 foot waves of various diameter hulls which had a BG equal to .45 of the diameter. Adequate stability was achievable in hull diameters between 2.5 and 4.0 feet.

At this point, a model was constructed to determine the best operating depth of the vehicle and its resistance or drag at various depth and with several different induction mast fairings. As well, the natural frequencies of the model were measured and a qualitative assessment of its dynamic performance was obtained.

The model had a L/D ratio of 6 and could be towed at depths of up to 6 diameters below the surface. A representative BG was achieved through use of a lead keel and in the trials its vertical position was varied to determine whether suitable stability could be achieved with a lesser BG.

It was determined that wave making resistance became negliglble at 2.5 diameters depth. Various fairings were trialled and it was found that a segmented freely rotating fairing was most suitable for use at the interface. It also proved critical to the overall design as it did not generate lift during turns, and its longitudinal positioning did not detract from the vessel's directional stability.

Trials with the model also confirmed that a BG in the order of 0.45 diameters was required to achieve adequate static stability. This is being achieved by the addition of a keel which will also provide roll damping and reduce leeway at slow speeds.

Resistance data obtained in the towing tank was used to determine the powering requirement for hulls in the 2.5 - 4.0 foot diameter range. From this a market survey of diesel engines was carried out to identify the smallest diameter hull for which there was a correspondingly suitable engine. It was determined that the minimum possible diameter was 39 inches and that the Ford Lehman 120 HP marine diesel would fit. Because some very conservative figures were used in estimating propulsion plant efficiency, it may ultimately be possible to reduce this diameter to 30 inches.

In July 1982 it was decided to proceed with the development of a DOLPHIN which would be 39 inches in diameter and 19.5 feet in length, and which could operate at 3 diameters below the interface. The displacement of the vehicle was determined to be 5300 lbs. and to achieve a BG of 17.5", a 1200 lb. lead keel would be attached to a faired frame 3 ft. deep and 4 ft. long.

DEVELOPMENT OF THE ACTIVE CONTROL SYSTEM

The dynamics of the vehicle were investigated by both calculation and model trials. In both cases, the vehicle equations of motion were assumed to be linear and either first or second order. Critical frequencies and damping co-efficients were determined and the results of calculations and model trials agreed, to within a factor of two. This was regarded as adequate for the design of the control system as it will be tuned in the field.

The large BG makes the vehicle very stiff about the pitch and roll axis. Natural frequencies of the model were obtained by rocking it at resonance while damping co-efficients were determined by releasing it from a set angle and observing its oscillations. These were then scaled to predict the behavior of the full sized vehicle.

Yaw and heave are modelled as first order systems because the restoring forces are nonexistent and negligible, respectively. Thus depth and heading must be controlled with active surfaces.

Asymmetry in the vertical plane and a corresponding difference in drag between the mast and the keel result in the DOLPHIN assuming a pitch up angle which is proportional to velocity squared. This angle is offset by the stern planes which control pitch.

A vertical displacement between the centre of effort of the rudder and the centre of mass of the vehicle can cause a snap roll when a turn is initiated. This displacement has been minimized by the location of the rudder in the vehicle. Heel during a turn which is generated by lift off the keel and rudder will be offset by the installation of a stabilizer mounted above the body to generate opposing lift. This stabilizer also serves to increase directional stability.

The vertical path of the vehicle in waves will be a compromise between following the wave contour and maintaining a constant mean depth. Factors that will promote contouring are drag, as the mast acts as a restoring force, and the incorporation of a depth transducer in the depth control system. On the otherhand, factors which will promote a constant mean depth are vehicle mass inertia and the incorporation of a heave rate transducer in the control system.

The active control system consists of pitch and roll force balanced inclinometers, and directional gyro, a three-axis rate sensor, a force balanced accelerometer with integrating filter, active planes and rudder with feedback pots, servo valve controlled plane mechanisms, and a single board microprocessor with analog interface cards.

The principle of operation of the control system is that setpoint errors create plane position commands which are damped by the rate sensors. All setpoints and gains are adjustable from the mothership for testing purposes.

DOLPHIN TELEMETRY SYSTEM

The Dolphin telemetry/control system consists of a Hewlett-Packard HP86 computer at the surface for display and control, an operator's console, an RMS telemetry system with analog, on/off, serial and parallel interfaces and a full duplex UHF radio, and the ISE active control electronics.

The HP86 inputs all bidirectional telemetry information. It graphically displays vehicle sensor information and alarms and, when enabled, has the capability to take over all the vehicle command signals. The active control system gains are controllable through the computer only.

The operator's console has controls for active control setpoints, engine speed, engine transmission, engine start/stop and enable venting and blowing forward and aft ballast tanks, HP air system disable, console/computer and auto/manual modes, and gyro power, cage and uncage commands. LED displays indicate flooding in atmospheric chambers and other emergency or mission-critical conditions.

The operator can control the vehicle in either the manual or automatic heading mode. In manual, the position of the joystick determines the position of the rudder. In automatic, the vehicle holds a preset course. This setpoint can then be jogged by the operator with the same joystick.

In the computer mode, console outputs are routed through the computer before being transmitted to the vehicle. In this mode, the operator can enter a heading setpoint from the keyboard.

The RMS telemetry system at the surface inputs HP86 data, operator console analogs and on/offs, and outputs to the HP86 and to the indicator lights on the console. At the vehicle it inputs and outputs to the active control electronics, inputs various analog and digital sensors and echo sounder data, and output on/off commands. The system is composed of circuit boards used in ISE tethered vehicles coupled via serial ports to the telemetry radio transceivers which are similar to those used in the Toronto transit system. The radio is full duplex UHF, uses differentially encoded phase shift keying, and transmits 1200 bits per second.

DETAIL DESIGN AND CONSTRUCTION OF VEHICLE

Detail design and construction of the DOLPHIN has been in progress since August 1982, and preliminary sea trials are scheduled for the end of February, 1983.

The following are the principle features of the vessel:

Length overall	19.5 feet
Beam	39 inches
Normal Draught	14.25 feet
Displacement (fully fuelled)	5300 lbs.
Weight (fully fuelled)	5200 lbs.
Maximum Speed	15 knots
Endurance	12 hours
Crush Depth	175 feet

The hull is constructed of ¼" 6061-T6 marine grade aluminum with four longitudinal strength members. Two water tight

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The hull is constructed of ¼" 6061-T6 marine grade aluminum with four longitudinal strength members. Two water tight bulkheads of 3/8" aluminum separate the engine compartment from the ballast compartments. A 4.5" OD aluminum induction mast is mounted at the forward end of the engine compartment. This mast is closed by a float and drag operated butterfly valve at the bottom. A rudimentary water separator is also fitted. A 1400 lb. lead keel is attached to a faired aluminum frame.

Ballast compartments are provided fore and aft of the engine room. A normal and an emergency blowing system is provided from 2 - 80 SCF air bottles charged to 3000 psi. With the engine room flooded and the ballast tanks blown there is a buoyancy reserve of 400 lbs. As well there is sufficient air to blow both tanks twice at 175 feet.

The propulsion system consists of 120 HP Ford Lehman marine diesel engine with a Borg Warner 2.5:1 reduction gear. The shaft is connected to the engine by a flexible coupling, and an Osborne manganese bronze propeller with a pitch: diameter ratio of 1.4 is fitted.

The engine exhaust is water cooled and passes through a spring loaded valve in a water trap then through a second spring loaded valve in the stabilizer. Back pressure caused by discharging the exhaust at depth has been calculated to reduce engine efficiency by 8 percent. The exhaust subsystem is constructed of 3/16" stainless steel. All elements of this subsystem are bolted to the main frame to allow for each replacement.

A Vickers PVB-6 engine driven hydraulic pump is the heart of the 1000 psi hydraulic system which supplies power to the planes and rudder. Atchely servo valves provide proportional control to the ISE designed plane and rudder actuators. A NACA 0025 wing section was chosen for the planes which have a effective aspect ratio of 1.75 and can generate a lift of approximately 900 lbs. at 15 knots.

Electric power for the vehicle and for starting the engine is provided by 2 - 105 ampere hour 12 V. DC lead acid batteries. These are charged by an engine mounted alternator. Electric power is also supplied to a Jabsco bilge pump with a capacity of 1750 gallon minimum.

TESTING AND EVALUATION

The DOLPHIN will be sea trialled in late February, 1983 for a period of 3 weeks in the Vancouver area. Following this trials period the prototype will be modified as required and given an at sea evaluation by ISE and the Bedford Institute of Oceanography in May, 1983.

CONCLUSION

The successful development of the prototype DOLPHIN will provide a valuable survey tool for the Canadian Hydrographic Service, and the basis for a family of similar vehicles which require a sensor platform capable of operating at high speed for prolonged periods.

UNITED
TECHNOLOGIES
HAMILTON
STANDARD

HAMILTON STANDARD PRECISION BUOYANCY CONTROL UNIT

BY

M. F. SHEEHAN

HAMILTON STANDARD DIVISION OF UNITED TECHNOLOGIES CORPORATION

JUNE 1983

1.0 INTRODUCTION

An increased interest in small undersea vehicles has become apparent in recent years. In particular, emphasis is being placed on the need for precision depth control of various unmanned, undersea vehicles for both military and commercial applications. Deployment of undersea surveillance platforms and offensive and defensive vehicles continues to be a priority tactical requirement of the military services. The capability for effective low-cost prospecting of the ocean floor, as well as the ability to implant, inspect and retrieve submerged equipment, has also become increasingly important. Many of these operations dictate the requirement for precise control of depth and, in some cases, precise control of vertical velocity.

In response to the above, Hamilton Standard, in late 1981, initiated a company-funded program to develop a vehicle which would be capable of very precise control of both depth and vertical velocity. Design, fabrication and assembly of that vehicle has been completed and test results to date have been very good.

The vehicle, in its present configuration provides substantial growth potential. Such features as an acoustic link or hydrazine gas generator subsystem could be incorporated with relatively minor modifications to the basic vehicle. The incorporation of a hydrazine gas generator subsystem is presently being explored.

This paper provides a brief overview of the program, reports on the results of development testing and discusses potential applications.

2.0 PROGRAM OVERVIEW

Assembly of the prototype vehicle, shown in Figure 2-1, was completed in October 1982. Development testing was conducted in the 100 foot deep escape training tank at the U. S. Naval Submarine Base New London, Groton, CT between November 1982 and February 1983. Further development testing was conducted at the Naval Surface Weapons Center, White Oak Laboratory and on 30 March the vehicle was successfully demonstrated to representatives of the Navy and industry. Further discussion of development testing is provided in Section 5.0.

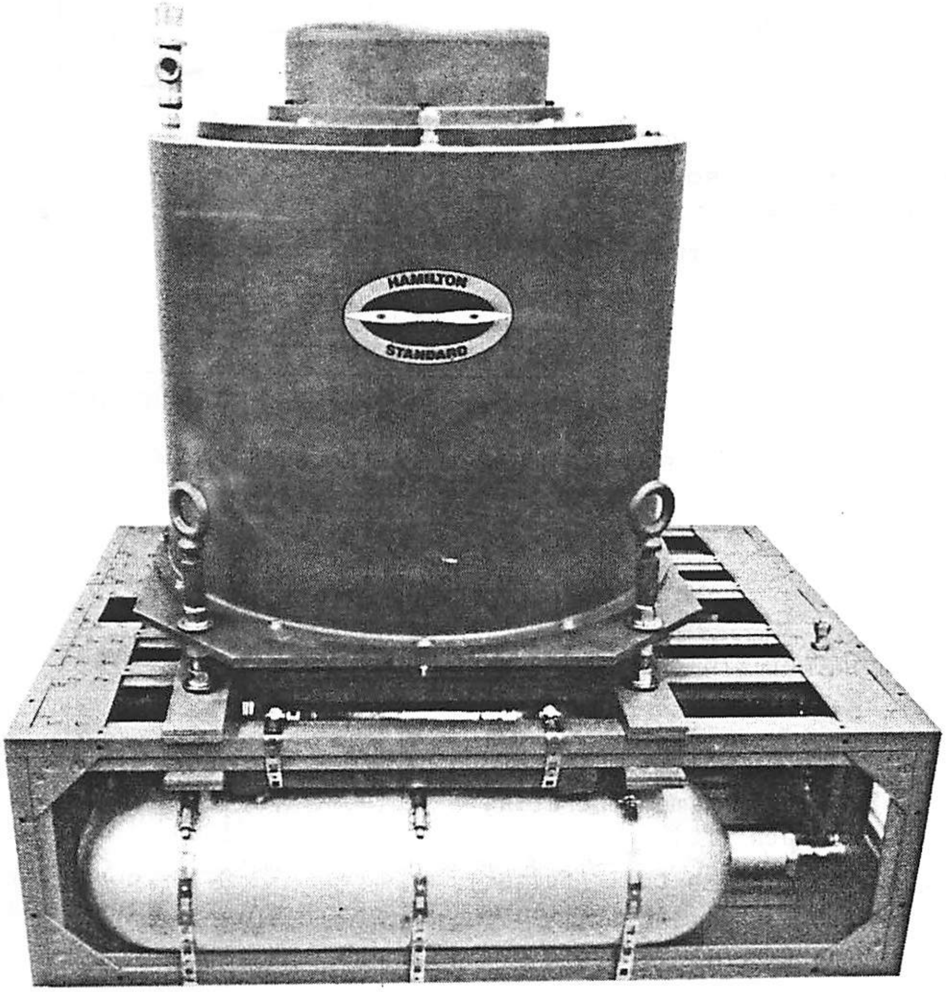


FIGURE 2-1. BUOYANCY CONTROL UNIT

3.0 VEHICLE DESCRIPTION

Hamilton Standard's Buoyancy Control Unit (BCU) is schematically depicted in Figure 3-1. The pertinent physical and performance characteristics are provided in Table 3-I.

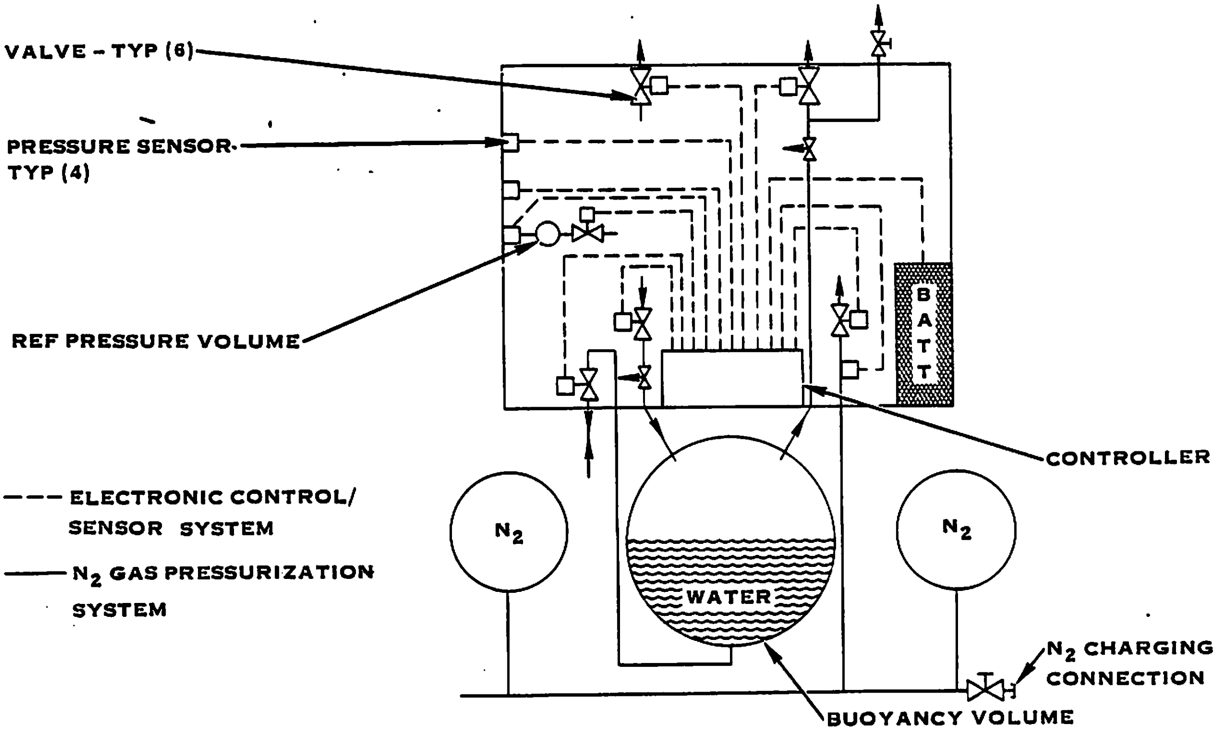


FIGURE 3-1. BCU SYSTEM SCHEMATIC

TABLE 3-I
BCU SYSTEM DESCRIPTION

-	Weight (lbs)	295
-	Displacement (ft^3)	5.0
-	Power source	Lead Acid Batteries
-	Design maximum operating depth (ft)	1000
-	Velocity control (ft/sec)	0.40 course control 0.02 fine control
-	Depth control (ft)	±5
-	Turnaround time (min)	10

3.0 (Continued)

As indicated in Table 3-II, all major components of the vehicle are off-the-shelf (OTS) except the microprocessor controller and pressure vessel that houses the system. The controller is a dedicated, Hamilton Standard-developed microprocessor which takes its input from four pressure transducers and controls the operation of six solenoid valves.

TABLE 3-II
COMPONENTS DESCRIPTION

Buoyancy tank	Off-the-shelf, air compressor tank, 3 gal.
High pressure nitrogen tank	Off-the-shelf, 3300 psi (2)
Valves	Off-the-shelf, solenoid type, (6)
Pressure sensors	Off-the-shelf, differential (2) ±7.2 psid/ ±30 psid - Absolute (2) 0-500 psia/ 0-2000 psia
Battery	Off-the-shelf, "D" size, lead acid
Controller	HS design, OTS circuit boards (50%)
Housing	HS design

4.0 VEHICLE FEATURES

In its present configuration, the Buoyancy Control Unit (BCU) offers many features and verified capabilities which have direct application to established subsurface operating requirements. Among those features are:

- Microprocessor Controlled

  The highly versatile microprocessor-based control subsystem is suitable for a wide variety of applications. In its current hardware configuration it is capable of operating at FOUR different depths during a single mission. This multi-depth capability is expandable to any desired number of depths and times with a minor modification to the input command module. The low power requirement of the electronic and electrical equipment allows several days of continuous operation with the present power source.

- Deep Depth Capability

  The depth capability of the BCU control subsystem is unlimited. For demonstration purposes, the structure is design limited to 1000 feet, however, with structural changes and a higher pressure bottled gas source or hydrazine gas generator, depths in excess of 15,000 appear to be achievable.

- Precision Depth Control

  The BCU currently controls to a depth band of ±5 feet. Depth control of ± 1 foot is achievable with the present configuration, however, greater precision requires higher gas usage and, consequently, lower endurance.

- Precision Control of Ascent and Descent Rates

  Current capability in the fine control mode of operation is 0.02 feet per second. For applications such as implantation of delicate instrumentation, this velocity equates to an impact of less than 0.1 Gs on a hard ocean floor. More precise control is possible but not required for foreseeable military or commercial applications.

4.0 (Continued)

- Simple, Reliable Design

  Sensors, valves and associated plumbing are all proven, off-the-shelf hardware. The Hamilton Standard designed microprocessor control subsystem is fully developed. These facts should significantly reduce the risk and cost of follow-on activity for development of a modification or derivative for a specific application.

- Recording Capability

  A recorder which is capable of storing vehicle performance data is incorporated into the electronics. After vehicle recovery, the data can be transferred to tape and displayed on a CRT or printed out as velocity, depth and depth error plotted against time. If required, payload data could also be stored in the recorder.

- Communications Link

  A one-way hardwired communications link has been incorporated into the system which displays, on a TRS-80 CRT, real time performance of the vehicle during a mission. Tentative plans are to modify the system to allow two-way communications which will provide the capability to modify the mission scenario at any time during a mission. A two-way communications link would also provide a valuable development tool in that the equations upon which the microprocessor logic is based could be modified at will and the dynamic effects of the changes could be observed in real time.

- Quick Turnaround

  For shipboard operation, the BCU offers a very short recovery - service - relaunch time capability. A five-minute gas recharge is all that is required. An additional five minutes is estimated for recovery and relaunch.

5.0 DEVELOPMENT TESTING

Initial testing of the BCU, conducted at the U. S. Naval Submarine Base New London, Groton, CT, revealed significant but not unexpected problems with the dynamics of the vehicle. Velocity control was erratic and the vehicle displayed overshoot tendencies when attempting to decelerate and stabilize at the assigned depth. Analysis of test data resulted in the identification of three factors which contributed to the dynamic instability of the vehicle.

- "Virtual Mass" was larger than originally assumed.
- Software deficiencies caused an unacceptable time lag between calculation of velocity and execution of buoyancy corrections.
- Electronic noise in the microprocessor circuits caused random interpretation of transducer signals resulting in erroneous buoyancy gas corrections.

Dynamic tests were conducted to better establish virtual mass and logic and software modifications were made to correct time lag and transducer signal interpretation problems. Succeeding test results were excellent.

BUOYANCY CONTROL UNIT NSWC DEMONSTRATION PROFILE
30 MARCH 1983

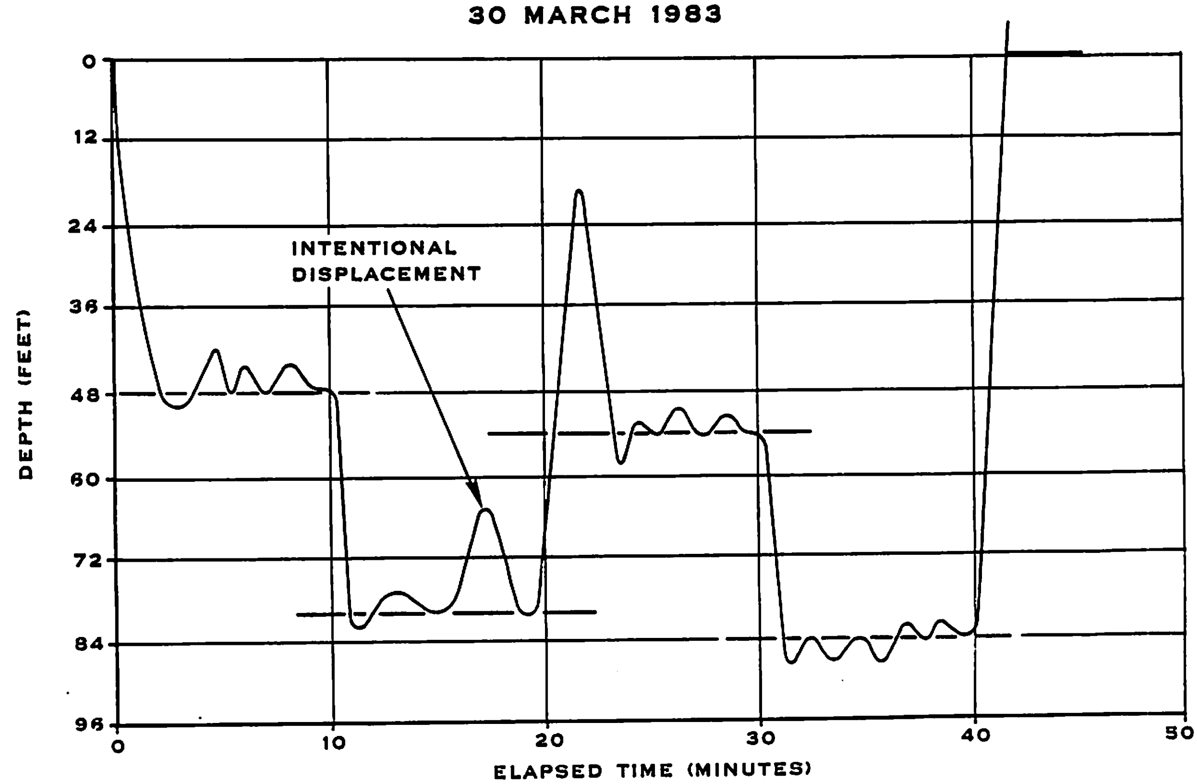


FIGURE 5-1. DEMONSTRATION

5.0 (Continued)

On 30 March 1983 a test was conducted at the Naval Surface Weapons Center which demonstrated the precision control and the multiple depth capability of the vehicle. A profile of that test is provided in Figure 5-1 above.

The microprocessor was instructed to hover at four different depths, three descents and one ascent to depth. All depth changes were conducted on time and on depth. Hover control was maintained within the ±5 foot depth band. At elapsed time of fifteen minutes the vehicle was intentionally displaced approximately fifteen feet above assigned hover depth. The vehicle re-established itself within the assigned depth band in four minutes. The temporary excursion to 18 feet upon ascent from the 80 to the 50 foot hover depth was expected and is inherent in the current design. The vehicle was initially designed to descend, hover at a single depth and ascend to the surface. The decision to more fully exploit the capability of the control subsystem by incorporating a multiple depth capability was made subsequent to final design and fabrication. A relatively simple hardware/software modification will eliminate the ascent excursion condition, however, the modification is not included in our present development plans.

6.0 APPLICATIONS

The vehicle described in the succeeding pages offers many features which represent direct benefits to potential users in several categories of military and commercial applications. Those features and associated benefits are summarized in Table 6-I.

TABLE 6-I. MULTIPLE BENEFITS FOR ALL APPLICATIONS

APPLICATION \ BENEFIT	MICROPROCESSOR CONTROLLED	DEEP DEPTH CAPABILITY	PRECISE DEPTH CONTROL	PRECISE ASCENT/ DESCENT CONTROL	SIMPLE, RELIABLE	QUICK TURNAROUND	ACOUSTIC LINK MOD	COVERT	LONG ENDURANCE (HYDRAZINE MOD)
UNDERWATER SURVEILLANCE/RECON.	X	X	X		X	X	X	X	X
SALVAGE	X	X		X	X	X	X		
IMPLACEMENT/RETRIEVAL	X	X		X	X	X	X		
WEAPONS SUPPORT PLATFORMS	X	X	X		X		X	X	X
MINERAL SURVEY/MINING	X	X	X		X	X	X		X
SUBMERSIBLE TRIM SYSTEMS	X	X	X	X	X		X	X	
MOBILE TRACKING RANGES	X	X	X		X		X		X

EAVE EAST - GOALS AND APPLIED TECHNOLOGIES

Jim Jalbert
Marine Systems Engineering Laboratory

The goal of the EAVE-East untethered submersible is to serve as a test-bed for developing and applying new technologies which, are those that pace the development of autonomous submersibles. The current technologies which we at the Marine Systems Engineering Laboratory are investigating are the following:

1. Use of powerful microcomputers and high level language programming. Programming in a high level language provides the opportunity to easily change a program and use the vehicle to perform multiple missions with minimum hardware changes. The UNH concept is basically one of distributive processors, that is, processors dedicated to performing specific tasks and communicating with the command computer only when necessary. This permits simultaneous running of parallel tasks which provides system efficiency.

2. Acoustic navigation systems for position, guidance and control.

3. Use of magnetic bubble memory for mass data storage in the subsea environment. A magnetic bubble memory system has been implemented which is used to store mission data. Magnetic bubble memory has the advantages of being non-volatile, has no mechanical moving parts and is transportable. Another advantage is that data can be accessed in a random manner; hence, there is no need to run through an entire tape to find the portion of interest.

4. Hydrodynamics and control of autonomous systems. (See paper by Hartwell and Limbert in these proceedings.)

5. Image processing and bandwidth compression techniques. This area is of great interest since it offers the potential of providing near real-time transmission of video signals to the surface via an acoustic link.

   This project is presently in the development stage. The device has not yet been put on the EAVE-East vehicle. Basically, it takes an image from a CCD (Charge Coupled Device) camera, compresses it in a 68000 computer, and transmits it to another 68000 for decompression and display. There is, as of now, no acoustic link involved. It operates on the order of 2 frames/second from a 100 X 100 element at 7 - 8 kilobits. (See Spatial Redundancy Reduction of Slow Scan TV Images by Shevenell in these proceedings.)

6. Sonar system for under-ice keel mapping and bottom mapping.

7. Development of "Expert Systems" applications.

Brief Vehicle Description: (Figure 1)

The vehicle is powered by lead acid batteries in two pressure-resistant tubes providing about 100 amp-hours and an operating duration of four to six hours. (Recharging is performed overnight.) There are six thrusters: two in each of the three axes. Four computers are housed in two tubes in the center of the vehicle (navigation computer, thruster computer, bubble memory computer, 68000 Command computer). Two buoyancy tanks provide floatation. Atop the vehicle are three acoustic transmitters/receivers, located about three feet apart. There is also a magnetic fluxgate compass. The vehicle measures 51" x 53" x 61" (L x W x H). It weighs 600 lbs. in air, has a positive buoyancy of 3 lbs., a maximum speed of 1.5 knots and maximum operating depth of 300'. Position accuracy is approximately ±0.25 m. A block diagram of the computer interconnection is shown in Figure 2.

Computer Timing

The EAVE vehicle processor timing is shown in Figure 3. The command computer runs a cycle in about two seconds; we are aiming at one second. The navigation computer runs 2 1/2 cycles/second.

The command computer reads bearing once/cycle, but can read as often as ten times/cycle. Depth is updated once/cycle also. Briefly, the following procedure is followed: The command computer reads depth, bearing and navigation computer, then performs a position translation from transmitter/receiver to vehicle center. It also computes deltas X, Y, Z, time, and bearing. It then performs the control algorithm. Based on the changes that have occurred since the last cycle, it commands the thruster computer to vary the thruster motors.

Abort logic is held in the command computer. At this time it is very simple. If navigation data is lost, the vehicle will hold depth and attempt to re-initialize its navigation system. If this cannot be done, then it turns off the thrusters and its positive buoyancy carries it to the surface.

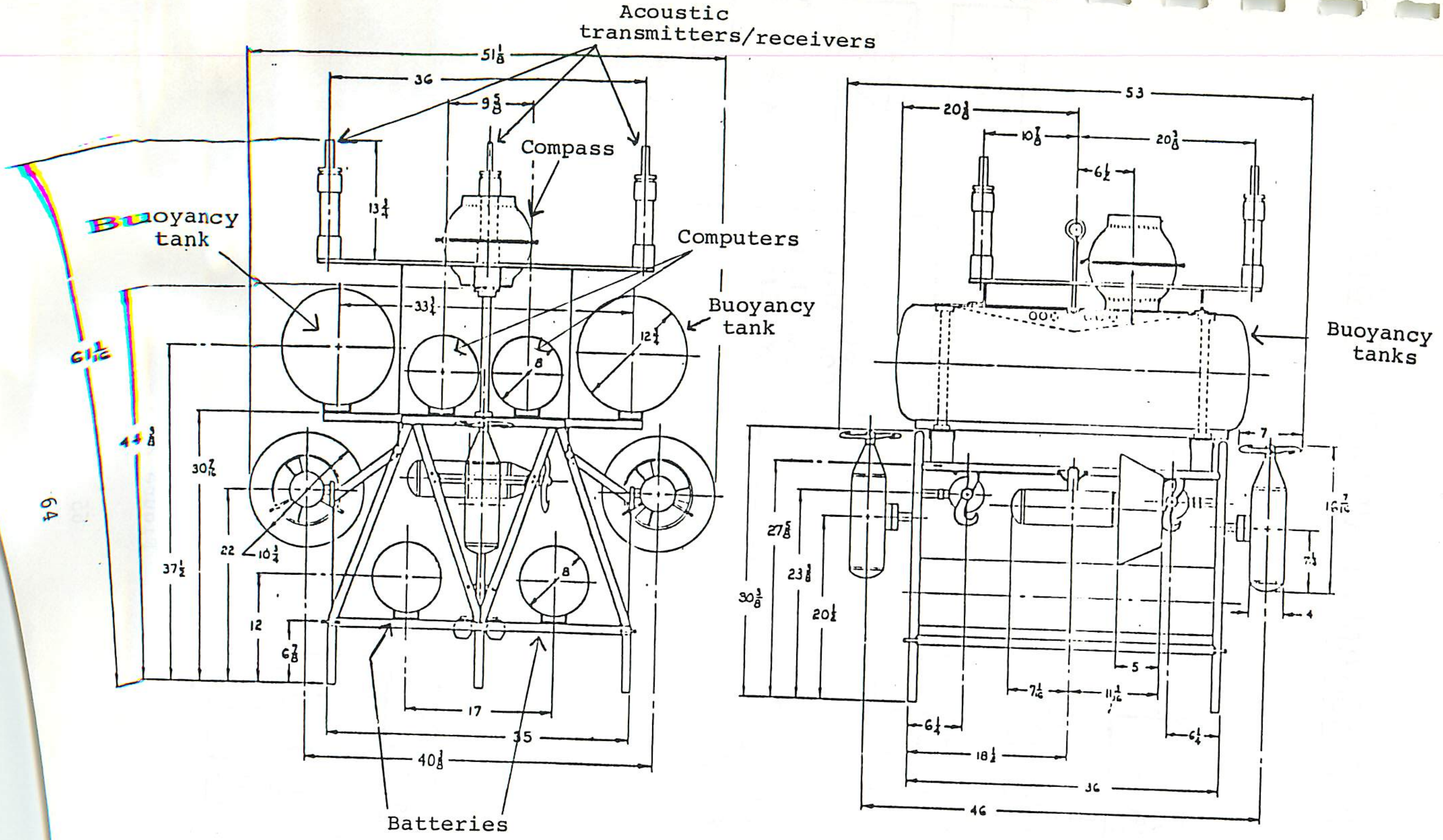


Figure 1

MARINE SYSTEMS ENGINEERING LAB

SCALE ½" = 1"

DATE 12-11-82

APPROVED BY:

DRAWN BY

EAVE. DIMENSIONAL OUTLINE

DRAWING NUMBER

BLOCK DIAGRAM OF VEHICLE SYSTEMS

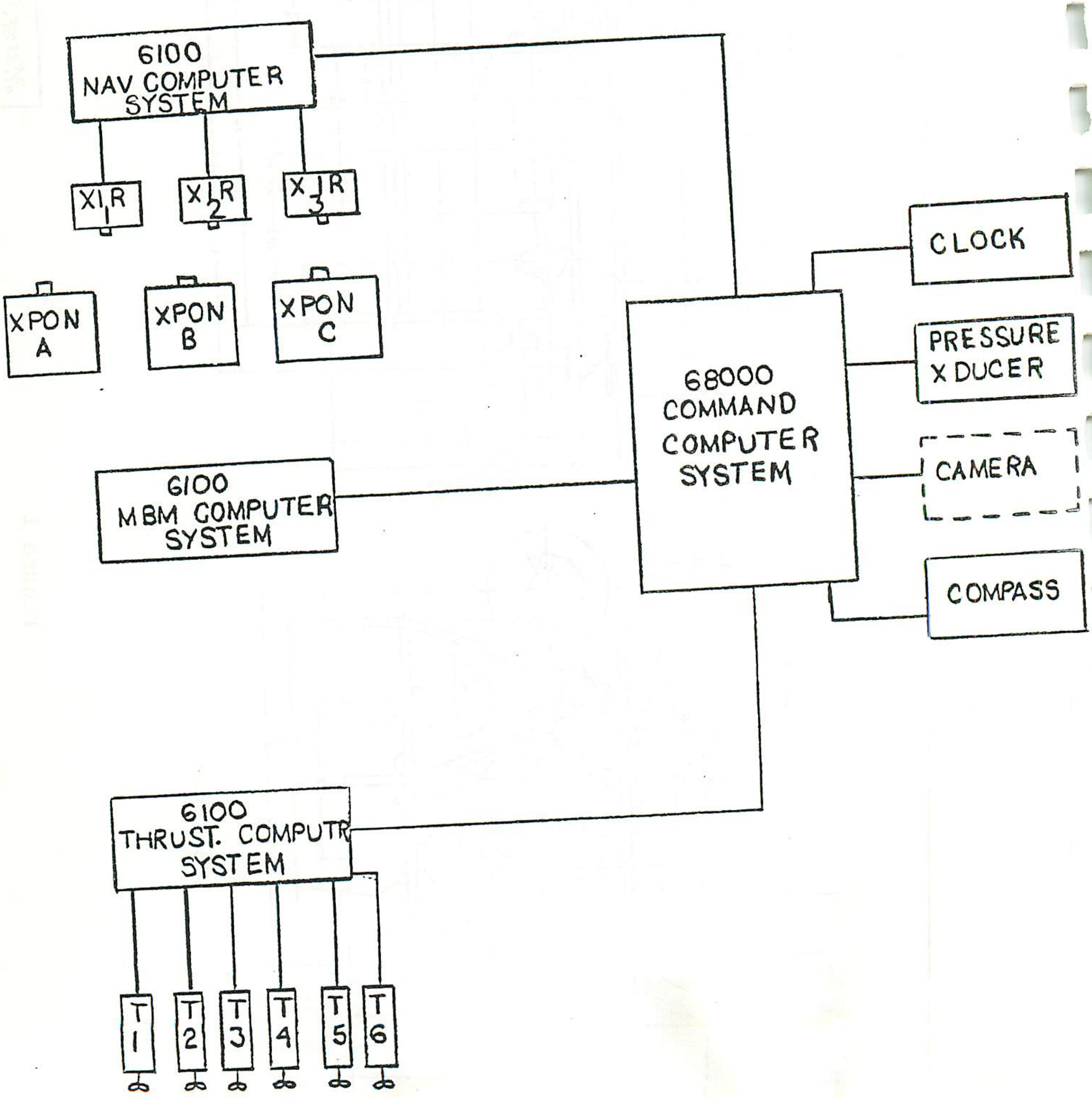


Figure 2

EAVE VEHICLE PROCESSOR TIMING

TIME	CYCLE 1							CYCLE 2		CYCLE 3	
COMMAND COMPUTER	READ PRESSURE	READ COMPASS	READ NAV	TRANSLATE X Y Z	COMPUTE $\Delta\theta$ ΔX ΔY ΔZ $\Delta +$	DECIDE BASED ON MISSION	COMMAND THRUSTER COMPUTER	REPEAT		REPEAT & STORE ALL DATA FOR 3 CYCLES IN MBM	
NAV COMPUTER	X MIT, RECEIVE CALCULATE X, Y				REPEAT			REPEAT	REPEAT	REPEAT	REPEAT
THRUSTER COMPUTER	TURN ON SELECTED MOTORS AT PROPER SPEEDS IN PROPER DIRECTION AS DETERMINED BY COMMAND COMPUTER.							REPEAT		REPEAT	
COMPASS	READ BEARING	REPEAT	10 PER CYCLE					REPEAT		REPEAT	
PRESSURE	READ PRESSURE	REPEAT	10,000 PER CYCLE					REPEAT		REPEAT	
MBM	SLEEP ⟶									⟶ STORE DATA IN MBM	

Figure 3

68000 Command Computer

The 68000 computer performs most of the decision making, and performs the following functions:

1. Maintains time clock.
2. Reads pressure and calculates depth (Z).
3. Reads compass and computes relative bearing (θ).
4. Requests X,Y position from navigation computer and translates it to center of vehicle.
5. Computes changes in time; X,Y,Z, and θ.
6. Decides how to control thruster motors through software control algorithm. Mission is pre-programmed in command list.
7. Passes data to magnetic bubble memory for storage.

Navigation Computer

A block diagram of the navigation computer is presented in Figure 4. It is a 6100 CPU-based system. The three transmitter preamplifiers are the three transmitters atop the vehicle. The system operates by frequency discrimination, time discrimination, and threshold detection of the envelope. In operation, the transmitter preamplifier transmits a 95 kHz, 1 ms pulse at 15 watts power. Three transponders are positioned in an equilateral triangle; each operating with different turnaround times, and frequencies (110, 114, 118 kHz). The preamplifiers have a 30 db gain, and receiver cards provide an additional 60 db gain. The signals are then passed through filters where they are detected. Nine counters provide timing for each return. The result is nine counts of data (three from each transponder). The computer then subtracts the turnaround delays built into each transponder and then, through logic, it discriminates and decides on the degree of reliability of each count. Next it decides which transponder returns to use in position calculations. It performs the calculation after asking the 68000 computer for depth. The result is stored in its buffer. Anytime the 68000 computer asks for a position update it is given the most recent position by the navigation computer.

In our test range at Lake Winnipesaukee, a transponder net is laid out in accordance with Figure 5. The transponders are approximately 60 feet apart. The round trip return counts from the transponder are fed into the computer which builds them into an array and performs an analysis of the data. The math processor used to calculate X, Y position is a 9511, based in the 6100 navigation computer.

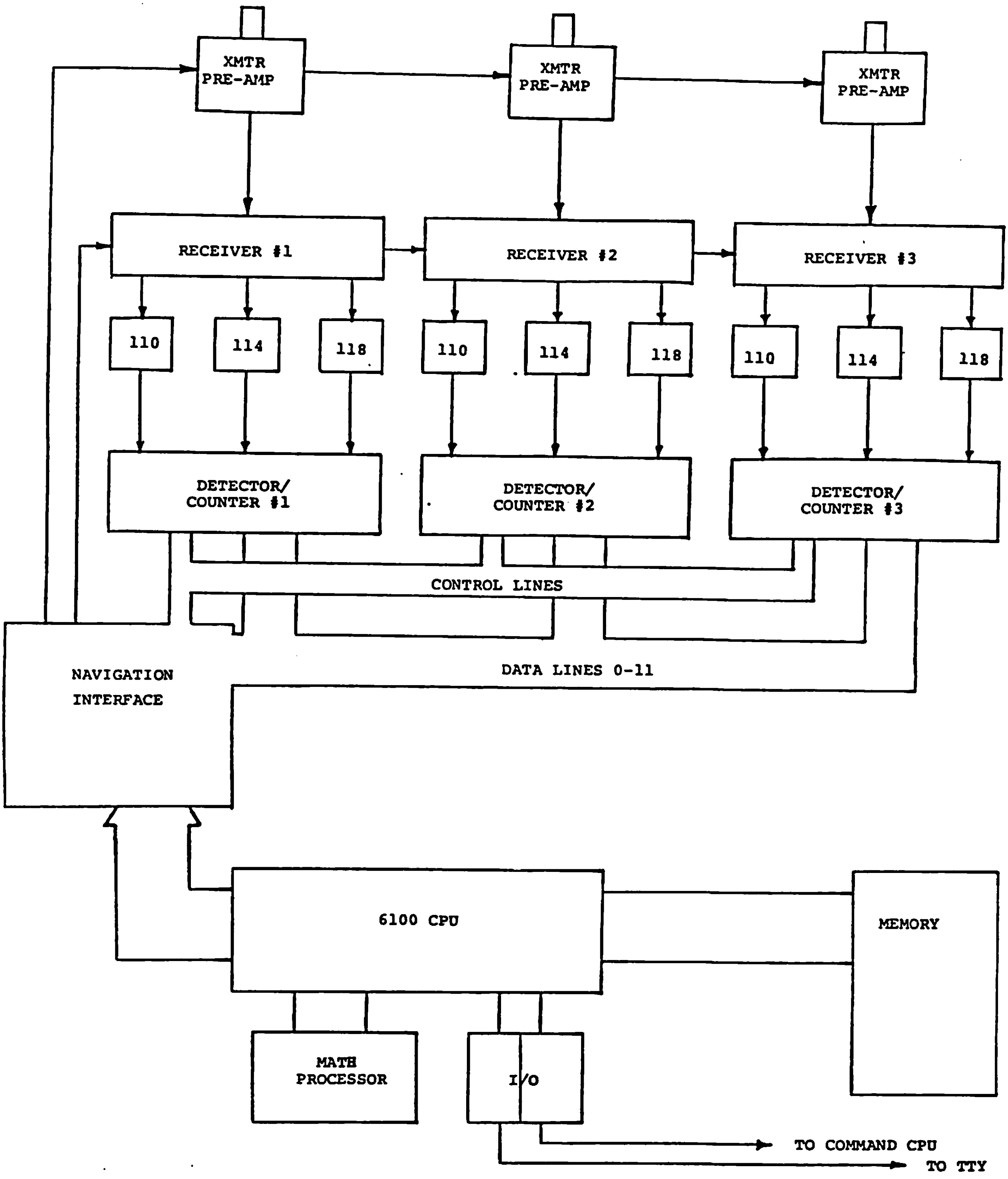
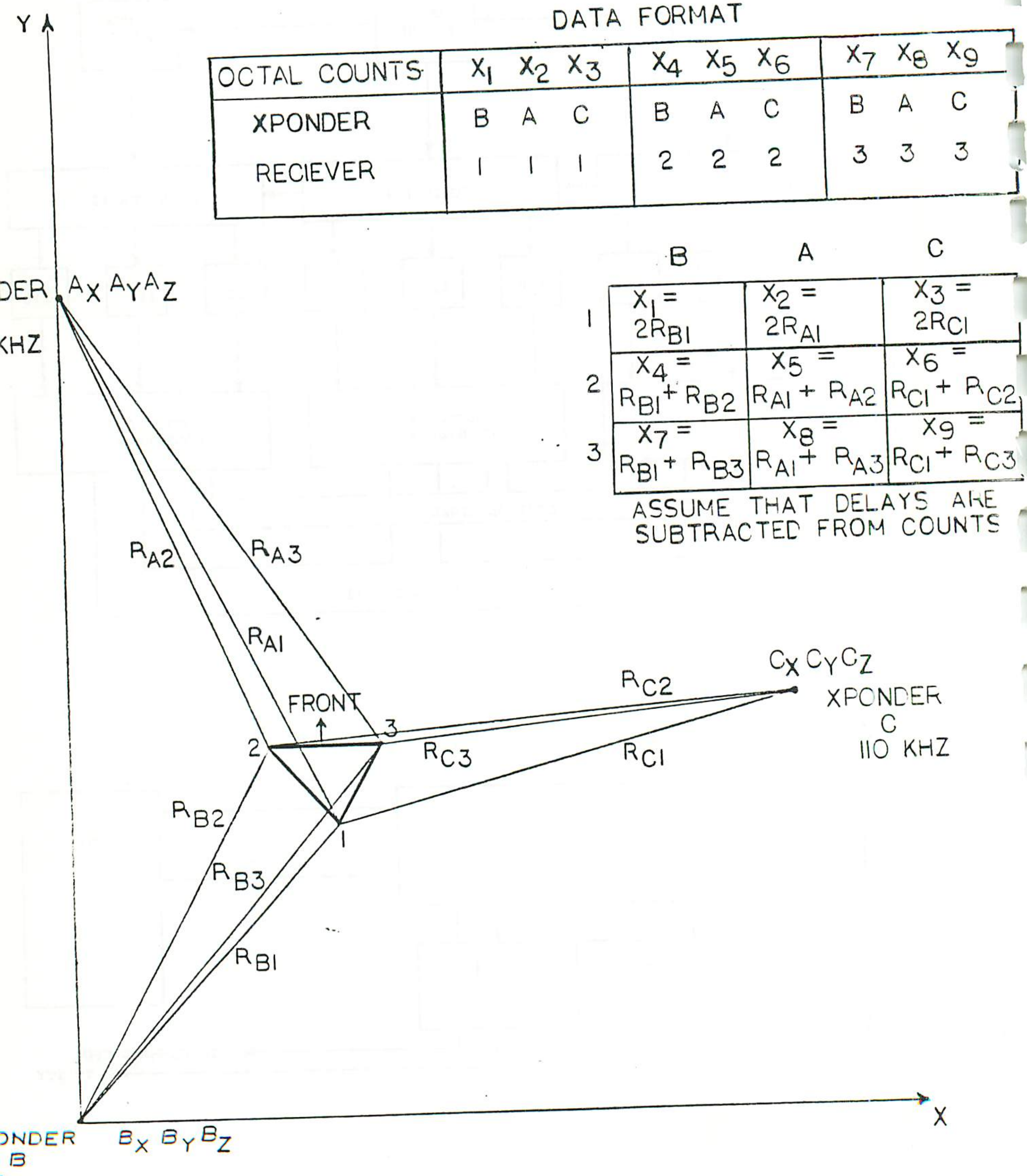

XMTR PRE-AMP
XMTR PRE-AMP
XMTR PRE-AMP
RECEIVER #1
RECEIVER #2
RECEIVER #3
110
114
118
110
114
118
110
114
118
DETECTOR/ COUNTER #1
DETECTOR/ COUNTER #2
DETECTOR/ COUNTER #3
CONTROL LINES
NAVIGATION INTERFACE
DATA LINES 0-11
6100 CPU
MEMORY
MATH PROCESSOR
I/O
TO COMMAND CPU
TO TTY

Figure 4



DATA FORMAT

OCTAL COUNTS	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
XPONDER	B	A	C	B	A	C	B	A	C
RECIEVER	1	1	1	2	2	2	3	3	3

	B	A	C
1	$X_1 =$ $2R_{B1}$	$X_2 =$ $2R_{A1}$	$X_3 =$ $2R_{C1}$
2	$X_4 =$ $R_{B1} + R_{B2}$	$X_5 =$ $R_{A1} + R_{A2}$	$X_6 =$ $R_{C1} + R_{C2}$
3	$X_7 =$ $R_{B1} + R_{B3}$	$X_8 =$ $R_{A1} + R_{A3}$	$X_9 =$ $R_{C1} + R_{C3}$

ASSUME THAT DELAYS ARE SUBTRACTED FROM COUNTS

Figure 5

Magnetic Bubble Memory System

1. This system stores mission data from the command computer upon request. It has one card, an IMB 72, capacity 1 megabit, interfaced to a 6100 computer. A second card can be installed in order to obtain a 2 megabit system. Intel has recently produced a 4 megabit device. With our configuration we need only to slightly modify the software to have 8 megabits available.

2. The file system is broken into 20 files each with 50 blocks of data where each block contains 128 bytes. The files can be addressed when reading out in random access manner. One advantage of the system is that the card can be taken back to the laboratory where the entire mission can be re-run to see exactly where the vehicle was at any given time, how it was issuing commands and what it was doing.

   When data is not being transferred to the bubble, the systems "sleeps" to conserve power.

In Lake Winnipesaukee we have installed a three dimensional steel structure which is shown in Figure 6. It is constructed of eight inch pipe; the windows are eight feet square. Our plan is to drive the vehicle through and around this structure to demonstrate navigation and vehicle control accuracy.

Test results indicate that the navigation system is accurate to within ± 4 inches.

Figure 7 is a plot of the vehicle operating under the control algorithm. The plot shows the vehicle performing a change of depth. The controller is all in software in the 68000 computer. There are basically four loops, one for vertical, one for forward and reverse, one for side (which is orthogonal to a forward motion), and one for rotation. There are, then, four complete sets of gain parameters to be set in the algorithm. Not shown was a 10 second burst built in to downthrust the vehicle. Time is shown in seconds. Depth is shown as holding to within three to four inches.

A plot of bearing vs. time is presented in Figure 8. The vehicle was told to turn to 90 degrees. The gain parameter set-up provided an angular velocity of 4 degrees/second. This rate can easily be changed by changing a gain parameter. The compass operates with ± 2 degrees of error with various thrusters operating. An attempt was made to hold with ± 6 degrees which was easily accomplished.

A series of commands are shown in Figure 9. The vehicle was told to dive to 10 feet, hold 10 feet, turn to 90 degrees and, once at 90 degrees, hold this bearing and climb to 5 feet. Once there, it was to turn to 177 degrees and exit the program. There

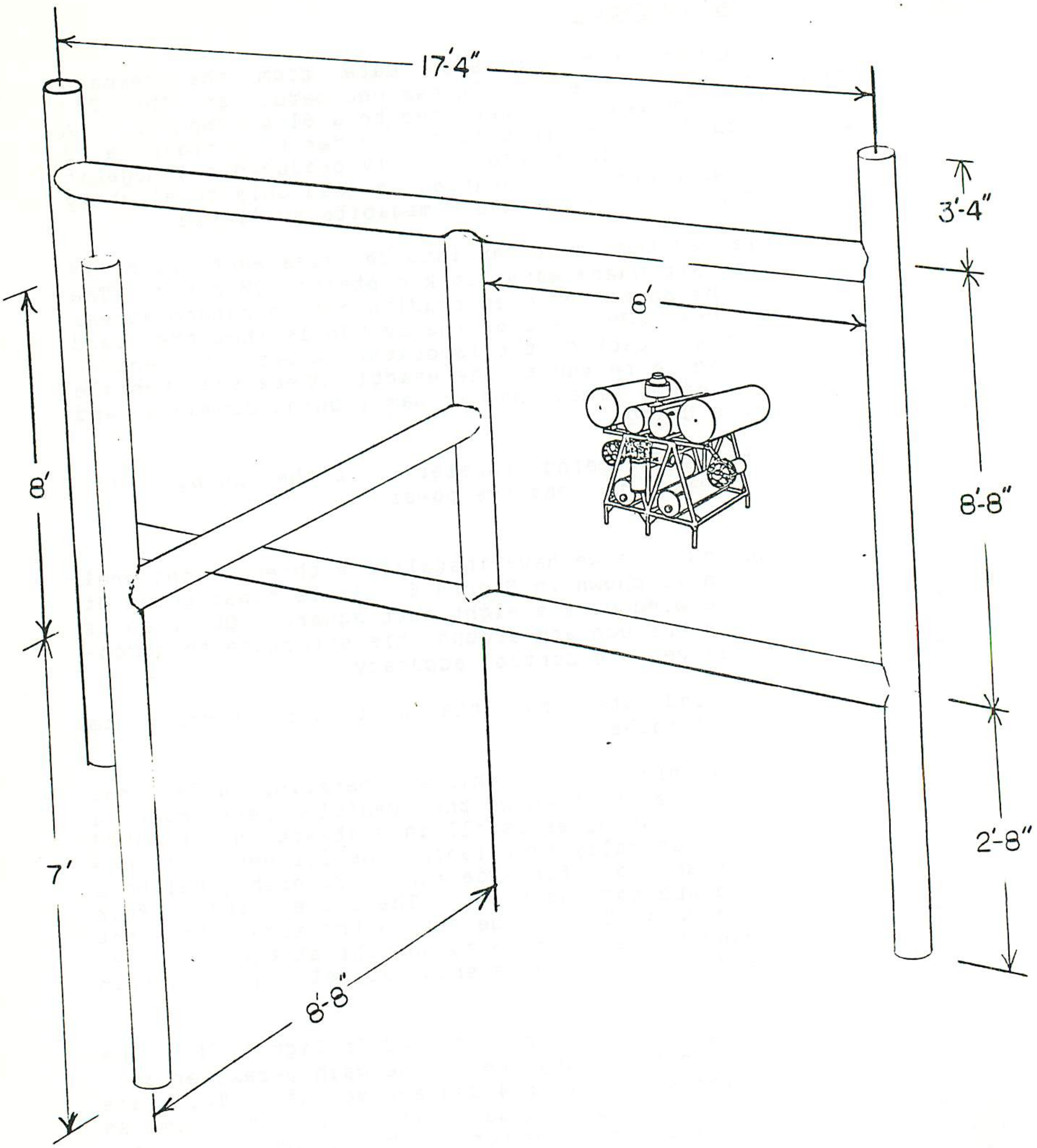


Figure 6 Structure for Testing

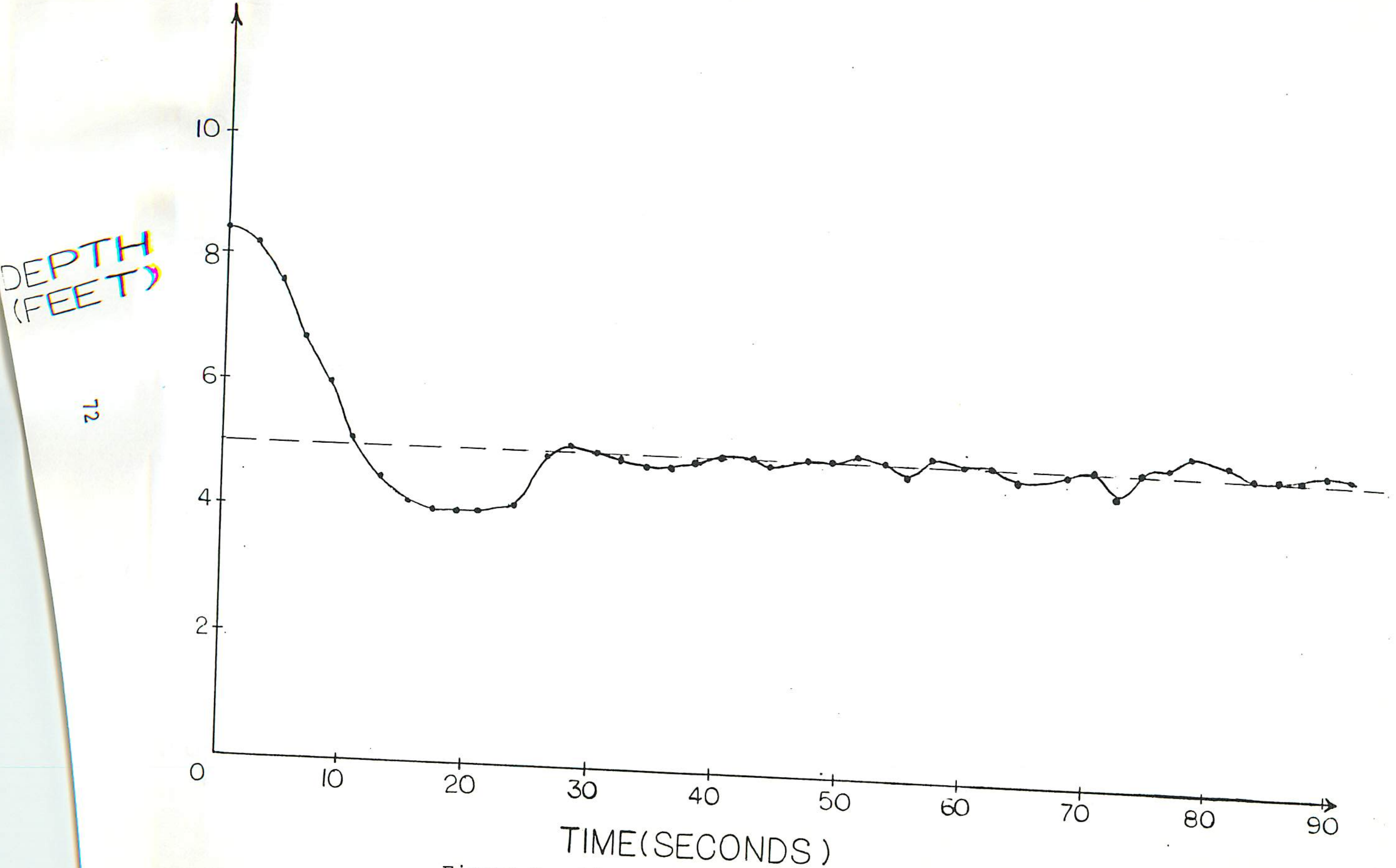


Figure 7. Plot of Vehicle Depth Change

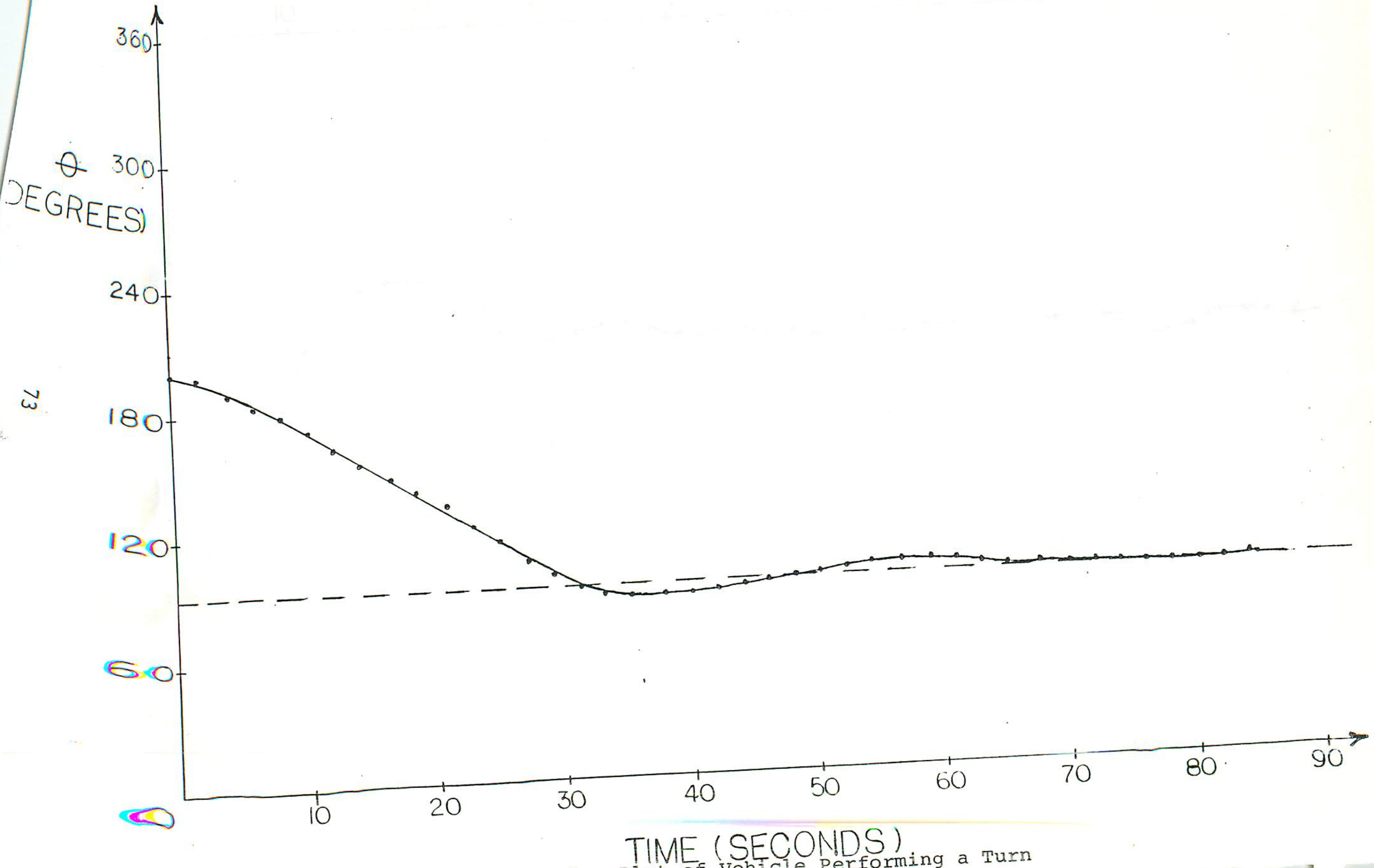


Figure 8. Plot of Vehicle Performing a Turn

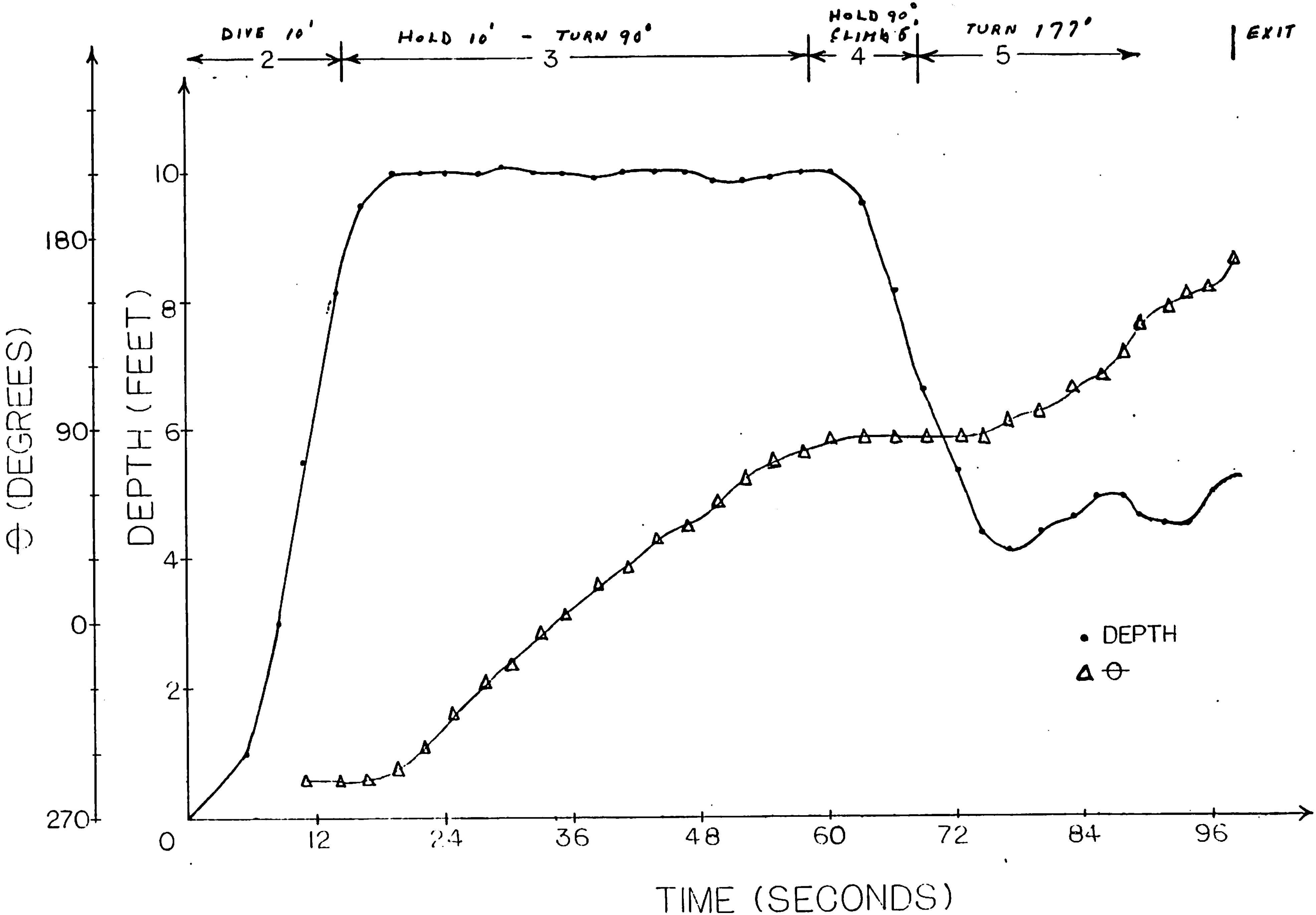


Figure 9. Series of Vehicle Commands

is another gain parameter that tells the computer how close it should be to a commanded position in space, X,Y,Z. In this example whenever all of the parameters were within one foot, it would proceed to the next command. We are now at the point where the gain parameters are established for turns and dives. Presently we are determining the horizontal motion gains and will continue with this work this summer.

Once we have determined the correct horizontal gains, our next phase will be to run the mission shown in Figure 10. The objective is to demonstrate that the vehicle can penetrate a structure, and remain under control while conducting an intricate series of maneuvers. Initially, the vehicle will begin at the point designated as MSL. It then moves along through the window of the structure to a mid-way point of the horizontal connecting pipe. Here it rotates 90 degrees (at point A). It will then climb to the horizontal beam level, move in to look at it, then move back. Next it slides along the horizontal beam, keeping the structure in view (D,E). Then it ascends to the top of the structure (E,F). The arrows indicate the subsequent path of the vehicle in crossing over to the other side of the structure to continue until it finally returns to its starting position and returns to the surface.

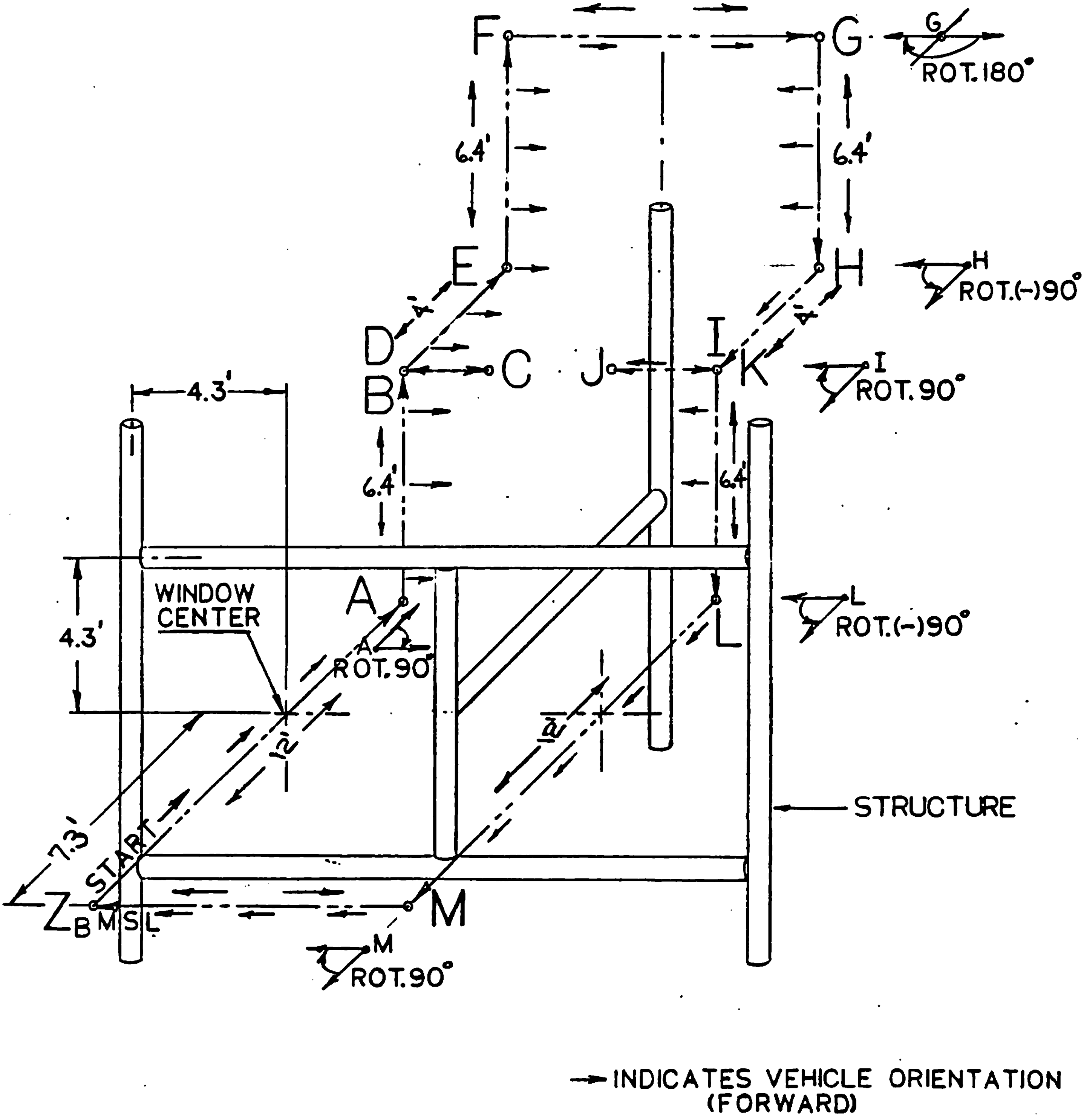


Figure 10. Proposed Path for Structure Inspection Mission

AUTONOMOUS REMOTELY CONTROLLED SUBMERSIBLE
"ARCS"
GENERAL DESCRIPTION

ERIC JACKSON
INTERNATIONAL SUBMARINE ENGINEERING LTD.

ABSTRACT

A family of autonomous survey vehicles is being developed by International Submarine Engineering Ltd. The design philosophy for various subsystems and an operational scenario are described and general vehicle characteristics are listed.

INTRODUCTION

ARCS is an acronym for a family of vehicles designed and manufactured by International Submarine Engineering Ltd. of Port Moody, B.C. These vehicles are autonomous, or unmanned and untethered, but have a supervisory acoustic data link with a surface station. Because the data rate of the link is low, the vehicles must have a high level of on board intelligence and can therefore be considered true underwater robots.

This type of vehicle has applications in areas where tethered vehicles would be constrained by their umbilicals and where large scale surveys are required. Initially ARCS will be used for survey and data acquisition, but as technological advance in the areas of video bandwidth compression and high energy density batteries is achieved, their use for manipulative work will become more common.

ARCS - 1, which is under construction for the Bedford Institute of Oceanography in Halifax N.S., will be used for under ice hydrography in the high Arctic. An ARCS package which is being considered by a leading operator of ROV's will be used for sea bed and under ice mapping and will be capable of acquiring a wide variety of data.

DEVELOPMENT OF THE ARCS VEHICLE

Feasibility of Positioning and Telemetry Systems - As a prelude to the award of a contract, in 1962, for the development of an autonomous unmanned under ice submersible, I.S.E. conducted a market survey of available acoustic positioning and telemetry systems in late 1981. The aim of the market survey was twofold:

a. To determine the feasibility of using both systems in the ARCS application.
b. To recommend the acquisition of systems which best met the requirements of the ARCS system and which could be acquired within the proposed budget.

A variety of acoustic positioning systems were available. Of these it was determined that the long baseline system would best suit the ARCS application and has the most probability of achieving an overall positional accuracy requirement of ±5 meters in the operating grid.

A study of available long baseline systems was conducted, and the acquisition of an Oceano long baseline system was recommended for the following reasons:

a. Its probability of meeting the specifications appeared to be higher than other systems.
b. It has been field tested worldwide, and has a good reputation for reliability and accuracy.
c. Its cost put it within the budget.

Several types of acoustic telemetry systems have been developed. Due to the problems of multipath interference and the inability to rely upon a direct acoustic path in the shallow under ice environment in the Arctic, FSK type telemetry systems were chosen to be the most suitable in achieving the ARCS system requirements.

A study of available FSK systems was undertaken and only one system was found. It, however, could not operate in a high doppler environment due to the fact that insufficient bandwidth was available between the transmitted tones. To overcome this inadequacy, a Doppler Synchronization system was proposed, but unfortunately, the cost of this and the system itself ultimately precluded acquisition of the system.

Subsequently, the decision was made that IST Canada, a subsidiary of ISE Ltd., was to build a FSK acoustic link. The link developed would have to achieve the following minimum capability:

a. Operate in the absence of a direct acoustic path.
b. Achieve a minimum data rate of 30 b/s.
c. Be capable of expanding data rate.
d. Afford redundant communication to overcome multipath fading.
e. Handle a ±5 knot doppler shift.
f. Operate over a range of 3 notical miles in poor conditions (shallow, under ice).

A decision was also made that the feasibility of the telemetry system should be demonstrated by developing breadboard hardware and trialling it at Resolute Bay, and that a long baseline acoustic positioning equipment should be tested under the same operational conditions.

These field trials were conducted in April - May 1982. These trials established that positioning and telemetry could be acheived over a range of 10 km in nominal depths of 100 meters and to a distance of 6 km in water depths of 27 - 30 meters. In all cases ranging acuracy was better than ±1.5 meters and a data rate of 100 bits/second was achievable.

ONBOARD CONTROL SYSTEM AND INSTRUMENTATION

In addition to the telemetry and positioning systems, the vehicle will carry on board a 2-axis doppler sonar, a gyrocompass, an obstacle avoidance sonar, an echo sounder and digitizer, pitch, roll and depth sensors, a data recorder and the control computer. The onboard control computer has the task of flying the vehicle along its pre-programmed survey path while recording bottom depth and position, communicating with the surface, and avoiding obstacles.

To achieve reliability while retaining economics in effort the onboard control system is implemented using distributed microprocessors.

The ARCS control system has been partitioned into seven major functional modules which will co-exist in a three processor distributed architecture. For increased reliability a second (minimum) control system will be installed, allowing the operator, or vehicle, to switch banks in case of failure. As well, a triply redundant 'fault tolerant monitor' is included to ensure a known recovery state in the event of failure of the control system.

Application software will be written in the PLM and PASCAL languages. A multi-tasking operating system, based on a message passing protocol, is ideally suited to the ARCS control system. Interprocessor communication is provided by an off-the-shelf software package, thus eliminating a potentially serious software work effort associated with designing an interprocessor message passing link.

Off-the-shelf microprocessor hardware will be used rather than custom designs. 16 bit single board computers will form a three node distributed system.

The basic philosophy behind the implementation approach adopted is the minimization of technical risk associated with designing a complex control system, use of industry standard processing boards and software tools to ensure a safe and known computer system environment, and finally to allow the design team to concentrate purely on the application rather than the development of a computer system.

STRUCTURE AND PROPULSION

Design of the structure and the propulsion system is an iterative process.

The requirements used in the design were:

- brushless DC motor for efficiency, reliability and ease of sealing

- direct drive for reliability and acoustic noise reduction
- component sizes known from instruments chosen
- known instrumentation power draw
- depth requirement of 400 m
- hull shape chosen for low drag and ease of handling
- aluminum chosen as the hull material for strengh/weight ratio and cost
- battery chosen for energy/volume ratio
- range goal of 100 NM at 5 knots

The desigh procedure was to estimate a battery requirement, design a hull around all the components with suitable weight and stability characteristics, determine the drag at 5 knots, and calculate the distance the vehicle could travel with an optimum practical thruster.

UNDER ICE SURVEY OPERATION

Two huts will be erected on the ice in the center of a 10 mile by 10 mile square which is to be surveyed. The square will be divided into four, 5 mile by 5 mile sectors, which will be surveyed individually. In the sector suspended from the ice will be four positioning transponders in a large square formation, the interrogator/receiver for the transponders in the center of the sector, a remote telemetry transponder towards the far corner of the sector, and another telemetry transponder at the base station.

Before the vehicle is launched, its memory is loaded with the mission way point pattern. After launching, the vehicle proceeds to traverse its way points, reporting heading, depth, obstacle information and any alarms back to the surface, and storing position and bottom depth on magnetic tape. The surface operator may request any particular sensor or status information, or he may edit the way point pattern, or command the vehicle to return home at any time during the mission via the acoustic telemetry link. He may also assume manual control of the vehicle, although it won't allow itself to be endangered. The vehicle is pre-programmed for obstacle avoidance strategies and behaviour during loss of telemetry or positioning.

Upon completion of the mission, low electric power, or other reasons for returning to base, the vehicle will navigate back to basecamp and look for the homing pinger on its obstacle avoidance sonar. It will head for the pinger either automatically or under operator control and fly into the recovery net.

ARCS VEHICLE - GENERAL CHARACTERISTICS

Length Overall	5.4 meters
Pressure Hull Diameter	60.75 cm
Displacement	1520 Kg
Weight	1510 Kg
Endurance (nominal)	5 knots for 20 hours
Maximum Speed	6 knots
Maximum Depth	400 meters
Propulsion and Onboard Power	177 AH x 115 V Nife Jungner Nicad battery pack 2 - 3/4 hp International Scientific brushless DC motors Single shaft with 21", 3 blade propeller
Speed Control	Proportionately variable
Onboard Control	Distributed microprocessor with double redundancy and fault tolerant monitor
Hardware	3 Intel 16 bit single board computers
Software	Operating system - RMX-86 application PLM and Pascal
Active Control	Closed Loop
Motions Controlled	Roll, yaw, heave, pitch
Sensors	Columbia SA 701 force balance inclinometers Robertson SKR-80 gyrocompass

	Bell and Howell pressure transducer
Actuators	Stepper motors
Obstacle Avoidance	Mesotech ISMI 100 Khz fixed beam sonar
Navigation	
Heading	Robertson SKR-80 gyrocompass
Drift	Ametek Straza MRQ 4015D 2-axis doppler sonar
Depth	Bell and Howell pressure transducer
Telemetry and Positioning	
Telemetry	Full duplex, synchronous FSK link
Data Rate	Variable between 25 - 200 bits/sec.
Modulation	Frequency shift keying
Frequency	To vehicle 7.5 - 10 Khz From vehicle 15 - 17.5 Khz
Diversity	Triple frequency diversity for data and clock channels
Coding	NRZ synchronous
Error Control	Parity checking or forward error correction
Range	6 km minimum in full duplex mode
Doppler Immunity	±8 knots
Data Input & Output	RS 232C asynchronous with DC 1 - DC 3 protocol

Positioning	Low frequency FM tones modulated on the carrier or Oceano long baseline positioning system
Sensors	150 Khz bilateral imaging sonar (optional) Digitized echo sounder and bottom profiler (optional) Fixed beam upward or downward looking 200 Khz ranging sonar (optional)
Surface Equipment	
Navigation	Oceano HP9845 with real time vehicle position display
Telemetry	IST electronics in 19" rack
Operator Interface	Control console in 19" rack plus IBM XT computer

AUTONOMOUS UNDERWATER VEHICLE SYSTEMS - HONEYWELL

Richard Tackabery
Hydro Products

Hydro Products and its parent organization, Honeywell Marine Systems, have embarked on a serious commitment in the field of Autonomous Underwater Vehicles (AUVs). A schematic showing Honeywell activities supporting AUV technology at Hydro Products is presented in Figure 1. These capabilities have significantly enlarged Hydro Product's scope in AUV's. The participation of both Hydro Products and Honeywell is shown in Figure 2. Hydro Products will have the program management responsibility for the overall system. The support from our other organizations is also identified in Figure 2. A survey of AUV applications is presented in Figure 3.

Hydro Products has been actively involved in undersea vehicles for well over ten years. Initially we began manufacturing oceanographic instruments, then TV systems. TV led us to development of the RCV-225, and from here to the RCV-150 and vehicles, sleds, etc.

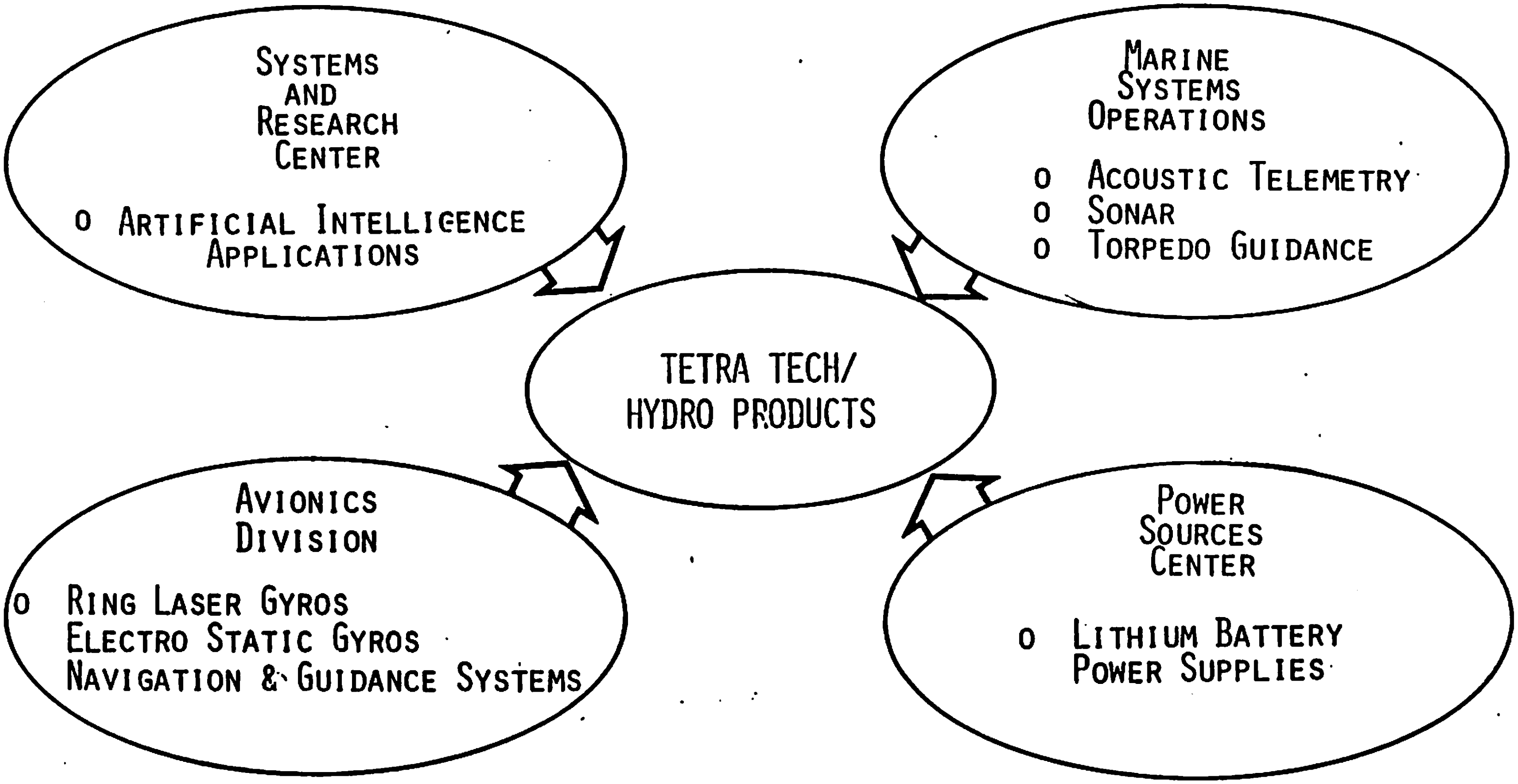
Past processes in our vehicle development programs are shown in Figure 4, an iterative process on parametric design of vehicle systems. Given the fixed parameters established for each system, subsystem, etc., through the processes of iteration we consequently produced a vehicle system. An example of the process is shown in Figure 5, a feasibility study for a Mine Development Vehicle.

A breakdown of an AUV system through to subsystems is presented in Figure 6. These are subsystems which we will be actively involved in during the process of our AUV development effort. The program, as established to date, is shown in Figure 7. The main goals, not shown in this figure, are to establish a vehicle of high reliability, robust in capability and modular such that we can evaluate future subsystems. During the course of this program we hope to participate - with Honeywell - in development of unique AUV sensors, such as target recognition, station-keeping, homing, etc. and subsystem development as listed in Figure 7. The test-bed program is scheduled for completion in December of 1984. At this stage we will continue with development of more sophisticated sensors, increase the system's intelligence level, and design more sophisticated effectors.

At this point in time we have not actually definitized any portion of the system. One of our primary efforts has been to accumulate data identifying the customers' potential requirements, and we have only recently reached the hardware development stage. Several of the systems we are considering at this time are shown in Figure 8. Lead acid batteries are now conceptualized simply on the basis of cost and recharging simplicity; plans are to upgrade these on the testbed near the end of its trials. Hydro Products has recently developed brusheless DC

MINE DELIVERY VEHICLE

HONEYWELL ACTIVITIES SUPPORTING AUVS TECHNOLOGY



SYSTEMS AND RESEARCH CENTER

- ARTIFICIAL INTELLIGENCE APPLICATIONS

MARINE SYSTEMS OPERATIONS

- ACOUSTIC TELEMETRY
- SONAR
- TORPEDO GUIDANCE

TETRA TECH/ HYDRO PRODUCTS

AVIONICS DIVISION

- RING LASER GYROS
  ELECTRO STATIC GYROS
  NAVIGATION & GUIDANCE SYSTEMS

POWER SOURCES CENTER

- LITHIUM BATTERY POWER SUPPLIES

Figure 1

ORGANIZATION

AUTONOMOUS VEHICLE SYSTEM PROGRAM	HYDRO PRODUCTS/ TETRA TECH	MSD	MAO	PSC	S&RC
PROGRAM MANAGEMENT					
SYSTEMS DEVELOPMENT	VEHICLE SYS	ACOUSTIC SYS TEST SUPPORT			
SUBSYSTEMS DEVELOPMENT	PROPULSION ENERGY & POWER CONTROL RECOVERY COMMUNICATIONS	ACOUSTIC TELEM ACOUSTIC TRACK	GUIDANCE & NAVIGATION		ARTIFICIAL INTELLIGENCE
COMPONENT DEVELOPMENT	SENSORS PROCESSING SOFTWARE	SENSORS PROCESSING SOFTWARE	SENSORS PROCESSING SOFTWARE	POWER SOURCES	IMAGE PROCESS. PLANNING EXPERT SYSTEMS

Figure 2

POTENTIAL UNTETHERED UNDERWATER VEHICLE APPLICATIONS

<u>COMMERCIAL/GOVERNMENT</u>

- UNDER-ICE SURVEY
- DEEP OCEAN SURVEY (20,000 FT)
- HIGH RATE SEARCH
- DEEP WATER PRODUCTION SUPPORT (5,000 FT TO 10,000 FT)
- PIPELINE SURVEY
- INTERNAL PIPELINE INSPECTION
- OCEANOGRAPHY
- NUCLEAR WASTE MONITORING

<u>MILITARY</u>

- MINE DELIVERY
- GENERAL PURPOSE DELIVERY
- UNDERWATER RECONNAISSANCE
- MINE COUNTERMEASURES
- SUBMARINE MODELING
- ASW TARGET
- TORPEDO DEFENSE

Figure 3

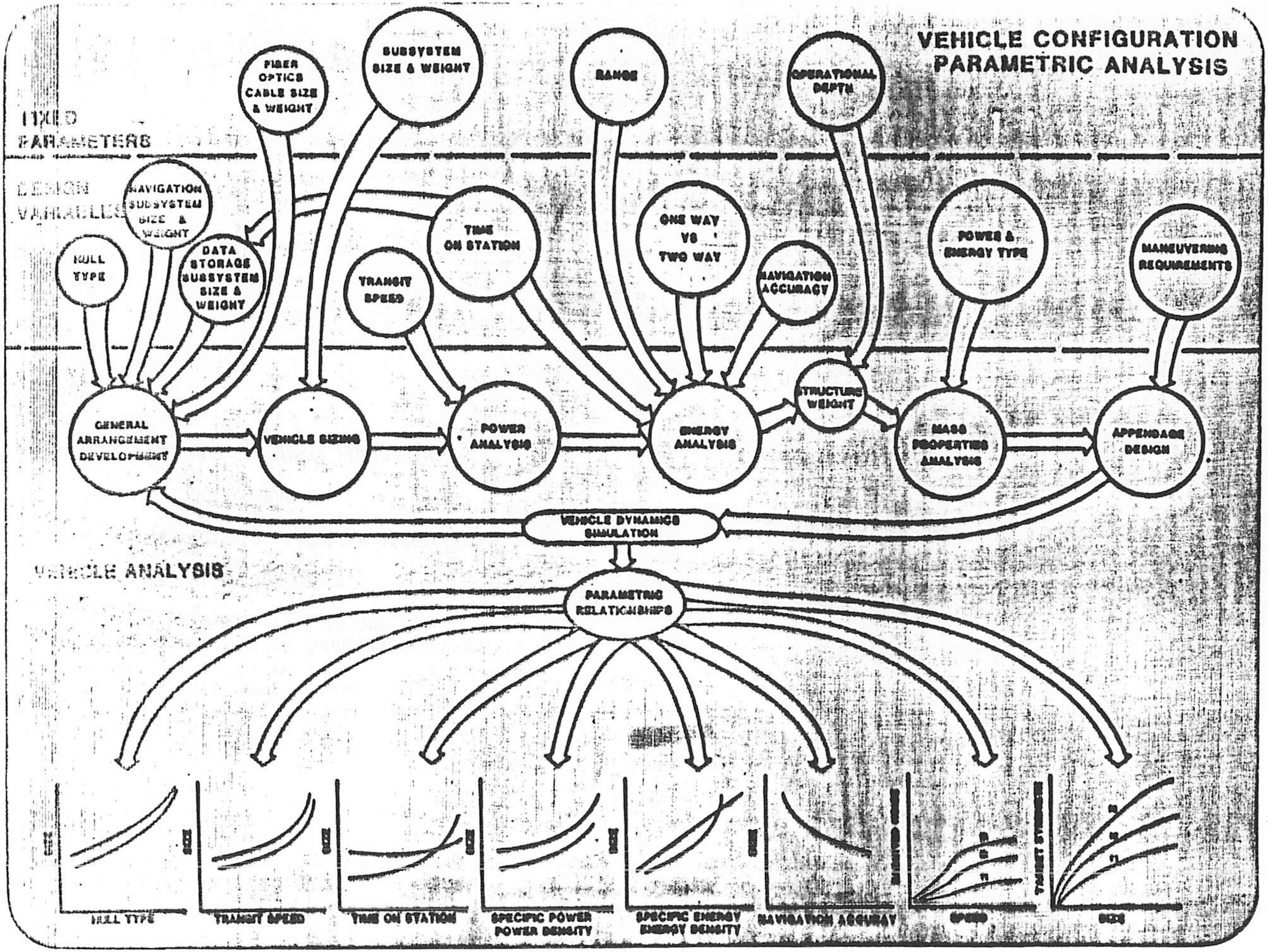

VEHICLE CONFIGURATION PARAMETRIC ANALYSIS
FIXED PARAMETERS
DESIGN VARIABLES
VEHICLE ANALYSIS
FIBER OPTICS CABLE SIZE & WEIGHT
SUBSYSTEM SIZE & WEIGHT
RANGE
OPERATIONAL DEPTH
NAVIGATION SUBSYSTEM SIZE & WEIGHT
HULL TYPE
DATA STORAGE SUBSYSTEM SIZE & WEIGHT
TIME ON STATION
TRANSIT SPEED
ONE WAY VS TWO WAY
NAVIGATION ACCURACY
POWER & ENERGY TYPE
MANEUVERING REQUIREMENTS
GENERAL ARRANGEMENT DEVELOPMENT
VEHICLE SIZING
POWER ANALYSIS
ENERGY ANALYSIS
STRUCTURE WEIGHT
MASS PROPERTIES ANALYSIS
APPENDAGE DESIGN
VEHICLE DYNAMICS SIMULATION
PARAMETRIC RELATIONSHIPS
SIZE
HULL TYPE
SIZE
TRANSIT SPEED
SIZE
TIME ON STATION
SIZE
SPECIFIC POWER POWER DENSITY
SIZE
SPECIFIC ENERGY ENERGY DENSITY
SIZE
NAVIGATION ACCURACY
SPEED
TARGET STRENGTH
SIZE

Figure 4

MDV FEASIBILITY STUDY

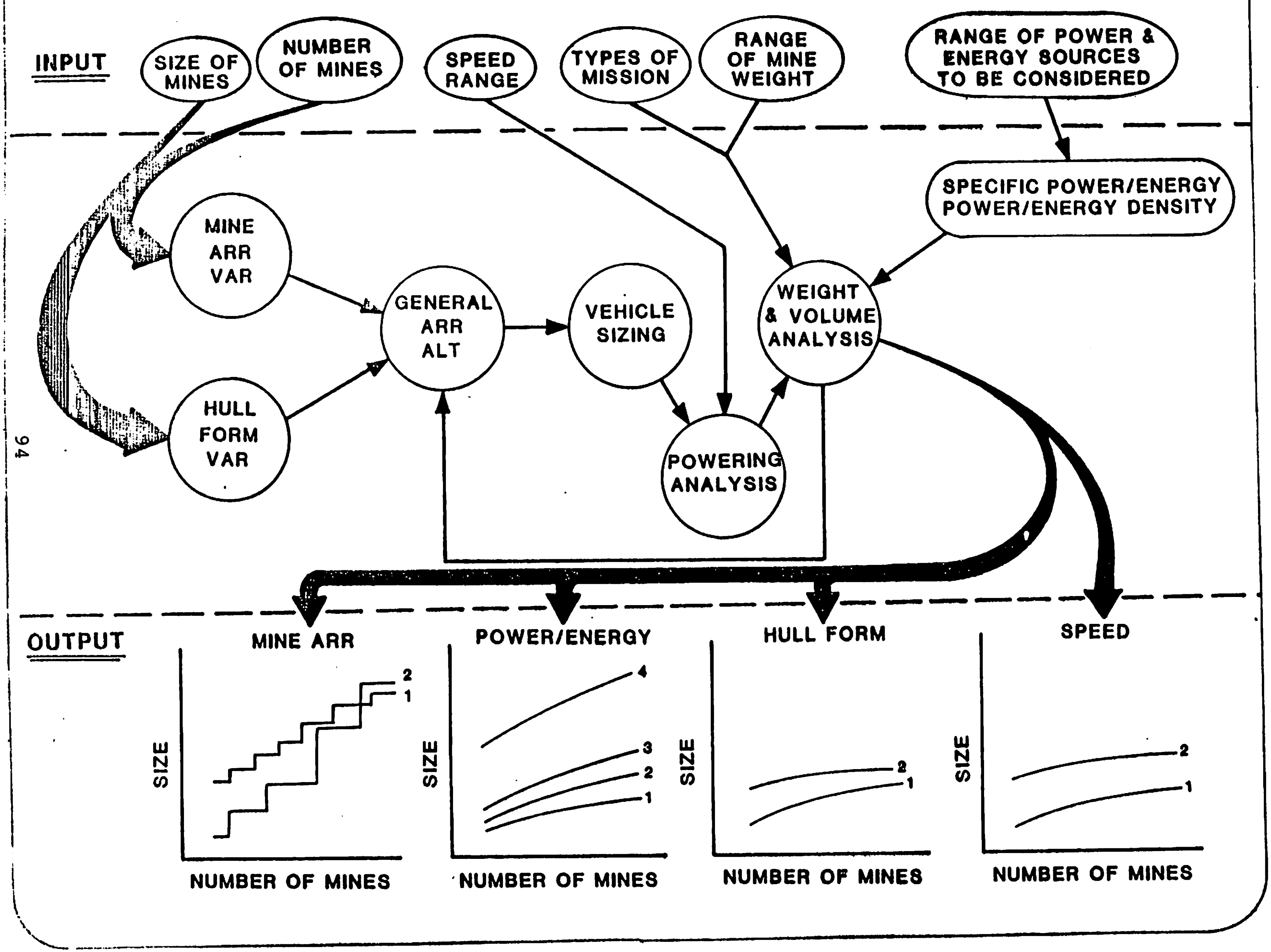
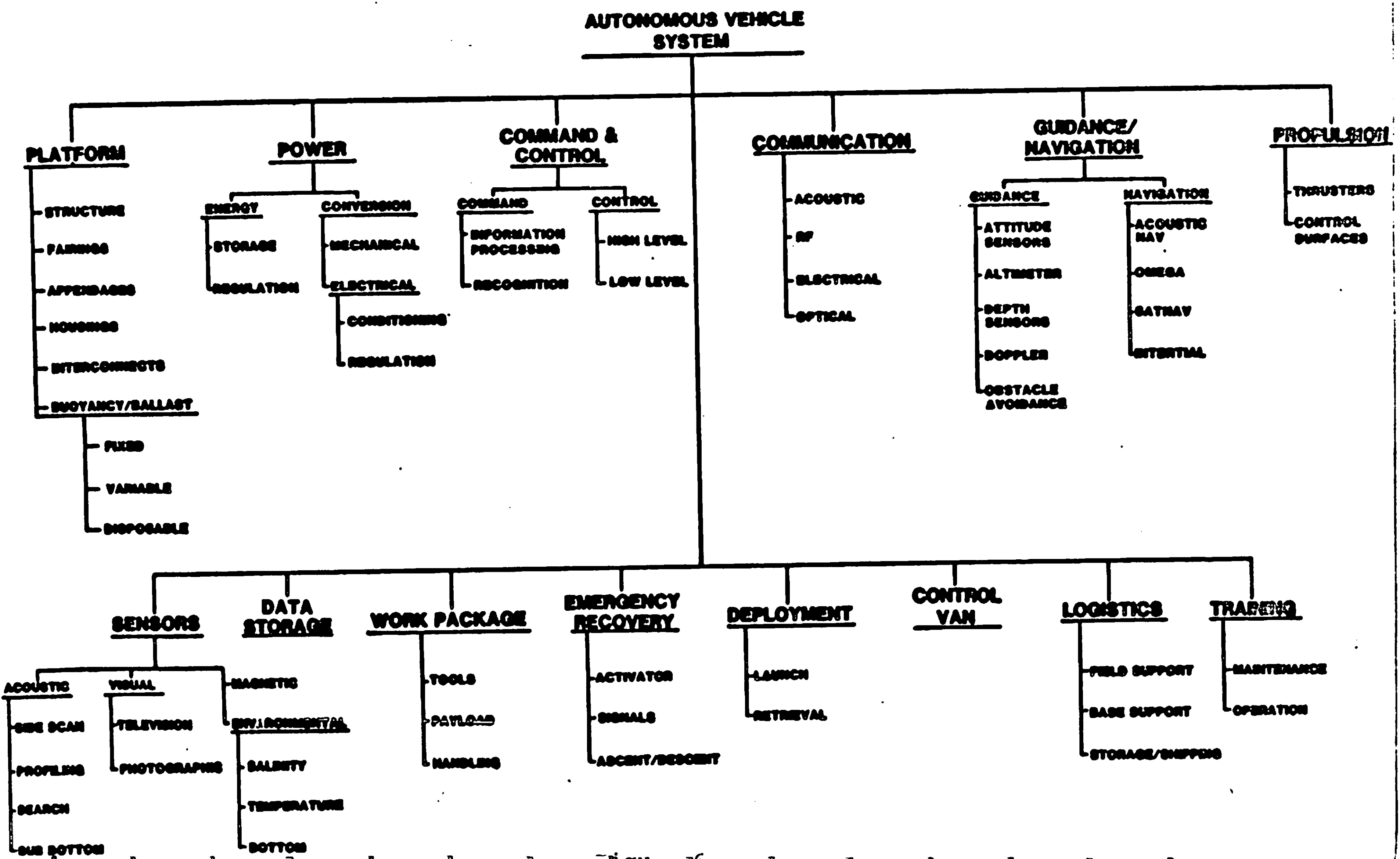


Figure 5

AUTONOMOUS VEHICLE SYSTEM SUBSYSTEM BREAKDOWN



igu 6

HYDRO PRODUCTS - HONEYWELL

OVERALL PROGRAM

- DESIGN, FABRICATE, ASSEMBLE AND EVALUATE A TEST BED.
- SCHEDULE - COMMENCE AT SEA TESTS IN LATE 1984.
- PRESENT TEST BED GOALS:
    - A) DEVELOP UNIQUE AUV SENSORS (I.E. TARGET RECOGNITION, STATION KEEPING, HOMING, ETC.)
    - B) DEVELOP UNIQUE AUV SUBSYSTEMS (I.E. NAVIGATION, COMMUNICATION, PROPULSION, LAUNCHING, RECOVERING, PROGRAMMING, AUTOMATIC CONTROLLING)
- FUTURE TEST BED GOALS:
    - A) DEVELOP ADVANCED SENSORS
    - B) EXPAND INTELLIGENCE LEVEL
    - C) DEVELOP ADVANCED EFFECTORS

Figure 7

PRESENT SYSTEM CONSIDERATIONS:

- ORTHOGANAL THRUSTERS FOR TRANSIT AND HOVERING.
- LEAD ACID BATTERIES WITH FUTURE UPGRADE POTENTIAL.
- BRUSHLESS D.C. PROPULSION MOTORS.
- STAND ALONE SUBSYSTEMS, I.E. DISTRIBUTED PROCESSORS FOR PROGRAMMING, INTELLIGENCE, COMMUNICATIONS, CONTROLS SYSTEMS, NAVIGATION, SONAR, ETC.
- ALL RECORDED DATA ON VIDEO TAPE.
- R.F. AND ACOUSTIC COMMUNICATION LINK.

Figure 8

propulsion motors for its RCV-225, these motors or upgraded versions are planned for the testbed vehicle. Stand alone subsystems are to allow a modular approach so that systems can be added or removed without interaction. Initially the RF link would be used to simply update controls or readout status, at intervals. At some time RF may be utilized for command/control or program modification, but this is not an immediate goal.

An endurance capability of six to eight hours is our immediate goal, with horizontal ranges in excess of four miles. Speed will be in the neighborhood of two to five knots. Navigation systems for the testbed vehicle are not yet established, but we are investigating utilizing doppler, and long baseline and short baseline systems. Inertial guidance has been ruled out at this time. The vehicle will probably be 5 to 6 feet long and 2 to 3 feet in diameter.

AN OVERVIEW OF COMMERCIAL UNDERWATER ACTIVITIES

Andre Galerne
International Underwater Contractors

For the past 20 or 30 years my competitors and I have called ourselves "diving" contractors. Now we call ourselves "underwater" contractors. This change has been brought about by the fact that we are not any longer only divers, we are underwater people who use, not only divers, but recompression chambers, submersibles, and ROV's with and without cables.

First, it is of interest to review how we arrived at the point we have reached today. In around 1817 a few Europeans, such as, Drager in Germany, Galenzzi in Italy, and Scebe-Gorman in England designed the first practical equipment for working underwater. The major drawback to their equipment was that it weighed roughly 200 lbs. in air and, divers were selected on the basis of their shoulder width, rather than their I.Q. Fortunately the equipment has changed and we went to scuba equipment, to fiberglass equipment which could be used by a wider variety of people.

The working conditions are often difficult. In some instances, such as working from offshore platforms, it is impossible to enter and leave the water safely with 200 lbs. of equipment on your shoulders. At other times the diver requires mobility which only scuba-type equipment offers. Conditions are seldom good. Only my friend Jacques Cousteau can dive in clear water all the time. Visibility is definitely a problem, not only for direct viewing, but for video and photography. Sometimes the weather is bad and the water may be covered with ice.

At International Underwater Contractors (IUC), we have established a diving school with a relatively sophisticated panel where we teach the students what to do and what not to do in shallow diving. One piece of training equipment consists of a barge that has, in its center, a vertical pipe through which the divers learn how to enter and leave the water. One of the advantages of this drill is to see whether or not the diver has claustrophobia. If so, we recommend that he pursue a different career so that he does not endanger his life or the life of somebody else. Each class consists of only 15 people, and we generally fail roughly 50 percent of the students before the end of the course. The school also trains students for deep water diving. To do this there is a large chamber in which a typical North Sea diving bell is situated. By pressuring the chamber to as much as 500 feet, the students can be taught to operate from the bell under deep water conditions. Our present limit of training is to 300 feet. We are proud that our equipment and training program makes IUC the only organization that has been reorganized by North Sea authorities for diver training. Our curriculum includes training in chamber operating procedures, gas and pressure analyses, and other aspects, in addition to diving.

The diving equipment we are using is highly portable and can be transported by truck and aircraft. Many of our jobs come with only a few days notice, which makes portability of equipment a necessity. The systems are, nonetheless, quite complex and require highly trained operators.

IUC's dedicated support ship is ALOHA. A work-boat modified to be a submersible and ROV tender. It carries a stern-mounted A-frame for launch/retrieval, and a short baseline navigation system. It is designed to handle our MERMAID submersible, a West German manufactured vehicle capable of 1000 feet depth. One of our jobs required cutting lines to which large subsurface buoys were attached. If a diver were used for this task it would require the support ship to stay directly over him. Hence, when the tether line was cut, the buoy would surface at a very rapid rate and possibly hit the ship's hull. In this case we used the submersible because, since it was not attached to the ship it permitted it to stand off at a safe distance clear of the buoy. In another instance we used the submersible to investigate a backup barge where gas was still coming out of the well which could jeopardize the diver's safety. IUC also has the 20 ton lock-out submersible BEAVER. It also is air transportable and has a longer range and duration than MERMAID. At a speed of 1/2 knot it can operate for 12 to 16 hours depending upon the water temperature. MERMAID, in addition to its diver lock-out capability, can be used for dry, 1-atmosphere transfer on a subsea production system or an immobilized military submarine.

We also have a deeper submersible, PISCES VI, tested to 10,000 feet with a depth capability of 8,300 feet. For four years PISCES VI has been on the drill ship DISCOVERER SEVEN SEAS. This contract has recently been awarded to an ROV operator. While we are not happy with losing the contract, we are aware that this is how technology operates. The ROV has not yet demonstrated that it can perform as well as the submersible, but there is a good chance that it will. PISCES VI is normally equipped with a television camera, a 35mm still camera (3-dimensions or normal). Three dimensional photography is frequently used, although, oddly, the customer does not seem impressed. To descend to 5000 feet in PISCES VI takes about 1 1/2 hours; ascent time is about the same. Descent and ascent is performed statically using ballast pumps. Compressed air is not used owing to the difficulties in controlling the vehicle as it nears the surface and the air bubble expands. One of the tasks PISCES VI performs is to observe the spudding procedures. Oddly, we have yet to have water depths, as determined by surface-oriented techniques, which agree with the length of drillpipe required to reach the bottom. There are a number of reasons for this, but we have learned never to trust depths acquired by surface (i.e.,echo sounding) techniques. After spudding in is completed the submersible is used to assist in installation of the permanent guide base which supports the Blowout Preventor tack (BOP). PISCES was present, but not employed, during a recent French drilling program where a new record depth for drilling over 6000 feet was established. On occasion we have assisted in re-entry (inserting the drill string into the guide base), but this is generally accomplished without the submersible and can take over an hour at times. With the submersible we arrange 12 minutes for re-entry.

IUC also uses a tethered, one-man submersible called MANTIS. Built in England by the OSEL Group. It is now working offshore near California. Interestingly, MANTIS is not much larger than some of the ROVs, such as TROV, which are now operating. The OSEL Group has recently modified the MANTIS to create a hybrid vehicle called DUPLUS. DUPLUS can operate either manned or unmanned or both modes concurrently. This latter configuration permits the surface to, for example, operate the manipulators, and the man in the vehicle to control the vehicle or vice versa. In the event of difficulty, the tether can be released and on-board batteries will provide 40 minutes of operation. The hull is of fiberglass and offers the advantage of being warmer inside than are vehicles composed of steel. The original vehicle was underpowered and we have now increased this by over 300 percent. This lack of power can be attributed to a lack of communication between manufacturer and user. As a general rule of thumb, we would encourage designers of such vehicles to at least triple the amount of power which calculations show is required. This is not the only vehicle which we have found to be underpowered. Indeed, all of the vehicles we have, regardless of manufacturer, are underpowered; it is a common problem.

One particular advantage of MANTIS is its mobility. In one instance we were contracted by Chevron, in California, to make a 1000 ft. dive. We were picked up ashore at 0900 by a helicopter. At 1000 the submersible was in the water. At 1015 it was on the bottom. At 1115 the job was finished and the vehicle surfaced at 1130. By noon we were back ashore. Had we used divers for this job, it would have taken in the neighborhood of 12 days. It is evident that sometimes the diver is not an economic alternative. But, nonetheless, there are some tasks which vehicles simply cannot perform and the diver must be used. This is particularly true of certain manipulative tasks where only a human can perform satisfactorily. We have also encouraged some operators to paint various values or components a different color. This greatly aids the diver in assuring that he is working on the proper component.

At times it is dangerous to use a man. During a job off Spain our submersible was at about 450 feet of depth and heading for the bottom at 4000 feet when the pilot heard a loud explosion. He assumed it was in the submersible's engine compartment. It was shortly discovered, however, that the drill string had broken at the surface. The LMRP, a connecting piece between the riser and BOP, was driven 30 feet into the bottom. The pilot acquired a transponder signal which was attached to the LMRP and then, with water jets, excavated down to where it was possible to attach a lift line and bring the LMRP to the surface from 4000 feet.

IUC also operates ROVs and has used the RCV-225, TREC, and recently purchased a RECON IV. The RCV-225 is essentially used only for viewing, although it does have a very small electric arm. Before acquiring the arm, we called the ROV VOYEAUR, because it could only look. We also have an untethered vehicle called the EPAULARD which recently completed a job for the US Navy and NOAA in the Pacific. The vehicle is tracked from the surface with a short baseline acoustic positioning system. The work we performed for the Navy was to locate and photograph an aircraft in 4000 feet of water off San Diego. The operation was highly successful and the Navy has already produced a 15 minute video tape of the operation.

The CMU Rover and the FIDO Vision and Navigation System

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1. Introduction

The CMU Rover is a small, highly mobile wheeled robot under construction at The Robotics Institute of Carnegie-Mellon University. It has independently steerable wheel sets, each of which has two wheels on a differential to provide smooth steering. Low level control of the Rover is by about a dozen microprocessors, doing everything from servoing the drive and steering motors and running the sensors to coordinating other microprocessors.

The Rover will navigate by stereo vision. The main sensor on the Rover is a television camera. The camera is mounted on a tilt-pan mechanism which is in turn mounted on a slider. The slider allows the camera to be moved from side to side. The basic idea of stereo vision is to take two or more pictures of the same scene with the camera at different positions along the slider. Then, if the same feature can be located in each picture, triangulation gives the location of that point, relative to the vehicle, in three dimensions.

The FIDO vision and navigation system will build up its map by locating new points by slider stereo. It must then plan a path to its goal that avoids known obstacles. It navigates along the path by using slider stereo to locate the same points from step to step. The apparent motion of those points (relative to the vehicle) gives the actual motion of the vehicle through the scene. The vehicle moves in a loop of: find points / plan a path / move / reacquire points / calculate motion.

The spiritual father of the CMU Rover is the Stanford Cart, developed by Hans Moravec as his thesis

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[1] The CMU Rover has been supported at the Carnegie-Mellon University Robotics Institute since 1981 by the Office of Naval Research under contract number N00014-81-K-0503.

project at Stanford University. The work at CMU on the Rover, and particularly on FIDO, benefits greatly from the Cart experience. Some of the interaction is as direct as borrowing programs, for instance to calibrate the camera. Other ideas, such as the slider stereo, are modifications of ideas developed at Stanford. And many of the interesting problems we are working on were pointed out by the Cart work.

A final legacy of the Stanford cart is the complete sets of images used on the cart's successful runs. A successful cart run usually took about 20 steps. At each step the cart would slide the camera from one side to the other, taking 9 pictures. All these images have been saved and are being moved to CMU. Since this is the exact data used by the cart, we can get precise performance comparisons. We are also making extensive use of this data for testing and debugging FIDO, pending the completion of the CMU Rover hardware and low level software.

It may seem strange to discuss a wheeled robot at a conference on underwater vehicles. But many of the problems, both hardware and software, are the same in both domains. For instance, FIDO's camera solver calculates an unrestricted camera motion with six degrees of freedom. This allows for uneven terrain on land, and for direct application underwater. Even our sensors are familiar underwater; besides a television camera, the Rover will have a variety of sonars for object detection and eventually for imaging.

2. The Stanford Cart

The Cart was a minimal remotely controlled TV equipped mobile robot which lived at the Stanford Artificial Intelligence Laboratory (SAIL). A computer program was written which drove the Cart through cluttered spaces. gaining its knowledge of the world entirely from images broadcast by the onboard TV system.

The Cart used several kinds of stereo vision to locate objects around it in 3D and to deduce its own motion. It planned an obstacle avoiding path to a desired destination on the basis of a model built with this information. The plan changed as the Cart perceived new obstacles on its journey.

The system was reliable for short runs, but slow. The Cart moved one meter every ten to fifteen minutes, in lurches. After rolling a meter it stopped, took some pictures and thought about them for a long time. Then it planned a new path, executed a little of it, and paused again.

It successfully drove the Cart through several 20 meter courses (each taking about five hours) complex enough to necessitate three or four avoiding swerves. Some weaknesses and possible improvements were suggested by these and other, less successful, runs.

2.1. A Cart Run

The Cart was then manually driven to its obstacle course (littered with large and small debris) and the obstacle avoiding program was started. It began by asking for the Cart's destination, relative to its current position and heading. After being told, say, 50 meters forward and 20 to the right, it began its maneuvers. It activated a mechanism which moved the TV camera, and digitized nine pictures as the camera slid in precise steps from one side to the other along a 50 cm track.

A subroutine called the *interest operator* was applied to the one of these pictures. It picked out 30 or so particularly distinctive regions (features) in this picture. Another routine called the *correlator* looked for these same regions in the other frames. A program called the *camera solver* determined the three dimensional position of the features with respect to the Cart from their apparent movement from image to image.

The *navigator* planned a path to the destination which avoided all the perceived features by a large safety margin. The program then sent steering and drive commands to the Cart to move it about a meter along the planned path. The Cart's response to such commands was not very precise. The camera was then operated as before, and nine new images were acquired. The control program used a version of the correlator to find as many of the features from the previous location as possible in the new pictures, and applied the camera solver. The program then deduced the Cart's actual motion during the step from the apparent three dimensional shift of these features. Some of the features were pruned during this process, and the interest operator was invoked to add new ones. This repeated until the Cart arrived at its destination or until some disaster terminated the program.

3. Rover Hardware

The major impediments to serious extensions of the Cart work were limits to available computation, resulting in debilitatingly long experimental times, and the very minimal nature of the robot hardware, which precluded inexpensive solutions for even most basic functions (like "roll a meter forward").

We are addressing these problems at CMU in an ambitious new effort centered around a new, small but sophisticated mobile robot dubbed the CMU Rover. The project so far has been focused on developing a smoothly functional and highly capable vehicle and associated support system which will serve a wide variety of future research.

The shape, size, steering arrangements and onboard and external processing capabilities of the Rover system were chosen to maximize the flexibility of the system (naturally limited by present day techniques).

The robot is cylindrical, about a meter tall and 55 cm in diameter and has three individually steerable wheel assemblies which give it a full three degrees of freedom of mobility in the plane. Initially it will carry a TV camera on a pan/tilt/slide mount, several short range infrared and long range sonar proximity detectors, and contact switches. Our design calls for about a dozen onboard processors (at least half of them powerful 16 bit MC68000s) for high speed local decision making, servo control and communication.

Serious processing power, primarily for vision, is to be provided at the other end of a remote-control link by a combination of a host computer VAX 11/780 an ST-100 array processor (a new machine from a new company, Star Technologies Inc., which provides 100 million floating point operations per second) and a specially designed high performance analog data acquisition and generation device. The Stanford Cart used fifteen minutes of computer time to move a meter. With this new CMU hardware, and some improved algorithms, we hope to duplicate (and improve on) this performance in a system that runs at least ten times as fast, leaving room for future extensions.

We hope eventually to provide a manipulator on the Rover's topside, but there is no active work on this now. We chose the high steering flexibility of the current design partly to ease the requirements on a future arm. The weight and power needed can be reduced by using the mobility of the Rover to substitute for the shoulder joint of the arm. Such a strategy works best if the Rover body is given a full three degrees of freedom (X, Y and angle) in the plane of the floor. Conventional steering arrangements as in cars give only two degrees at any instant.

3.1. Rover Details

Three degrees of freedom of mobility are achieved by mounting the chassis on three independently steerable wheel assemblies. The control algorithm for this arrangement at every instant orients the wheels so that lines through their axles meet at a common point. Properly orchestrated this design permits unconstrained motion in any (2D) direction, and simultaneous independent control of the robot's rotation about its own vertical axis. An unexpected benefit of this agility is the availability of a "reducing gear" effect. By turning about the vertical axis while moving forward the robot derives a mechanical advantage for its motors. For a given motor speed, the faster the Rover spins, the slower it travels forward, and the steeper the slope it can climb. (Visualization of this effect is left as an exercise for the reader.)

To permit low friction steering while the robot is stationary, each assembly has two parallel wheels connected by a differential gear. The drive shaft of the differential goes straight up into the body of the robot. A concentric hollow shaft around this one connects to the housing of the differential. Turning the inner shaft causes the wheels to roll forwards or backwards, turning the outer one steers the assembly, with the two wheels rolling in a little circle. The assemblies were manufactured for us by Summit Gear Corp.

Each shaft is connected to a motor and a 4000 count/revolution optical shaft encoder (Datametrics K3). The two motors and two encoders are stacked pancake fashion on the wheel assembly, speared by the shafts. There are no gears except for the ones in the differential.

The motors are brushless with samarium-cobalt permanent magnet rotors and three-phase windings (Inland Motors BM-3201). With the high energy magnet material, this design has better performance when the coils are properly sequenced than a conventional rotating coil motor. The coils for each are energized by six power MOSFETs (Motorola MTP1224) mounted in the motor casing and switched by six opto-isolators (to protect the controlling computers from switching noise) whose LEDs are connected in bidirectional pairs in a delta configuration, and lit by three logic signals connected to the vertices of the delta.

The motor sequencing signals come directly from onboard microprocessors, one for each motor. These are CMOS (Motorola MC146805 with Hitachi HM6116 RAMs) to keep power consumption low. Each processor pulse width modulates and phases its motor's windings, and observes its shaft encoder, to servo the motor to a desired motion (supplied by yet another processor, a Motorola 68000, the *Conductor* as a time parameterized function). Though the servo loop works in its present form, several approximations were necessary in this real-time task because of the limited arithmetic capability of the 6805. We will be replacing the 6805 with the forthcoming MC68008, a compact 8 bit bus version of the 68000.

The shaft encoder outputs and the torques from all the motors, as estimated by the motor processors, are monitored by another processor, *the Simulator*, a Motorola MC68000 (with all CMOS support circuitry the power requirement for our 32K 68000 is under one watt. The new high performance 74HC series CMOS allows operation at full 10MHz speed.) , which maintains a dead-reckoned model of the robot's position from instant to instant. The results of this simulation (which represents the robot's best position estimate) are compared with the desired position, produced by another 68000, *the Controller*, in the previously introduced *the Conductor*, which orchestrates the individual motor processors. The Conductor adjusts the rates and positions of the individual motors in an attempt to bring the Simulator in line with requests from the Controller, in what amounts to a highly non-linear feedback loop.

Other onboard processors are:

Communication	A 68000 which maintains an error corrected and checked packet infrared link with a large controlling computer (a VAX 11/780 helped out by an ST-100 array processor and a custom high speed digitizer) which will do the heavy thinking. Programs run in the Controller are obtained over this link.
Sonar	A 6805 which controls a number of Polaroid sonar ranging devices around the body of the Rover. These will be used to maintain a rough navigation and bump avoidance model. All measurements and control functions of this processor and the following ones are available (on request over a serial link) to the Controller.
Camera	A 6805 which controls the pan, tilt and slide motors of the onboard TV camera. The compact camera broadcasts its image on a small UHF or microwave transmitter. The signal is received remotely and the video signal captured by a high bandwidth digitizer system and then read by the remote VAX. There are tentative plans for a minimal vision system using a 68000 with about 256K of extra memory onboard the Rover, for small vision tasks when the Rover is out of communication with the base system.
Proximity	A 6805 which monitors several short range modulated infrared proximity detectors which serve as a last line of defense against collision, and which sense any drop off in the floor, and contact switches.
Utility	A 6805 which senses conditions such as battery voltage and motor temperature, and which controls the power to non-essential but power hungry systems like the TV camera and transmitter.

Communication between processors is serial, via Harris CMOS UARTs, at a maximum speed of 256 kilobaud. The Conductor talks with the motor processors on a shared serial line and the Controller communicates with the Sonar, Camera, Proximity, Utility and any other peripheral processors by a similar method.

The processors live in a rack on the second story of the robot structure, between the motor and battery assembly (first floor) and the camera plane (penthouse).

The Rover is powered by six sealed lead-acid batteries (Globe gel-cell 12230) with a total capacity of 60 amp hours at 24 volts. The motors are powered directly from these, the rest of the circuitry derives its power indirectly from them through switching DC/DC converters (Kepco RMD-24-A-24 and Semiconductor Circuits U717262). Each 6805 processor draws about one eighth of a watt, each 68000 board only one watt.

Physically the robot is a meter tall and 55 cm in diameter. It weighs 90 kilograms. The maximum acceleration is one quarter g, and the top speed is 10 kilometers/hour. With appropriate onboard programming the motions should be very smooth. The great steering flexibility will permit simulation of other steering systems such as those of cars, tanks and boats and other robots by changes in programming.

4. Vision and Navigation

There are several software problems that need to be addressed by any mobile robot, including vision (or other sensing), path planning, system architecture, and processing efficiency. In the earliest days of mobile robots, every system had to attack each one of those problems. Since we have the software from the Stanford cart available, FIDO will be able to address the above problems one at a time, and use the existing software for the rest of the system. The main effort of building FIDO is on vision and navigation. Other questions that also need to be considered include systems architecture and processing efficiency.

4.1. Vision

There are two crucial parts of the vision system used by the Stanford Cart that deserve attention: the interest operator and the correlator. The interest operator is responsible for picking points to be tracked from slider position to slider position, while the correlator does the actual tracking. The actual tracking uses a "pyramid" of reduced-resolution versions of each image. A point in one image is located in a second image using a coarse-to-fine strategy. First, the correlator is used to find the area around the point in the smallest version of the search image. That area constrains the part of the next larger version of the image that the correlator has to search, and so on up the pyramid. The effectiveness of this "zooming-in" process is closely tied to the algorithms used by the interest operator and the correlator.

4.1.1. Interest Operator

A good interest operator will pick points that can be reliably tracked from image to image. Bland areas, for example, are not very "interesting" points. Neither are points on the edges of objects: while they are easy to track in one dimension, their location along the edge is hard to determine. Good points are corners of objects and surface markings. The Moravec interest operator, used on the Stanford Cart, looks for image patches with high variance in all eight orthogonal and diagonal directions. More precisely, the measure of "interestingness" is the minimum of the variance in any of the eight directions, taken over some (typically 6 pixel square) window. Patches whose interestingness is a local maximum are candidate points.

There are at least two problems with this measure. First of all, it does not reject edges unless they are aligned in one of the 8 directions. Edges that run at odd multiples of 22.5 degrees can produce spurious interesting points. A second problem has to do with the way points are tracked from image to image. The interest operator is applied only at one resolution, often to the 120 by 128 image. Just because a point is interesting, and therefore easy to find, at that resolution doesn't mean that it will be interesting at other levels of the pyramid of reduced images. For instance, the interest operator might pick a small patch of texture surrounded by a bland area. At lower resolutions (smaller versions of the image), the local texture could get smoothed out, making the point hard to locate. A final problem is with interesting points that are not the image of a unique physical point in the scene. Specular reflection (lighting highlights) or the apparent intersection of a nearby edge and a distant object will be interesting points, but may not stay fixed as the viewpoint moves. This adds error to the navigation.

One solution that we have implemented uses autocorrelation at all levels of reduction. Once a candidate point is picked, a small patch around it is correlated with the surrounding area. A point that is easy to find will have low correlation coefficients at every place except at its origin. We can do this at every level of the pyramid, and find that place where the spurious correlation coefficient is highest. That value is related to the minimum amount of noise allowed before the correlation will go astray. Points that are unique at all levels of the pyramid by this measure should be easier to track from image to image. Note that this interest measure deals with the first two objections (limitation to 8 principle angles and limitation to one level of the pyramid), which are image properties. It does not, however, address the third problem mentioned above (interesting points that are not the image of a single physical location), which is a property of the scene and much harder to deal with. In a sense, this is a chicken and egg problem: if we knew which corners were formed by two different objects, we wouldn't have to find interesting points.

4.1.2. Correlation

At any level of resolution, a point is located by correlation. Correlation compares the pixels in a small area around the given point with the corresponding pixels in the other image. The patch is moved around looking for the best match, which is the location with the largest correlation coefficient.

There is no one method of calculating correlation coefficients that is always best. The most common technique is "normalized correlation", which compares the covariance of two image patches with the product of their variances. The term "normalized" means that any linear or scalar transformation of either image patch does not affect the correlation coefficient.

Moravec points out two problems with this measure. First, it is insensitive to changes in contrast. This is useful for many applications, but wastes information in image comparison where contrast is important. Secondly, it has a degeneracy when one of the two image patches in completely uniform. When this measure is used over small (e.g. 4 pixels square) windows, such a degeneracy is not uncommon. In order to deal with these two problems, Hans defines a new measure of correlation, which he calls "pseudo-normalized". This new measure incorporates the contrast differences (it varies as the cosine of the slope of the line of best fit). Furthermore, it only has a degeneracy when both image patches are uniform. This should be a very rare occurrence, since the patches from the first image come from areas picked by the interest operator and should therefore have a lot of texture and variation.

Pseudo-normalized correlation is a step up from normalized correlation in that it uses the information provided by contrast, but it still wastes information by throwing away the means of the windows. We are developing a third correlation coefficient, similar to pseudo-normalized but also taking into account the average brightness of an image patch. The exact rule used by such a coefficient will depend on the internals of the camera, and possibly on other factors. Part of the reason for ignoring intensities in Moravec's pseudo-normalized correlation is that the camera used by the Stanford Cart had an automatic gain control. Especially in the outdoor runs, where some images contained large areas of white cardboard in direct sunlight, the gain control could vary considerably from one image to the next. This made absolute intensity of the image of the same scene point change. Some use of intensity may add reliability to the correlator for the runs at Stanford; use with the CMU Rover will depend on the type of camera used.

4.2. Path Planning

Finding a path from the current vehicle location to a goal location in a cluttered environment is difficult and time-consuming. For the CMU Rover, path planning must deal with the following problems:

- Uncertainty in position of a point. The accuracy in determining a point's position is limited by the resolution of the camera and the accuracy of the correlation process.

- Uncertainty in extent of objects. FIDO only knows about individual points and has no concept of objects. This is not as bad as it seems, though, because the interest operator often picks points on the outlines of objects. It will also tend to see more points on an object as the Rover approaches closer.

- Unmapped areas. Typical camera-lens combinations have about a 60 degree field of view. This leaves a large part of the world literally out of the picture. For the old Stanford cart, this wasn't too much of a problem. Since the vehicle had a large turning radius, during a short move it would stay within the area it had seen from previous locations. The new CMU Rover, in contrast, can drive off in any direction at any time. So the path planner must ensure that the next step stays within charted terrain. A planned path may go through unseen territory further away, but the chances of encountering unexpected obstacles go up with the amount of uncharted terrain included in the path.

- Occluded areas. The area behind an object will be blocked from view. Paths that go through an occluded area are more likely to encounter unexpected obstacles than paths that go through visible areas.

- Vehicle location error. This has two facets. First, the dead reckoning of the vehicle may be off by 10 or 20 percent. So any individual step must take that into account and be sure to clear obstacles by some safety margin. Second, the vision system will have some error, so the motion it deduces for a step will not be exactly correct. So the world model may drift. Points that are being tracked continuously will still be in the right location relative to the vehicle, but points that were seen earlier and were not reacquired will appear to drift. In some of the Stanford Cart runs, the same corner of the same object was represented in the world map at several different locations, since it had been seen and lost several times. This had the effect of enlarging the object and blocking off paths that were actually open. One possible solution is to dissipate objects that have not been reacquired even though they should be in view.

- World model update. As the Rover moves, it sees new objects and enters them into its world model. This means that the planned path has to be reviewed, and perhaps replanned from scratch, at every step.

- Data sharing between navigation and path planning. The same data is used both to plan an obstacle-free path to the goal and to derive vehicle motion from apparent object motion. If the data were just used for path planning, we could afford to use finer resolution near the path and coarser resolution on the periphery. Unfortunately, precise navigation requires data from points spread as far apart as possible. So we have to keep as much detail as we can, even off in the fringes.

Most path-planning algorithms abstract the search space to polygonal or round obstacles. There are two ways to attack the resulting abstract problem. One school of thought searches for as short a path as possible, just grazing the edges of obstacles. The other approach looks for paths that stay as far as possible from obstacles.

One problem with such methods is that neither of the above types of paths is always "best". Paths that clip corners have little margin for error, and restrict the field of view of the robot. Paths that stay as far away from all obstacles as possible can go much further out of their way than needed.

Another problem with such methods is that they throw away too much information in the abstraction. There is much more information that should be explicitly considered, including uncertain positions and unmapped areas.

One method we are exploring is to search in a geometric space rather than in a graph abstraction. The floor can be divided in squares. The cost associated with a square will include a factor for closeness to obstacles, a penalty for being out of the current field of view or being occluded by another object, and an uncertainty factor if it has never been seen. By adjusting the relative weights of the cost factors, we can make the robot more or less "curious" about unmapped areas, and more or less "cautious" about staying away from know objects. This also provides a framework for gradually dissipating objects that have been lost by the visual tracking system.

4.3. Architecture Issues

FIDO, and the Rover it controls, will run in the "real world": an unconstrained office environment, with little or no control over lighting or object placement and no *a priori* knowledge of the world. The Rover is a complicated machine, with plans to incorporate other types of sensors besides vision. The possibilities include proximity, imaging sonar, contact, active rangefinding, inertial, satellite-based navigation, and others. The complexity of the environment and the complexity of the Rover both point out the need for a flexible control architecture. In the construction of FIDO, we may be forced into more expert system-like control schemes. Things we would like to try include:

- Reacquire pruned points. Some points aren't correctly tracked from step to step. After the vehicle's motion has been determined, we can go back and look for those points in a constrained area.

- Varying the number of points that need to be tracked as part of a time/accuracy trade-off. This could also vary from place to place during a run, depending on the richness of the visual environment.

- Update estimates of point and vehicle location errors. It would be nice to know how accurately the vehicle's dead reckoning system is working. This will change as the vehicle moves from one type of surface to another.

- Running the correlator "backwards". Sometimes too few points are tracked for reliable navigation. Then it may be better to use the interest operator to pick points in the current image, and to try to find them in previous images. This is the opposite of the usual direction of processing.

- Optical flow techniques. These use a single camera position rather than slider stereo to deduce camera motion. Optical flow is the way a person watching a movie gets a very realistic feeling of depth and motion with no stereo clues.

FIDO is not intended to be an "expert system". We are explicitly ignoring some of the interesting expert systems issues, such as sensor degradation. At the same time, other elements of the problem such as interpretation of data from multiple sensors suggest that at least our thinking, if not the final software, should reflect an expert systems philosophy.

4.4. Multiple Computers

Many of the algorithms used by FIDO decompose cleanly into parallel tasks. For instance, each point found in the central image has to be located in all the other images (8 other images for the Stanford data). Calling the correlator 8 times for each point can easily use 50 percent of the total run time. All 8 correlations could go in in parallel with little communication needed. One possibility is to use eight processors going at the same time. At CMU we have a large number of Perqs, a powerful personal computer built by Three Rivers Computer Company and connected to each other over a Xerox Ethernet. The code used for image correlation is relatively small and straightforward, and uses almost exclusively integer arithmetic. Microcoded integer arithmetic on a Perq can be a factor of two or more times faster than the same code running on an unloaded DEC Vax-11/780, the machine on which FIDO currently runs. So with eight Perqs going in parallel, spectacular speedups may be possible.

There is a catch: the time spent shipping images to the Perqs from wherever they are stored or generated. As long as we are running from stored image sequences, it will be possible to prefetch the images for the next step while the Vax controlling the process is busy updating its world model, doing path planning, and generating displays. And there is a possibility that all eight Perqs could be interfaced to the digitizer that will some day sit on the CMU Rover. The Perqs will certainly be much more likely to get interfaced to the digitizer if there is already a program running on them that could use it to good advantage.

Acknowledgements

The CMU Rover would not be possible without the efforts of a large number of people: there are about 15 full- or part-time members of the Mobile Robot Laboratory. In particular, Larry Matthies is collaborating with me on the design and implementation of FIDO. I would particularly like to thank Hans Moravec, first of all for running the project and making it fun and interesting to work on, and second for permission to abstract the sections in this article on the Stanford Cart and Rover Hardware from another article. Finally, Raj Reddy has done a lot to make the CMU Robotics Institute a good place to do research, and deserves our thanks.

Update on Remotely Operated Vehicle Research at the MIT Man-Machine Systems Laboratory

Dana R. Yoerger

May, 1983

1. SUMMARY

Research is underway at MIT on a variety of problems concerning the remote control of underwater vehicles and manipulators. This research is sponsored by Office of Naval Research and the MIT Sea Grant Program. Under investigation are topics pertaining to both tethered and untethered systems. In this paper, these efforts will be summarized and one particular project demonstrating manipulation techniques through simulated acoustic channels will be discussed.

2. REMOTE MANIPULATION PROJECTS

Research on remote manipulation has been conducted at the MIT Man-Machine Systems Lab (MMSL) since the early 1960's, when work was begun on time-delayed remote manipulation in the context of performing remote manipulation on the moon. This work gave rise to the notion of supervisory control [1,2].

Work is currently being done that could allow manipulation to be performed using systems with acoustic telemetry. These projects use computer-graphic displays, computer-aided manual control techniques, and supervisory command languages and control systems to allow the human operator to tolerate the time delays and limited bandwidth imposed by the acoustic link.

3. COMPUTER GRAPHIC DISPLAYS

Several types of computer graphic display aids for remote manipulation are currently being used at MMSL. The first of these was a vector graphic display showing movements of the remote manipulator arm in real-time, designed by Winey [3]. This type of display could be used with very low bandwidth from the remote system, as only the joint angles need be transmitted. Fyler [4] extended this display technique, allowing models of the remote environment to be built up by probing with a touch sensor.

The newest display superimposes a computer generated vector image of the arm with a video image of the remote environment. This system utilizes a high resolution (1024x1024) color bit-map display. The generated image of the arm includes perspective effects [5]. This system could be used in conjuction with a predictor or could be used to "fill in" between new video frames with a slow-scan television system.

4. COMPUTER-AIDED MANUAL CONTROL TECHNIQUES

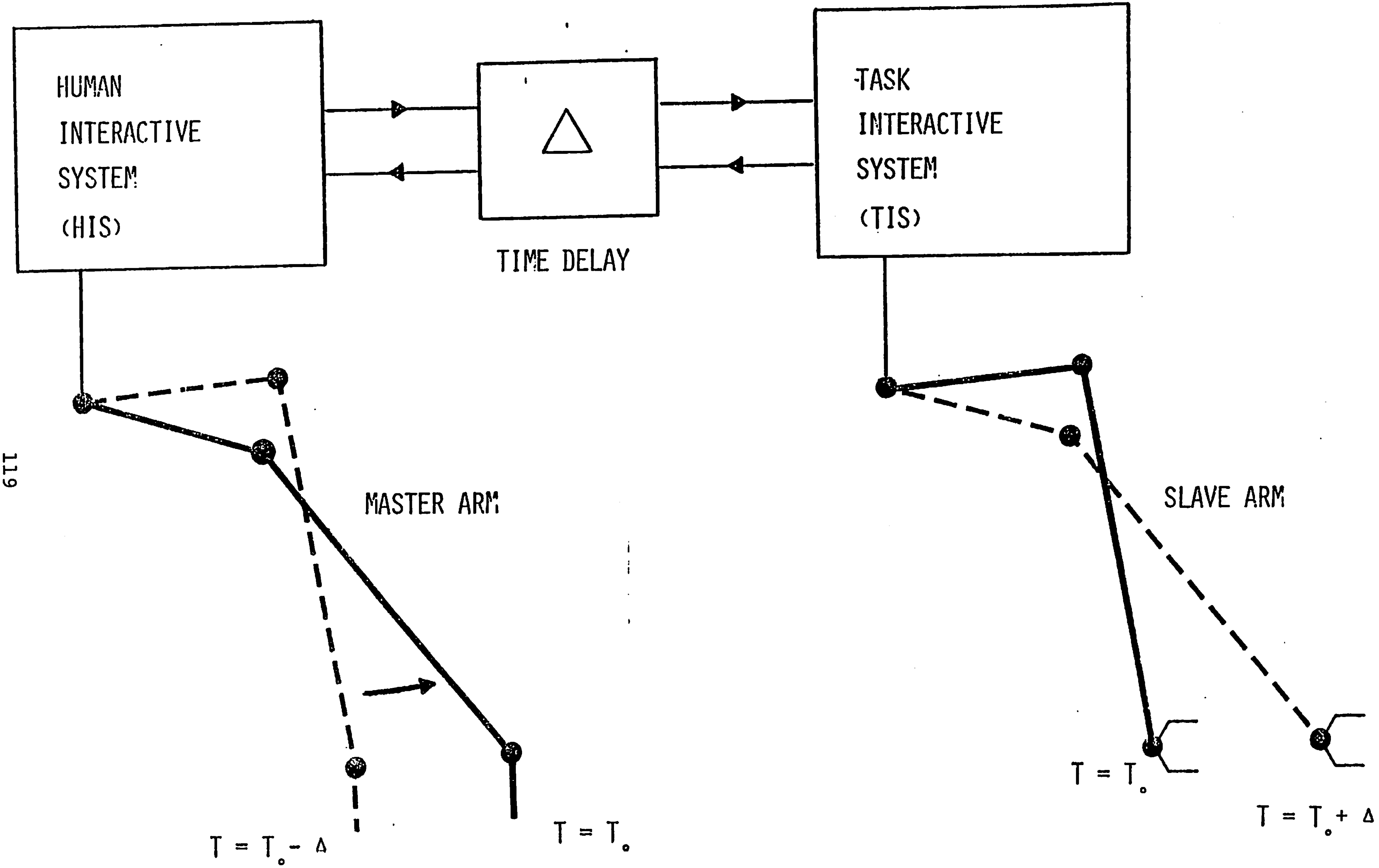
Time delays in a control loop can give rise to a variety of instabilities. In the case of a remote manipulator operated through an acoustic link, the time delays rising from propagation and data processing can lead to problems. Ferrell [1] showed that these delays made traditional master-slave control with force feedback unstable.

Unilateral master-slave control does not suffer from this problem. In this type of control, the master issues position setpoints for the slave arm servo loops which are closed on the remote vehicle, but the master is not servo-controlled to keep it in register with the slave. This mode of control does not allow the operator to gain useful information from the mechanical interaction of the arm with the remote environment, negating one of the main advantages of master-slave control.

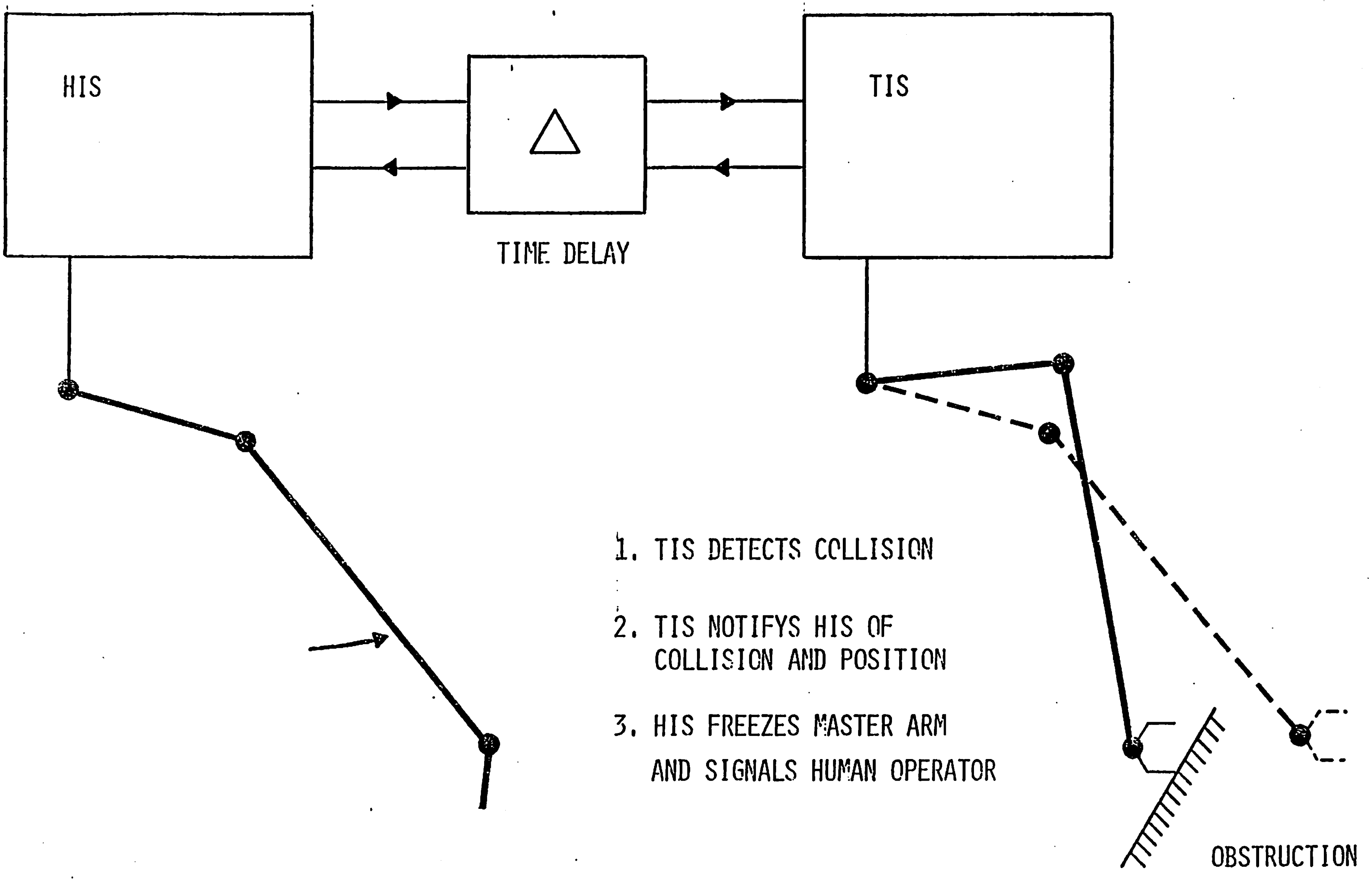
A computer-controlled system that addresses this problem is shown in figure 1. The Human Interactive System (HIS) manages the servo loops that control the position of the master arm, and the Task Interactive System (TIS) manages the servo loops that control the position of the slave arm. The HIS and TIS communicate through a telemetry link which imposes a total round trip time delay (Δ) for the operator's video feedback and manipulator control information.

When the remote arm is unconstrained, it will appear to follow the master arm after the time delay. Until the remote system contacts a fixed obstruction, the arm is controlled in a unilateral mode, that is the slave follows the master, but the master is not controlled to follow the slave.

Unilateral control works well until an obstruction is encountered. Figure 2 shows how this is handled. If the operator commands the slave to move through an obstacle, he won't see that this has occurred until later because of the time delay. In this system the remote system can detect a collision and unilateral control is ended. The TIS freezes the slave and notifies the HIS that a collision has occurred. The HIS then signals the operator and freezes the master arm. These actions prevent the operator from getting the system into further trouble and certainly doesn't allow any instability to arise. However, the entire



THE SLAVE FOLLOWS THE MASTER WITH APPARENT TIME DELAY Δ



1. TIS DETECTS COLLISION

2. TIS NOTIFYS HIS OF COLLISION AND POSITION

3. HIS FREEZES MASTER ARM AND SIGNALS HUMAN OPERATOR

system is now totally locked up.

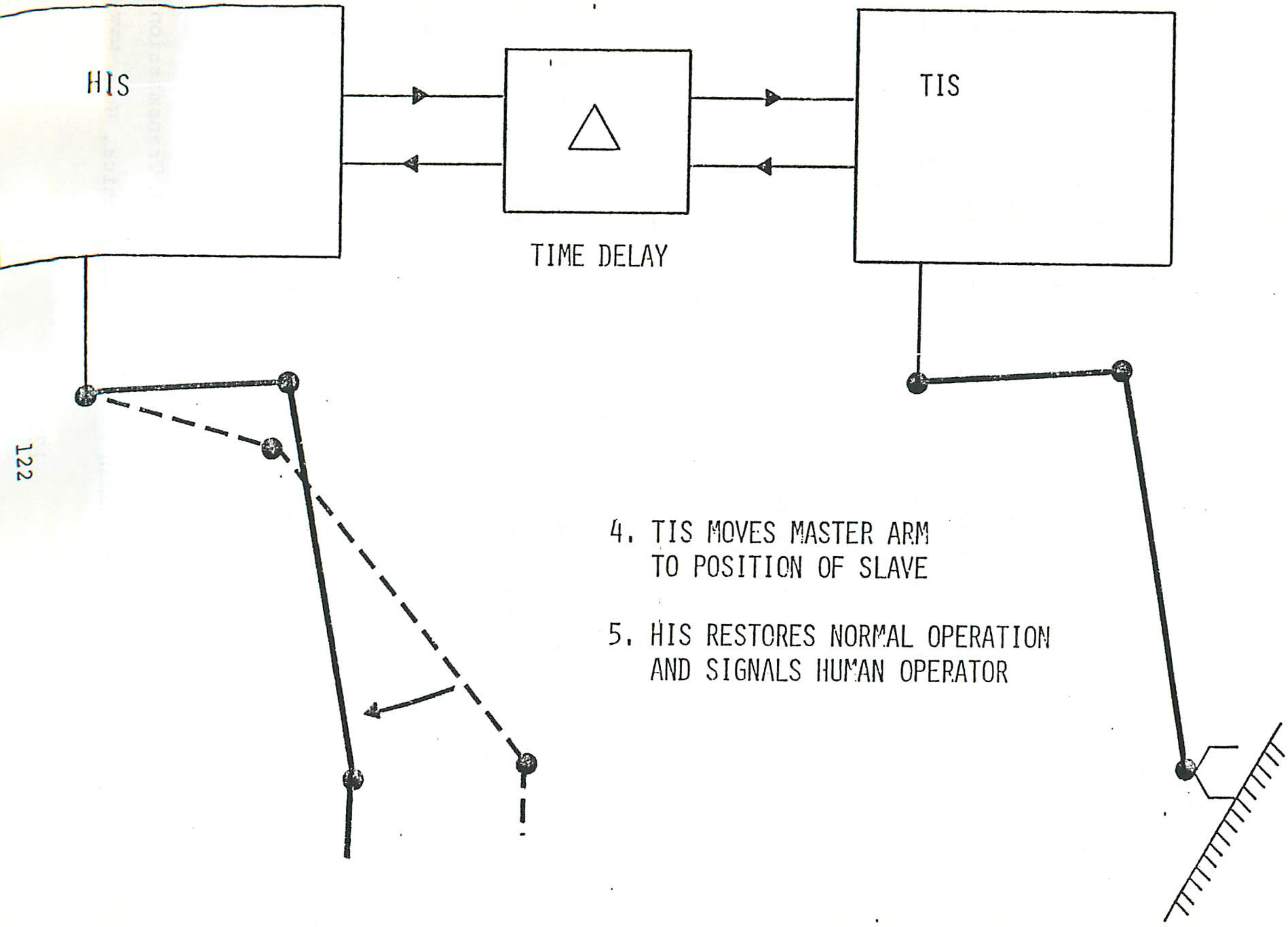
Figure 3 shows how the system shows the operator where the obstruction is and gets the system back in the normal operating mode. The HIS moves the master back into register with the slave, which is still located at the position where the collision occurred. The operator then can see and feel where the obstruction is, the operator is signalled, and the system is placed back in the normal operating mode.

This type of operation allows the operator to build his own "local model" of the remote environment by repeatedly probing at obstacles. It aids in resolving ambiguities in distance into the television image. He does not need to worry about generating excessive forces or damaging the remote manipulator even though his feedback is delayed.

5. SUPERVISORY COMMAND LANGUAGE AND CONTROL SYSTEM

A supervisory command system for control of remote manipulators has been designed and reported on elsewhere [6,7]. This language and control system allows the manually controlled remote manipulator to be used to teach the system enough about the remote environment so that the manipulator can be programmed to execute the task while the human operator monitors. This system allows inspection and maintenance tasks to be performed more accurately with a greatly reduced amount of manual control activity.

The method for dealing with time delay in a master-slave system described earlier is ideal for doing the teaching of the remote environment. In a video tape that accompanied this



4. TIS MOVES MASTER ARM
   TO POSITION OF SLAVE

5. HIS RESTORES NORMAL OPERATION
   AND SIGNALS HUMAN OPERATOR

demonstration, it was shown how the geometry of a curved object resembling a weld could be taught to the system using a time-delayed slow-scan video system and the computer-aided master slave control mode.

The experimental system was designed to simulate a system using an acoustic link. The video system has programmable sampling rate and a programmable time delay can be placed in the forward manipulator control path. In the demonstration shown, the delay was fixed at 1.5 seconds and the time between frames was 1.0 seconds. The resolution of the screen was 320x240, and each pixel has 4 bits of greyscale. These operating parameters correspond roughly to those attainable with a 9600 baud acoustic channel using demonstrated images compression techniques if the resolution was reduced to approximately 128x128.

The system could be programmed to follow a variety of trajectories based upon the geometry of the weldthat would be useful for cleaning the weld, doing close-up photography, and NDT task. In addition to the slow-scan television, the operator could monitor the progress of the system using a computer-graphic display.

This demonstration indicates that useful manipulation work can be done from an acoustically controlled system. Existing acoustic link, image compression, and manipulator supervisory control system design can be used to do this work.

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AN EXAMINATION OF THE APPLICATION OF KNOWLEDGE-BASED SYSTEMS IN UNMANNED UNTETHERED SUBMERSIBLES

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Introduction

The key ingredient needed to make an intelligent underwater vehicle autonomous is - KNOWLEDGE. To date most work on untethered submersibles has dealt with systems built around intelligent controllers.

The intelligent vehicles of the recent past control themselves with clearly defined mathematical functions that relate numerical inputs to desired responses. To be truly autonomous, however, control must be capable of going beyond just mathematical interrelations of input and output to employing a body of knowledge, or judgement, to solve the sophisticated problems of a complex mission. Traditionally, in tethered ROV's, this ability was supplied by a human expert, or pilot who was coupled to the vehicle by the tether. The pilot, with human intelligence, with a life-long data base of experience, and familiar with similar problems, would come equipped with an internal set of proven "logic rules" to apply in time of emergency.

Today autonomous vehicles are being considered for operations far beyond the physical reach of a human and beyond coupling by a communications channel. Serious hazards may be encountered, some of unexpected nature. Mechanized strategies must be found to cope with their consequences, as well as possible sub-system failures. The vehicle must have the skill to cope with adversity, to fulfill its task as well as possible, and to return home with the highest possible reliability.

System Considerations

An experienced vehicle designer, long accustomed to specifying a system response in terms of time varying inputs, will find it strange to think of a system in terms of heuristic and quantified input functions to be operated on by "production rules". As required responses become more judgemental and results are judged probablistically, intelligent systems must incorporate knowledge as well as comprehension.

As normally perceived, the autonomous vehicle will have relatively few tasks. The unmanned, untethered submersible vehicle must:

1) navigate within its environment.
2) accomplish defined mission goals.
3) maintain required operational capabilities despite subsystem faults.

These tasks must be accomplished with the intelligence that is available on board, with the energy that is initially supplied, and with at best, only minimal supervision from human operators.

Evaluation of these three tasks leads to the definition of some system characteristics which impact the control/guidance of the autonomous system. The system must:

1) contain an initial model of the environment within which it will operate.
2) contain a list of specific mission goals or objectives.
3) be able to acquire new information about its operating environment and update its model of that environment.
4) understand the effects, on the entire system, of subsystem malfunction and be able to adjust system response to compensate for those malfunctions.
5) cope with unpredicted events or hazardous situations.
6) be able to plan the method by which mission goals will be accomplished.

The autonomous vehicle control/guidance system must also:

1) deal with time explicitly.
2) use imperfect data.
3) bound its decisions with external parameters.
4) continue to function in any situation.

External parameters will heavily impact the decisions made concerning control and guidance. The parameters which will have major impact have been reviewed to be:

1) previous information (historical trends).
2) new data (quantity and quality ill-defined).
3) mission status (current position within the mission profile).
4) system/sub-system status.
5) external environmental parameters (current situation).
6) risk level (how much risk is acceptable).

An Approach to the Time Constrained Expert

An initial investigation of the use of a knowledge-based system in real time guidance has considered an architecture as diagrammed in Figure 1. The controller is developed as if it were a classical real time controller. Its data base includes a set of parameters which establish the control system transfer functions. These may be any or all of the essential system functions; gains, bandwidths, timing or integration constants. The data base may indeed modify the control system algorithms themselves if advised to by the expert pilot. The data base also includes acquired sensor input data. The determination of this data base is perhaps the most important aspect of the control/guidance system design.

Under normal operation the controller would act as a real-time system would follow pre-programmed algorithmic instructions, employing established parametric constants as stored in the data base to accomplish the system operations.

Meanwhile, a parallel system, the knowledge-based system is accessing the same temporal data, plus its own added sensors, and as well monitors the controllers data base. It has a total mission viewpoint along with a full representation of a pilots understanding of causes consequences and implications. It views status, trends and objectives. The judgements are stored as decision rules, the mission and related data are stored as a separate data base. Decisions of the expert are placed, as changed constants, in the intelligent controller's data base.

We see the impact of an operating system doing the days work and an executive modifying the operation as required to meet broadly defined objectives. The intelligent controller operates in real time; the expert system possibly orders of magnitude more slowly.

When an unexpected event or situation is recognized by the guidance system through its decision rules it will update the control system with parameters that represent its best judgement. The control system dynamics, of course, are not effected beyond the demands imposed by the new parameters.

This knowledge-based guidance system will act essentially as the pilot of the vehicle with the knowledge of the mission goals, environmental parameters, threats, and other pertinent data.

Considering the architecture diagrammed in Figure 1, it is possible to begin to characterize the real-time controller and the knowledge-based system.

Four characteristics of the required real-time controller are: 1) a real-time operating system must be chosen to meet the needs of the system. 2) care must be taken to allocate the processing capabilities resulting from the distributed architecture. It is important that a situation not exist where

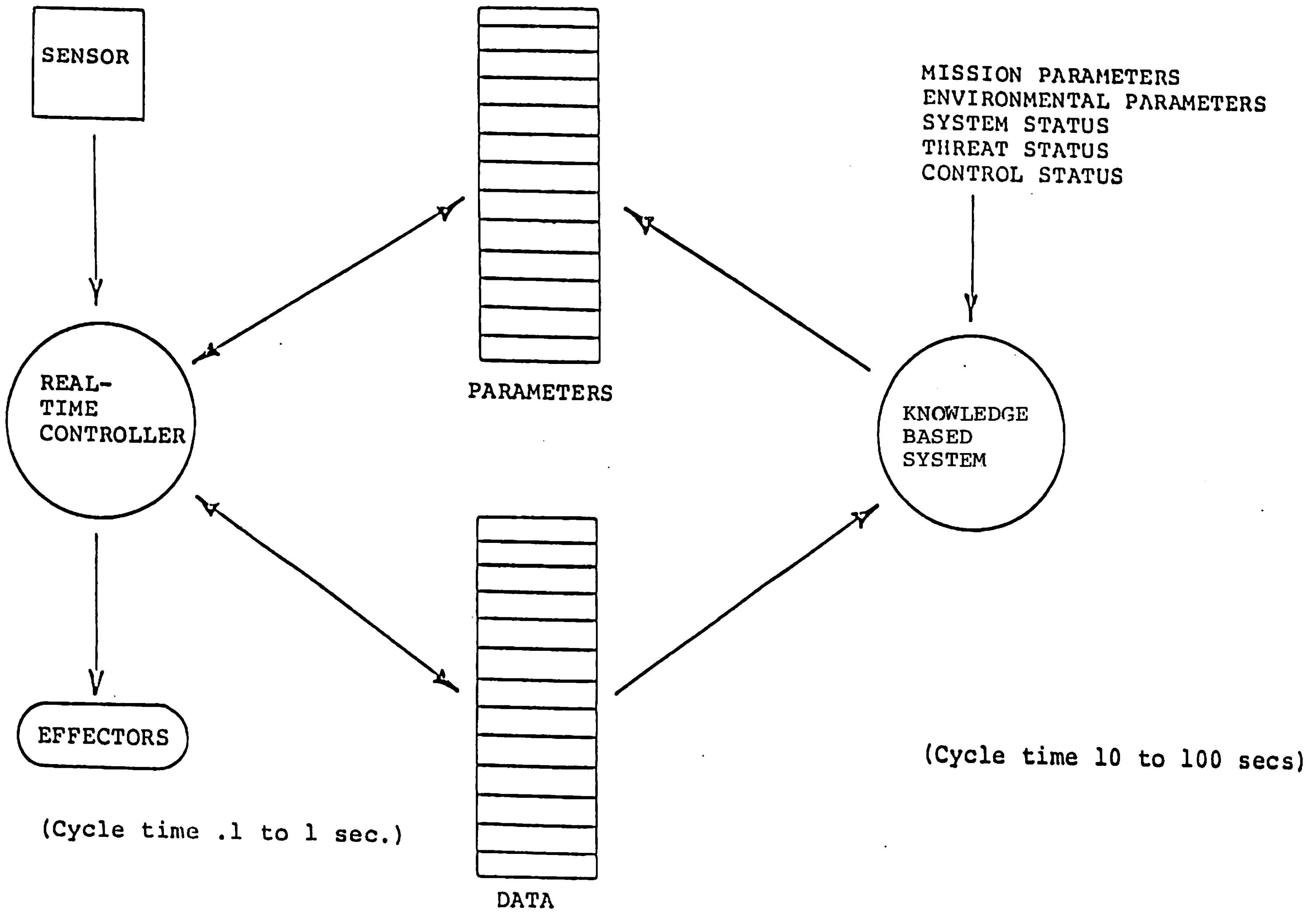

Figure 1. A Knowledge-based, Adaptive Guidance and Control System

one processor is overloaded while another has little to do. 3) data and parameter blocks must be defined such that it is possible for the expert system to interact with the data base in a manner allowing it to define the overall response of the real-time system. 4) A communication strategy is required allowing asynchronous communication between different computer systems which will be compatible with the hierarchical nature of the controller. It is important to realize that the real-time controller be independent of the expert system part of the overall controller.

Characteristics have been defined for the "expert" part of the controller. These definitions are much less specific although they do infer design boundaries. The expert controller will: 1) make adequate rather than optimal decisions, that are heuristic rather than analytical 2) break large problems into smaller sub-problems, 3) may use more than one technique to solve the problems associated with making a control decision.

Although Artificial Intelligence offers many techniques some seem more applicable than others to the control of systems constrained in time.

1) Frames: A frame defines the logical setting of the data, parameters, and procedures for a defined situation. The frame seems to be particularly useful for dealing with the types of data available to a real-time system (relatively small number of sensors). The concept allows for default values, thresholds, and exceptions, among other attributes.

2) Scripts: This concept is best defined as a sequence of events. It allows for the development of predefined control procedures which can be triggered by the external situation.

3) Production Rules: The if - then rule allows for interaction of unrelated data and, if developed properly, can make logical decisions within a relatively complex environment or situation.

4) Search: Some of the heuristic search techniques are applicable to the problem of vehicle control/guidance.

Time, in terms of problem dynamics, is scarcely a factor in most of the classical applications of expert systems. In a dynamic problem, such as the transit of an underwater vehicle, however, guidance data must be updated at periods often less than one second to assure safe operation.

An Example: A Knowledge-Based Navigation System

We consider here the precision navigation system employed on the EAVE-East vehicle, which we employ as a trivial example of the application of decision rules and a data base to introduce the essence of an "expert" to hardware.

The navigation system is short range (50 meters), is precise to five or ten centimeters and is competent to cope with multipath and acoustic shadowing within a structure. It is a Range-Range system currently employing three remote transponders; and three on-board transponders spaced one meter apart on the vehicle.

The system copes with multipath, shadowing and low signal-to-noise ratios through the use of redundancy of range measurement. Not all paths will face similar hazards, some data will be valid, some not. Some errors may be random and subject to averaging, some will not. The position of the vehicle in its work space will affect safe velocity, appropriate turning directions, and recommended paths of motion. This information is generally available to the vehicle as a data base. Obstacles may be detected by on-board sensors and the effect of their presence also subjected to decision rules that control the vehicle guidance. The objective is to acquire reliable data, to understand the characteristics of this signal, and to modify the detection system in sensible ways as the environment changes.

The vehicle receives nine range measurements on each interrogation, a redundant data set. In addition, the system develops time histories as a basic 9 x 9 matrix and establishes criteria for data reliability, while observing vehicle response characteristics, heading, relative speed, and depth. It possesses a knowledge of the work space characteristics.

Each of the nine acoustic paths, thus, is described as a time sequence of up to 10 echo returns. A continuous measure of signal quality - its amplitude, and appropriate times of arrival, is made, according to criteria in it's data base. These include the number of samples to be considered and the weighting of past information. Similarly the velocity gates and pulse acceptance windows, are managed by numerics in the data base.

The ideal value of these controller constants depends on an overall, long term judgement that is performed by the knowledge-based system. It knows the problem geometry; has rules for safe turns and maximum velocities that derive from knowledge of the geometry. It has general knowledge that permits an estimate of which paths may be shadowed, and has an understanding of multipath effects. A limited set of production rules (IF -- THEN statements), are being established which will allow the knowledge-based system to modify the parameters of the real-time system within the context of this knowledge and understanding. The consequence is a navigation system with improved accuracy and reliability of vehicle position. The concept of the deliberative expert, controlling the coefficients of an operating system, appears to be a worthwhile approach.

GUIDANCE AND CONTROL OF THE EAVE SUBMERSIBLE

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Abstract

The EAVE path and position controller has the task of guiding the submersible through the water during an inspection task. The path that EAVE is to take is defined by a) its location relative to the axis set defined by the sonar transponders with x and y in the horizontal plane, b) its depth determined from pressure measurements, c) its heading, d) its speed, and e) the time it is to maintain a particular activity. A list of commands is given to the controller before a mission is begun. The list can include such functions as: a) go to a depth, while holding the present heading and, if required, holding the present x,y location; b) rotate to a specific compass heading, and go clockwise or counterclockwise at some maximum rotation rate (allows for a slow or fast "look around"); c) go to a specific x,y location at the same depth while going frontwards, backwards, or sideways at some maximum speed; d) go in a particular direction at some speed for a certain length of time; e) hover for a specific length of time.

From two (or more) successive commands to go to a specfic target point, the controller determines the line in space that EAVE must follow. The navigation routines provide the controller with the present location, heading, and speed of the vehicle relative to the transponder coordinate system. The controller then determines the off-track distance, the distance from the next target point, and the difference between the desired and actual heading. These differences are used to create a speed command. If this speed is greater than the maximum speed requested in the command list, the maximum speed from the list is used as the command speed. This speed is compared to the actual speed, and the thrusters are then adjusted to correct actual vehicle speed. To assure that the vehicle will home in on the track and on the final target point even in the presence of small drift currents, an integral control term is added to the speed command for depth, lateral, and forward motion. The terms are added to each control function separately when the difference between the desired position and the actual position for that motion is less than a meter. The controller is designed to allow the addition of a similar term to the heading control if it is found to be necessary during trials. All controller parameters such as gains and limits at which certain functions begin to operate can be modified in the field.

A.R.A.P. Tech. Memo. No. 83-8

EFFECTS OF FIN ASYMMETRY ON THE DYNAMIC RESPONSE OF A REPRESENTATIVE UNTETHERED SUBMERSIBLE

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INTRODUCTION

The majority of today's autonomous, unmanned, untethered vehicles are slow speed (less than 6 knots) with nonhydrodynamic faired shapes. As experience with these vehicles is accumulated and propulsion technology is advanced, speeds are likely to increase to the 10-25 knot range. With the increase in speed comes the requirement for lower drag by hydrodynamic fairing in order to keep propulsion power requirements practical. For open framed and nonhydrodynamic faired vehicles, it is well known that strong hydrodynamic coupling exists between yaw and roll and pitch whenever a maneuver is executed. It is generally assumed that congruent to the reduction in drag due to hydrodynamic fairing, there is a virtual elimination of the strong coupling in yaw-roll-pitch. The purpose of this paper is to demonstrate the effect of speed and typical hydrodynamic asymmetries on the resulting unwanted coupled motions due to control fin inputs and disturbance inputs.

HYDRODYNAMIC MODEL FOR UNDERWATER VEHICLES

The motions of a rigid body in space can be described by a system of six differential equations resulting from an application of Newton's second law. In general, the equations are nonlinear and coupled. The hydrodynamic forces and moments functionally represented in these equations are normally described by a Taylor series expansion about the equilibrium condition, typically resulting in approximately 150 terms necessary to describe the dynamics of today's underwater vehicles. To solve these equations requires the simultaneous solution of the nonlinear differential equations in the time domain. Computer programs that solve the six-degree-of-freedom equations of motion are in common usage.

A second method for representing vehicle dynamics is the frequency response transfer function method. Here the forces and moments are represented by terms linearized about a selected equilibrium condition. This has many potential applications for underwater vehicle design and is used in some aspect of every vehicle design with which the authors have been involved. Reference 1 gives a description of the development of the linear equations of motion and transfer functions.

Whether one uses a nonlinear or linear model for the equations of motion, the critical element required to account for the unique characteristics of a given vehicle is the hydrodynamic coefficients. The lack of accurate methods for predicting vehicle hydrodynamic characteristics, given the vehicle's external geometric configuration, has been a recurring problem and an uncertain process in submersible vehicle design. Traditionally, extensive testing and modification of models and full-scale vehicles are required before an acceptable configuration is defined - an approach costly both in time and money.

Prediction techniques that currently represent the state of the art use semi-empirical methods, consisting of theoretical formulae and data correlations of systematic data bases which have been developed by NACA, NASA, USAF, and USN over the past forty years. The heart of the semi-empirical method is the body build-up technique in which hydrodynamic coefficients for isolated components are determined, interference effects between various components are predicted, and the contributions are totaled to give the hydrodynamic coefficients of the complete vehicle. Because semi-empirical methods are generally algebraic in form, they are rapid, computationally inexpensive, and thus provide a means for analyzing many geometric variations during the design/analysis cycle of an underwater vehicle development. These techniques have been applied to the design and analysis of approximately 60 underwater vehicles by the authors. For more details on the estimation methods, see references 2 through 7.

DISTURBANCE MODELS FOR UNDERWATER VEHICLES

The passage of a vehicle through a stratified ocean environment has been an area of specific interest over the past few years. The characteristics of this environment and its influence on submersibles, both towed and self-propelled, have been an area of intensive study and development during this period. The analytical models and methods resulting from this development now make it possible to investigate the motion response of submersibles to typical ocean environmental characteristics.

Specifically, internal wave models for both the fluid displacement and velocity effects in a stratified medium in both frequency domain and time domain models are available. Vertical internal wave displacements cause waves in the density stratification through which the vehicle travels. The vertical and horizontal velocity fluctuations cause angle-of-attack and sideslip angle variations. On a smaller length scale, ocean turbulence causes a similar variation. Models for this turbulence are also available. The time domain realization of the internal wave displacements and velocities is based on the work of Garrett and Munk (ref. 8). A spectral representation of the vertical displacement due to internal waves is based on the oceanographic observations reported by Katz and Briscoe (ref. 9). The spectral representation of the ocean turbulence is based on work presented by Phillips (ref. 10), some of which is originally due to Grant, et al. (ref. 11). Thus, for a deeply submerged vehicle, two mechanisms for vehicle motion response to disturbances can be modeled. The first is apparent time-changing density due to displacements in the stratified ocean environment. The second is fluid velocity variations appearing as time-varying changes in "relative wind" direction. Proximity to the thermocline, and the steepness of its gradient, is an influential parameter in estimating the intensity of these disturbances. Consequently, depth with respect to thermoclines of various different strengths is a

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The passage of a vehicle through a stratified ocean environment has been an area of specific interest over the past few years. The characteristics of this environment and its influence on submersibles, both towed and self-propelled, have been an area of intensive study and development during this period. The analytical models and methods resulting from this development now make it possible to investigate the motion response of submersibles to typical ocean environmental characteristics.

Specifically, internal wave models for both the fluid displacement and velocity effects in a stratified medium in both frequency domain and time domain models are available. Vertical internal wave displacements cause waves in the density stratification through which the vehicle travels. The vertical and horizontal velocity fluctuations cause angle-of-attack and sideslip angle variations. On a smaller length scale, ocean turbulence causes a similar variation. Models for this turbulence are also available. The time domain realization of the internal wave displacements and velocities is based on the work of Garrett and Munk (ref. 8). A spectral representation of the vertical displacement due to internal waves is based on the oceanographic observations reported by Katz and Briscoe (ref. 9). The spectral representation of the ocean turbulence is based on work presented by Phillips (ref. 10), some of which is originally due to Grant, et al. (ref. 11). Thus, for a deeply submerged vehicle, two mechanisms for vehicle motion response to disturbances can be modeled. The first is apparent time-changing density due to displacements in the stratified ocean environment. The second is fluid velocity variations appearing as time-varying changes in "relative wind" direction. Proximity to the thermocline, and the steepness of its gradient, is an influential parameter in estimating the intensity of these disturbances. Consequently, depth with respect to thermoclines of various different strengths is a parameter of interest for specifying disturbance conditions.

Density and velocity variations with wavelengths much longer than submersible lengths are represented by a general mode structure of internal waves. The energy density at a given depth can be represented in a way completely analogous to the treatment of suface waves (ref. 10). If the depth is constant and horizontal currents are neglected, vertical stratification can be specified in terms of normal modes. Garrett and Munk (ref. 8) have proposed a universal spectrum of internal waves based on the best available measurements of frequency spectra, wave-number spectra, spectra of fluctuations in vertical sections, and coherences of various kinds. The mode structure resulting has the form of Bessel functions, which they approximate. The observed lack of directionality in towed measurements leads to an assumption of horizontal isotropy of the internal wave field. The Garrett-Munk spectrum has been shown to be a useful representation of the observational data concerning internal waves. It, and other similar approaches to mathematically modeling internal waves, is used to characterize large-scale vertical displacements and horizontal and vertical velocities that cause submersible disturbances. Smaller-scale ocean turbulence in the mixed layer has significant intensity at length scales near the chord length of submersible control surfaces. Further, patches of high intensity turbulence are observed near the thermocline that can be a source of intermittent disturbances.

When the vehicle is near enough to the surface to be affected by waves, then the wavelengths cannot always be considered large with respect to the vehicle's length. The hydrostatic coefficients must be computed from exact integrations of the buoyancy force over the hull (ref. 12) in an approach analogous to that used for ships. When the wavelengths cannot be considered large with respect to the chord lengths of the appendages, then other effects must be accounted for. To properly account for these effects, the coefficients of the appendages are computed in their own reference frame and transferred into the body axis to determine their contributions to total vehicle coefficients. Interference effects due to a lifting surface being in the presence of a body and vice versa must be computed as well (refs. 2, 5, 13).

For towed or towed-tethered vehicles, the surface wave excitation of the towing ship or, more precisely, the towpoint on the ship, becomes a major source of towed or tethered vehicle disturbance. Typically, the most significant motion of the tow cable attachment point is its variation in depth. Ship speed variation can also be an important source of towed body depth variation. The wind-generated waves are normally modeled using spectral representations like the Bretschneider (ref. 14) or JONSWAP (ref. 10). The towing ship is usually modeled by response amplitude operators that are a function of heading with respect to long-crested waves (refs. 14, 15). Lateral disturbances (sway at the towing ship) are modeled similarly but are typically not of as much concern on a well-designed towed body and towed body cable attachment. In many cases, a linear cable model is sufficient for design and analysis purposes.

Figure 1 shows a typical vehicle response spectra computed using the methods described above.

EFFECTS OF SPEED AND HYDRODYNAMIC ASYMMETRY

To investigate the effects of speed and asymmetry on vehicle motions, a body of revolution with a 2:1 elliptical nose, 40% parallel midbody, and 4:1 elliptical tail cone is chosen. This 10:1 ℓ/d shape is taken as a representative hydrodynamically faired shape. Four fin surfaces of 1.5 ft^2 area each in a cruciform arrangement are used to provide vehicle stability and control. The asymmetry is represented by a vertical fin whose leading edge is located 20% from the nose. Simulations at 11 speeds of 5 to 25 knots and 7 vertical fin areas from 0 to 3.6 ft^2 for a total of 77 runs have been conducted. The asymmetry effect is accounted for by varying the vertical fin area from zero to 3.6 ft^2 while keeping the aspect ratio constant. The large fin 3.6 ft^2) and the medium fin (1.8 ft^2) are shown on the body in Figure 2.

Figure 3 and 4 show the roll amplitude-frequency response (Bode plot) characteristics of the vehicle for a 1-degree rudder input and horizontal velocity disturbance of 1 ft/sec, respectively. These curves are for the vehicle with the large fin at speeds of 5, 15, and 25 knots. From the Bode plots, it is seen that the roll amplitude due to a rudder input of 1 degree increases from 2 degrees to 24 degrees when the speed is increased from 5 to 25 knots. The larger hydrodynamic forces exerted on the forward fin, producing a larger roll moment, cause this considerable increase in roll response due to rudder. In the case of roll produced by velocity disturbances, the maximum roll angle decreases as the speed increases (fig. 4). This is explained by an effectively lower angle of sideslip (since the side velocity is held constant as the speed is increased) and an increase in hydrodynamic damping relative to the diminishing effects of the CB-CG restoring moment.

Figures 3 and 4 show the roll response characteristics for 3 of the 77 runs analyzed. For the present study, the most useful information from each of these plots is the peak amplitude. A compact and meaningful method of presenting all of the peak amplitudes from these runs is the contour plot. The lines of equal peak amplitude for the roll due to rudder response functions are plotted as a function of vehicle speed and asymmetry, as shown in Figure 5. Each of the contour line values have been multiplied by 100 to eliminate the decimal point. Thus, for low speed-zero asymmetry, the peak in roll is seen to be 0.2 degrees per degree of rudder input. At low speed-large asymmetry, the roll is increased to 1.0 degrees. At the high speed, 25 knots, the roll is seen to be 6.0 degrees per degree of rudder input for a vehicle with no asymmetry and 24.0 degrees per degree of rudder for a vehicle with a large asymmetry. In the latter case, a rudder deflection of even a few degrees will produce unacceptably large roll angles. Of course, these peak amplitudes are based on linear transfer functions and, for larger rudder inputs, nonlinearities start to take over. However, the linear analysis is quite effective for showing trends for a large number of cases since the computational burden is low compared to the cost of nonlinear trajectory simulation.

The effects of nonlinearities are shown in Figures 6 through 8 where nonlinear time-domain simulations were conducted for 9 of the 77 cases under consideration. Figure 6 shows speed, depth, pitch, and roll time histories for a speed of 5 knots for the zero asymmetry, medium asymmetry (1.8 ft^2), and large asymmetry (3.6 ft^2) cases. These trajectories are produced for a rudder step input of 5 degrees. At this low speed, we see that small roll angles are produced even for vehicles with large asymmetries, which is the same conclusion derived from the linear analysis.

Since the equilibrium condition for which the linear model was derived was for zero side and vertical velocities ($V_0 = W_0 = 0$), no lateral-to-longitudinal plane coupling was present. Linear analyses can be used effectively to investigate this coupling (ref. 16,17), but this was not attempted here. Rather, a nonlinear trajectory analysis is used to study the coupling between the lateral plane dynamics and the longitudinal plane dynamics. This is seen in Figure 6 where small pitch angles are apparent. This coupling is more apparent at the higher speeds, as shown in Figures 7 and 8. In Figure 8, pitch angles in excess of 60 degrees for a 5-degree rudder input at 25 knots are seen. The pitch response is also seen to exhibit a "snap-pitch" characteristic in that the peak amplitude occurs at 11 seconds, then begins to level off at a value of 30 degrees around 20 seconds. Along with this nose-down pitch comes a depth excursion of 400 feet after 20 seconds. The enormity of this excursion is even more disturbing when one considers that the vehicle has lost depth in excess of 13 body-lengths in just 20 seconds.

Returning our attention to the roll angle in Figure 8, it is seen that a "snap-roll" peak value of 55 degrees occurs at approximately 8 seconds for the large asymmetry case at 25 knots. Even the medium asymmetry can produce 37 degrees of roll at 25 knots.

Effects on roll response due to horizontal velocity disturbance inputs are shown in Figure 9. For low speed-zero asymmetry, the roll due to a 1 ft/sec velocity disturbance is seen to be approximately 4 degrees. As speed is increased to 25 knots, the roll response is reduced to approximately 1.6 degrees. In the case of a large asymmetry, the roll is seen to be approximately 8 degrees at 5 knots and reduces to approximately 6.5 degrees at 25 knots.

The amount of roll produced is also affected by the vertical CB-CG separation. Figure 10 shows the peak in roll amplitude due to a rudder input for a speed of 15 knots. When asymmetries are present, CB-CG separation has a significant influence in minimizing the roll. This is due primarily to the asymmetrical fin producing roll due to side velocity. The larger the asymmetry, the more the vehicle rolls in a turn, and the CB-CG restoring moment, being approximately proportional to roll angle, becomes larger to counter this roll moment. On the other hand, when there is no hydrodynamic roll moment due to the asymmetric fin (i.e., symmetric vehicle), the roll angle response remains essentially the same for CB-CG separation of 0.01 ft to 0.5 ft. (For

ZCG = 0, the vehicle is neutrally stable, meaning that its equilibrium conditions in roll can be any angle from 0 to 360°).

In the case of roll caused by horizontal velocity disturbances, the results are similar as seem in Figure 11. For the case of large asymmetries, small CB-CG separation produces large roll angles, as is the case for rudder input. For the symmetrical vehicle, small CB-CG separation produces small positive roll angles (for positive v) and large CB-CG separation produces large positive angles. This effect is more clearly understood by examining the terms in the equations of motion. The CB-CG contribution comes through the inertial term (ZCG)(m)(v + ur). For positive rudder inputs, v is small and positive and the r term is large and negative. The overall effect is to produce a negative roll angle. For velocity disturbances, the v term is large and positive and the r term is small and negative; the overall effect is to produce a positive roll angle. Adding an asymmetrical fin to the top of the vehicle contributes a negative roll moment for either a positive side velocity or a positive rudder deflection.

CONCLUSIONS

The effects of speed and vehicle asymmetry have been investigated for a representative, untethered vehicle for speeds of 5 to 25 knots. The asymmetry is represented by a fin located 20% back from the vehicle's nose. Seven fin areas ranging from 0 to 3.6 ft were analyzed. Results of this investigation show that for low-speed vehicles, such asymmetries cause roll and pitch angles of only 2-3 degrees. As speed is increased, the coupling effects become significantly more pronounced. At 25 knots, the large asymmetry case showed excursions of 55 degrees in roll, 60 degrees in pitch, and a depth loss of 13 body lengths for a small rudder input of only 5 degrees.

As the speeds of future untethered vehicles are increased, these coupling phenomena will play an increasingly important roll in the design of the guidance and control software and hardware. Further, the effects of disturbances on a submerged vehicle can now be assessed with respect to both sensor and control system requirements.

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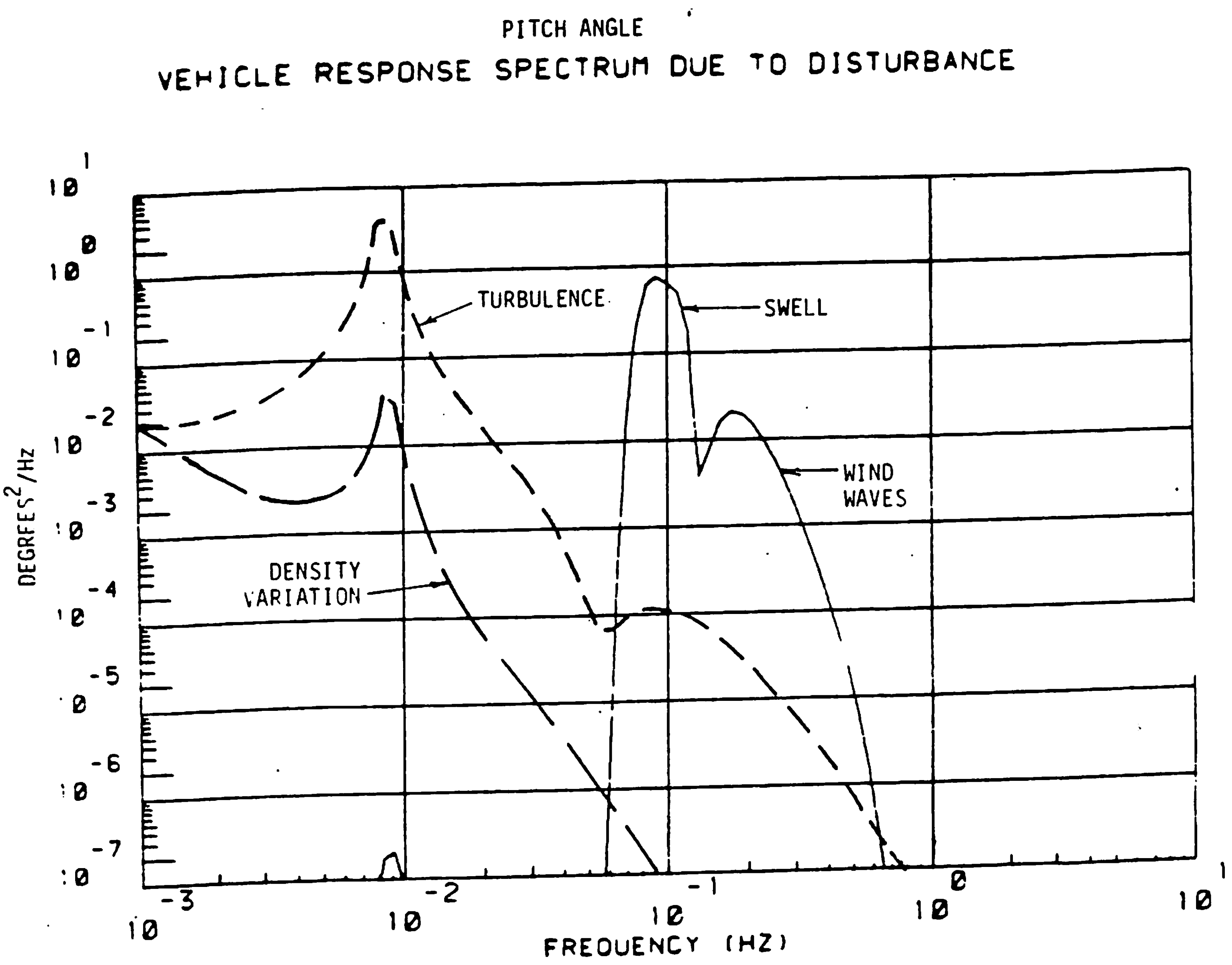

Figure 1. Example vehicle pitch angle spectrum due to distances of internal wave small-scale turbulence, surface wave swell, and wind waves

```
1 0.          0.
2 0.006       0.0670
3 0.015       0.1059
4 0 03        0.1498
5 0.06        0.2116
6 0 12        0.2984
7 0.24        0.42
8 0 48        0.5878
9 0.9         0.7901
 10 1.2        0.9
 11 1.8         1.0712
 12 2.1         1.1399
 13 2.4         1.2
 14 2.7         1 2527
 15 3.          1 2990
 16 3.6         1.3747
 17 4.2         1.4309
 18 4.8         1 4696
 19 5.4         1.4924
 20 6.          1.5
 21 7.0909      1.5
 22 8.1818      1.5
 23 9.2727      1.5
 24 10.363      1.5
 25 11 454      1.5
 26 12.545      1.5
 27 13 636      1.5
 28 14 727      1 5
 29 15.818      1.5
 30 16.909      1.5
 31 18.         1.5
 32 19.2        1.4924
 33 20.4        1.4696
 34 21.6        1.4309
 35 22.8        1.3747
 36 24          1.2990
 37 24.6        1.2527
 38 25 2        1.2
 39 25.8        1.1399
 40 26 4        1.0712
 41 27.6       0.9
 42 28.2       0 7901
 43 29.04      0.5878
 44 29 52      0.42
 45 29.76      0.2984
 46 29.88      0.2116
 47 29.94      0.1498
 48 29.97      0.1059
 49 29.988     0.0670
 50 30         0.
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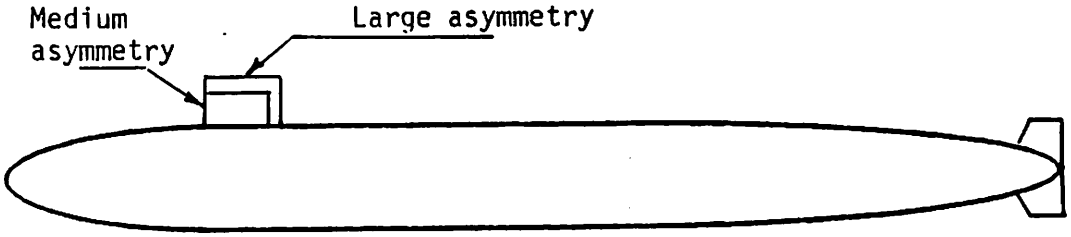

Figure 2. Representative vehicle geometry

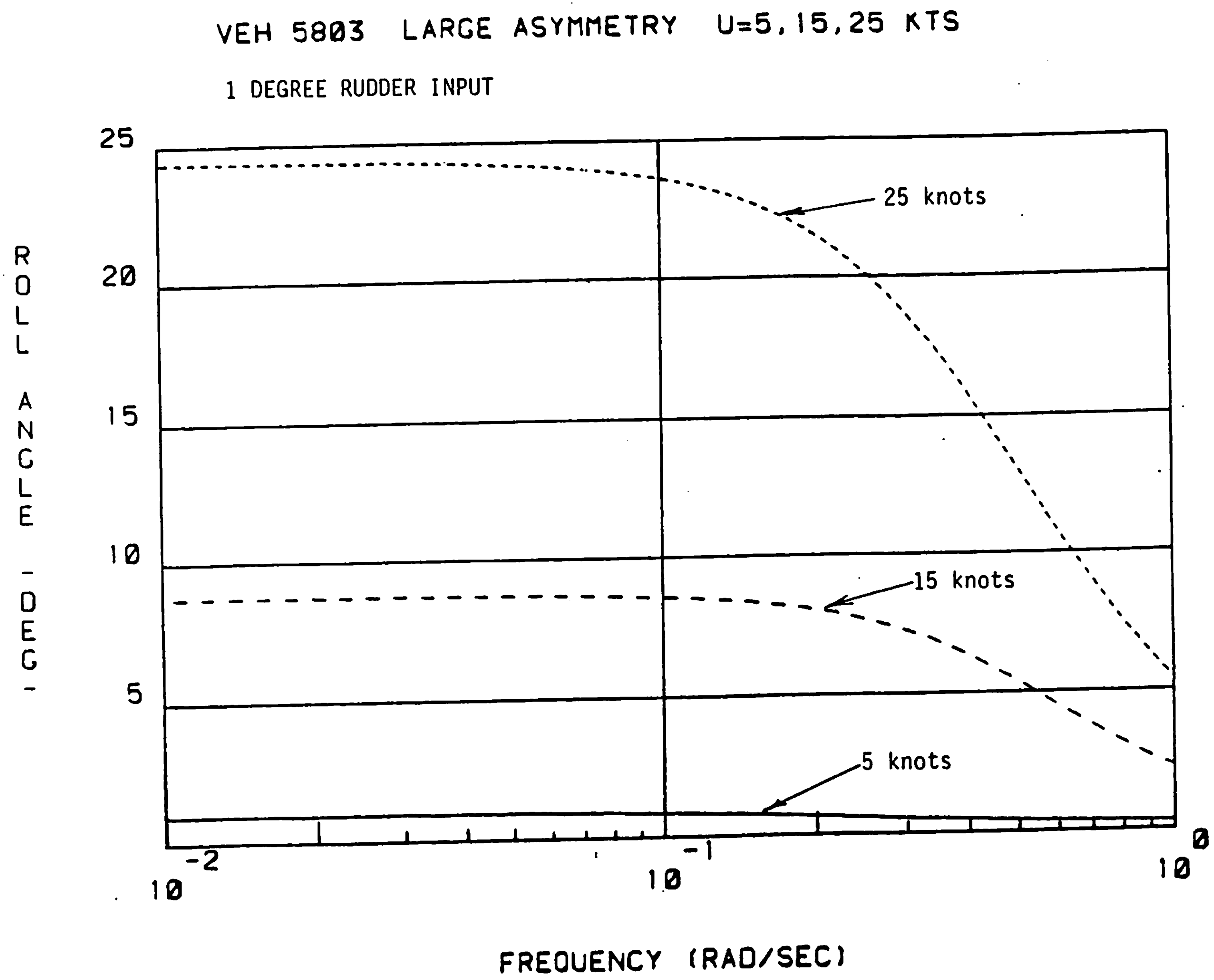

Figure 3. Bode plot of roll response to rudder input for vehicle with large asymmetry at 5, 15, and 25 knots

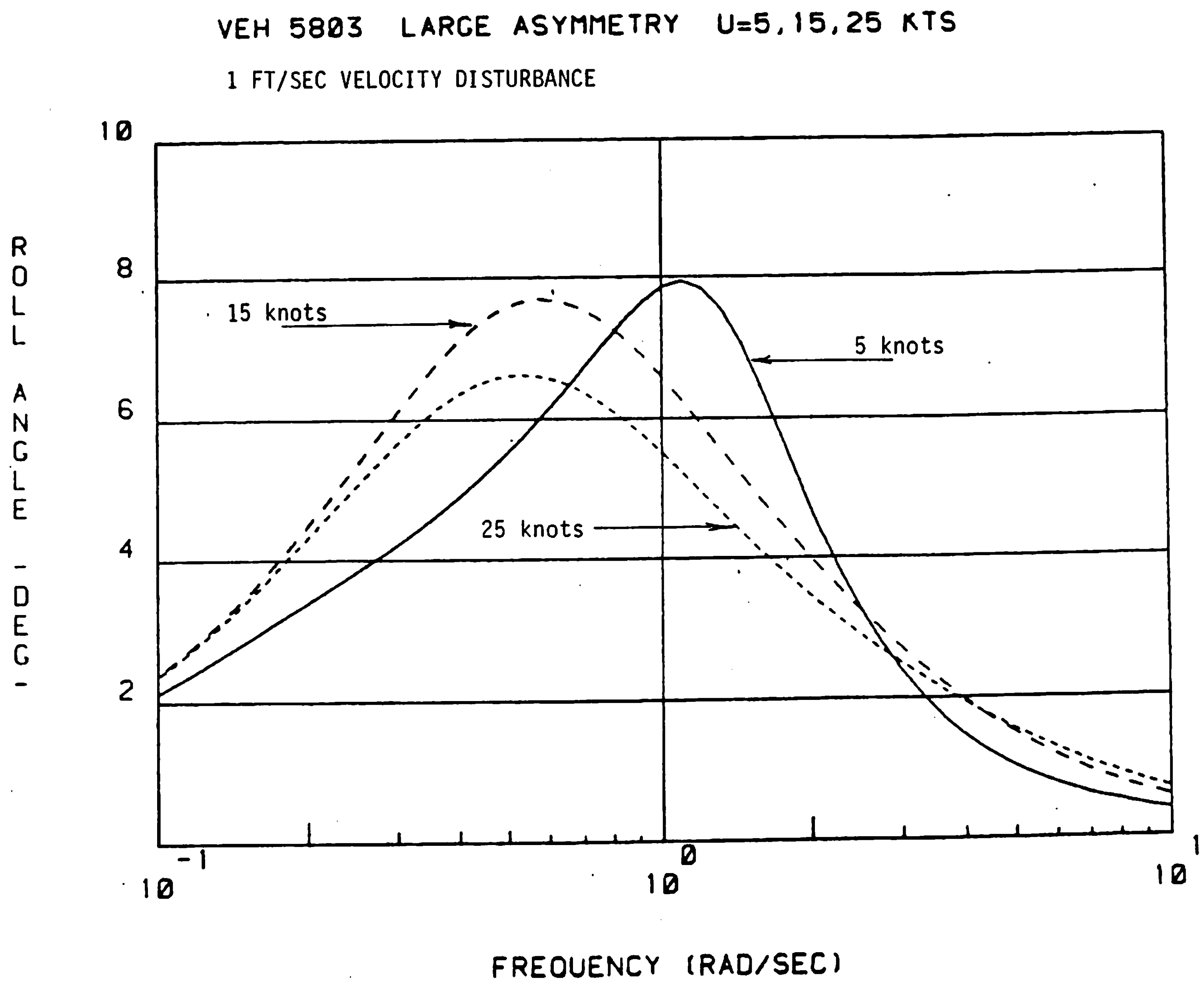

Figure 4. Bode plot of roll response to horizontal velocity input for vehicle with large asymmetry at 5, 15, and 25 knots

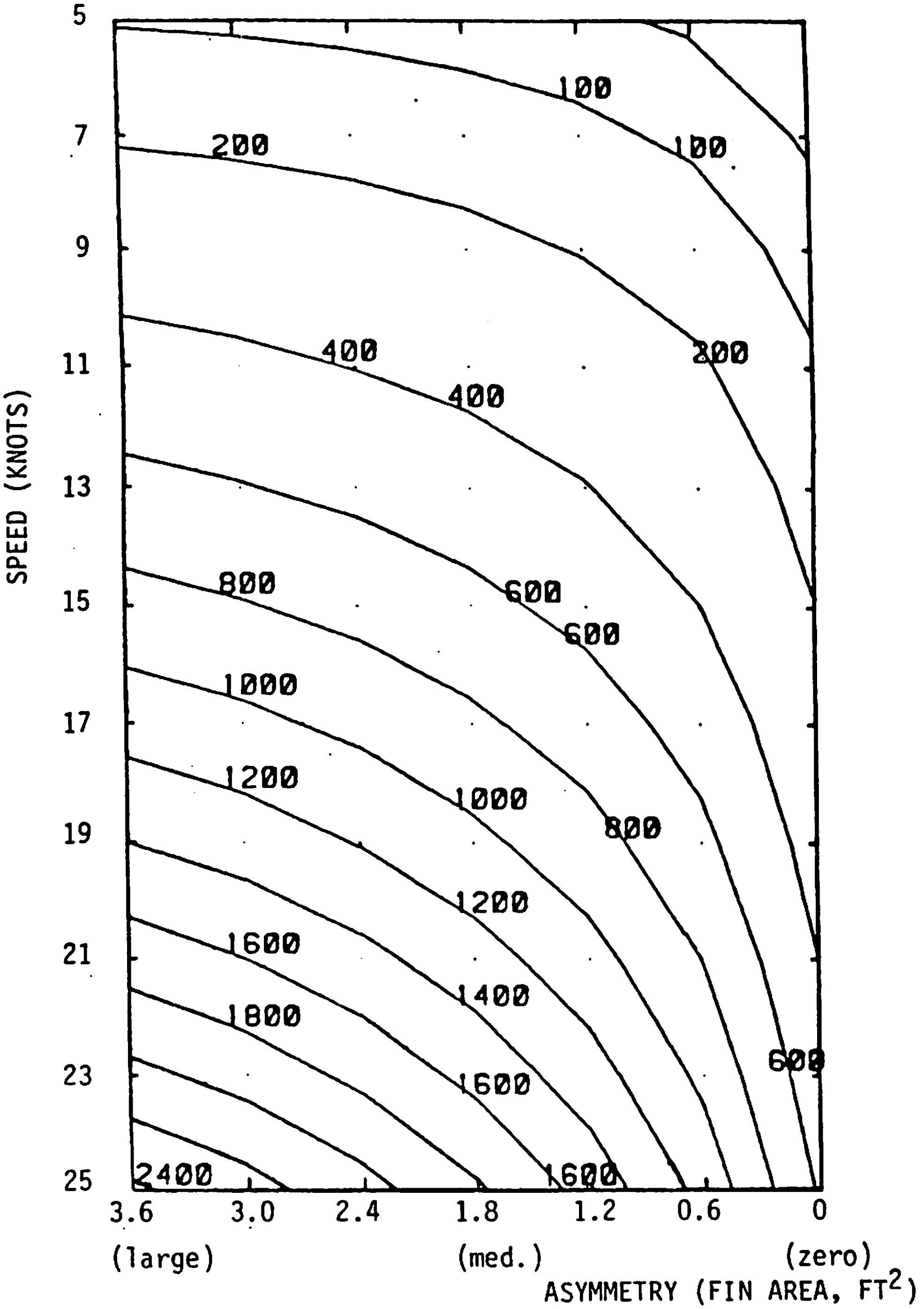

Figure 5. Contour plot for roll/rudder transfer function peak values

SPEED = 5 KNOTS

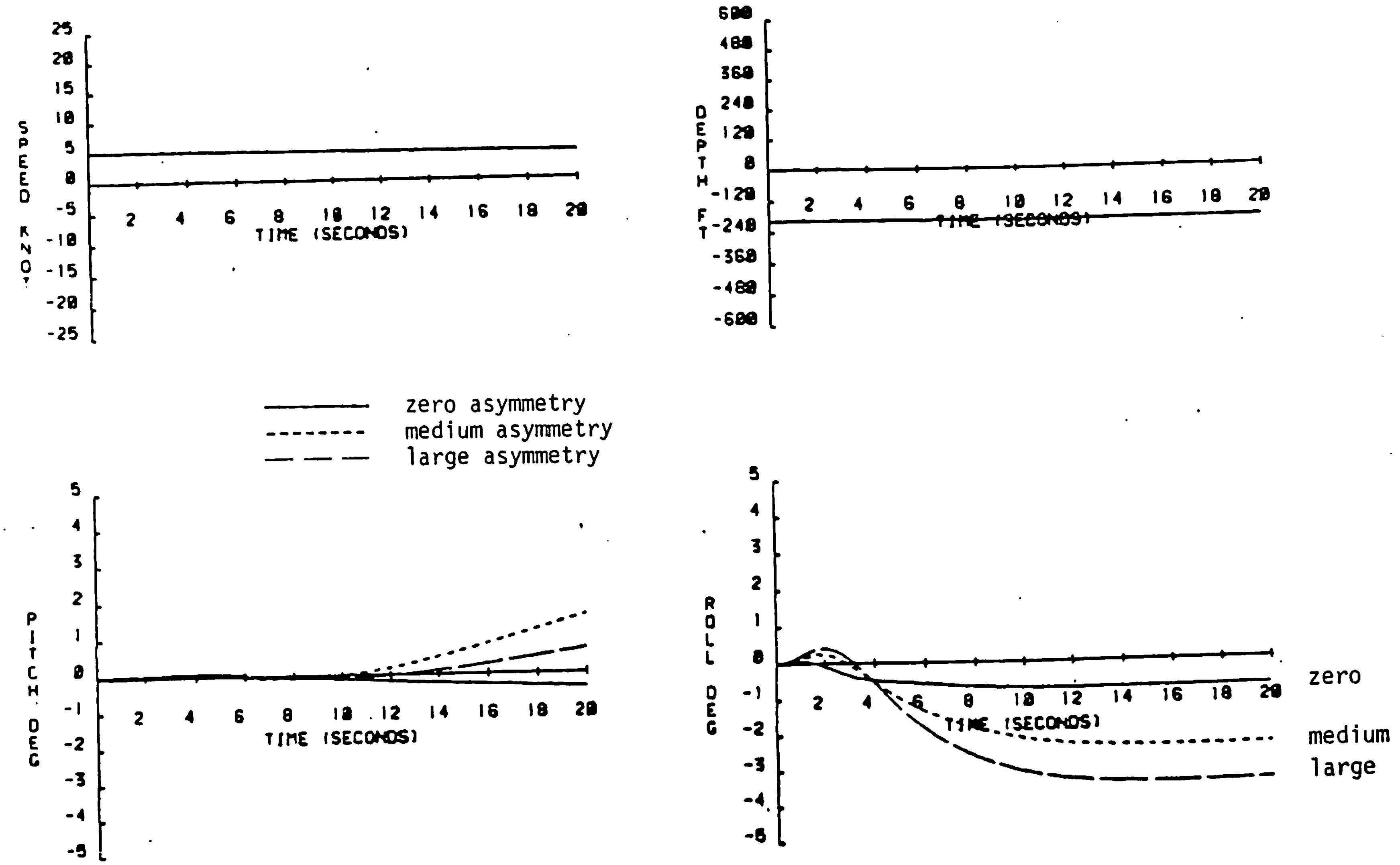

Figure 6. Nonlinear trajectory for 5-degree skip in rudder, speed of 5 knots, for zero, medium, and large asymmetry

SPEED = 15 KNOTS

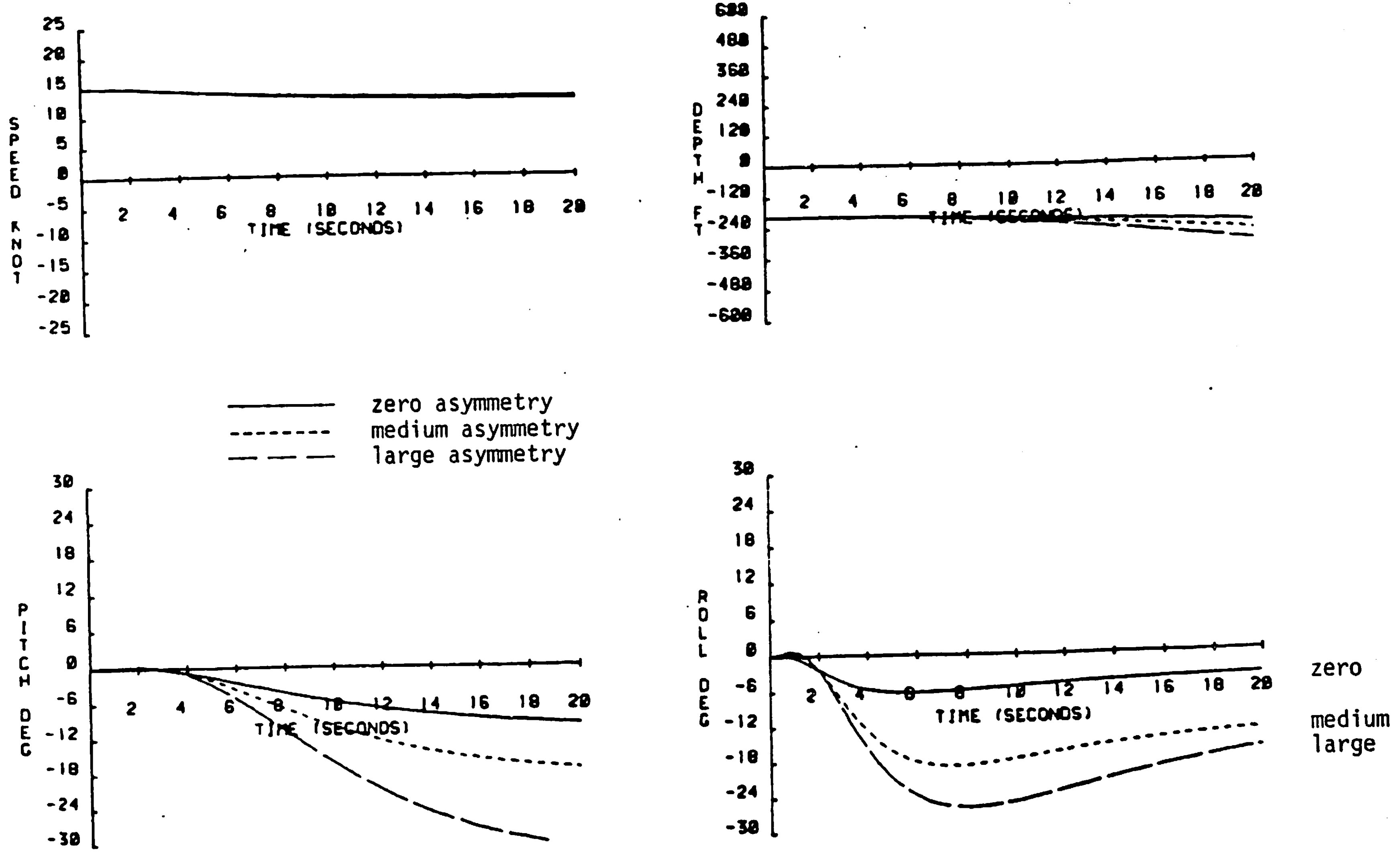

Figure 7. Nonlinear trajectory for 5-degree step in rudder, speed of 15 knots, for zero, medium, and large asymmetry

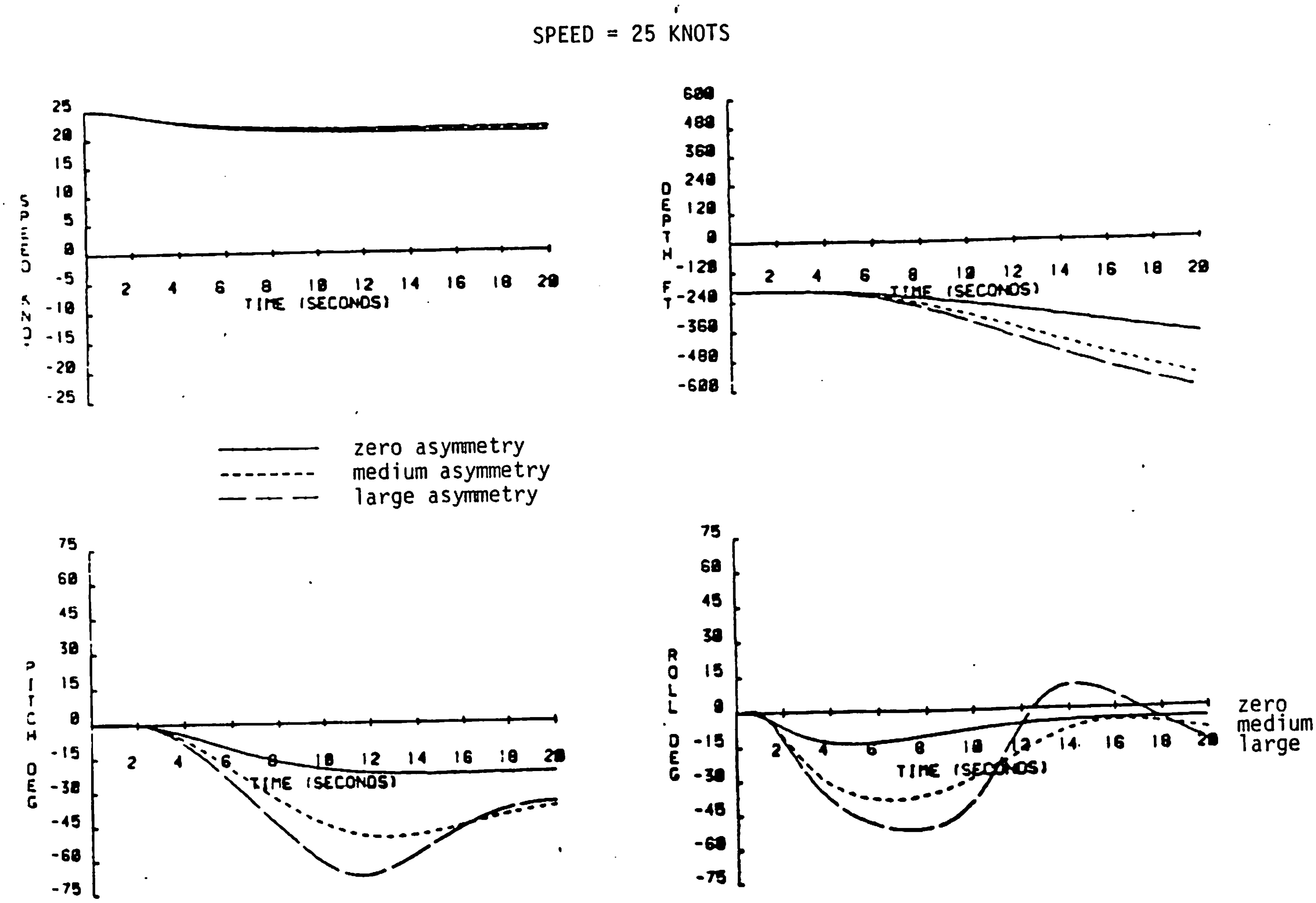

Figure 8. Nonlinear trajectory for 5-degrees step in rudder, speed of 25 knots, for zero, medium, and large asymmetry

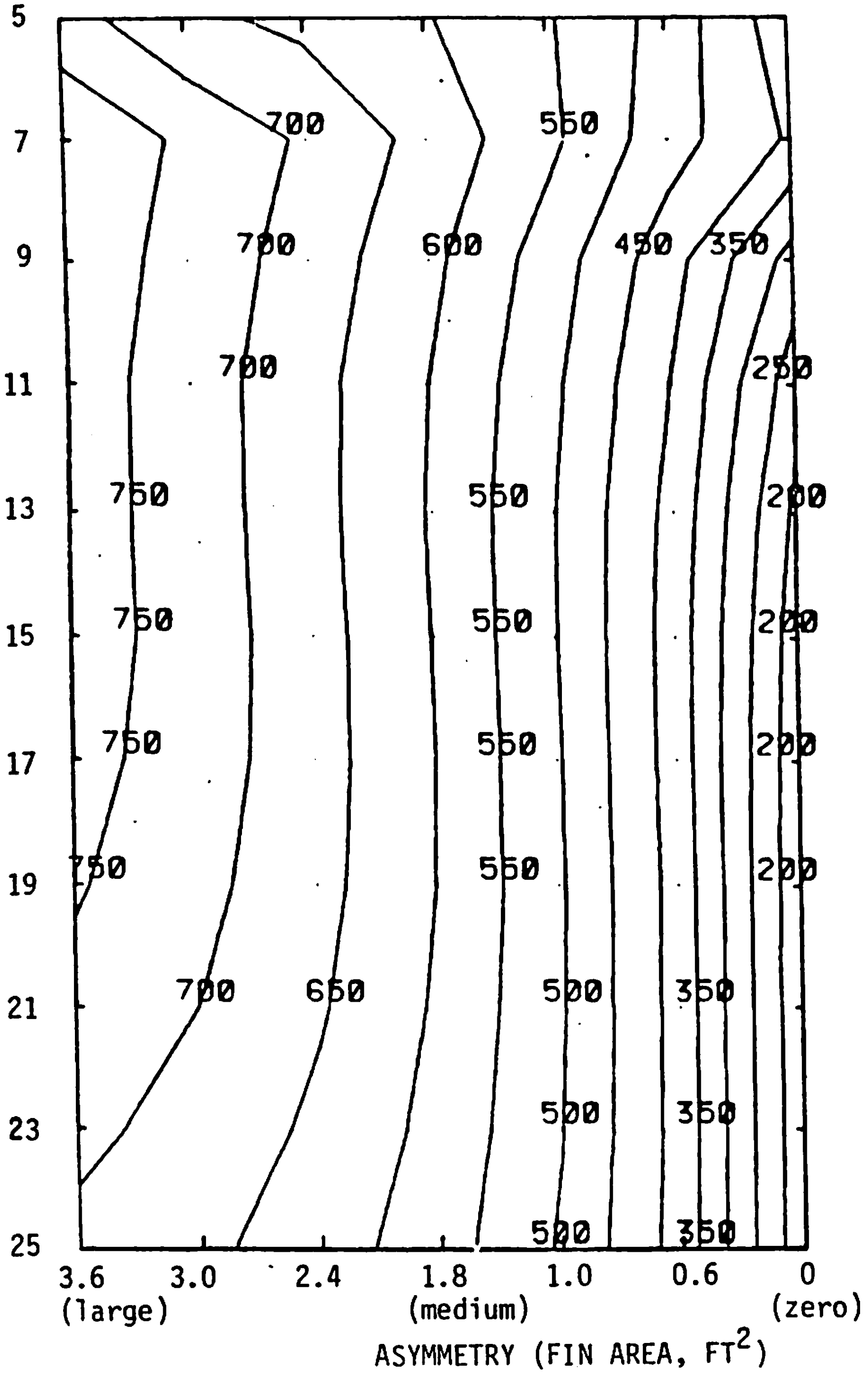

Figure 9. Contour plot for roll/velocity disturbance transfer function peak values

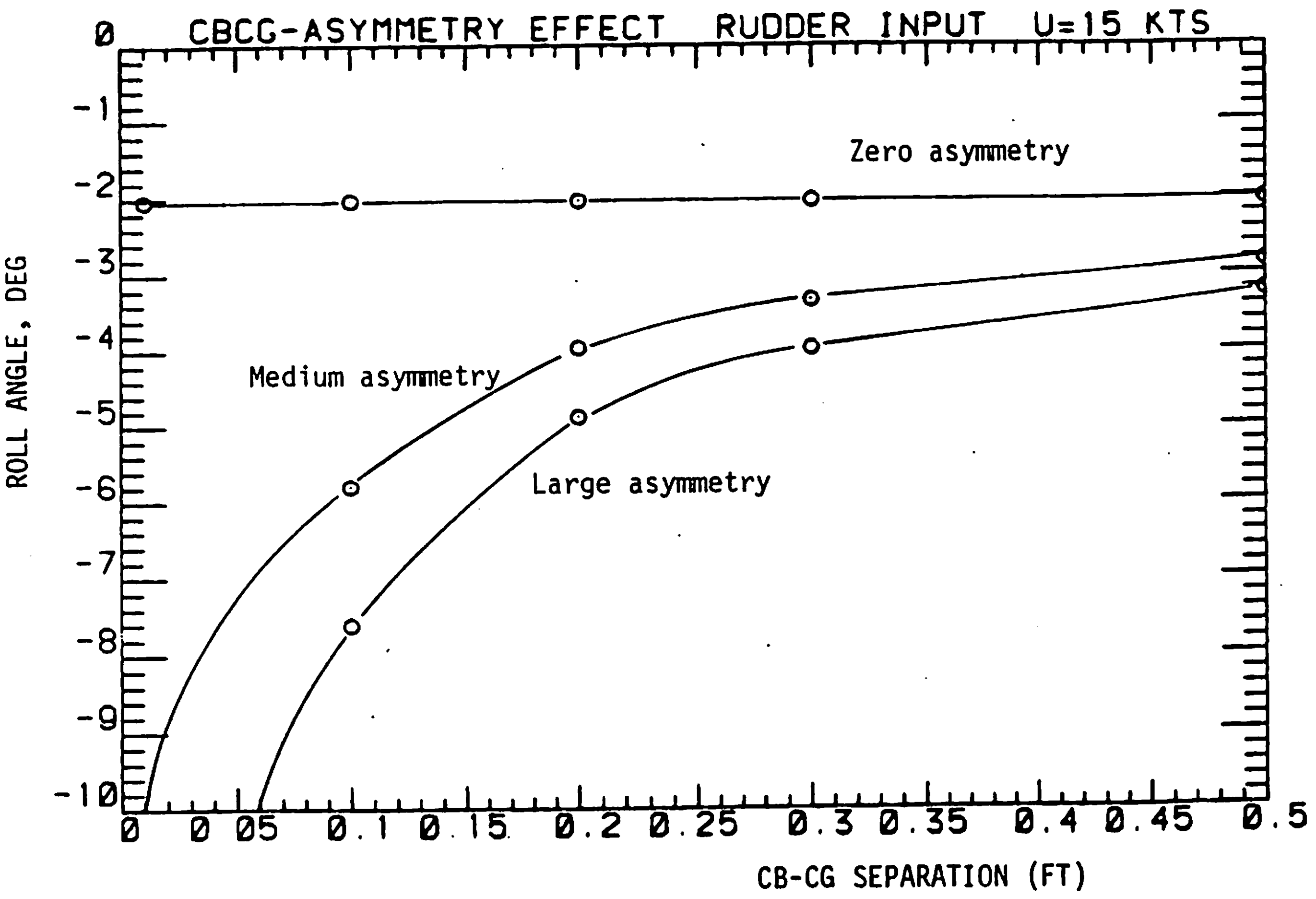

Figure 10. Effect of vertical CB-CG separation on roll response due to 1-degree rudder input, speed = 15 knots, for zero, medium, and large asymmetry

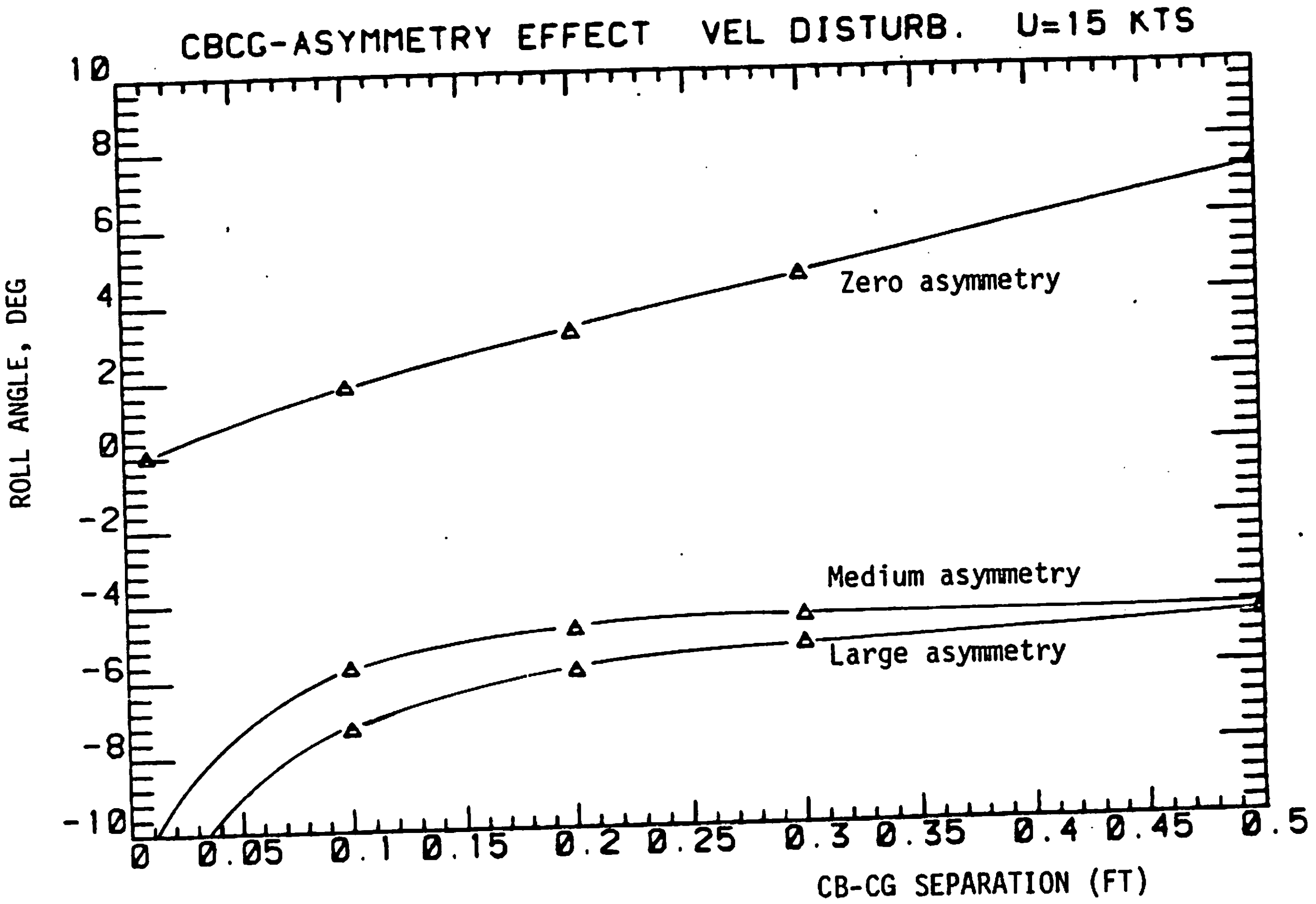

Figure 11. Effect of vertical CB-CG separation on roll response due to 1 ft/sec horizontal velocity disturbance, speed = 15 knots, for zero, medium, and large asymmetry

LIFT, POWER, AND PROPULSION ALTERNATIVES FOR DEEP OCEAN SUBMERSIBLES

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United Technologies Research Center/Hamilton Standard

INTRODUCTION

With the advent of more sophisticated guidance and control subsystems - acoustic transmission links, robotics, and artificial intelligence - manned or unmanned, untethered submersibles will be able to embark upon extended deep sea work and salvage missions. However, in order to fully exploit these newfound capabilities, a one-to-two order of magnitude improvement in stored power, lift, and propulsion capability will be required. A survey of available options indicates that a 94% blend of monopropellant hydrazine, N_2H_4, with 6% water or ammonia is a most attractive fuel at great depths, featuring the highest capacity for gas generation along with an energy density for propulsion and electric power generation at least equal to the more hazardous lithium battery systems. Also, with essentially neutral buoyancy, relatively large quantities of this propellant can be stored and consumed at depth over a range of throttle settings to meet power, propulsion, and lift requirements with no adverse effect on salvage vehicle buoyancy. This feature greatly simplifies vehicle supply logistics. It is shown that for these purposes 523 cubic foot of hydrazine, equivalent to the contents of a 10 foot spherical tank, has the potential to lift more than 100 tons from a depth of 10,000 feet, or to enable the generation of 3500 kWh of electric power, or, in a more streamlined storage configuration, such as a 6 foot diameter underwater "blimp", could supply the energy required for a trans-Pacific mission of a speed of approximately at 3 knots. For power and propulsion alone, and for missions where a gas bubble wake must be avoided the Stored Chemical Energy Propulsion System (SCEPS) Li + SF_6 and the cryogenic H_2/O_2 fuel cell systems are superior, the SCEPS propellant system for short-duration, high-velocity sprints, and the fuel cell for longer-duration missions featuring a more modest cruise velocity.

DISCUSSION

Hydrazine decomposition typically occurs via a two step reaction:

$$N_2H_4 \longrightarrow 4/3NH_3 + 1/3N_2 \qquad (1)$$

$$4/3NH_3 \longleftrightarrow 2/3N_2 + 2H_2 \qquad (2)$$

Reaction (1) is highly exothermic, and once initiated either catalytically or by temperatures above approximately 600° F, readily proceeds to completion. Reaction (2) is endothermic, relatively slow, and never reaches completion. For use as a heat source to drive a power/propulsion module, it is convenient to use any of a number of catalysts which promote the first reaction while supressing the second (endothermic) reaction; whereas for buoyancy gas generation, a catalyst which promotes the second ammonia breakdown reaction is better.

Buoyancy Gas Generation

For deep ocean buoyancy gas generation, hydrazine is the premier choice of propellants. Not only does hydrazine feature the highest specific performance (in terms of buoyancy gas generated per cubic foot of propellant, Figure 1), but in addition to the other system advantages discussed, it is also the least expensive.

An advanced ruthenium-on-aluminium catalyst has recently demonstrated the potential of obtaining lifting gas yields with 90% NH_3 decomposition or higher at moderate depths (10,000 feet). This represents a specific lift capability of approximately 400 pounds (wet weight) per cubic foot of propellant at this depth. Moderate regenerative heating of the liquid monopropellant is also required for best efficiency. At greater depths, up to 24,000 feet, the same strategies are expected to give a specific lift capability of 200 pounds per cubic foot of propellant or better, even though the ammonia decomposition efficiency may be only 80%. Lithium hydride and some of the solid gas generators are competitive, as shown in Figure 1, but, unlike a hydrazine gas generator system, they do not feature essentially infinite throttleability. The need for "pressure hull packaging" to maintain dryness until the moment of use is a further disadvantage with some of the competitive systems shown in Figure 1. (i.e. At a depth of 20,000 feet this requirement for some of the alternative buoyancy gas systems considered would entail an added pressure vessel weight of approximately 200 pounds per cubic foot of stored propellant and, therefore, a substantial negative buoyancy of syntactic foam.)

A somewhat interesting result depicted in Figure 1 is the great superiority of all the gas generation systems over the best bottled gas combination at 10,000 feet. In the case of gas storage in a pressurized sphere it can be analytically shown that there is an optimum storage pressure where the specific lift or lift per pound of filled vessel weight maximizes. For hydrogen in a high strength, appropriately lined titanium pressure vessel (150,000 psi yield with safety factor of 3) this pressure is approximately 15,000 psi. At higher pressures more gas can be stored within a given volume, but container weight is increasing so rapidly with the increasing wall thickness required that the system specific lift capability (i.e. lift per pound of gas plus container weight) is actually reduced.

An example of a hydrazine gas generation subsystem which has been optimized for space use is the reactor system shown in

COMPARATIVE GAS GENERATOR PERFORMANCE
10,000 Ft. Depth

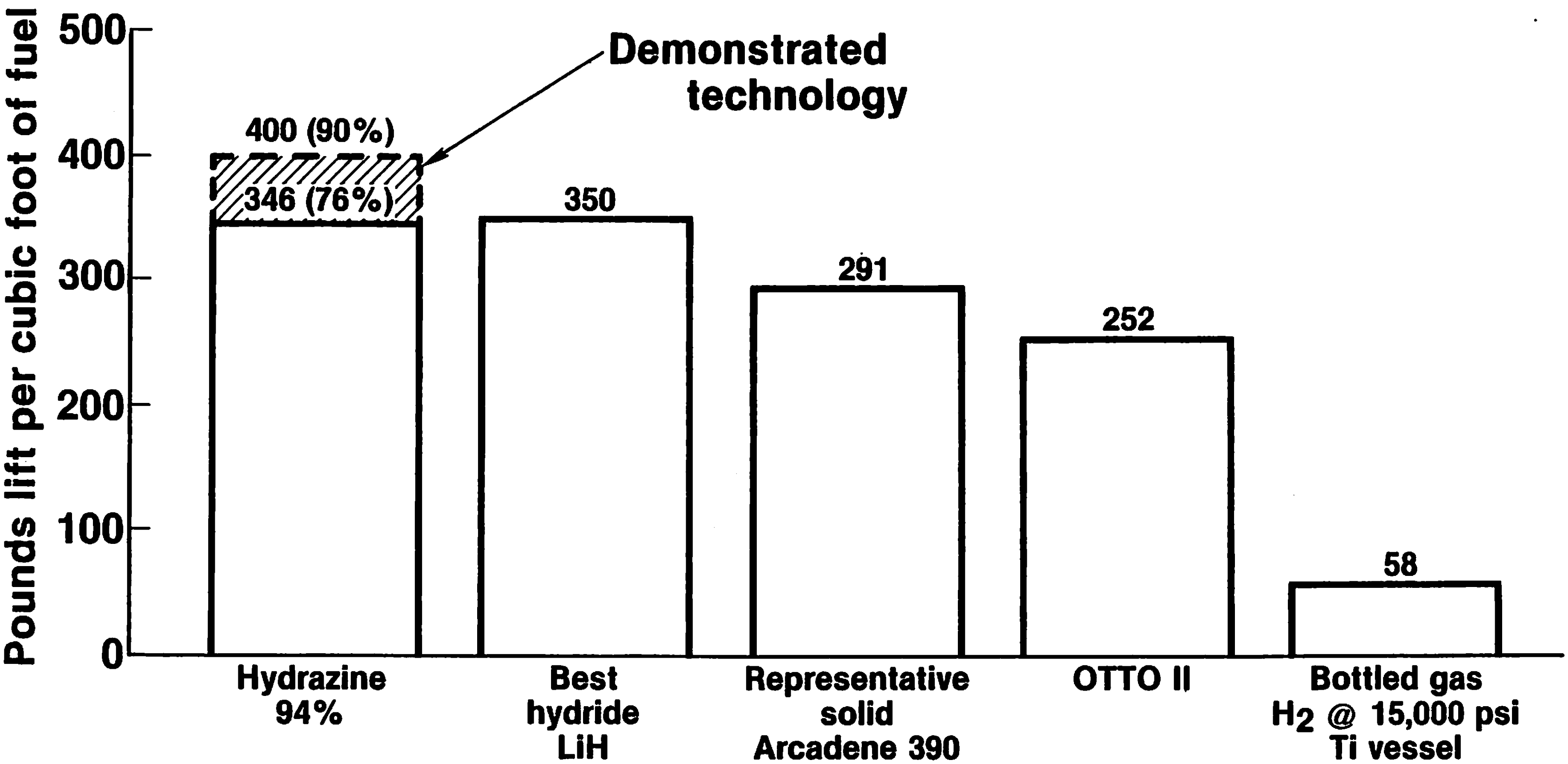

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FIGURE 1.

Figure 2. This system, or one like it, could be adapted for deep ocean use with few modifications. The reactor shown in the figure would produce approximately 25 pounds of lift per minute if used to generate buoyancy gases at 10,000 feet.

Power and Propulsion

A number of heat-engine/electric generator systems provide an attractive alternative to batteries for the generation of vehicle power or propulsion. At great depths it is always necessary to use the thermal energy of a propellant system to drive a comparatively low pressure closed (Rankine) power cycle. The reason for this is readily apparent from Figure 3, which depicts the maximum (isentropic) efficiency of converting heat into work as a function of pressure ratio across an expansion device (turbine, gear motor etc.). (i.e. Since the noble gases and air are impractical as working fluids, a pressure ratio of 10:1 or better is required for acceptable thermodynamic efficiency, and, with an open cycle, which must reject spent exhaust gases at sea pressure, this requirement would lead to impossibly high upstream pressures at great ocean depths.) As shown in Figure 3, a steam cycle, which can be readily operated over a 50:1 pressure ratio, if expanded from 1400°F and 1000 psi, gives reasonable energy conversion efficiency. In Figure 3 the steam cycle is the only closed cycle depicted. During expansion alone it would fall between the curves shown for air and "combustion products", i.e. from the combustion of a hydrocarbon fuel.

Proceeding to Figure 4, approximate cycle efficiencies are shown for the conversion of heat into work, heat into electric power, and electric to work (propulsion). As shown, a well designed electric motor or generator is 90% efficient in transforming electric to mechanical energy or vice versa, whereas, a well designed closed steam Rankine cycle system might convert heat into work with an efficiency of 34%.

A schematic of a hydrazine fueled power/propulsion module is depicted in Figure 5. In the figure the hydrazine is contained in an elastomeric bag at essentially sea pressure, and is pumped to a sufficient overpressure (50 to 100 psi above ambient sea pressure) to enable forcing it through a catalytic reactor where it decomposes to yield hot gases which then exchange heat to a working fluid flowing within the boiler tubes of a closed Rankine type power cycle. The net heating value of the hydrazine propellant is approximately 1250 Btu/lb, and approximately 34% of this energy or 0.125 kWh/lb can be obtained as a mechanical output. A throttle valve controls the rate of energy release. Through appropriate clutching mechanisms this output can be either utilized directly for propulsion or to produce an electrical output or both. In the case of electric power production a 90% mechanical to electric conversion efficiency would result in approximately 0.112 kWh/lb of hydrazine consumed.

A practical embodiment of the heat engine into a closed cycle power system is shown in Figure 6, which depicts the ALWT

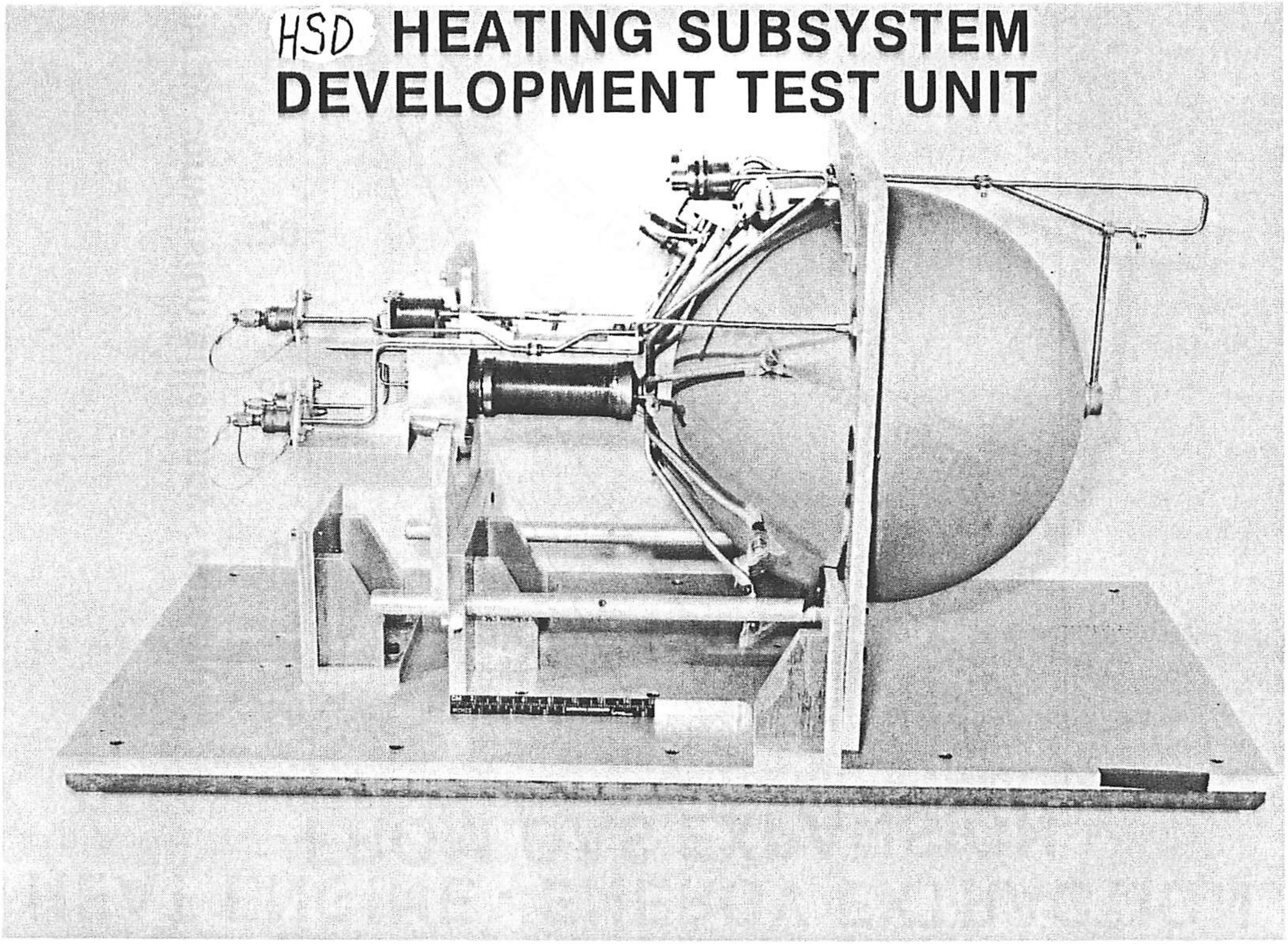

FIGURE 2.

HEAT ENGINE - ENERGY EXTRACTION FROM GAS EXPANSION

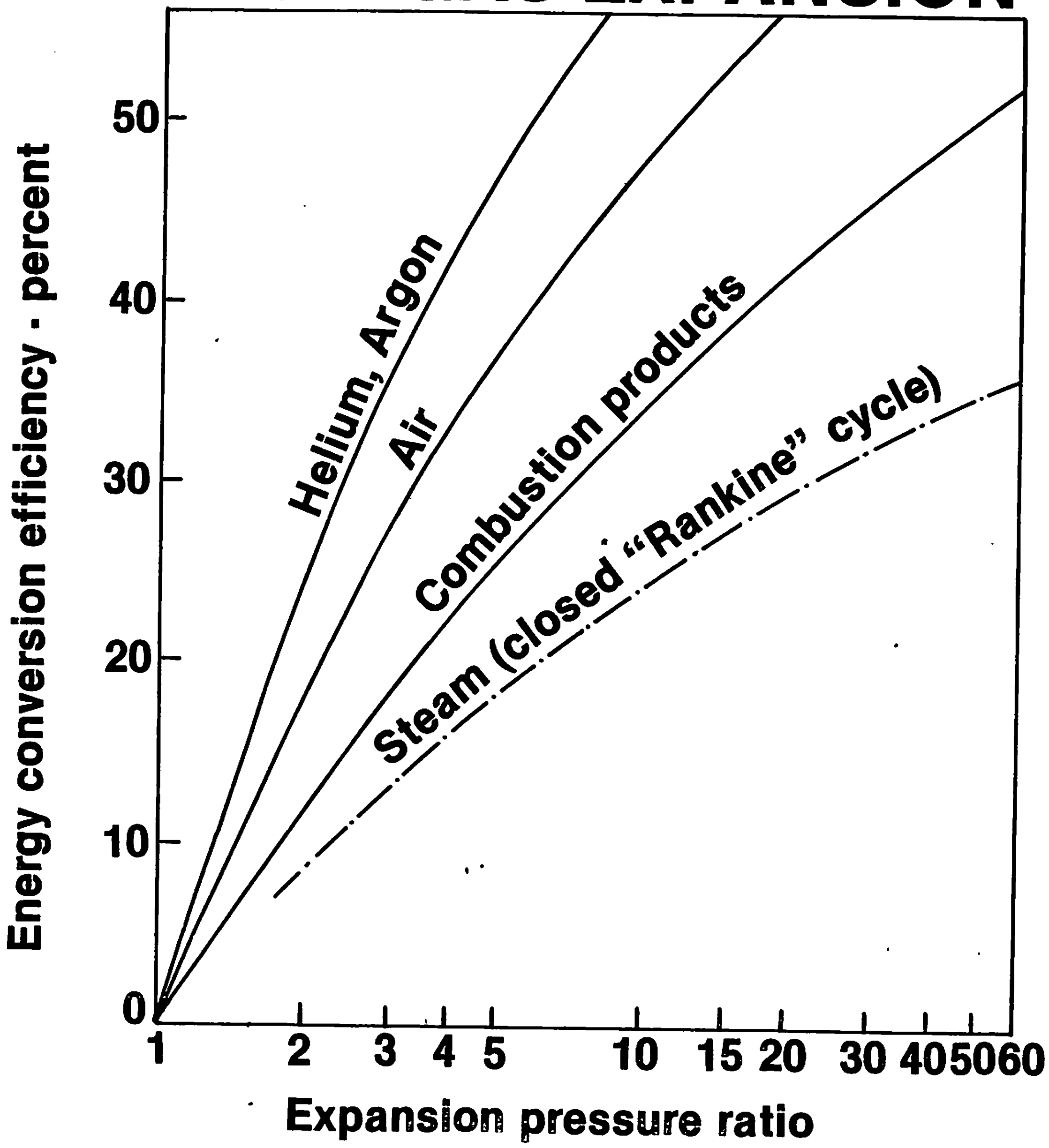

FIG. 3.

DEEP OCEAN ENERGY CONVERSION CYCLES

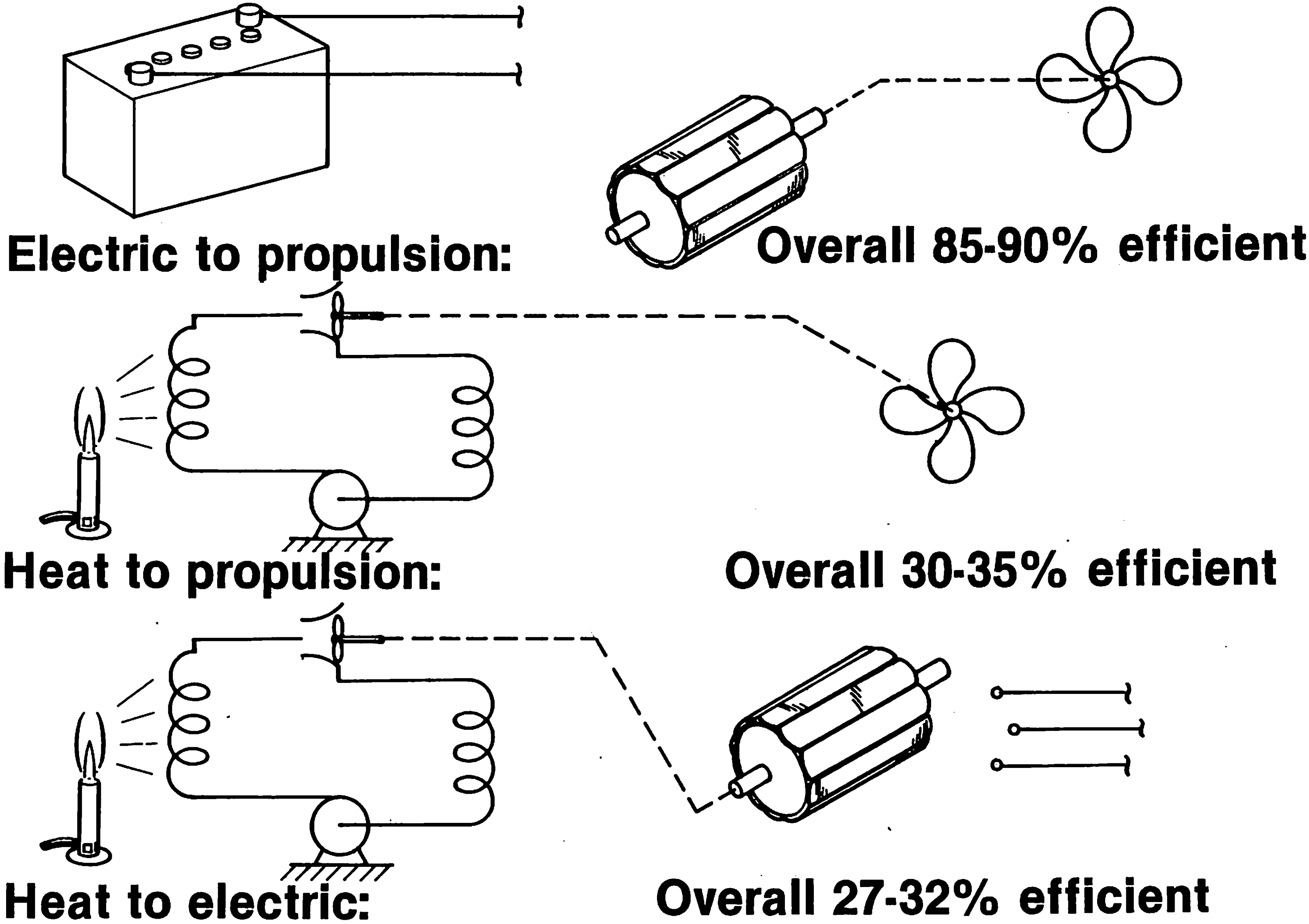

FIGURE 4.

SCHEMATIC

Deep Ocean Long Range Propulsion/Power System

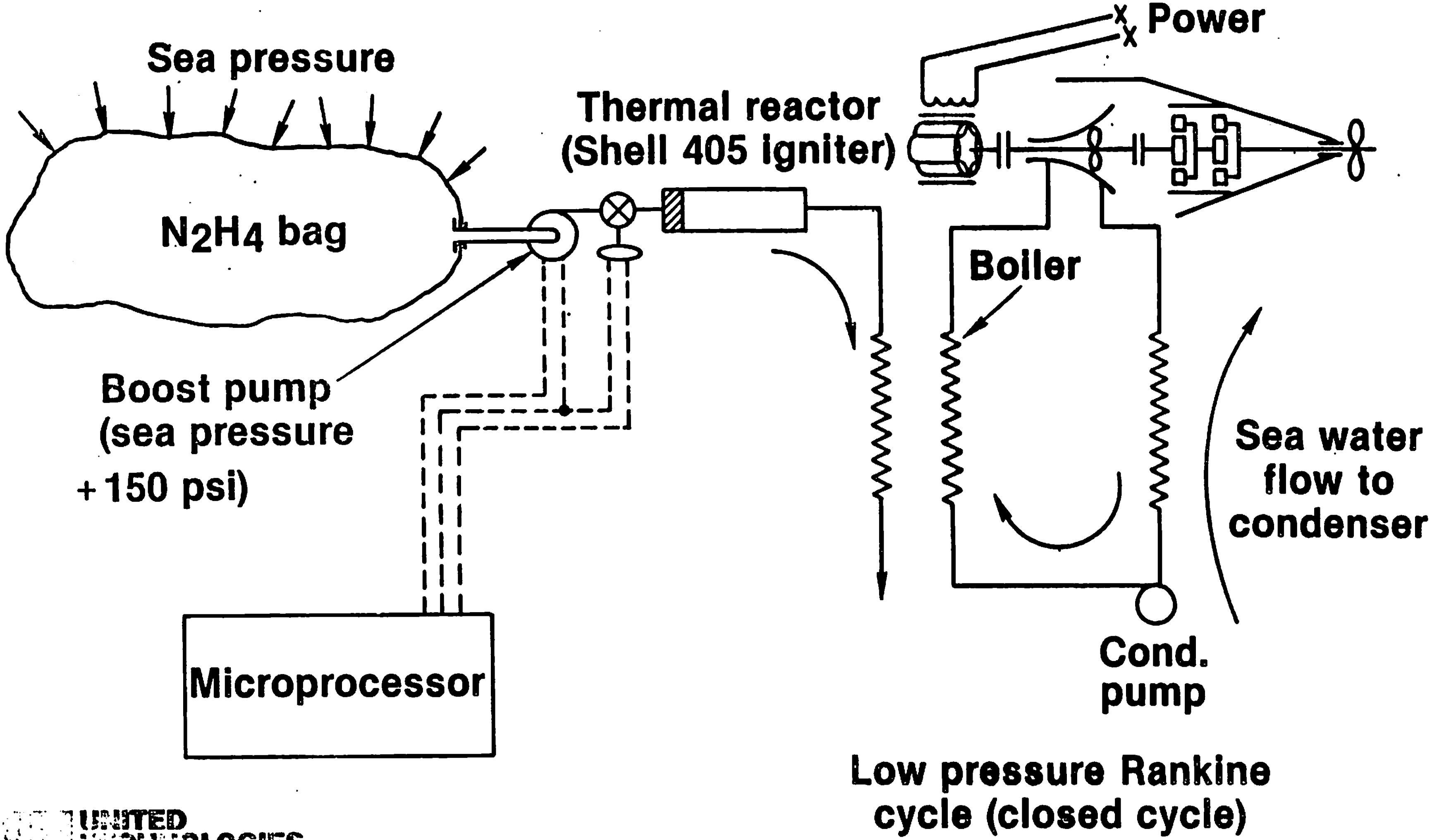

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Figure 5

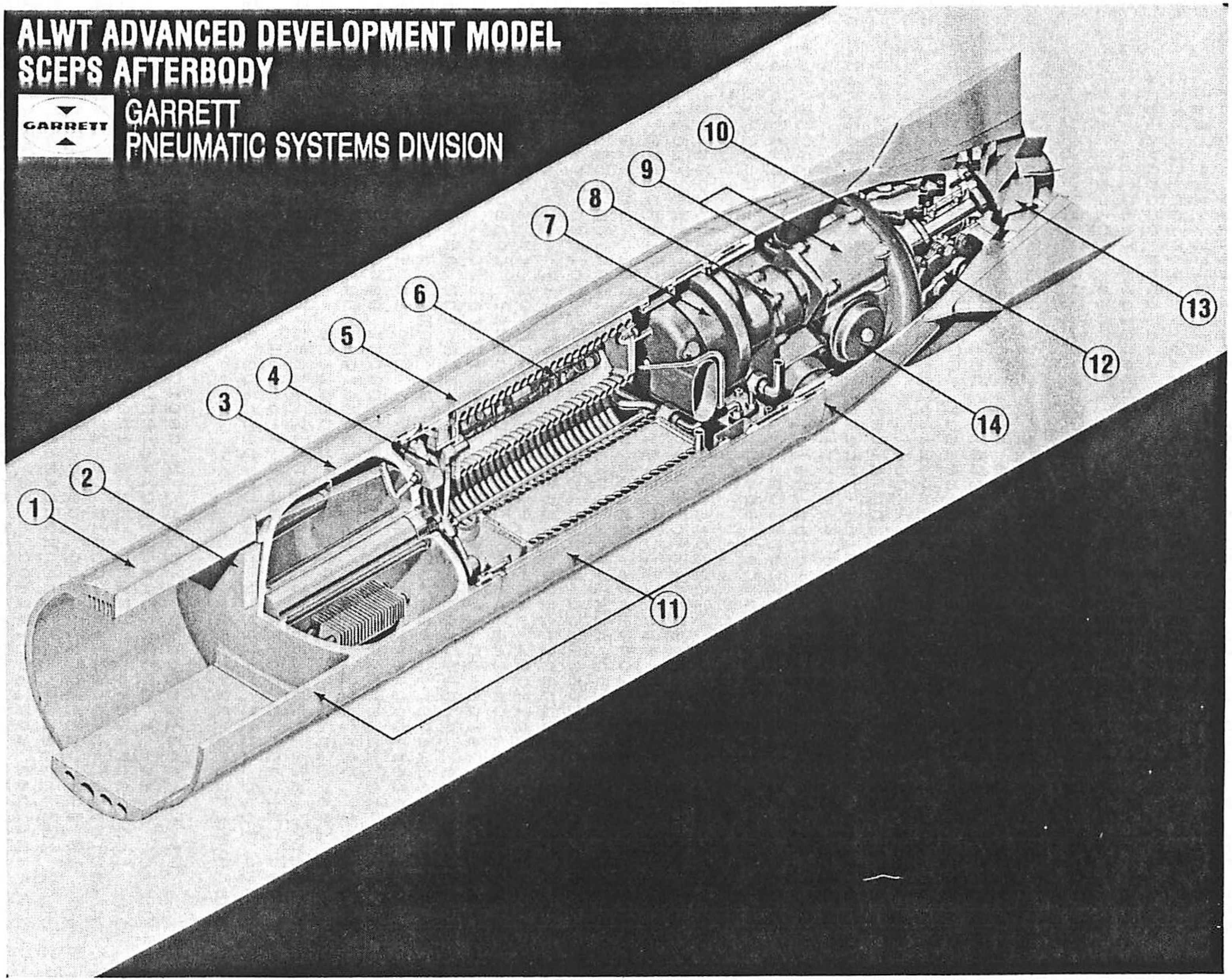
ALWT ADVANCED DEVELOPMENT MODEL
SCEPS AFTERBODY
GARRETT
GARRETT
PNEUMATIC SYSTEMS DIVISION
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FIGURE 6

afterbody featuring a SCEPS Li + SF_6 propellant system. In this embodiment, water is the working fluid. It is pumped to a high pressure by the feedwater injector, boiled and superheated in the coils enclosing the lithium reactor/reservoir system, expanded through a turbine to produce power, and finally, condensed in a seawater condenser which is integral with the hull. The propellant system was selected for its very high thermal energy density and because the products of reaction occupy less volume than the lithium reactant and are therefore readily accumulated within the lithium reactor/reservoir. This vehicle develops more than 200 hp in a relatively compact configuration.

For other applications, alternative power/propulsion options may be desirable. As shown in Figure 7, the SCEPS powerplant of Figure 6, with a Li + SF_6 fuel, has a much higher intrinsic energy density than its predecessor (OTTO II fuel), and on a per pound basis, is the best power alternative which does not leave a gas wake except for the fuel cell. In Figure 7, the total bar length for the heat engine alternatives represents the total chemical energy available, whereas, the cross hatched areas represent the anticipated electric power available, (ie., 34% heat into work x 90% mechanical into electric -->30.6% overall). The fuel cell is the exception. The fuel cell provides a direct 57% conversion of chemical energy into electric energy, and also does not leave a gas wake, but it is better suited to longer duration, low power missions where a relatively compact fuel cell can operate with high efficiency. Except for the fuel cell, none of the very high specific energy density options are attractive for long duration missions without further development. For instance, in the ALWT powerplant, the lithium and accumulated reaction products must be maintained in a molten state (>1000° F) for the components to function properly. This requirement effectively places an upper limit both on run duration, or a lower limit on the rate of output power consumption, and on powerplant size in its present configuration. However, these limitations could be circumvented with the advent of a reliable lithium/seawater (or SF_6) burner at some point in the future. The seawater battery is competitive, but it is also intrinsically suited to a short duration power burst because once wet, the seawater battery will self-discharge whether or not power is drawn from it. Finally, the hydrazine, OTTO II, and lithium battery all represent presently feasible throttleable power alternatives which are at least 5-6 times more energetic than the best lead acid battery, with perhaps some advantage accruing to the hydrazine system.

In conclusion, Figure 8 depicts the capabilities of 523 cubic feet of hydrazine (equivalent to the internal volume of a 10 foot sphere). Using the principles discussed above, this quantity of propellant could be used to generate 106 tons of lift at 10,000 feet for deep ocean salvage or for the generation of 3500 kWh power. If the hydrazine were stored in a somewhat more streamlined configuration, say a 6 foot diameter undersea blimp, this amount of power would be sufficient to travel 5500 nm at a speed of 3 knots.

INTRINSIC ENERGY DENSITY
(BTU/LB)

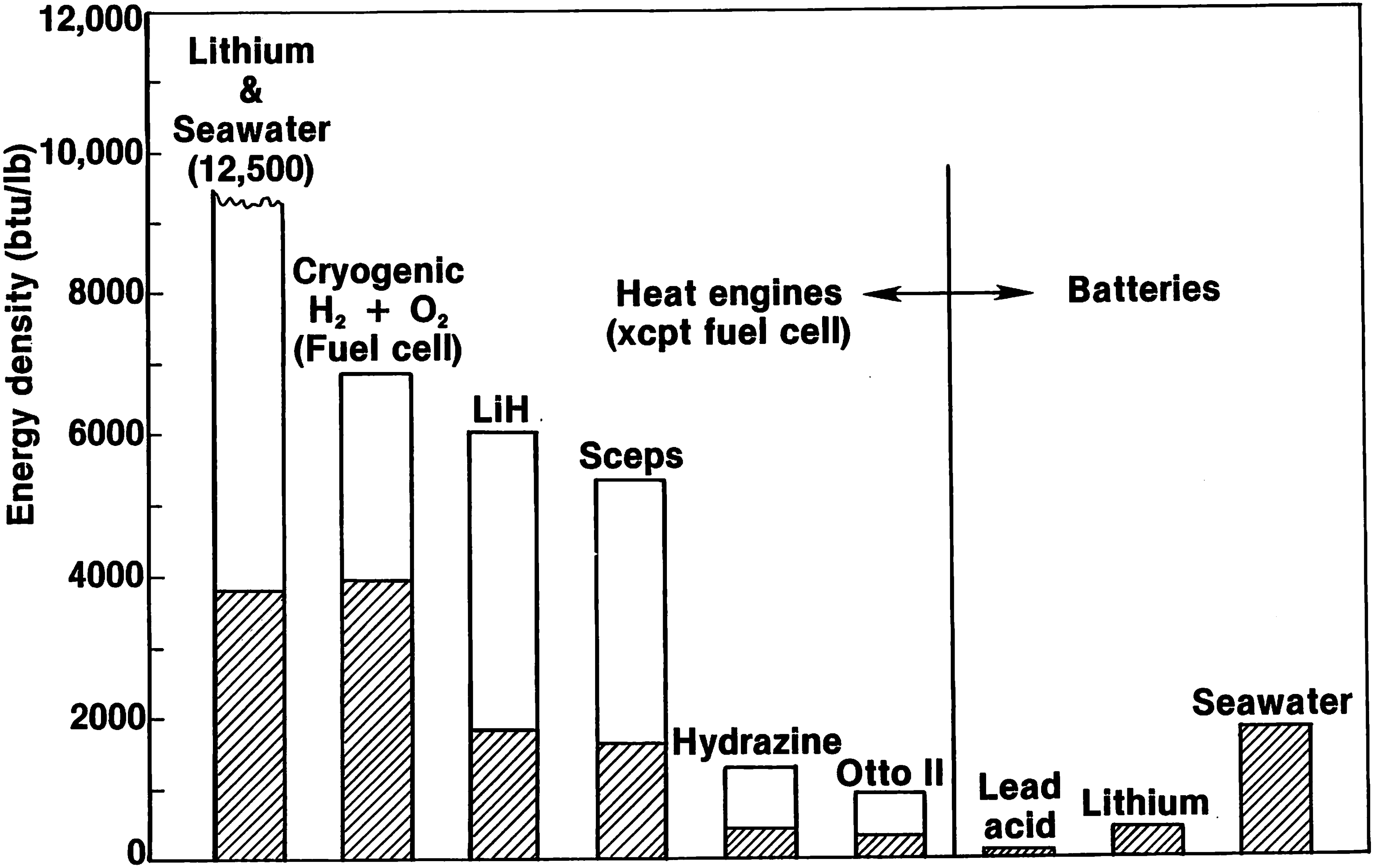
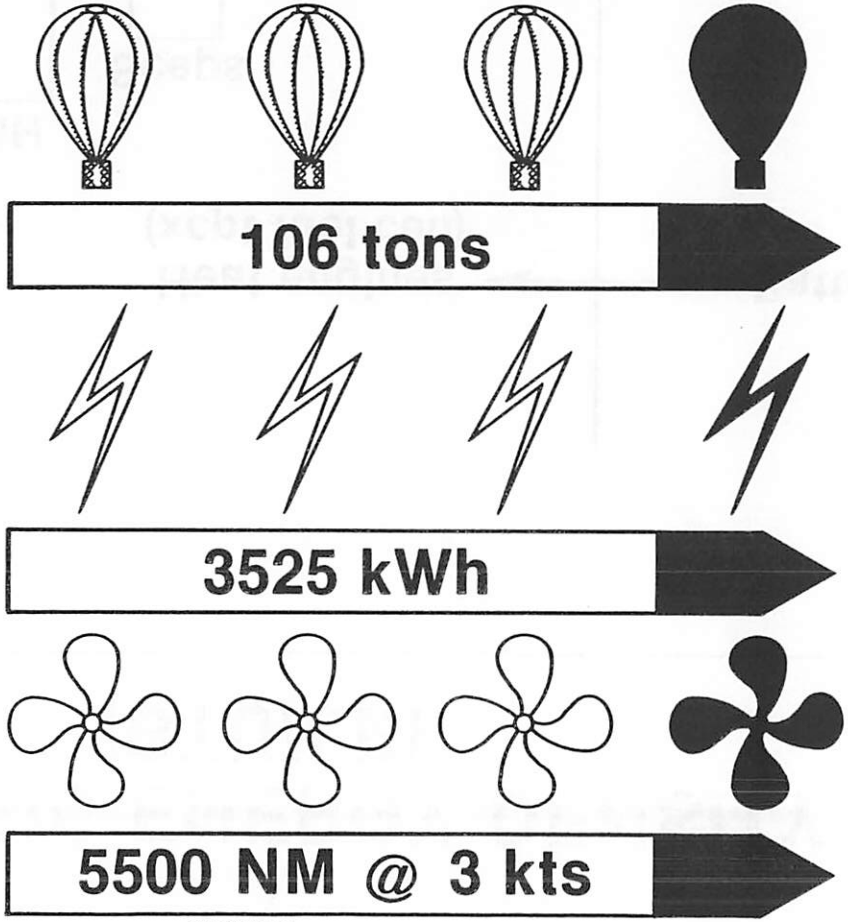


FIGURE 7

ADVANCED CAPABILITIES
Deep Ocean Hydrazine Systems

Given: 10,000 ft operation
10 ft sphere (523 ft^3 N_2H_4)



Lift

106 tons

Power

3525 kWh

Propulsion

5500 NM @ 3 kts

UNITED
TECHNOLOGIES
HAMILTON
STANDARD

FIGURE 8

SOFTWARE ORGANIZATION IN AN AUTONOMOUS VEHICLE

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Marine Systems Engineering Laboratory
University of New Hampshire

Description

In the EAVE-East vehicle, EAVE, there are presently four microcomputers. The command computer, a Motorola 68000, and three slave 6100 computers. The three slaves are used to control certain vehicle devices and are named according to their function. The thruster computer administers to the vehicles' propulsion motors, the navigation computer handles the interrogation of the external transponder net, and the bubble computer controls a 128 Kbyte bubble memory device for storing mission data. Figure 1 symbolizes this hardware in block form. Also shown in Figure 1 are the software modules required to run the vehicle. Each 6100 has an operating system written in assembler language. These simple operating systems provide I/O capability to a tty and control the hardware specific to each 6100.

The software for the command 68000 is more complex. This computer has eight I/O channels numbered from 0 to 7. Channels 0 through 4 are communications ports employing UARTS. Number 0 is the operator's console and is used to give commands to the vehicle. Figure 1 indicates which channel number communicates with which hardware device. The compass, pressure transducer, and clock are memory mapped I/O devices. Finally, Figure 1 indicates the six software modules in the command computer.

There are three distinct "personalities" to the command computer depending on which modules are running. As the modules are loaded and run, the command computer evolves from a raw 68000 to a full vehicle command system. Figure 2 shows the loading sequence and the module names.

The first and lowest level personality is provided by the AIMS bootstrap monitor. This PROM'd assembler program provides typical monitor-type features: memory examine, modify, and test; interrupt test, program loading and tracing, and transparent communications through UARTS 1 through 4. When the higher level software runs correctly, this monitor is simply used as a bootstrap loader. When crashes occur, it is a useful tool for examining the other module memory images to learn why the crashes occurred. Except for certain low-level drivers in VOS, the PROM'd monitor is the only assembler code used in the command computer; the rest is written in the "C" language.

The second command computer personality is provided by the vehicle operating system (VOS) and its command interpreter monitor. These two systems programs are loaded and started via the bootstrap loader, which then hands control over to them.

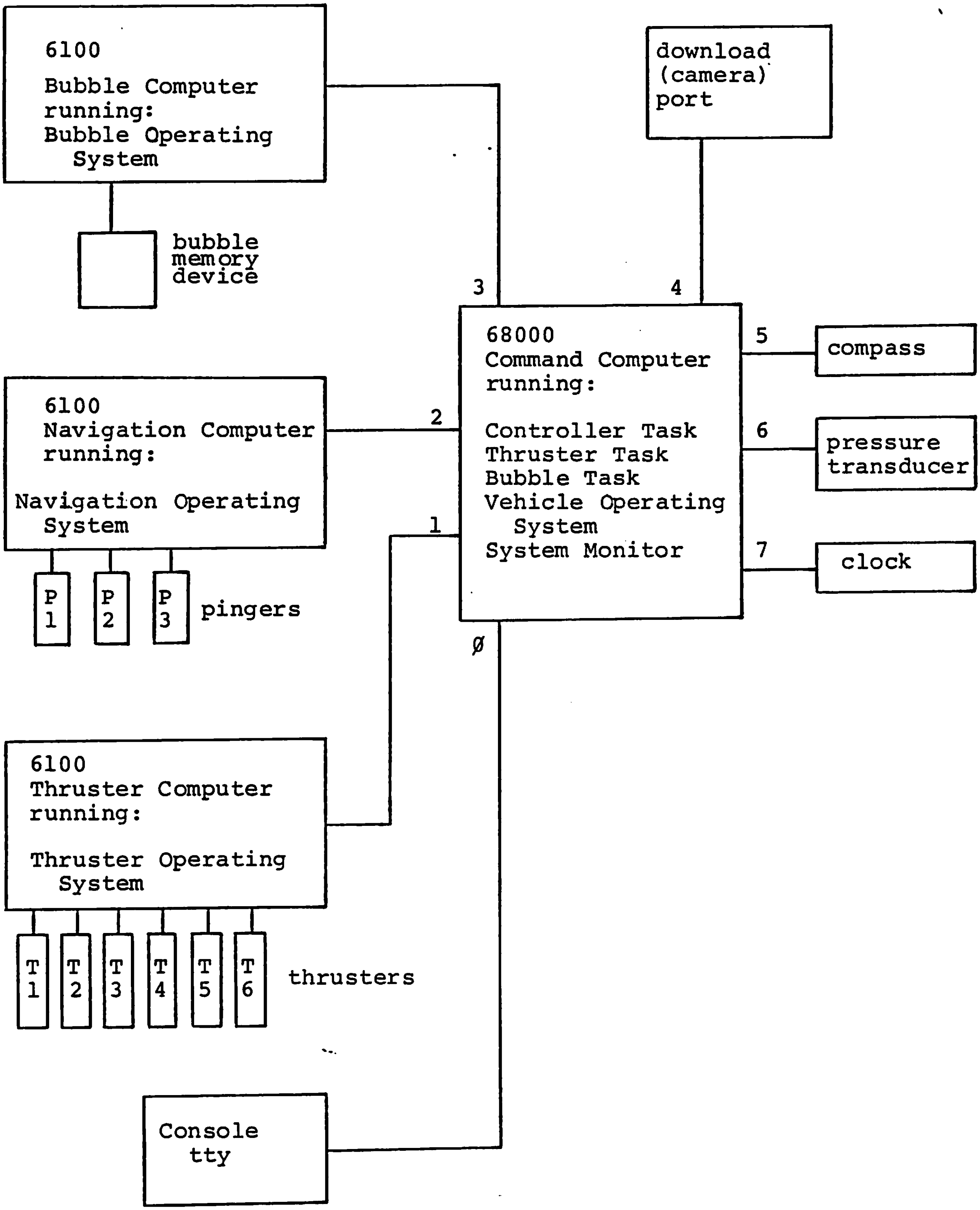

Figure 1. Block Diagram of Major Vehicle Components

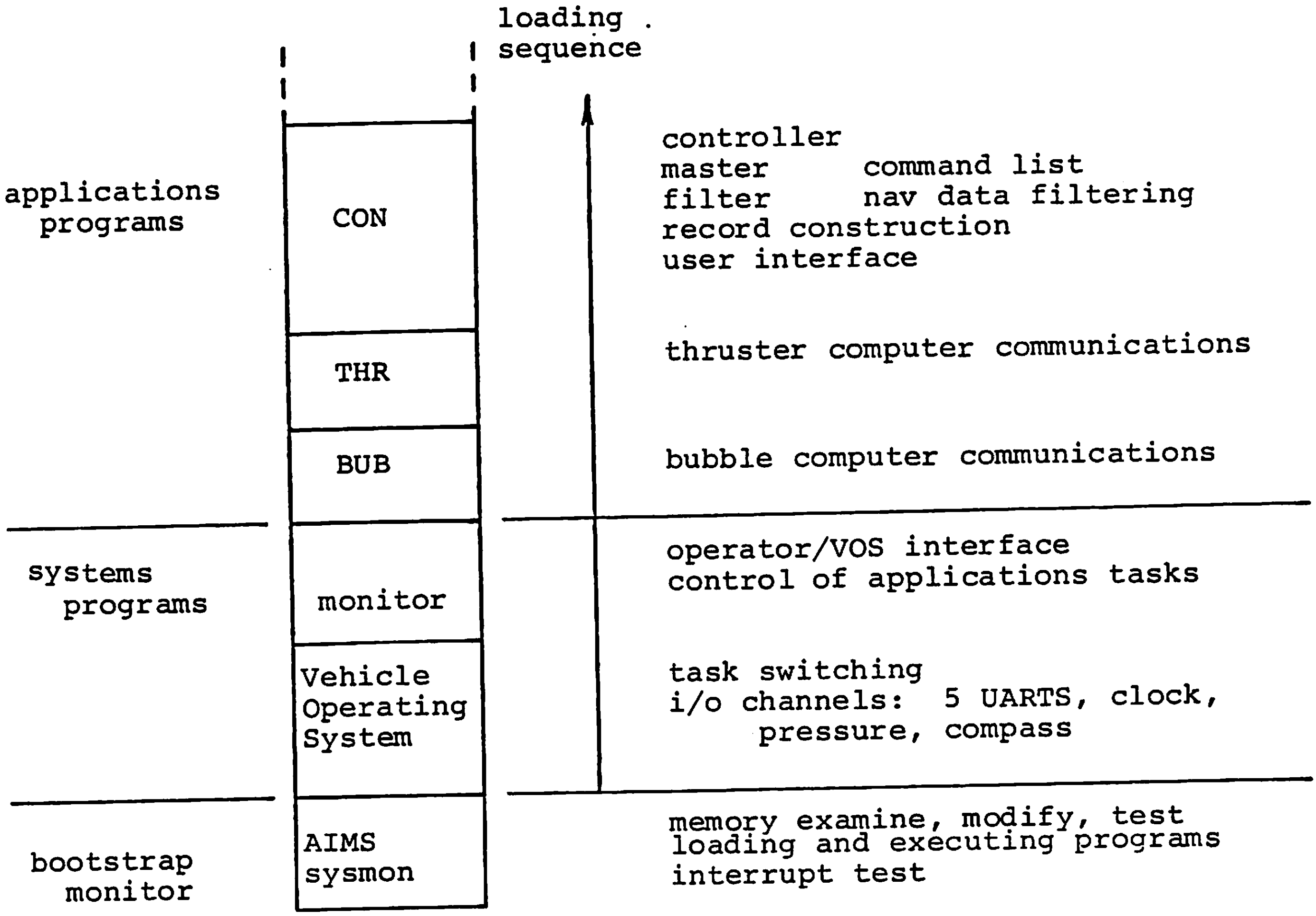

Figure 2. Vehicle Software Modules

VOS is a multitasking operating system. Its most important functions are task switching and I/O channeling. It is the software in VOS that allows the five UARTS, compass, pressure, and real-time clock to be read and written as I/O channels, rather than simple hardware devices. VOS's monitor gives the operator a small suite of commands that view the system as a vehicle computer. For example, the DEPTH command returns the depth (in inches) as read by the pressure transducer. DATE returns the system time or alters it. The current command list is:

HELP	prints this command list
THRUST	go transparent to thruster computer
NAV	go transparent to navigation computer
MBM	go transparent to bubble computer
CAMERA	go transparent on camera (download) port
COMPASS	print bearing in degrees
DATE	print or set the date
SET	used to start, stop, control tasks
SLICE	used to control a task's CPU time
OFFMULT	print or set pressure transducer's offset, multiplier
LOAD	load a new task

In addition, there are two control characters that cause immediate responses (they need not be followed by a carriage return). Control-t produces a chart of all tasks and their current status, and control-f generates a chart of which tasks are performing I/O on which channels. These two controls provide the operator with a window into the system's performance.

The third personality of the 68000 is produced when the applications tasks are loaded and running. The LOAD command and SET command are used to accomplish this. These tasks extend the vehicle command computer into a full vehicle system by providing the machinery to communicate with and operate the peripheral hardware. When the applications tasks are running, the vehicle has its eyes, fins, and memory in the form of navigation, thruster, and bubble memory hardware.

As shown in Figure 2, there are currently three applications tasks that run in the vehicle: BUB, THR, and CON. BUB is loaded first and deals only with bubble computer communications. BUB first has a short dialog with the operator to determine which data storage mode will be used, and then becomes transparent. BUB goes about its business waiting for records to be sent to it from the controller and handling the packet communications with the bubble computer. BUB is really a background utility task that manages the secondary storage.

The thruster task, THR, is also a background utility. When started, THR displays its version number and then fades into the background waiting for messages (holding thruster commands) from the controller. This task is so simple and small, that one may question the validity of making it a separate task (instead of a procedure for the controller) and thus incurring some extra overhead for VOS. The overhead of the VOS's task switch is negligible, however, compared to the delays between command characters that the thruster computer requires. One controller cycle generates thruster commands that require close to one second for the thruster computer to execute. Rather than force the controller to lose one second of valuable CPU time delaying for the thruster computer, the commands are simply "handed off" to the THR task. Since the tasks are running concurrently, THR does the waiting for the thruster computer while the controller may proceed with the vital control computations.

In addition to this increased system efficiency, multi-tasking provides a means of detecting and reacting to system malfunctions. Currently, for example, THR will tolerate ten seconds of silence from the controller before it turns all thrusters off. If the controller were to crash sometime during a mission, THR will turn off the thrusters ten seconds after the last message was received, allowing the vehicle to float to the surface (rather than charging off in the direction the last command sent it until the batteries are drained).

The third task, CON, contains the controller and a sizeable body of other code presently required for vehicle testing. Figure 3 shows the major divisions within CON, as well as the general algorithms of BUB, THR, and the monitor. In addition, the I/O channels and control sections of VOS are diagrammed (with channel numbers). Finally, communications paths in the system are shown by the arcs.

As evidenced by Figure 3, CON is a rather complex module. CON's most important portion is the controller code. This is where the actual controller equations are implemented. The filter portion of CON is a procedure that is designed to detect and filter out any "bad" position the navigation computer might calculate. A position is determined to be bad if it falls outside a specified window around a predicted position. The prediction is also part of the filter. Master is a short procedure that manages the mission command list. This is a script of preprogrammed motion commands that direct where the vehicle is to go. There are at present, five types of commands:

HOVER	hover at specified x,y,z bearing
HORIZ_MOVE	move to specified x,y relative bearing
VERT_MOVE	move to specified z bearing
ROTATE_ONLY	rotate to specified bearing
EXIT	exit controller loop

The final portion of CON is a user interface that allows the operator to alter default values of many of the applications tasks' variables. Using this interface, the field operator may trim controller coefficients, adjust failsafe parameters, and enter new motion command scripts.

It should be evident that the CON task is too large and unwieldy. Work is presently underway to replace the filter

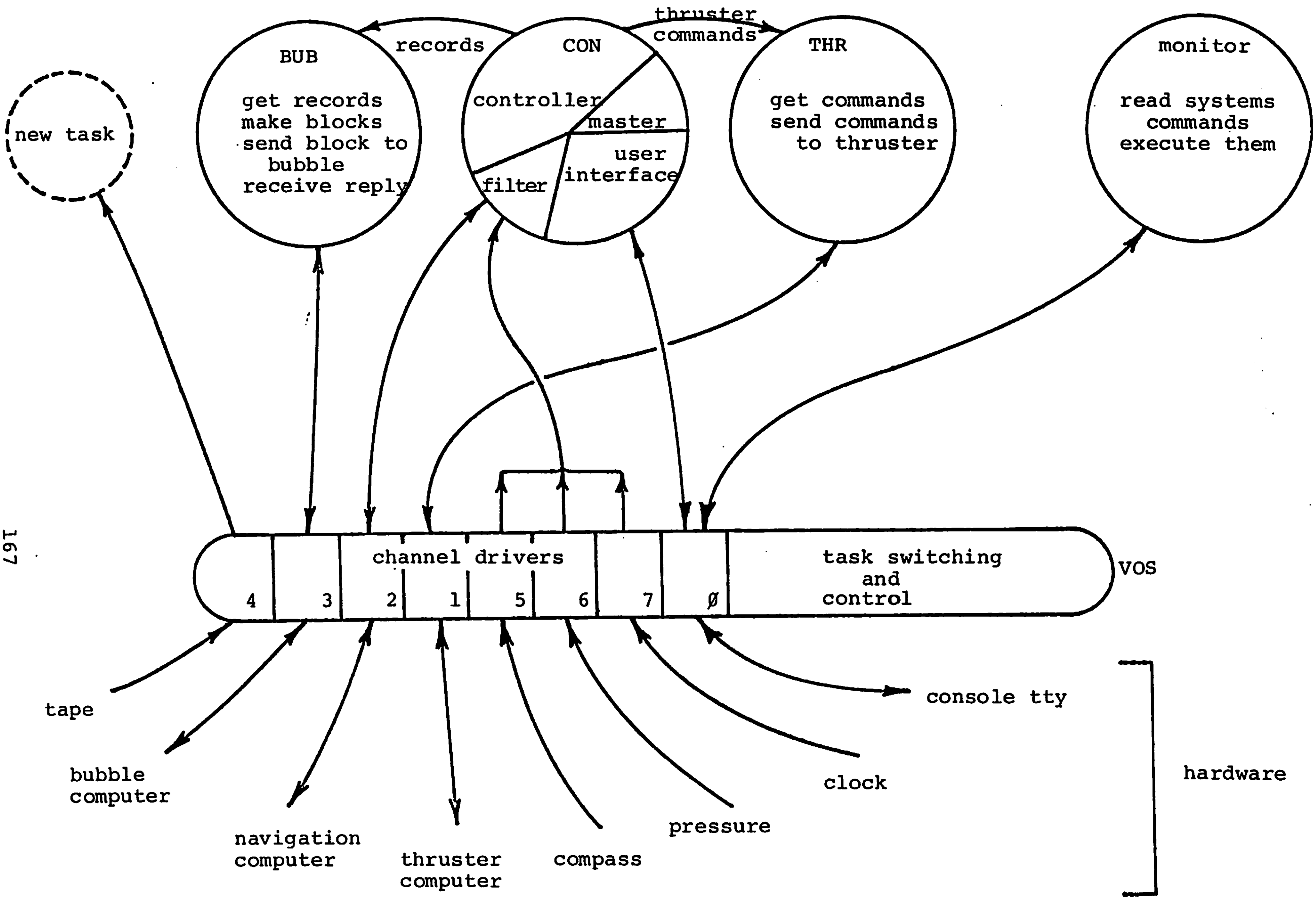

Figure 3. Vehicle Task Configuration

procedure with a filter task to allow concurrent filtering and controlling. This will speed up the controller's cycle time significantly, the same way the creation of the thruster task did (the thruster task was originally a procedure in CON). In addition, it is projected that the master procedure and the user interface will be evolved into separate tasks. Figure 4 shows how the proposed system will look.

Further Work

There are several critical areas that must be addressed to improve the vehicle's performance. The most important is conversion of the filter procedure to an independent task. The controller cycle is currently running slower than the original design specifies (1.5 seconds as opposed to a desired minimum of 1 second). Timing experiments have indicated that each filter cycle consumes 0.7 seconds, the bulk of that duration spent waiting for the navigation computer to respond to a position query. Tasking of filter will allow it to run essentially synchronously with the navigation computer and asynchronously with the controller. When the controller requests a position, the filter task will provide the last known position immediately.

Both Figures 3 and 4 show two tasks competing for one resource; the vehicle console tty. Work is being done to develop a non-clumsy manner for the operator to specify which task receives a command input on the console.

As the number of tasks in the command computer increases several software concepts must be developed. A scheme for complicated intertask communications must be devised. The underlying information transfer mechanism exists, but concepts about exactly which information is to be exchanged are not fully developed. Such concepts will be expanded to consider interprocessor communications when the current 6100 navigation computer is replaced by a 68000. Presumably, the filter code will be exported from the command to the navigation computer at that time.

Methods for monitoring and trimming the efficiency of the applications programs running as a whole must also be developed. Such methods will help determine the maximum number of tasks VOS may run without serious system degradation and may permit VOS to self trim the entire system for maximum efficiency during a mission.

Conclusions

High level programming techniques have worked very well in the vehicle. By utilizing multitasking to provide external devices with their own "driver tasks" within the command computer, the efficiency of information throughput to and from the commanding computer is being maximized. As the system becomes more complex, strategies to monitor and control complex multitasking environments in real-time must be developed.

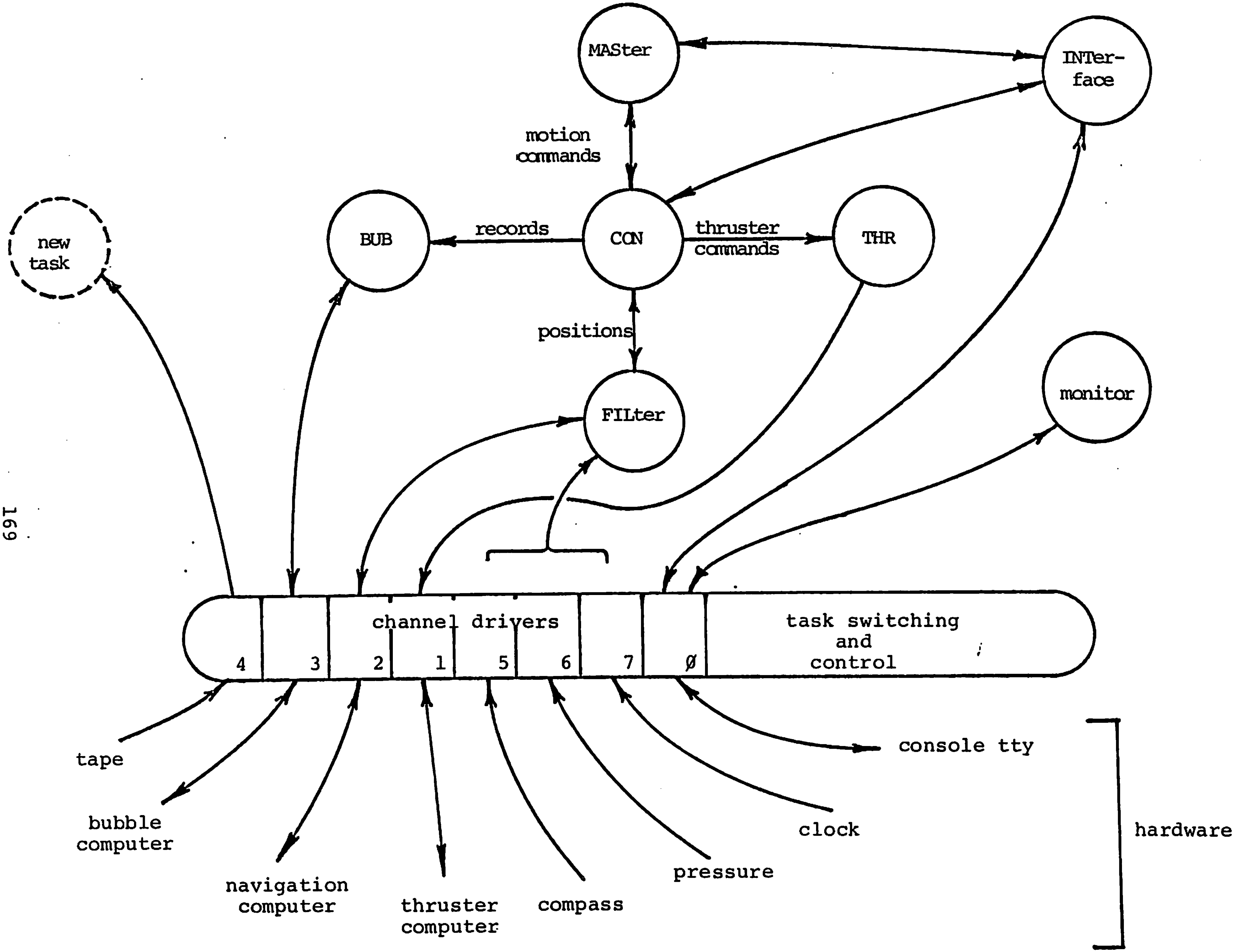

Figure [illegible] Projected Vehicle Task Configuration

MICROCOMPUTER HARDWARE/SOFTWARE

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SEA, Inc.

The following discussion concerns software and software problems from the point of view of the Project Engineer or Program Manager. Not from the Software Engineer or the individual that is specifically related to the generating code.

Advantages of Microprocessors

Microprocessors are being used in a variety of applications with increasing sophistication. Generally, the reasons for using microprocessors are established from the point of view of their advantages.

1. Minimum PC Board Area Required

The use of microprocessors reduces the required circuit board area; this allows powerful designs to be "crammed" into extremely restrictive spaces. This is very important in terms of underwater vehicle applications where minimizing size and weight is always a major goal. For any vehicle, because of the buoyancy of water, the size and the weight of the vehicle are relatively equivalent numbers. Making the vehicle lighter requires making it smaller. Since the goal of vehicle development is to provide more capability, more power and more effectiveness in the vehicle; the weight to performance ratio is constantly being increased.

2. High Reliability

Reliability has been improved by the higher level of integration and reduced parts counts. With fewer parts to fail the reliability is higher. The probability of any one particular part failing and bringing the entire system to a halt is quite low.

3. Design Flexibility

This is often touted as being a key reason for using microprocessors. New system or performance requirements for any specific application can be met without making expensive or difficult hardware changes. It is frequently said that it is a simple matter of software to tailor a system to meet the requirements of a specific application. This statement - with its, hopefully, intended humor is one of the key points of this paper.

There are also secondary reasons for using microprocessors, not the least of which is the Design Engineer's simple desire to work with a microprocessor. This sort of illogical or irrational justification all too often finds its way into design activities.

Disadvantages of Microprocessors

One of the least discussed aspects of microprocessors are their disadvantages. From a System Engineer's viewpoint, the use of standard computer hardware eliminates a great deal of hardware design. In reality, however, one is not really eliminating a design task, he or she is instead, replacing the hardware design task with a software design task. A key point to remember, is that effort is not necessarily being eliminated. Instead, one type of effort is being exchanged for another. One should therefore consider: which is the easiest to perform.

History

In the early 1970's when microprocessors first came into use system development costs were dominated by hardware development tasks. Since standardized computer designs did not exist it was necessary to share with individual chips, create your own designs, make your own circuit board, and work out your own bus structures and communications. All of the hardware, therefore, was a specific design performed by a specific individual, usually for a specific application. Also, the application programs were relatively simple. People did not understand the power of available systems, the support hardware was unavailable, support software development systems were not available, and the sophistication of the Applications Engineer had not yet arrived.

During this time, the first project in which I was involved that used a microprocessor had design costs - in the computer section alone - that were 90% hardware related and 10% software related. This ratio has gradually shifted toward a more dominant cost position for software. By the late seventies the system development costs were dominated, by far, by software costs. There are two primary reasons for this. First, more systems are being developed using standard, off-the-shelf computer boards. For example, multibus, S-100, and STD buses, all of which have a wide variety of very powerful cards readily available. Hence, most of the current systems are those for which an individual has selected a particular bus structure or a particular computer, and then simply purchased the hardware. There is, as a consequence, very little current hardware development. The second reason is that application programs are becoming more complex and more sophisticated. As an example, one of the latest projects of SEA called for a very simple winch controller in which a microprocessor was employed; the total hardware cost was about $1,700 and the software cost was over $15,000. The message is that it is necessary to develop the capability not only to create the software, but also to control the software-oriented tasks if the project is going to be successfully completed on time, and within budget.

The same types of problems were experienced in the early 1960's when the space program started to balloon. This was a very large, complex project. So large, in fact, that no single activity could perform the task. It required being split up and distributed amongst a wide variety and large number of individual groups. This is where the idea of system engineering, at least in the U.S., developed. It entailed taking an individual task and breaking it into separable and identifiable parts that could be parceled out to a large number of supporting activities. This must be done in a manner that insures when these parts come back together they will be compatible and function properly. Over the past 20 years the Electrical and Mechanical Engineers who worked in this country on fairly sophisticated projects have been educated in the necessity of performing their functions in a specific manner oriented toward: strong discipline, preliminary and specific definition of the task, and a sensitivity to interface requirements. There is a certain incubation period over which a profession must educate itself and, in general, the Electrical and Mechanical Engineering professions have had adequate time for such education. Unfortunately, in the type of applications we envision for undersea vehicles, the software profession has not had adequate time nor has it reached the maturation point to develop these kinds of capabilities on a broad scale.

As an example, Table 1 presents the normal steps one would take in a typical systems oriented mechanical design activity compared with a similar software design activity. The only real difference between the two is that the mechanical design results in tangible hardware; the software design, in general, does not.

The first step is to establish specifications. The problem here is that very often there is not a full meeting of the minds between the buyer/user and the designer/provider. Specifications established by the customer are, very often, expectations rather than actual necessities. They may be oriented toward the specific hardware rather than the function of that hardware. They may or may not be appropriate. But all too often they are poorly defined and poorly understood by all the parties involved in the development activity. The types of information really needed in the specifications are functional requirements, size, weight, interface specifications, and a limited number of additional items which would be unique to the specific application.

Once the preliminary specification has been established and agreed upon by both the design activity and the customer, the layout begins. The layout is usually a physical cross-section of the hardware showing the individual pieces, the envelope and internal emplacement of individual components.

Equipment breakdown begins after the layout is complete. This is simply a listing of the primary equipment groups. In a vehicle, for example, the equipment breakdown generally includes a structural group; an electronics group (broken, perhaps, into

MECHANICAL DESIGN	SOFTWARE DESIGN
Specifications	Specifications
Functional Requirements	Functional Requirements
Size	Memory
Weight	Operating Speed
Interface Specifications	I/O Description & Hardware I/F
Layout	Program Outline
Equipment Breakdown	
Indentured Drawing List	Indentured Routine List
Assembly Drawings	Flow Charts ("D" Charts)
Sub-Assemblies	Major Routines
Detail Drawings	Program Modules
PRELIMINARY DESIGN REVIEW	**PRELIMINARY DESIGN REVIEW**
Complete Design Approach	Complete Software Design
Sketches	Module Definition
Schematics	I/O Description
Final Trade Studies	Memory Description
Breadboard Tests	Timing Analysis
	Test Requirements & Procedures
(no detail drawings)	(no code)
INTERIM DESIGN REVIEW	**INTERIM DESIGN REVIEW**
Detail Design/Drafting	Code Software
Complete Test Procedures	Test Software
Complete Engineering Input to Tech Manual	Complete Engineering Input to Tech Manual
CRITICAL DESIGN REVIEW	**CRITICAL DESIGN REVIEW**
Fabrication	

Table 1

power, power distribution, power conditioning); emergency recovery groups; payload and auxiliary equipment groups. In essence, it breaks the equipment down into a verbal listing of the various major component groupings. Once this is completed the indentured drawing list is begun.

The indentured drawing list, in outline form, identifies the individual parts and pieces down to the nut and bolt level. As the design is completed and as the indentured drawing list is maintained, the end result is a comprehensive listing - in outline form - of every piece and part in the entire system. All being consistent with the original equipment breakdown and layout. The reason for doing this is to identify the individual assemblies and sub-assemblies. If these have been identified properly, then it is fairly certain that documentation of each sub-assembly in an individual documentation package can be made. This means that the task of designing the particular unit can be assigned to an individual who can properly perform his task virtually independent of others. This is the ultimate goal; with the designer still meeting all of the specifications, especially the interface specifications. At this point the preliminary design review is started.

One of the key functions in the preliminary design review is to review the individual equipment breakdown and the overall layout. Having gone through this, the point has arrived where, essentially, authorization is given to complete the design. Now the entire design effort is reviewed, necessary schematics are generated, more final engineering calculations and trade studies are completed, and testing at the breadboard level is conducted. Final hardware is not built at this point, nor are final drawings completed. The design is, however, essentially completed. Adequate information should be available to know where the problems lie, and in most instances, the solutions should be known. At this point, the interim design review is held.

The interim design review essentially provides authorization to move into the detailed design and drafting phase. Once these and the test procedures are completed, critical design review commences. Subsequent to this the design is released for fabrication. It is possible that procurement of items requiring a long lead time will already have commenced earlier. The entire task does not have to remain as rigid as shown in Table 1. However, it is important to have some sort of format which encourages the sort of discipline and provides the sort of framework that is necessary to:

1. identify and define each task as early as possible in the program, and

2. to provide a framework through which evaluation and monitoring of the tasks can be performed on a consistent basis.

If monitoring cannot be performed, then the task cannot be controlled. If it can't be controlled, then the project is headed for a cost and schedule problem. This is not intended to force the designer into a particular approach or solution. He is still allowed all the flexibility and creativity that he may want to exercise. But he is also provided with additional support that helps him perform his job within the constraints of the program.

Software design can be performed in essentially the same manner. The specifications should be established very early; they include the items listed in Table 2, and they establish the very fundamental characteristics of the potential hardware configuration. For example, how fast should the processor be; does it have to be 8 bit, 16 bit, or is 4 bit adequate; what type of I/O capabilities are required; how much memory is necessary, etc. These establish the configuration of the computer. It is emphasized that the steps shown in Table 2 are not performed once and then never considered again in the course of the project. Instead, constant returning to these tasks for review and update is the rule. This is done to review the preliminary decisions and to improve the analyses and estimates.

Once again, we are laying out what the fundamental performance characteristics will be, and then, will move into an indentured routine list (IRL) which is very similar to indentured drawing list described earlier. The IRL begins as an outline which, hopefully, increases in detail as the program development proceeds. It is, in essence, a listing of all the various routines and functions that the program will accomplish. Instead of individual drawings, this is supported by a variety of documentation which may include Flow Diagrams "D" Charts, identification of major routines and identification of individual modules which support the major routine requirements.

The foregoing provides a preliminary definition of the overall computer system. It includes the hardware, the functional requirements of the overall system, and the software definition. At this point a preliminary design review, as described for mechanical design, is performed. If the concepts appear satisfactory, then authorization is given to begin the detailed software design. At this point nothing has been coded; the code is still being defined in terms of what it is going to do once created.

The next procedure is outlined in Table 3. The entire activity is carried one step further by now identifying the individual modules; individual I/O requirements; port assignments, etc. Additionally, memory requirements and timing requirements begin now to be quantified. This is a convenient method of estimating the accuracy of the original estimates. If they are widely divergent, it is an indicator that perhaps the costs and schedules are unrealistic also and should be reconsidered. In short, this phase establishes the discipline to identify, as well as possible, what the task is as early as

PHASE I

CUSTOMER SPECIFICATIONS (EXPECTATIONS)

INTERPRET SPECIFICATION

- Develop Preliminary Response

DEFINE TECHNICAL APPROACH

- Task Outline — Preliminary IRL
- Computer Functional Block Diagram
- I/O and Interface Description
- List of Inputs and Outputs
- Rough Estimate of Memory Requirements
- Scheduler Definition
- Preliminary Timing Analysis

PRELIMINARY SCHEDULE

PRELIMINARY DESIGN REVIEW

Table 2

PHASE II

SOFTWARE DESIGN

- Module Partition/Definition/Description
  - Purpose or Function
  - Communication
  - Working IRL
  - Supporting Information
    - Flow Diagrams "D"-Charts, etc.
    - Detailed Outline
    - Calculations
- Completion of
  - I/O and Interface Description
    - Port Assignments
    - A/D & D/A Requirements
    - Scale Factors
    - Display Requirements & Format
    - Initialization Requirements
  - Memory Description
    - Memory Requirements
    - Memory Medium
    - Memory Map
  - Scheduler Definition
    - Interrupt Requirements
    - I/O Service Timing
    - Method & Timing for Calling Routines
  - Timing Analysis

TEST REQUIREMENTS AND PROCEDURES

SCHEDULE

INTERIM DESIGN REVIEW

Table 3

possible and to provide a stable framework that permits continuous monitoring of the program's status against the original estimates. Flexibility to change is still available, but you have the capability to assess whether or not any of the changes that are occurring in the program may have an effect on other portions of the program estimate. If this monitoring/control process becomes a hindrance rather than a help, then something is being done incorrectly. The goal herein is not to infringe on the designer's creativity, but is instead, to obtain better software in a shorter amount of time at a lower cost. If followed, the software should integrate easier, the modules will join and function more appropriately, the overall software package will function more efficiently, effectively, faster and better, and will be easier to support and adapt.

Having completed this definition in terms of what the software will be, the interim design review is conducted and, if satisfactory, authorization is received to commence coding the software. The software coding phase is shown in Table 4.

It should be noted, that if the task is small enough to be performed by one person, then the foregoing procedures are essentially moot, and are probably more trouble than they are worth. However, applications are reaching a level of complexity where the probability of one task/one person is remote. If there is any realism to the requirements, the probability is quite high that someone else at some point in time will be required to pick up the code and adapt it, modify it, or improve it. Hence, reasonable documentation of the code is necessary.

This structure can be in the form of Pascal. There is, however, no reason why Basic cannot be used in the same manner. One does not need to rely on the individual language being used, but can develop his or her own procedures and virtually any language can be applied to those procedures if they are adaptable.

There is a critical difference between a mechanical product and a software product. When a mechanical product is completed and the initial trials reveal a mechanical problem, it can usually be corrected whether or not there is a mechanical drawing. However, with a software product, all there is is a bit pattern stored somewhere in a ROM. Without the documentation showing precisely what is involved, the chance of making successful changes is very much reduced. Unlike a mechanical product which is tangible, the software product is, to all intents, ethereal; hence, there must be documentation.

Referring again to Table 4, when software is coded a list is created. This does not have to be done as a separate manual or document. It is very effective to do it directly in the source listing. This avoids the possibility of having another document which can be lost. A revision history should be included and, also, a table of contents and comments. The comments should not be brief, the more elaborate they are, the

PHASE III

- CODE SOFTWARE
    - Listing
        - Revision History
        - Table of Contents (Section of IRL)
        - Comments (As extensive as possible, at least as large and preferably much larger than the code sections. Should be written to another engineer or individual competent in software)
        - Code
    - Supporting Documentation
        - Verbal Description of Routine
            - Purpose
            - Operation
        - Outline
        - Flow Diagrams or "D"-Charts
        - Calculations
        - Discussion of Algorithms
- TEST PROCEDURES
- TEST RESULTS

FINAL DESIGN REVIEW

Table 4

better. The supporting documentation will generally consist of items which are either impractical or inappropriate to put into the comments section. There are two audiences being addressed: the "Listing" group is for use by another software engineer, or for someone who may need to return and modify the code at a later date. The "Supporting Documentation" is generated for use by other project engineers or non-software types concerned with operation and maintenance.

The foregoing is not meant to be the only approach to software design or a solution to software problems. The emphasis herein is to establish discipline adequate to create an initial task definition and, then, the discipline to adhere to that definition.

WHY A SUPER MICRO?

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One of the obvious questions is: Why do we put a super microprocessor, as I define a 16 bit machine, into an underwater vehicle? As we have seen from other papers at this symposium, a great deal of the imaging and image referencing involves relatively high technology procedures. A number of the tasks which need be done on an untethered vehicle involve quite intelligent processing. One particular example is the work of Shevenell reported elsewhere in these proceedings. This involves transmitting images through water in an acoustic channel. Although the picture he is obtaining at present is relatively crude (100 X 100), it is, nonetheless, 10,000 pixels worth of information. Initially, this procedure calls for filtering, crunching the data into larger pixels and then transmitting the data and reconstructing it. This is a significant amount of data to handle and transfer. Another important aspect concerned with having the intelligence aboard the vehicle is the notion that, rather than "talk" to the vehicle in terms of "flying" by a joystick, perhaps it makes more sense to direct it to, for example, "go over and look at area X for a while". In essence, to give the vehicle directions which are more high level in nature. An example of this was given by Yoerger in following the surface of a weld and letting the computer keep track of the activity. In the area of dynamic control we are interested in the fact that the vehicle is not particularly well designed hydrodynamically, but for various reasons it might be possible to control around this which will result in much more complex control algorithms. Also, considering adapting to changes in the work configuration: if the robot arm changes the balance or drag coefficients, or if different work packages are used, a system is needed that does not have to be carefully fine-tuned. What is desired is a system that can figure out its own dynamics by performing some impulse modes in several axes until it has determined what it looks like. Another aspect which is being discovered is that optimum paths through a structure should be chosen so that much of the limited power is not used up as a result of bad controlling. Hence, the need for more on-board vehicle intelligence is of great importance.

In terms of navigation, it is desireable to combine inertial and absolute information so that the features of both are optimized. It is possible to obtain a SONAR reference quite accurately if we can wait to listen and, then, average a number of responses. Only one return is not accurate considering the multipath problem. At the same time, the inertial system can be very good in the short term, but is subject to significant drift in the long term. If these can be combined a vastly improved navigation system is possible.

Presently we have a short baseline system with three transducers on the vehicle, if three transponders are placed around the structure it is possible to zero in or calibrate the transducers merely by traveling to a few places in the work area and solving a few equations. It is not necessary to know exactly where the transponders are, consequently, much of the difficult surveying work is eliminated.

In regards to image referencing. One of the subjects discussed earlier by Thorpe (see the CMU Rover..., in these proceedings) is the notion of letting the image drive the vehicle. While full control may not be necessary, it would be desireable to use the image as part of the feedback controls, especially during inspections where reference to the image coordinates are desired rather than reference to the transponder net. Terrain following also figures in with this, in that the image is used to drive the control.

In terms of more complex missions and enhanced survivability, we would like to attain the ability to use another strategy if for some reason the control is not performing well. In this respect we would like the vehicle to be sufficiently intelligent to think about how to get out of a situation, instead of merely automatically ascending when it might be under a structure.

In another aspect it is desireable for the vehicle to be capable of adapting to an environment. It is not always possible to know exactly what the environment is in all instances. Consequently, it might be necessary to modify the original plans once the vehicle is in situ.

WHY PUT HIGH LEVEL LANGUAGES IN THE VEHICLE COMPUTER AS OPPOSED TO BEING IN THE DEVELOPMENT TOOLS THAT ARE USED WITH THE COMPUTER?

One advantage is that it provides higher quality documentation and clearer concepts of what you are trying to accomplish. If a well-structured, high speed language is used, it can be broken down into modules which are small enough to be clearly understood. Modularity also permits team development; it allows modification of one module - because that module is involved in a piece of hardware that is changing - without impacting the entire vehicle and it permits controlling of the interfaces between sections of the software. The parallel languages also allow portability between the development system and the system that exists on the vehicle. It also eases the interface between the researchers and the implementors. Scientists associated with the project do not need to know the details which make the vehicle work internally. In this instance, the scientist can interface to a package which has already been designed to do the internal control tasks work and he merely has to decide what he wants the vehicle to do. Higher level languages offer better communication from project to project, both internally and the possibility for sharing research with other colleagues. They also offer better performance between the operator and the vehicle. By communicating directly with the vehicle underwater in a higher level language constructs can be developed that would be very difficult to implement and adapt if performed strictly in the machine language.

The foregoing aspects are the driving forces behind our desire to put a 68000 or equivalent high level processor in the vehicle. To this end we now have a single 68000/computer system and we are considering adding a 68000 to the navigation system in addition to the control system computer. To date, we have only built systems that have one processor. There are some applications where multiple processors could be advantageous. The printed circuit cards we have developed consist of a CPU card, CPU support card, communications card, and memory card. The CPU card contains the 68000 and bus buffers. The support card contains 4K of ROM, 4K of RAM and a UART. These two cards, together, can make a basic system which can then be expanded with 32K cmos memory cards. Serial communications to other systems are provided by a card with 4 CMOS UARTs.

In addition to the standard PC boards above, we have wire-wrapped several cards for specific system applications. The vehicle control computer has an application card which contains a date-time clock, a task interrupt clock, an interface to the flux-gate compass and a 12-bit AID converter for the pressure transducer that measures depth. Other special cards have been built to digitze and display video images from a low-light CCD video camera.

Everything is CMOS, except for the 68000, because of the power problem. This is a 32 Kbyte memory card which is not particularly high density, but it is CMOS and very low power. Six of these systems have been constructed to date; four have been in continuous use for approximately one year. The only major problems we have encountered is with a zero insertion force socket in the CPU which we will probably avoid in the future now that the processors are getting less expensive. We have also had some difficulties with the ribbon cables. Otherwise, those have been the only major problems.

At this stage of development, we have a package with up to 256K of memory, There is a multi-tasking capability which allows us to run 5 to 6 tasks continuously in the system. The entire system requires less than 4 watts of power."

At present we have samples of 8K x 8 memory chips which are only slightly larger than the 2K x 8's that are being used in the present system. They consume the same amount of power; they are battery backable and, if they are put into a flatpack configuration, 128K bytes can probably be put on the same card. If the normal configuration is used, then 96K bytes are obtainable. At this stage memory becomes affordable. This appears to be a good replacement for mass storage devices because it can be locally battery-backed and is independent of vehicle cabling. With the type of densities now obtainable in memory, it is beginning to be practical to store a knowledge base for an artificial intelligence system within the computer. This is in lieu of bringing it in from discs or other conventional storage media which are not very practical in this environment. Motorola now has a prototype 68020 which is a full 32 bit wide implementation of the 68000. The present 68000 is a 32 bit machine that looks like a 16 bit machine on the bus. Motorola also has a floating point coprocessor which they are about to release that permits the entire package to perform very sophisticated tasks. We are considering installing 1 to 16 megabytes of RAM into a system without a serious deficit in power consumption. We are also considering the ability to have multiple processors serving a common bus; shared memory which is owned by two processors, such that one system can be performing a continuous control task with 128K bytes of memory which is shared with another processor that is attempting to conduct an overview of what is happening and will adjust the parameters. We can perform image processing wherein there is something supplying the image and then have two or three processors working on parts of the image simultaneously. Probably within one or two years we will be carrying two or three VAX's work of computation power on the vehicle using only five or six watts of power. This means that software specifications can be less rigid, and packages can be written which are convenient to use, easy to interface and easy to change.

Acoustic Telemetry Links and High Resolution Sonar

by

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Acoustic Systems, Inc. (ASI) is currently working on an acoustic telemetry system and a multibeam sonar for autonomous remotely controlled vehicles.

The telemetry system, 'SONARLINK', is in the final stages of development and will be available by year end. The sonar, which will operate over the acoustic telemetry link, will not be available for another year. However, several other small vehicle sonars which can be made compatible with this telemetry system or with a hard-wire tether will be available this year.

The ASI acoustic telemetry system incorporates both FSK (Frequency Shift Keying) capability and a PSK (Phase Shift Keying) capability for a wide variety of data rates for different applications and environmental conditions. The FSK technique is utilized in applications where very high data rates are not required such as for command and control of a vehicle. It is also used in adverse multipath situations; for example, when the horizontal range is considerably greater than the water depth, or when operating in and around a structure such as an offshore platform.

The FSK portion of the telemetry system uses an expandable modular multi-tone approach for data rates in the order of a few bits/second to about 400 bits/second. This data rate can be increased by plugging in the additional expandable capability tone cards.

The PSK portion of the system is used for very high data rates of 1200 bits/second to nearly 20,000 bits/second. On an automous vehicle the PSK digital technique would be used for transmitting various kinds of data, such as sonar and reduced bandwidth TV, from the remote vehicle to the surface support ship or other platform. ASI has performed an extensive analysis of allowable data transmission rates for different operating frequencies and power levels, offset angles, signal-to-noise ratios, multipath conditions, ranges and depths, ambient noise, and bottom and surface conditions.

Since the entire system is completely microprocessor based, it can be programmed and configured as an optimal system for a particular application. The central processor unit (CPU) controls the data rate, mode of operation (FSK/PSK), operating frequency from 5 to 50 kHz (dependent on transducers used), and output power level. In a full-blown system configured with both FSK and PSK circuit cards, the FSK and PSK transmission can even occur simultaneously. The system's CMOS circuitry has been designed for the lowest possible power consumption with individual circuit boards only drawing a few microamps in the standby mode. The selection of the standby mode for the various circuits is controlled by the CPU.

The principal constraint on the transmission of data for autonomous vehicle sensors is the telemetry link. With this system, a typical maximum allowable data transmission rate for deep ocean applications is in the order of 4800 bits/second. This rate is adequate for slow scan TV, and as we have seen in several of the papers presented on bandwidth compression at this conference, we are on the verge of getting real-time TV of possibly 2-4 frames per second (excluding the acoustic delay in the water).

The transmission of high resolution sonar data is an even more difficult problem than TV because lost pixels can mean a real target may have gone undetected. With a TV picture the viewer does a good job of "filling in" and smoothing over lost pixels.

ASI is developing a multibeam high resolution electronically scanning sonar that will perform data compression without loss of sonar resolution at the vehicle. This unique sonar is being designed for compatibility with the ASI 'SONARLINK' telemetry system previously described. In one of its typical configurations, its circular array will have 2° beams throughout a sector coverage of up to 360° and can be configured to simultaneously "view" the entire 360° sector or any portion of it. However, the acoustic viewing constraints encountered on various vehicles generally only permits a typical sector coverage of about 200° centered in the forward direction. The system will have a range resolution of 0.4 yards at a range of 600 yards when operating at 150 kHz.

The unique detection and bandwidth reduction scheme (initial patent disclosure has been submitted) uses the sonar's full resolution at any given time by defining a selected number of pixels representing a surface consisting of the number of selected range and azimuth resolution cells. The only targets digitized for telemetry transmission are those which exhibit amplitudes which "protrude" through the adjustable threshold plane. The inherent resolution of the sonar is preserved and the system continues its search and classification function while data is being simultaneously sent to the surface over the 'SONARLINK'. On targets of interest, as defined by an internally programmed algorithm, three or four preformed beams can be combined to home in on a particular target for more detailed analysis and classification. In fact, if desired, it is not even necessary to telemeter the basic target detection information because the sonar can go directly to its classification mode and simply provide the range and bearing coordinates where the classification occurred. This effectively defines that a detection had already occurred at the indicated location.

Although both the telemetry system and the multibeam sonar system are being developed with autonomous vehicle applications in mind, the systems can be used on manned and tethered vehicles. In addition, the telemetry system can be configured for virtually any subsea communication requirement.

ON THE FEASIBILITY OF A MICRO-PROCESSOR BASED IMAGE SYSTEM

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Abstract

There are many instances where remote users might want the services of an image analysis system. Most image systems are large with little or no portability. Until recently micro-processor based systems were too slow to provide efficient service. A system is proposed using Progressive Transmission as a basis to exploit the strengths of a "State of the Art" micro-processor which will provide the benefits of low cost and portability without sacrificing performance.

Keywords: Progressive Transmission, hierarchical image structures, micro-processors.

I. Introduction

In the past several years a substantial amount of resources has been expended in research in such areas as pattern recognition, image analysis and low level computer vision systems. A result of this research has been the development of a number of hierarchical structures such as pyramids [Tanimoto, 75], overlapped pyramids [Dyer, 82], process cones [Hanson, 81] and recognition cones [Uhr, 72] to cite a few examples. All hierarchical structures are constructed in a similar manner, by stacking progressively smaller image arrays on top of one another. Each new image array is reduced in resolution by a $\frac{1}{4}$ ($\frac{1}{2}$ in each dimension) with the new pixels (picture elements) resulting from some operation (usually averaging) on a neighborhood of four pixels from the larger image. The bottom array or level is the image of interest and the top level contains a single value usually very close to the average of all the pixels in the original image. The underlying function of these hierarchical structures is the reduction and transformation of the immense amount of data that is inherent to a complex image into a form that lends itself to some interpretation by a computer system. The hierarchy provides a structure where information obtained at a level of low resolution can influence or direct detailed processing at levels of increased resolution. The cost of implementing such a system in terms of hardware and computational overhead is very high. As a result many computer image systems are very large with special architectures to address the image processing memory and computational requirements [Hwang, 83]. Even an image analysis system based on a mini computer such as a VAX-11/780 or PDP-11 requires an array processor [Hanson, 81] or a multiprocessor environment [Tanimoto, 82]. As a result there is very little portability or maneuverability; the user must collect and transport an image of interest to the image analysis system. One can envision a number of situations where a portable image system might be of use, such as the cockpit of an aircraft, a remote field situation where a course on site analysis expedites the field work, or possibly a robotics environment where the robot is not stationary and has some area in which to perform work. An obvious solution to the portability problem is to design an image system that is micro-processor driven. Recent work in this area has produced the Massively Parallel Processor [Batcher, 80 & Potter, 83] which is not portable and an Intel 8086 based system [Stewart, 83] which in its present state is too slow.

In this paper, we investigate the feasibility of implementing a microprocessor driven image analysis system based on the Progressive Transmission (hereafter PT) method [Knowlton, 80] and transmission cones [Walker, 83 & Hill, 83]. In the following sections we give a brief overview of the PT method, a short discussion of which micro-processors have the computational power to drive such a system, and finally a discussion of a possible uniprocessor architecture as well as some functions that can be off loaded to a specialized chip in an array processor environment.

II. Overview of Progress Transmission and the Transmission Cone

The PT method was devised by Ken Knowlton [83] as an alternative to quad-trees [Pavlidis, 82] and progressive refinement of images [Sloan & Tanimoto, 79] in transmitting images over low bandwidth communication channels. The PT method is a clevel scheme to encode, transmit and decode an image so that the user receives pertinent information early in the reception phase. The method is simple, efficient and there is no loss of information if the decoding operation is allowed to continue to completion. The method is viewed in a "Transmission cone" [Hill, 83] context which is an architectual extension of the image pyramid family of hierarchical structures. The transmission cone provides the structure necessary for PT to be used as a basis for an image analysis system.

IIA. Progressive Transmission

When using the PT method to transmit an image, the original r (row) * c (column) * b (bits/pixel) bits of the image are first encoded into a new set of r * c * b bits at the archive site, and stores in encoded format. When an image is requested by a remote user, bits are sent so that the received image fills in. As shown in Figure 1, the image is successively bisected (alternately in the horizontal and vertical directions) by sending b bit quantifies which Knowlton called DIFFERENTIATORS (hereafter "diff"). Each diff combins with a displayed COMPOSITE ("comp") value to produce two new comp's for the new smaller pixels. The process begins by sending b bits for the comp of the single fat pixel, and each splitting requires b bits more. Hence after M * b bits have been received the displayed image consists of M 'fat pixels'. The b bit color/intensity in each fat pixel approximates the average of all the small pixels contained within the fat pixel. An important advantage in Knowlton's PT method is that all quantities are b bit integers, and the usual numerical roundoff errors which would accumulate in finding the averages are avoided. Instead of calculating averages, look-up tables are used to map a comp and diff pair into two new comp's. One may find it illuminating to view this process as a set of transformations T_E and T_D which maps b bit pairs into similar pairs, denoted:

$$\begin{aligned} T_{Decode}(\text{comp, diff}) &= (\text{comp1, comp2}) \\ T_{Encode}(\text{comp1, comp2}) &= (\text{comp, diff}) \end{aligned} \tag{1}$$

The possible comp and diff values are used as indices, and the resulting pair of decoded comp's are found in the table.

The tables are arranged so that each comp will split into two new comp's whose average is as close as possible to the original comp. Inspection of the table in Figure 2a shows an error (error = true average - original comp) distribution as in Figure 2b. For instance, along the i = j diagonal the error can be made 0 by using i as the comp. In general, the error values are bounded by 2 ** (b - 2). Recall, however, that these errors do not accumulate, and if the decoding is allowed to proceed to its conclusion, there will be NO error in the recovered pixel.

Corresponding to the decoding process which goes on at the user's terminal, there is an encoding process which maps original pixel pairs into (comp, diff) pairs. This goes on at the image archive site, after which the image is stored in PT format. Adjacent image pixels are combined in pairs, the two comp values producing a single fat pixel comp and a new diff. Knowlton again used look-up tables for this mapping.

A significant limitation in the original PT scheme is the requirement for the two look-up tables. In Knowlton's examples each pixel was represented by only four bits, hence the tables were only 16 by 16. However, the much richer images associated with remotely sensed data may contain 24 bits/pixel, requiring a user to construct two 8.5 gigabyte tables to use PT: clearly an unmanageable size.

We have replaced the look-up tables with efficient integer procedures that are independent of the number of bit planes and require at most four compares and seven integer adds to execute an encode or decode. A remarkable property of the tables which are generated by this approach is that they are involutions: i.e., T is its own inverse. Applying the mapping twice recovers the original indices pair: T(T(i,j)) = (i, j). The implementation of this transformation as a procedure as well as a detailed explanation of the PT method, can be found in [Hill, 83 & Walker, 83].

IIB. Transmission Cone

It is very useful to view PT in the context of a 'transmission cone' as shown in Figure 3, analogous to 'processing cones' and 'quadtree pyramids' used in image processing [Hanson, 81 & Pavl, 82]. (Important differences in our use of such structures are discussed below.) The encoding process at the archive site progresses down the cone until the single fat pixel at level 0 is reached, while decoding using a stream of diff's progresses up the cone to the level desired.

To obtain a level L + 1 image from one at level L requires the transmission of an additional 3 * (4 ** L) diff's taking four times as long to receive the data for each successive level. For this reason it is particularly advantageous for a user to be able to decide at a low level whether or not an image in interesting. For instance, if Time(L) is the time required to transmit an image at level L, then Time(t)/Time(9) = 1/64, and the user can move on to the next image in 1/64 the time!

Although the transmission cone is very similar to processing cones and quadtrees, there are several significant differences worth noting:

a) The Progressive Transmission encoding algorithm is used in liew of numerical averaging.

b) Two passes over the image are required to move from one level to the next. The resulting intermediate stage is not normally available with the quadtree structure. The user can take advantage of having this intermediate data if desired, and thus attain a smoother increase in resolution for a given volume of data.

c) The transmission cone is envisioned as hierarchical array architecture with a perfect shuffly interconnection [Stone, 73].

III. Hardware Considerations

In the past micro-processors have had the reputation of low cost at the sacrifice of slow execution time and a small primary memory. Recent attempts to implement an 8086 driven computer vision system [Stewart, 83] appears to have added credence to that reputation. What we would like to accomplish is to design a system that retains the benefits of low cost and portability without a substantial increase in the time to perform image analysis algorithms. Figure 4 shows the results of a performance comparison [Patterson, 82] of Intel's iAPX432, 8086, 80286, MC68000 and DEC VAX-11/780. A detailed explanation of the benchmark algorithms can be found in [Hanson et al, 82]. We may summarize by stating all four are accepted as standard benchmarks for evaluating a processor's integer capabilities. In the relative performance table (Figure 4) a value greater than one indicates a performance faster than the VAX running Pascal under

VMS (Digital's resident operating system on the VAX) and a value less than one indicates a performance slower than the VAX. As can be seen from Table 2, the 80286 and the 68000 perform as fast as or faster than the VAX. Since many image systems are VAX or PDP-11 based, it would appear that a micro-processor system based on either the MC68000 or Intel 80286 would perform reasonably well.

The reason we choose to use the PT method of building a transmission cone image hierarchy is that it is based on integer arithmetic that exploits the strengths of either of the two micro-processors. Floating point arithmetic is performed off chip by an auxiliary unit (MC68881 for the MC68000) hence floating point operations are substantially slower and do not compare as favorably to the VAX system. Since most image hierarchies are constructed using averaging, they tend to expose the fundamental weakness of micro-processors--floating point operations. An additional advantage of PT in a small system is that the transmission cone requires no more memory than the original image.

If one had to choose between either the 68000 or 80286, the 68000 should be given serious consideration, even though its performance is below the 80286 for the following reasons.

a) The 68000 has a 32 bit internal architecture.

b) The 68020, an enhanced version of the 68000, has an on chip cache and virtual memory management [Egan, 83].

c) We would like to be able to perform fast floating point arithmetic, for portions of image analysis session such FFT's or convolutions. The MC68881 floating point arithmetic unit performs very favorably against other such units (IBM PC floating point unit for example [Stewart, 83]) as well as some mini's [Stockton, 83].

IV. Enhancements to System Performance

IVA. Memory Interleaving

One potential area that could impede the use of PT in a micro-processor environment is the organization of memory. Most micro computers are organized with one block of contiguous primary memory which means that only one memory access (read or write) can occur at any time. Figure 5a depicts the timing diagram of a typical operation that would be used in image analysis such as "A(1, 1) + A(1, 2)" and Figure 6a shows how a 4 × 4 array would be organized in contiguous memory in row major form. The example uses dimensionless time units for demonstration purposes with a request to access memory being two units and a read or write being 16 units. To perform the operation the processor must request A(1, 1) (two units) and wait for the read (16 units), request A(1, 2) (two units) and wait for the resulting read. After 36 units the processor is ready to continue with the operation. Performance may be increased by using memory interleaving [Stone, 80] where consecutive words are stored in different memory modules that may be accessed concurrently. Figure 6b shows this new organization and Figure 5b shows the results of the same operation with a simple two way interleave: even words in modulo 0 and odd words in modulo 1. Theoretic results indicate that one could expect a 47% improvement in effective access times [Bell, 83]. Remember from Section II that PT operates on alternate pixel pairs in rows (horizontailly) then vertically (columns) which means that not only will the processor perform

"A(1, 1) + A(1, 2)" operations but "A(1, 1) + A(2, 1)" operations as well. From Figure 6b we see that on alternate passes the timing diagram will resemble 5a with the net effect of slowing the system down. Once again, we may improve the performance with a technique called "skewing" [Stone, 80]. The result is shown in Figure 6c where we decide which module to place the data by doing a modulo operation on the sum of the rows and columns. In the case of two way interleaving it is modulo 2. It follows from Figure 6c that no matter what pass the PT encoding is following (horizontal or vertical) the two operands will be in different modules and the optional timing diagram will prevail.

IVB. Possible Array Architectures

One way to simplify the image analysis problem would be to off-load the image to a special array processor that would create the desired image in the hierarchical structure and return it to the user for viewing or the system would continue some sort of further analysis. An array processor consists of a certain number of Processing Elements (PE's) under the control of a special computer called a Control Unit. For a detailed explanation of special purpose array processors, see Stone [80] and Bell [83]. A good deal of attention has been directed to the design of such special-purpose array processor devices which are suitable for VLSI implementation [Hwang, 83, Rosenfeld, 83, Dyer, 82]. We are currently investigating the design of an array processor where each PE has a pipelined version of the PT encode/decode algorithm. The result of such an implementation will be a Transmission cone. The properties of the PT transmission cone that lends itself to VLSI implementation are a) interconnections between cells are simple and regular, b) only a limit number of cell types are required, and c) operations may be pipelined. We assume here, for the sake of discussion, that the design of such a specialized chip is a tractable problem, although this may not be the case [Rosenfeld, 83]. With these constraints in mind we will address the interconnection problem and demonstrate how PT provides an elegant implementation of a hierarchical image structure.

We view the interconnections of the transmission cone as having a "perfect shuffle" -- "exchange" interconnection. This means that each PE or PT modulo communicates with only four other PE's in two dimensions. When this is considered in light of pyramid machines [Tanimoto, 82] in which each node communicates with 13 others, quadtrees 9 others and hyper cubes 2 log n others [Rosenfeld, 83] the designs of which are intractable in two dimensions, then this interconnection scheme has the potential to greatly simplify the design problem. The perfect shuffle of a word N bits in length is a rotate left: $D_{ps}(b_{N-1},b_{N-2},\cdots,b_2,b_1,b_0) \Rightarrow (b_{N-2},b_{N-3},\cdots,b_1,b_0,b_{N-1})$ and an inverse perfect shuffle is a rotate right: $D_{ip}(b_{N-1},b_{N-2},\cdots,b_2,b_1,b_0) \Rightarrow (b_0,b_{N-1},b_{N-2},\cdots,b_2,b_1)$ [Stone, 73]. If one were to apply the inverse perfect shuffle to the 3 bit string (101) which is a 5, the result is (110) which is a 6, i.e., the inverse shuffle of 5 is 6. An exchange is as the name implies: odd-even pairs exchange data. It follows that if we have a perfect shuffle interconnection, then an inverse perfect shuffle interconnection is also present. Figure 7 shows the effect of the inverse perfect shuffle in one dimension while doing an encode or moving up the transmission cone. After each inverse perfect shuffle the diff's are moved out of the way and the new comp's are in the correct position for the next encode operation. When we want to project down the transmission cone we use the perfect shuffle interconnection. Since PT is an involution, there is no need to alter the function of the PE. As we move down the transmission cone, the current diff's and comp's are moved into position to create the new image just as in the encode operation. The result is that we can move between different levels on the transmission cone with relative ease. Figure 8 shows a three dimensional interpretation of the transmission cone.

V. Conclusion

Knowlton's innovative scheme for transmitting images has been extended to several low cost micro-processor based image analysis systems. Some methods for eliminating computation limitations in micro-processor systems were discussed and a variety of new approaches were presented to improve the feasibility of such a system.

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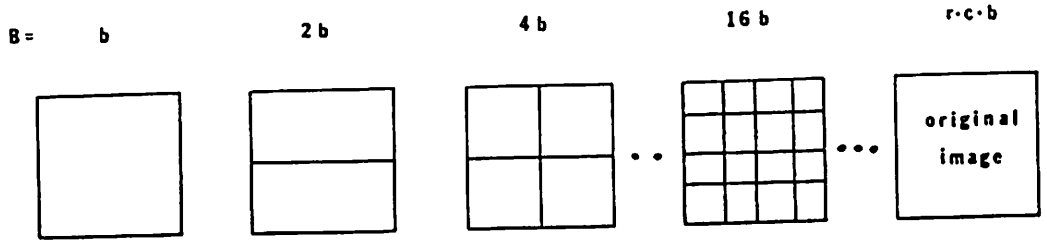


Image Seen After Receipt of B bits

Figure 1

a.)

	0	1	2	3
3	23	33	32	31
2	13	22	21	30
1	03	12	11	20
0	02	01	00	10

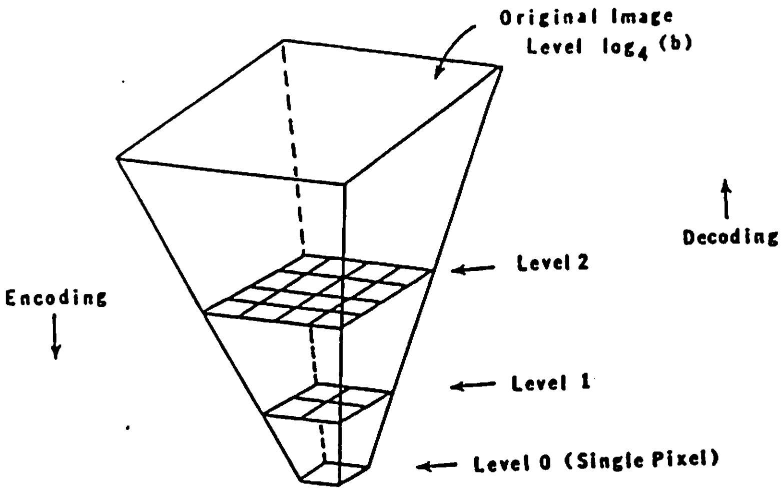
Look-up Table

b.)

	0	1	2	3
3	$-\frac{1}{2}$	-1	$-\frac{1}{2}$	0
2	0	$-\frac{1}{2}$	0	$-\frac{1}{2}$
1	$\frac{1}{2}$	0	$\frac{1}{2}$	0
0	0	$\frac{1}{2}$	1	$\frac{1}{2}$

Error Distribution

Figure 2



The Transmission Code

Figure 3

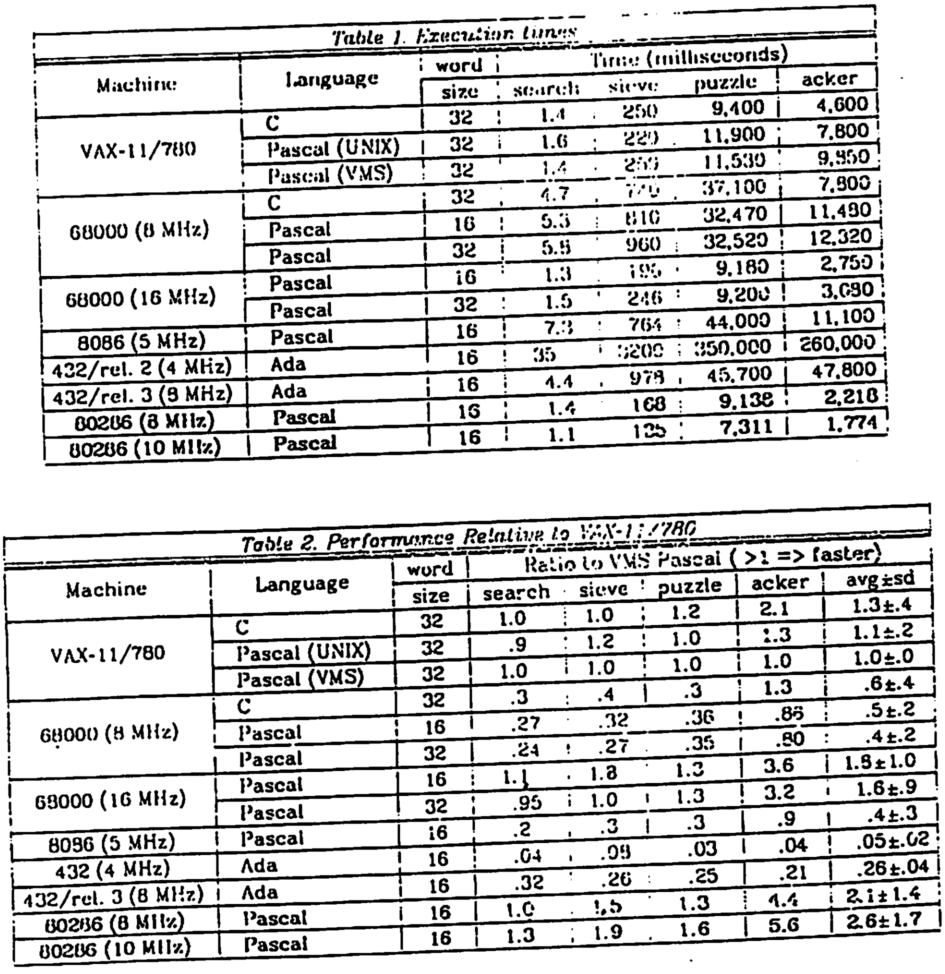


Table 1. Execution times

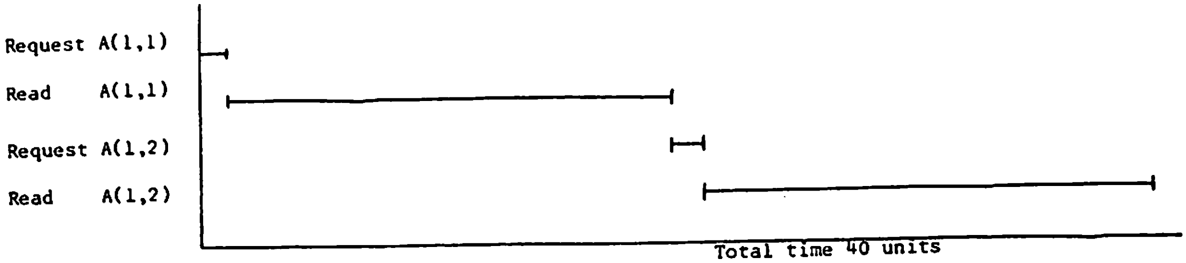
Machine	Language	word size	Time (milliseconds) search	sieve	puzzle	acker
VAX-11/780	C	32	1.4	250	9,400	4,600
	Pascal (UNIX)	32	1.6	220	11,900	7,800
	Pascal (VMS)	32	1.4	259	11,530	9,950
68000 (8 MHz)	C	32	4.7	770	37,100	7,800
	Pascal	16	5.3	810	32,470	11,480
	Pascal	32	5.8	960	32,520	12,320
68000 (16 MHz)	Pascal	16	1.3	195	9,180	2,750
	Pascal	32	1.5	246	9,200	3,090
8086 (5 MHz)	Pascal	16	7.3	764	44,000	11,100
432/rel. 2 (4 MHz)	Ada	16	35	3200	350,000	260,000
432/rel. 3 (8 MHz)	Ada	16	4.4	978	45,700	47,800
80286 (8 MHz)	Pascal	16	1.4	168	9,138	2,218
80286 (10 MHz)	Pascal	16	1.1	125	7,311	1,774

Table 2. Performance Relative to VAX-11/780

Machine	Language	word size	Ratio to VMS Pascal (>1 => faster) search	sieve	puzzle	acker	avg±sd
VAX-11/780	C	32	1.0	1.0	1.2	2.1	1.3±.4
	Pascal (UNIX)	32	.9	1.2	1.0	1.3	1.1±.2
	Pascal (VMS)	32	1.0	1.0	1.0	1.0	1.0±.0
68000 (8 MHz)	C	32	.3	.4	.3	1.3	.6±.4
	Pascal	16	.27	.32	.36	.85	.5±.2
	Pascal	32	.24	.27	.35	.80	.4±.2
68000 (16 MHz)	Pascal	16	1.1	1.8	1.3	3.6	1.8±1.0
	Pascal	32	.95	1.0	1.3	3.2	1.6±.9
8086 (5 MHz)	Pascal	16	.2	.3	.3	.9	.4±.3
432 (4 MHz)	Ada	16	.04	.09	.03	.04	.05±.02
432/rel. 3 (8 MHz)	Ada	16	.32	.26	.25	.21	.26±.04
80286 (8 MHz)	Pascal	16	1.0	1.5	1.3	4.4	2.1±1.4
80286 (10 MHz)	Pascal	16	1.3	1.9	1.6	5.6	2.6±1.7

Figure 4 [Patterson,83]

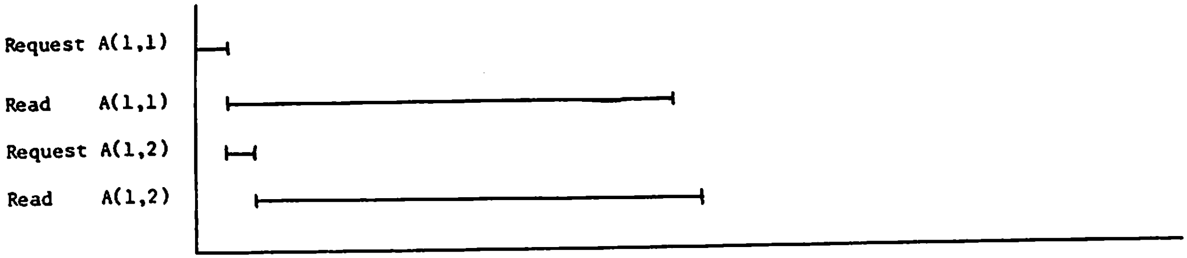
Figure 5a



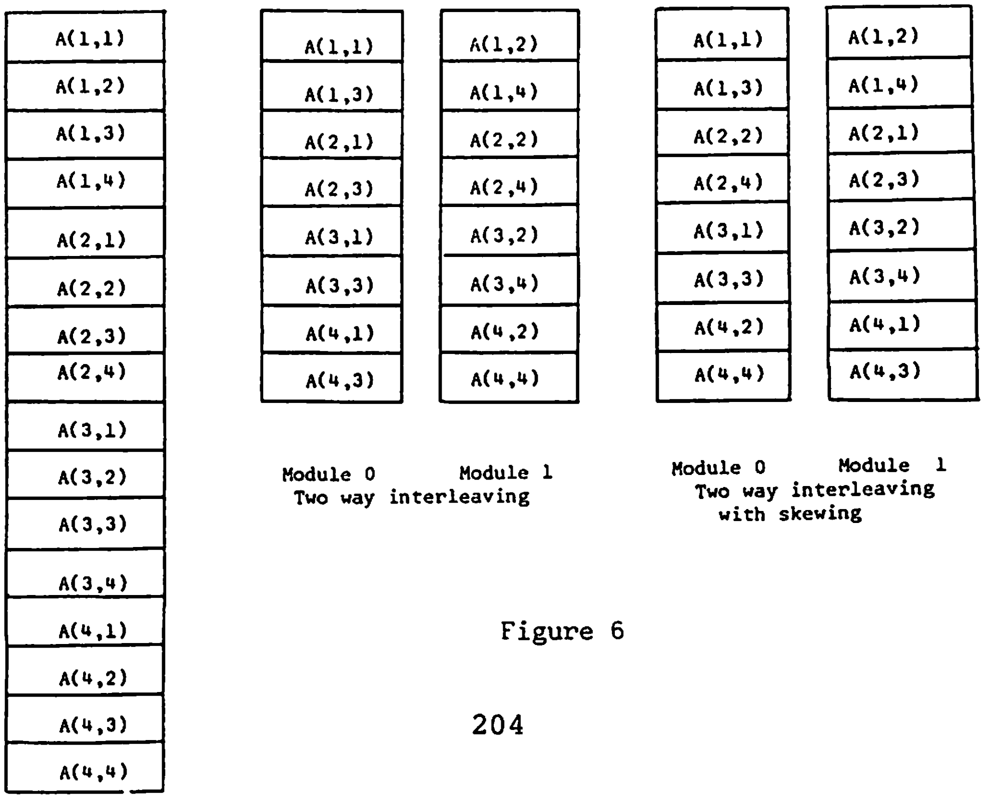
Total time 40 units
No interleaving.

Requests to read/write 2 units
Read/write 16 units

Figure 5b



Total time 20 units with two way interleaving



A(1,1)
A(1,2)
A(1,3)
A(1,4)
A(2,1)
A(2,2)
A(2,3)
A(2,4)
A(3,1)
A(3,2)
A(3,3)
A(3,4)
A(4,1)
A(4,2)
A(4,3)
A(4,4)

Module 0	Module 1
A(1,1)	A(1,2)
A(1,3)	A(1,4)
A(2,1)	A(2,2)
A(2,3)	A(2,4)
A(3,1)	A(3,2)
A(3,3)	A(3,4)
A(4,1)	A(4,2)
A(4,3)	A(4,4)

Two way interleaving

Module 0	Module 1
A(1,1)	A(1,2)
A(1,3)	A(1,4)
A(2,2)	A(2,1)
A(2,4)	A(2,3)
A(3,1)	A(3,2)
A(3,3)	A(3,4)
A(4,2)	A(4,1)
A(4,4)	A(4,3)

Two way interleaving
with skewing

Figure 6

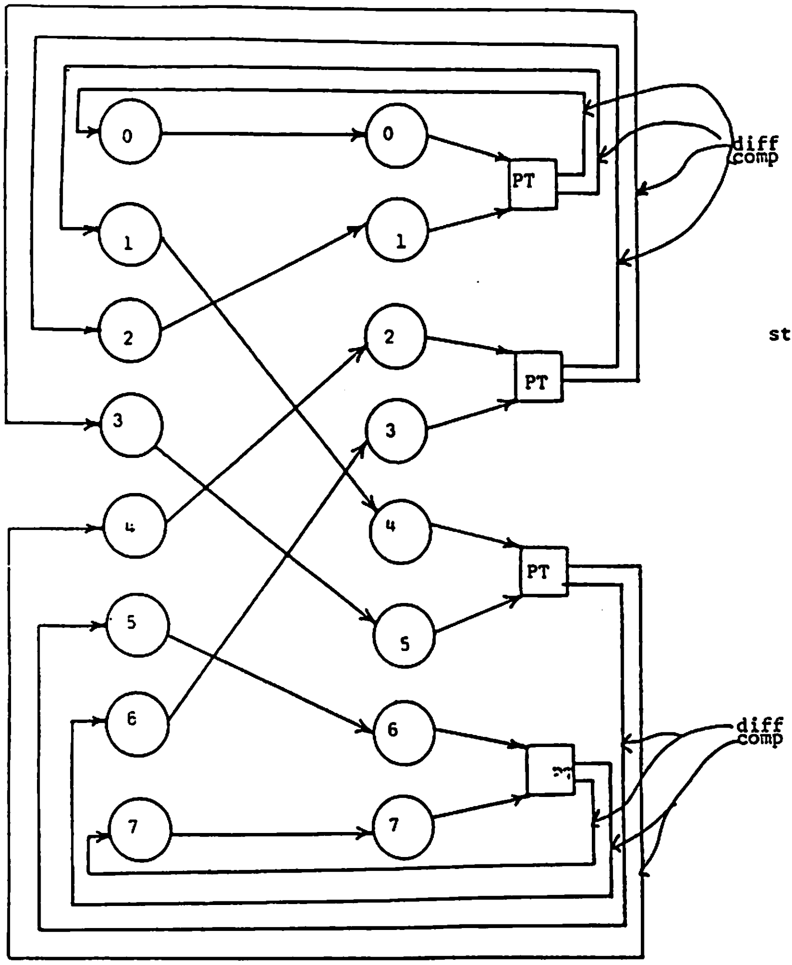


Figure 7

start	pass 1	pass 2
c	c	c
c	c	c
c	c	d
c	c	d
c	d	d
c	d	d
c	d	d
c	d	d

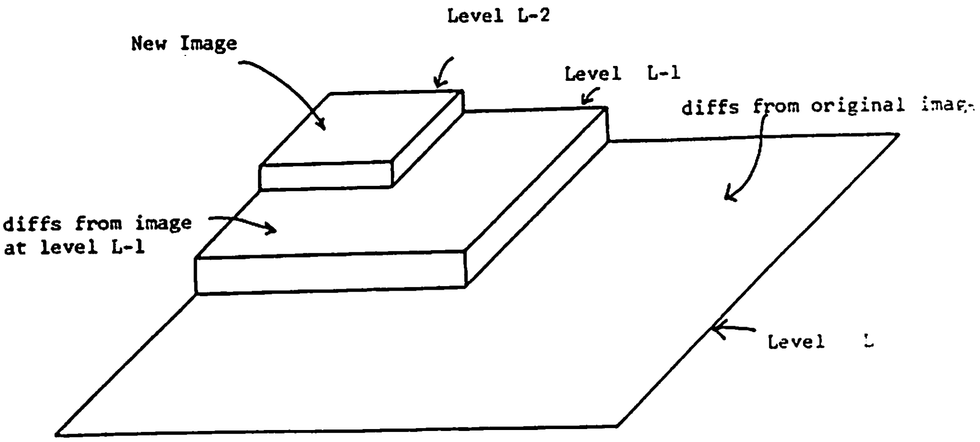


Figure 8

SPATIAL REDUNDANCY REDUCTION OF SLOW SCAN TV IMAGES

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Abstract

This paper deals with the application of a spatial redundancy reduction algorithm to slow scan TV images acoustically transmitted from an untethered submersible. The goal of this research effort is to implement a bandwidth reduction technique which provides suitable data compression, fidelity and channel error tolerance so that meaningful images are received. These images must allow the remote operator to direct the submersible through its tasks of navigation, inspection, maintanence and repair of submerged structures.

Image Processing in the Water

In the past decade one has seen a rapid transition of computationally expensive image processing techniques from large mainframe computers to advanced microprocessors in autonomous systems. It is this development which increases the potential of transmitting reliable images from an untethered submersible. Not only can the submersible perform sophisticated imaging tasks such as image noise reduction, contrast enhancement and data reduction, but it can also be programmed with more complex mission tasks. In almost all applications there is a need for increased vision capability - more information of higher quality and reliability.

Video Bandwidth Reduction

Whenever the possibility of transmitting images from an untethered submersible is considered the notion of data reduction is almost essential except for very short transmission ranges, (less than 100m) or low frame rates. Typical home quality television occupies an analog bandwidth of about 4 MHz. If the monochrome information of this signal were digitized at 4 bits/pixel the data transmission rate would have to be about 26 million bits per second, (488 lines X 452 pixels X 30 frames/sec X 4 bits/pixel). This transmission rate is impractical for acoustic telemetry in the ocean by three orders of magnitude. The acoustic channel can reliably support between 2 and 20 kBps for vertical transmission at medium depths (0 - 3000m). As can be seen by this great mismatch of data rates, there is a need for data reduction before acoustic transmission.

The parameters of slow scan television are better suited to the ocean acoustic channel. An image of 96 X 96 pixels being updated at 2 frames/second and digitized to 4 bits contains 73.7 kbps. Still this lies outside of the practical operating limits of the acoustic channel and a data reduction of

$$\frac{7.37\ \text{kbits (image data)}}{10\ \text{kbps (channel capacity)}} = 7.37 : 1$$

is needed. (See Figure 1 for a plot of the necessary compression ratio as a function of frame rate and channel capacity.)

Several algorithms exist which can perform video bandwidth reduction; they vary greatly in their implementation complexity, computing requirements, compression ratio and image quality. Transform coding techniques such as Two-Dimensional Fast Fourier Transform and Discrete Cosine Transform have long histories of use as data reduction techniques with good results. These algorithms have been implemented on large mainframe computers and special purpose hardware configurations for military and space programs. The drawback of most transform coding techniques is the very high execution rate necessary to operate in real time. Another class of redundancy reduction algorithms, Spatial Coding, places a lighter demand on computing power while giving comparable compression ratios and image fidelity. Several techniques exist under this heading: Run Length Encoding, Micro Adaptive Picture Sequencing (MAPS), Differential Pulse Code Modulation (DPCM) and many more. This class of coding tries to exploit the natural correlation which exists in most images. After all factors of compression ratio, fidelity and complexity were considered, MAPS was judged to be a practical algorithm for use with acoustic slow scan TV.

The original MAPS algorithm was developed by Anton La Bonte for use on high resolution aerial reconnaissance photographs before transmission. Its characteristics are well suited for implementation on a microprocessor with a limited instruction set and memory. The computations are all-integer, avoiding time consuming floating point operations, and only add and shift arithmetic operators are necessary. The logic of the algorithm is somewhat like Run Length Encoding except that it works in two dimensions. Data compression occurs because most images have local clusters of pixels whose intensities are highly correlated. Instead of transmitting an area of 4 X 4 pixels a pixel at a time, MAPS combines the area by performing an arithmetic average and includes a size code in the data stream.

The MAPS compression algorithm operates on digitized monochrome images by scanning and searching for redundant pixel groups. The compressed areas are limited to certain sizes because of the coding overhead needed to represent the block size. After considering the trade-offs between compression ratio and coding overhead the following sizes were chosen:

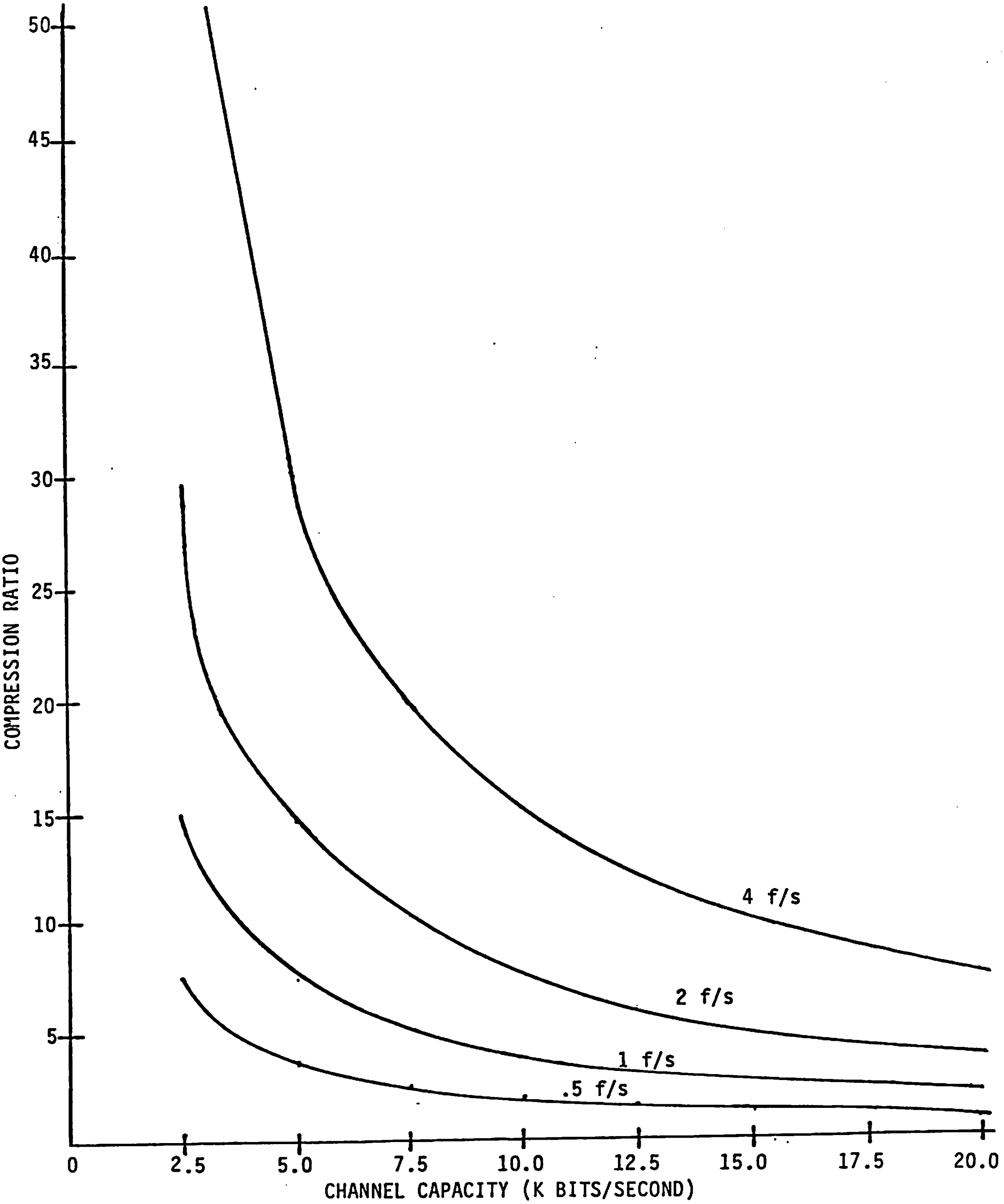


Fig. 1 Channel Matching a 96 X 96 X 4 bit image

Mnemonic	Code	Size (pixels)
L0	00	1 X 1
L1	01	2 X 2
L2	10	4 X 4
L3	11	8 X 8

As can be seen by the table, MAPS seeks to combine the data in an image into one of four block sizes; the block size and intensity information are then transmitted. It is not necessary to transmit position information since it remains implicit in the MAPS coding scheme; the compression and decompression routines have identical addressing patterns.

The MAPS compression follows the flowchart in Figure 2. First, the digitized image is sectioned into several 8 X 8 pixel areas; each area is independent from other ones in terms of MAPS data reduction. The redundancy search begins by reading 4 pixels that form a 2 X 2 pixel square. The intensities of these pixels are sorted by decreasing gray value and the difference between adjacent pixels in the sorted group are found. These differences are then tested against a threshold matrix, to determine whether or not these pixels can be averaged into a larger block size. If any of the four differences falls above threshold value the pixels are not combined, but output as L0 elements. Since the MAPS operator always works on square groups of four elements, the next three groups of 4 pixels are processed similarly. Then if all previous L0 pixel groups have been combined to L1 blocks, these four blocks are sorted and tested to see whether an L2 block can be made. This process iterates until the largest block has been made (L3 - 8 x 8 area) or a threshold violation occurs. When a violation occurs, all pending MAPS blocks are output.

It is important to note that a real benefit of MAPS lies in the threshold matrix. This 3 X 4 matrix of thresholds determines what pixels or blocks can be combined; its entries are based on the fact that certain detail in images can be ignored without destroying the scene. Since the compression ratio and fidelity of an image is determined by the threshold matrix, it is also very easy to change the compression ratio by simply using a different threshold matrix. Hence, MAPS has the benefit of being easily adapted from scene to scene; no recoding or recomputing is necessary.

The MAPS compression and decompression algorithm has been successfully implemented using separate Motorola 68000 microcomputer systems. Figure 3 shows a block diagram of the image compression test bench. Images are sensed by a 100 X 100 pixel CCD camera and digitized to 4 bits and stored in the image digitizer memory. The information is then moved to the display controller which displays the digitized image on a video monitor.

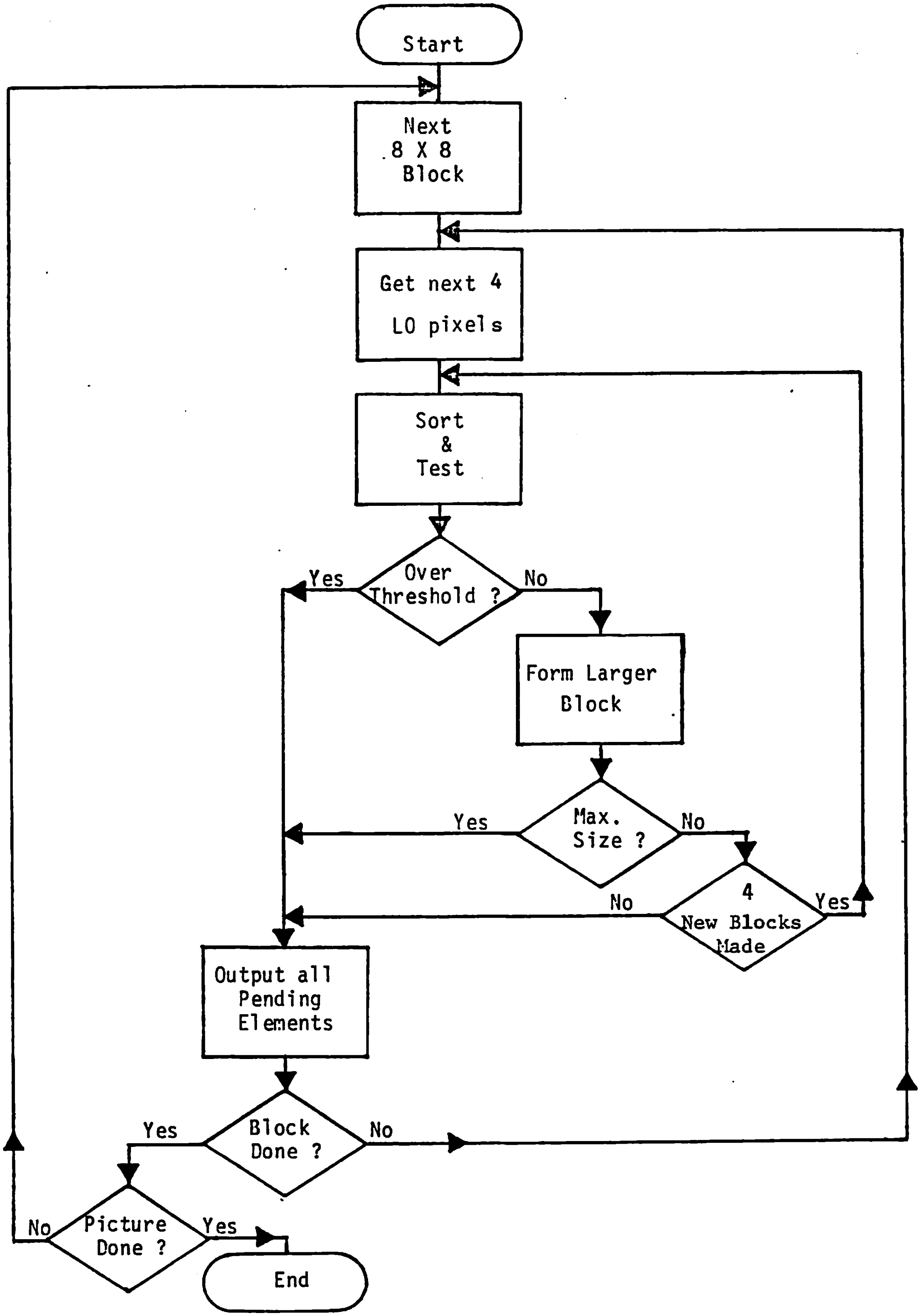


Fig. 2 MAPS Flowchart

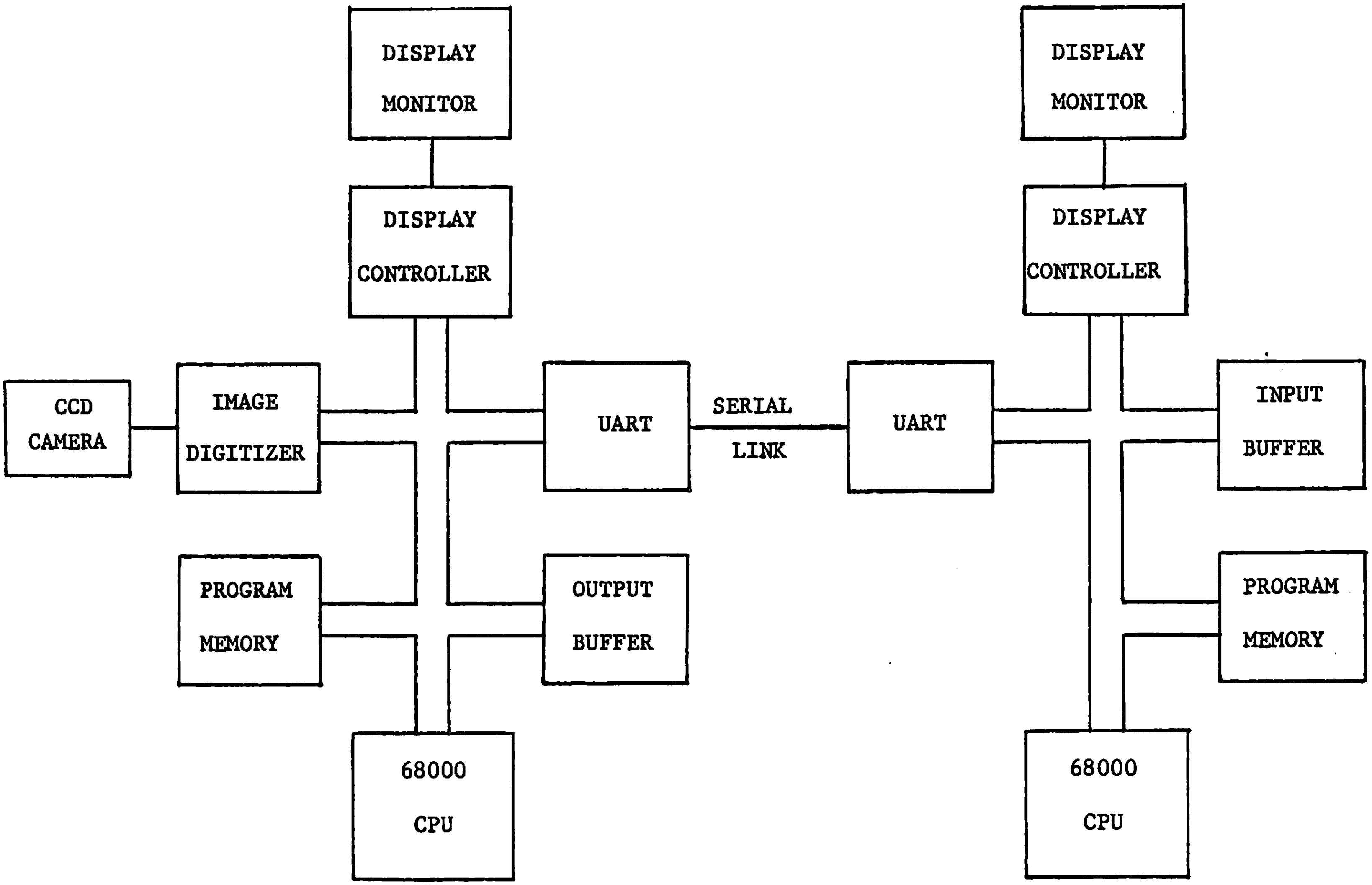


Figure 3 Block Diagram of Image Compression Test Bench

The process continues as shown in Figure 4. Once the data is compressed, transmitted and received, it is reconstructed and displayed in the decompression system. Each frame in the MAPS coding scheme is independent, and after the next frame is fully received, it replaces the previous one in the display refresh controller.

Compression Results

Figures 5 and 6 are examples of images that have been digitized, compressed and reconstructed. MAPS can operate in either an information preserving or nonpreserving mode. This is also determined by the threshold matrix, if the thresholds are all set to 0, larger blocks will be formed only if all input pixels are identical. This feature is useful in circumstances where a high quality image is necessary and the operator can tolerate the lower frame rate because of the small compression ratio. But, in navigating the vehicle around a structure, the operator will need a higher frame rate and a lesser quality image may be tolerated. The more information that is removed from an image, the less it resembles the original; therefore,the actual compression ratio should be determined by the task.

The images shown in Figures 5 and 6 represent the following information: original, original digitized, and the image at two compression levels. The compression results are summarized in Figure 7. For each trial, two sets of bit rates and compression ratios are given. Each corresponds to the same compressed image coded in a different manner. The column headed by Standard uses the coding scheme discussed previously - 2 bits for block sized code and 4 bits for the block intensity. The enhanced coding scheme assigns a block size code based on the occurrance of each block size in a typical compressed image; this Huffman coding results in a bit savings. Another improvement made to the Standard coding comes in the intensity representation. Instead of using a 4 bit absolute intensity representation, a 3 bit logarithmic differential intensity scheme is used. This results in another one bit savings per output block.

Figures 5 - 7 (images and table) show that very good images can be obtained at the lower compression ratios. As the compression ratio (actually threshold matrix) is increased, more information is removed from the image. Yet, even at very high compression ratios, many scene features ares still recognizable.

Image Reliability

An important concern in the research of video bandwidth reduction techniques is the susceptability of the compressed data to the channel errors that are present in acoustic telemetry. If a single bit error causes several frames of data to be lost, a more robust compression algorithm should be chosen, otherwise the overhead for conventional error correcting coding will be so high

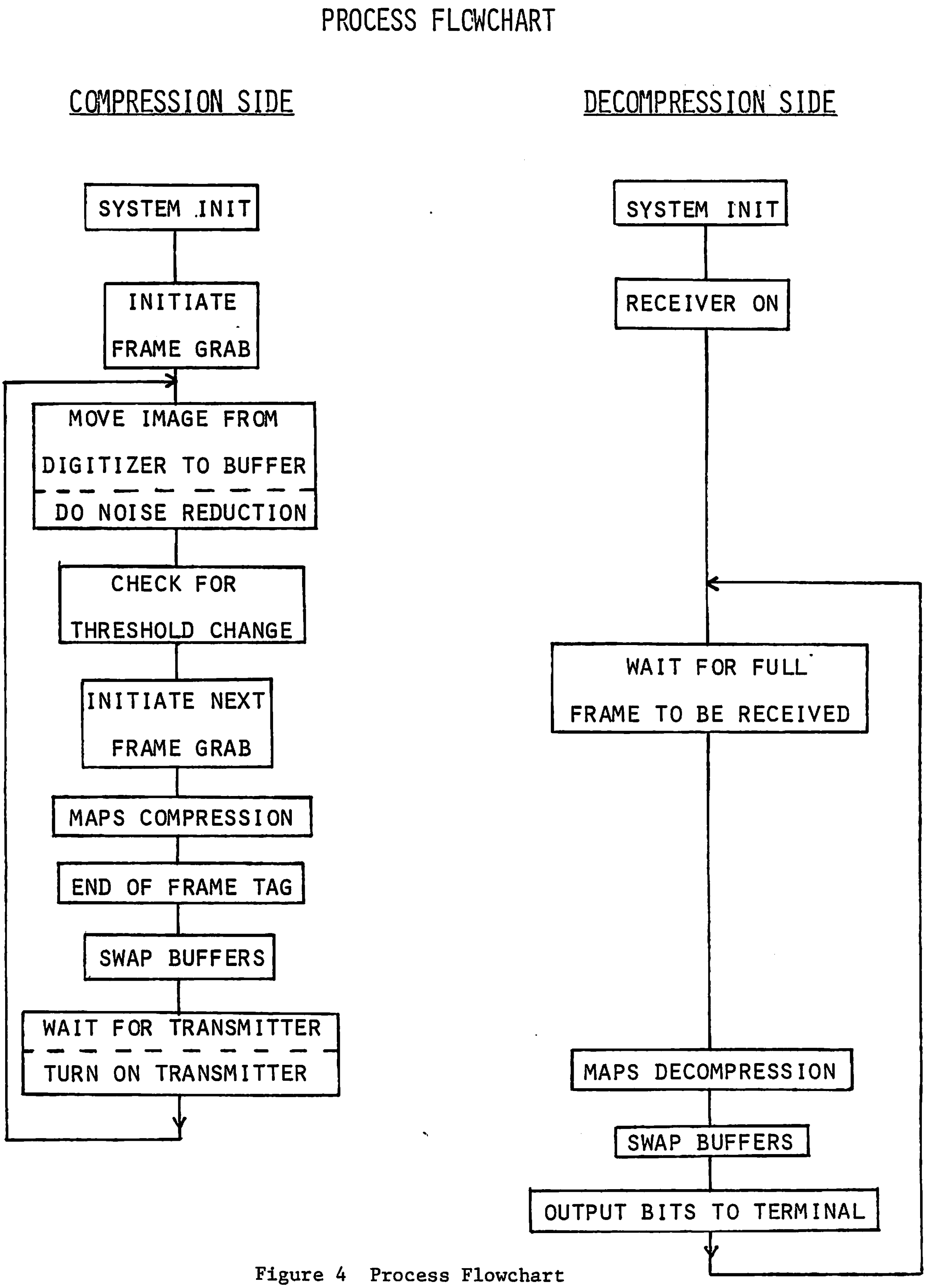
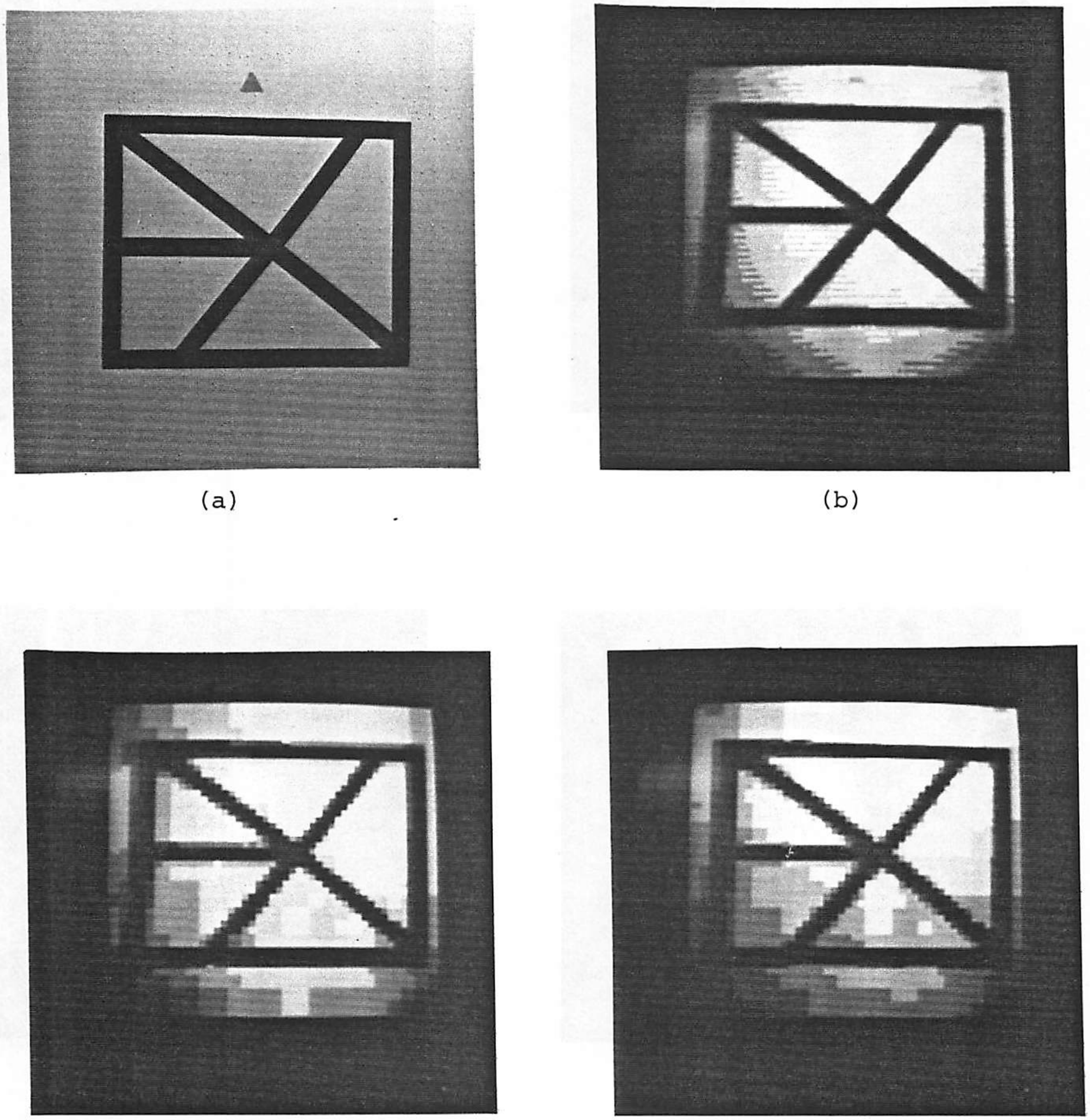


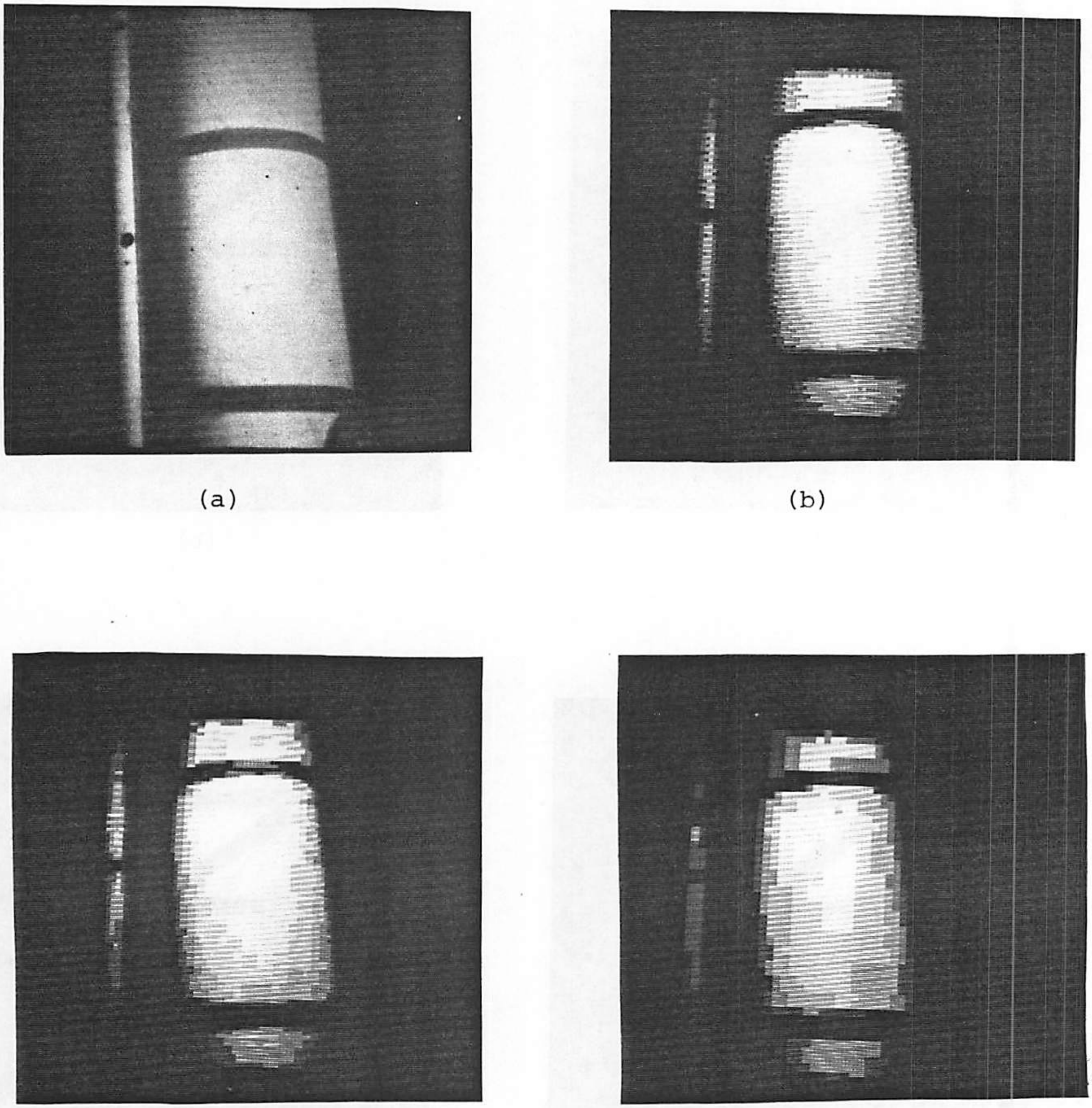
Figure 4 Process Flowchart



(a) (b)

(c) (d)

Figure 4 Scene A; (a) Original, (b) Digitized, (c) Compression 1: 6232 bits, (d) Compression 2: 4818 bits



(a)

(b)

(c)

(d)

Figure 5 Scene C; (a) Original, (b) Digitized, (c) Compression 1: 12,764 bits, (d) Compression 2: 4514 bits

Image	CCM	Enhanced Bits	Enhanced CR	Standard Bits	Standard CR
Scene A	-	36864	-	36864	-
	3	6232	5.9	8856	4.2
	7	4818	7.7	6426	5.7
Scene C	-	36864	-	36864	-
	2	12764	2.9	20412	1.8
	3	4514	8.2	5778	6.4

Figure 7. Compression Results

that any benefits gained by data compression will be lost. It should be noted that data compression and error correcting coding are mutually exclusive concepts. For this reason it is important that the compressed data be easily protected against random errors. Not all errors in MAPS transmission streams are equally critical. In Standard MAPS coding an error in the intensity code causes the block to be reconstructed at the wrong intensity; this error is limited to one block. But, if an error occurs in the block size code, the results are more serious. A block that was transmitted as an L1 (2 X 2 pixels) could be received as an L2 (4 X 4 pixels). In this case the entire scene structure can be destroyed, therefore, it is most important to protect the block size code.

Fortunately, there is a significant amount of redundant information present in the block codes. A consequence of the MAPS coding technique is that all received blocks must fully reconstruct the image. An error in block size code could cause successive images to be corrupted and the data stream to become unsynchronized. This situation could be avoided by inserting a high reliability code into the data stream after each image is transmitted. This sync signal limits error propagation to one frame, but it would be advantageous to limit the error to an even smaller interval. Since MAPS operates on independent areas of 8 X 8 pixels (recall flowchart in Figure 2), it is possible to bound the error to an 8 X 8 pixel area by sending a sync mark after each area has been compressed and transmitted. In the present implementation the image is segmented into 12 X 12 independent areas for processing, although the overhead due to the sync marks can be reduced by signaling every two or three areas, error correction becomes more difficult because of the increased number of possibilities in that interval. After each sync is received, the processor could check the block codes received since the last sync mark to determine if they describe an 8 X 8 pixel area. The following equation could be solved:

$$64 \#L3 + 16 \#L2 + 4 \#L2 + \#L0 = 64$$

Where #L3 is the number of L3 blocks received. When the sum isn't 64, an error is detected, assuming a single error in the interval.

An aid to error correcting would be instantaneous checking of blocks as they are received. This great advantage is possible because the MAPS data stream is structured such that only certain block sizes can occur at particular pixel locations (Figure 8). Notice that an L3 block must be received at the beginning of the 8 X 8 area, i.e. right after the sync and before the next sync. L2 and L1 also must occur in certain locations or an error can instantaneously be be detected. It is possible for L0 blocks to occur at any position in the area but they must occur in groups of four because MAPS always operates on four elements at a time. Any L0 blocks not occurring in groups of four can be detected in error. As can be seen in Figure 8, there are certain locations where any block size can occur; no instantaneous detection

0,1, 2 or 3	0	0 or 1	0	0,1, or 2	0	0 or 1	0
0	0	0	0	0	0	0	0
0 or 1	0	0 or 1	0	0 or 1	0	0 or 1	0
0	0	0	0	0	0	0	0
0,1, or 2	0	0 or 1	0	0,1, or 2	0	0 or 1	0
0	0	0	0	0	0	0	0
0 or 1	0	0 or 1	0	0 or 1	0	0 or 1	0
0	0	0	0	0	0	0	0

Figure 8 Possible Correct Block Locations for an 8 X 8 Pixel Area (Numbers Represent Block Sizes)

	Error Received	Possible Corrections	% Errors Detected	Average % Detected
L0 sent 42%	L3	63/64	98.5%	89.1%
	L2	60/64	93.8%	
	L1	48/64	75.0%	
L1 sent 39%	L3	60/64	93.8%	56.3%
	L2	48/64	75.0%	
	L0	0/64	0.0%	
L2 sent 15%	L3	48/64	75.0%	25.0%
	L1	0/64	0.0%	
	L0	0/64	0.0%	
L3 sent 4 %	L2	0/64	0.0%	0.0%
	L1	0/64	0.0%	
	L0	0/64	0.0%	

Figure 9 Summary of Instantaneous Detection

Total Inst. Detection = .42(.891) + .39(.563) + .15(.25) + .01(0.0) = 63.1%

potential exists at these places. Errors falling in areas where there is ambiguity may be caught by the error checking equation which can detect single errors in a sync interval. In the correction of errors priority should be given to checking these ambiguous locations where errors are most likely to slip through. Figure 9 shows a tabulation of the instantaneous error detection potential.

Once an error has been instantly detected it may be possible to do instant correction or it may require further processing after the error checking equation is evaluated. At this point the error correction algorithm would proceed sequentially through the received data in order to determine an acceptable block combination for that interval. Also it would be possible to use classical error correction techniques such as line to line correlation or past frame data to resolve errors that are unretrievable by the MAPS error checking.

Conclusion

A video bandwidth reduction technique, MAPS, has been implemented on slow scan images with good compression and fidelity results. The data rates achieved are suitable for use in short range underwater acoustic telemetry. Also, the potential for simple and reliable error correction exists as a result of MAPS' structured block size information. The mating of a proven bandwidth reduction algorithm with an error detecting and correcting scheme shows promise for acoustically transmitted images from an untethered submersible.

DEEP OCEAN SCIENCE

Dr. Bruce Robison
University of California, Santa Barbara

Firstly, it is the belief of many in the oceanographic community - and the author's belief as well - that there will be no acceptable substitute for the in situ human mind and eye in many research applications. At the same time, there is a clear need for unmanned, free-swimming submersibles, to compliment the work of manned submersibles in areas where they are inefficient and in tasks which they cannot accomplish.

There are several ways of dividing this problem of applications for analysis: a disciplinary approach (discussing the needs of the biologist, chemist, geologist, etc. in turn) or the habitat approach - the latter seems to be most useful in this instance. Scientific missions for an AUV would thus fall into two categories: benthic work and mid-water work. The fundamental difference between these two categories being that benthic processes occur in a two-dimensional environment, while mid-water studies are three-dimensional. Benthic studies have a head start. Twenty years of ALVIN experience have allowed us to identify and investigate a variety of natural benthic processes. The present limitations are chiefly those of score. For example, how much can be seen from ALVIN's port; how much of the bottom can be covered in a single dive or by a series of dives. The next step in benthic submersible research should be to expand our coverage of the sea floor, and the best way to achieve this is through application of robotic submersibles. Now that we have the ability to identify and categorize scientifically significant benthic phenomena, we need the capability to qualify these on a larger scale to see how extensive and varied these phenomena are over space and with time, and to learn how they integrate and interact.

Mid-water submersible research is several steps behind, largely because most of the submersibles available for research were designed to work on the bottom. They lack the maneuverability and the buoyancy control necessary to work in mid-water. The Z axis is the problem. Most mid-water research is still done remotely, but from the deck of a ship. This does not allow the insight provided by direct viewing which offers a detailed characterization of research needs. In general, there is a need for more mid-water research from manned submersibles before we can properly identify specific research problems that would be best handled by robotic submersibles. However, it is extremely important to design the mid-water robotic submersibles now, so that there is not a long lay time between the discovery of significant mid-water phenomena by manned submersibles and their qualification by robots. Additionally, the specific characteristics needed for work in the water column, such as precise depth control and maneuverability, will also be of considerable benefit in benthic applications.

A few of the characteristics which will be required for the successful applications of an autonomous ROV for both benthic and mid-water research are as follows:

-Maneuverability

-Hovering and precision buoyancy control

-Excellent Vision: Requires high resolution, low light level, video cameras with real-time output to the surface.

-Unobtrusive: Should be as small as possible, quiet and with propulsion and trim systems that do not disturb the sediment or water at the end of the vehicle where sampling is taking place. For biological work options for red light observations are necessary since most deep sea animals are insensitive to red light.

-Synoptic or Juxtaposed Sonar and Video Sensors: These would be used for comparative analyses. Additionally, the ROV should be readily detectable from surface SONAR so that down-looking SONAR can be integrated with horizontal SONAR and video transects for real-time analysis of scanning in both planes.

-Ranging Data on the Reference Frame of Observations: Owing to the highly variable nature of particulate matter, water clarity of SONAR and optical systems is also highly variable. At all times it will be necessary to know what volume of water is being observed. This is required to obtain reliable distribution information.

-Highest Quality Manipulative Capability. This would require the manipulator having its own video system separate from the main scanning system.

-Instrumentation with Real-Time or Near Real-Time Data Readout on Deck: These should include the standard hydrographic sensors (depth, temperature, salinity, oxygen, turbidity, light), but also a capability for flow injection analysis. This latter permits analyzing for water organic compounds, such as nitrate and ammonia by a single and compact instrument that could be readily adapted to robotic ROVs.

-Integrate Data to Control the ROV: In this respect the vehicle could automatically follow gradients or discontinuities in environmental parameters. If this can be accomplished, the other ROV sensors (sonar, video, etc.) could make comparative surveys along either side of a gradient or discontinuity. This might be accomplished with paired sensors that would impart a sense of binocularity, much as do the human eyes and ears. Or it might be accomplished with single sensors; the ROV could be directed through a scanning mode (up/down/port/starboard) to follow the sensory clues that would identify the location and positioning of the gradients.

-<u>Sample Collection, Storage and Retrieval Capabilities:</u> These would be needed for rocks or fish or particulate matter. The types of samplers needed are derivations of those now available. One type of sampling system required for development is an effective slurp gun that would draw in a large volume of water rapidly to allow the capture of free-swimming animals.

Future Applications of AUVs

Most of the applications which we can see at present would be:

1) To expand the scope of our research along traditional lines of inquiry in benthic and mid-water oceanography.

2) Under-ice Research. Not only investigations of the ice keels, but also water column and benthic surveys in situations where conventional methods will not work. (For example, long distance bottom dredging.)

3) Synoptic Observations. In this aspect, the AUV would be used in conjunction with remote sensing by satellites and aircraft. Here the AUV could provide subsurface "sea-truth" data to correlate with that data collected from the surface.

There is a clear need for AUVs for a broad range of research applications, most of which are linked to what is presently known about the oceans. It is worth remembering, that what is known about the ocean is a result of the means available to learn. The new perspectives provided by AUVs will teach a great deal more than what we might anticipate. Any new window carved in the deep sea environment provides a view of the environment from different perspectives. In the past, each time a new window was provided, a great deal more was learned than what we thought we knew. This new data lead to radically different understandings about the way in which the oceans work. It is gratifying to observe that the underwater engineering community is addressing these issues and, it is likely that in the long run, the manned submersible will give way to technology which permits us to sit aboard ship and obtain direct readouts of data and observations to depths as great as 6000 meters.

POTENTIAL APPLICATIONS OF AUTONOMOUS UNDERWATER VEHICLES

Brian Thomas
Gulf Oil Exploration Production Co.

Gulf began Arctic oil exploration in Canadian waters in the early 1970's and subsequently, expanded its activities to include the US Arctic. Unlike other of my colleagues at this symposium I will not present a list of potential AUV applications to Gulf's Arctic structures. Instead, I will present a sampling of the types of structures Gulf and the rest of the industry is employing or plans to employ, with the hope that you who are on intimate terms with this burgeoning AUV technology will be able to see areas of potential application.

Oil is presently being produced from the North Slope, but none is from offshore. Most of our leasing has been in Canadian waters, but in 1979 Gulf became active in Alaskan or US leasing. Gulf's most recent activities, however, are focussed in the Diapir Field which is offshore and west of Prudhoe Bay.

One of the most obvious and most significant problems in Arctic oil exploration and eventually production, is sea ice. When ice begins to form it takes the shape of what is termed Pancake Ice; this does not pose a serious threat to either transportation or structure design. As the ice thickens and grows it becomes a problem which significantly impacts transportation and structure design in shallow as well as deep water. Since ice is three-dimensional, its effects must be accessed below sea level, and in this area (under-ice) there is difficulty in obtaining any type of information, such as geometry, temperatures and ice strength. Typical of Arctic ice features are shear ridges which may extend for 20 to 30 miles. Some of these ridges can migrate several miles owing to wind stress, while other ridges are, to all intents, stationary. Typical ridges can be five to six feet thick and the forces they can apply to a structure must be understood.

In some instances there are large pieces of ice under a surface of sheet ice which may or may not be bonded to the sheet, but are floating freely. This presents a design problem by posing the question of designing for the total thickness of the sheet and the free-floating ice, or only the thickness of the sheet. There is very little information regarding the bonding of sheets when they are rafted together.

Another ice feature is the multi-year ice. This type of ice originates from the Polar Pack and may be two years old or 20 to 30 years old.

One part of Gulf's Arctic studies has been to assess the geometry and strength of the ice to derive some structural design parameters. One such area is 110 miles northeast of Pt. Barrow which we have been investigating for the past three years; since it is well into the Polar Pack it probably represents the extreme design conditions.

Another area of investigation has been the Hibernia field off Newfoundland where icebergs are a major threat. So far we have developed structure designs based on a very limited iceberg data base. From this data base we have developed design iceberg sizes with a conservative approach. If, for example, the design iceberg is two million tons, a design can be made which is satisfactory. If the design iceberg is ten million tons this will require a completely different structure design which will be significantly more expensive. A further problem is that icebergs enter the Hibernia field only once every two years or so. Consequently, it is difficult to develop a data base and in addition, we have a very trying time attempting to define the underwater geometry of icebergs.

Another Arctic ice feature is the ice island which is a large detached piece of the Ellsmere Ice Shelf. They could pose a serious design problem for production platforms in the Canadian and US Beaufort Sea. However, at this point, it is believed that their occurrence is so rare that they can be ignored. This philosophy may change as data on their occurrence increases. Ice islands may be upwards of 200 feet thick and several miles across.

Obtaining data on ice geometry is generally straightforward manual labor which involves drilling holes through it to measure its thickness. These holes can be as little as six feet deep to as much as 55 feet deep - a great deal of effort for merely one data point. Another means of obtaining this data is to lower a transducer down on a pole and scan the ice keel. Divers are also used, but sparingly. The Navy has provided us with SONAR data of the under-ice taken from nuclear submarines. The problem is that to be useful for our purposes the data must be correlated with concurrent surface data, which is not available.

Using the SONAR and drilling approach we have developed the geometry of a first-year ridge. Taking this data we then .pa hypothetically move the ridge against a structure. The problem is that confidence in the ridge model is lacking.

In a joint project with Gulf Canada, we are investigating a natural shoal area in less than 60 feet depth where the ice accumulates and often perseveres throughout the summer. In this instance the ice itself acts as a structure against which the polar pack ice is exerting forces. We are using this to investigate the nature of the pressure exerted by the pack ice. In order to assess the pressures upstream of the polar pack, the weight on the bottom of the entire feature must be determined. Our desire is to acoustically (scanning on side-scan SONAR) define how much of the feature is grounded. From this it is possible to calculate its weight on the bottom and thusly, its resistance to the pack. This has not been achieved to date.

An ice feature composed of rubble was located which was 93.5 feet above sea level in 100 feet of water. If a structure was placed in this area, it is possible that a 93 foot pile of ice could have been in front of the structure. This could cause both a design problem and a logistic support problem.

In an effort to investigate pressures which are transmitted through the polar pack to a grounded feature, pressure panels have been placed in the ice to record maximum pressure.

Remote environmental sensing is a far less expensive method of data collection. One method has been to use synthetic aperture RADAR from which we produce geometries of particular features. Another useful tool has been LASER work which characterizes the surface roughness. Unfortunately, this is only the ice surface and not what is below sea level.

The goal of all this work is to realize a structure design that will accommodate the ice forces. At present the simplest and most successful structure has been the gravel or earth island with slope protection. The protection has been bags of gravel (two cubic yards each) to resist wave and ice forces. Inspection of these bags takes place when there is no ice using side-scan SONAR. But it is possible that a vehicle of some sort could be employed in this task.

In deeper waters the gravel island approach is not satisfactory. In the Canadian Beaufort Sea, Gulf has constructed a caisson retained island in 60 feet depth, consisting of four concrete units held together at each corner. It is submerged onto a prepared beam. Its existence has caused a substantial accumulation of rubble around the structure. This can be advantageous since the polar pack forces are exerted against the soil instead of the structure. A task of assessing the amount of rubble which is grounded is carried out by the only method we have, drilling holes - a not entirely acceptable solution.

Dome Petroleum has advanced into 90 feet of water this year with their Single Steel Drilling Caisson (SSDC). This is a tanker which has been cut in half to provide a drilling platform.

Gulf Canada will be using, for the first time, a conical drilling unit this summer in the Canadian Beaufort. This is a floating vessel which is unique in that it is intended to break the ice downward. It is moored by twelve anchor cables and is planned for use into the ice season, but not all year round. .pa Inspection of the anchors and cables, and the BOP stack is a requirement which could possibly be performed by an ROV.

Another aspect of Arctic work is the application of ice-breakers. The ice is particularly damaging to propellers and Kort nozzles on these vessels and the only method of inspection available to date is by divers. This is another aspect for which we would like to have an option.

POTENTIAL AUV APPLICATIONS TO NUCLEAR POWER PLANT INSPECTION

Michael Krabach
Yankee Atomic Electric Co.

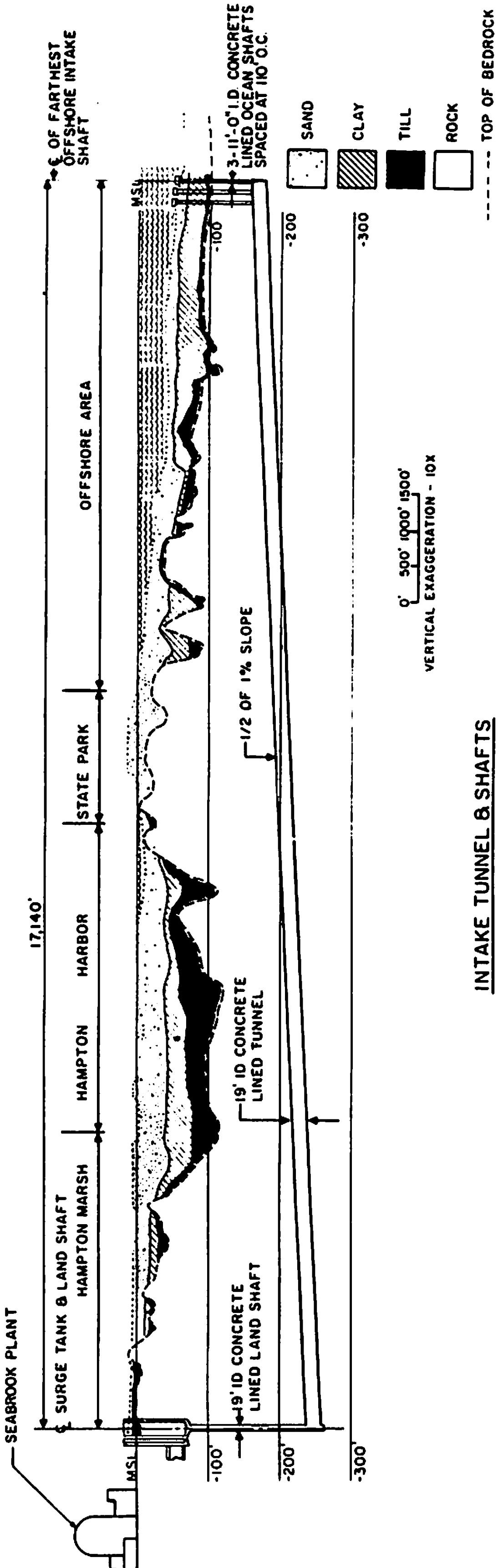
Yankee Atomic Electric Company is employed by the Public Service Company of New Hampshire to provide engineering consulting and advising services on the Seabrook nuclear power plant. The plant is two units, 1150 megawatts each, which is currently being constructed.

Our particular interest in underwater vehicles is their potential application for inspection of the cooling water tunnels which bring in and discharge cooling water used by the plant for heat dissipation. The ocean water is taken offshore through three intake structures at a depth of 50 feet and is brought through a tunnel into a pumphouse, then it is pumped through the plant condensers and is discharged back into the ocean through a diffuser at the seaward end of the tunnel. (Figure 1.) The discharge water temperature is about 40 degrees F above ambient.

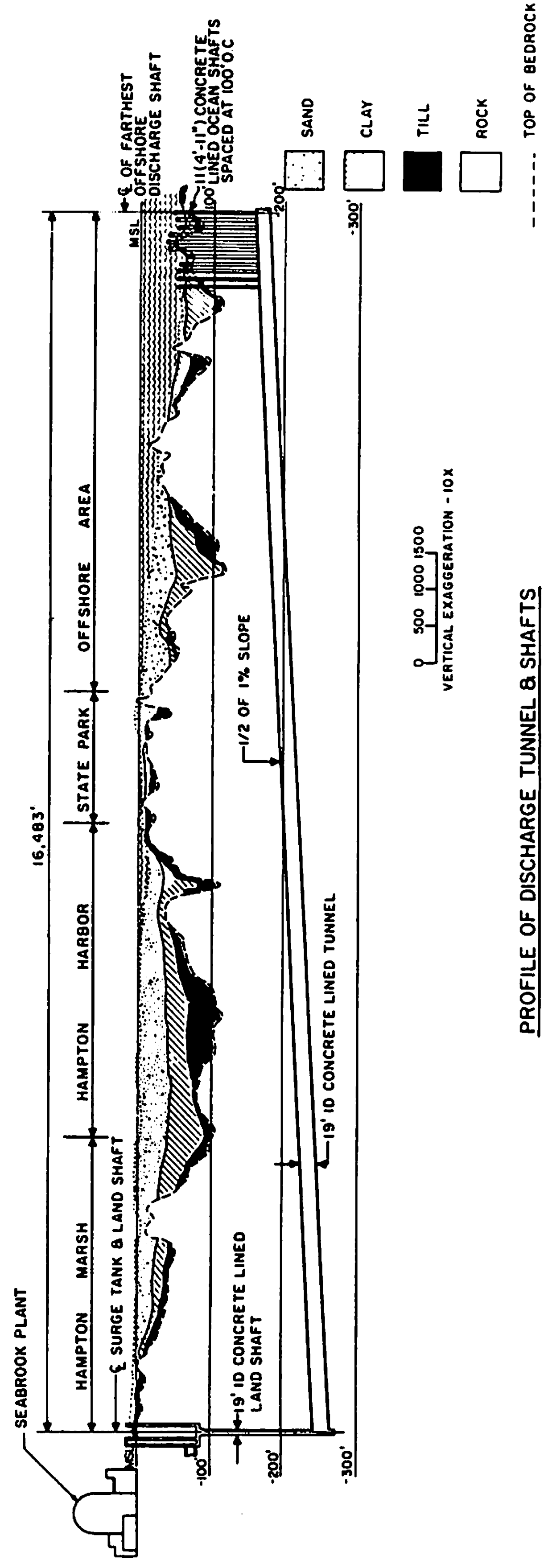
Each tunnel is 17,000 feet long and 19 feet in diameter. Riser shafts (19 feet diameter) connect the tunnel with the pumphouse; the horizontal tunnels are approximately 240 feet below sea level at the plant end. (Figure 2.) Access to the tunnels is through the pumphouse roof. Inspection of the tunnels will be performed to determine the degree of biofouling and the extent to which it reduces the diameter of the tunnels. The present anti-fouling approach is to inject chlorine. If this is not successful, then the approach will be to backflush the intake tunnel with 120 degree F water which should kill any fouling organisms. This would be performed every two or three weeks, depending on the fouling growth rate.

The time span over which the water travels from the intake into the plant (Figure 3) is 45 minutes with two units operating, the water particle speed is six feet per second. With only one unit operating (which will be the case for the first year of operation) it will take one and one half hours for the water to reach the plant. The flow rate is about 800,000 gallons per minute.

It is anticipated that the discharge tunnel will have no appreciable fouling owing to the warmer (90 - 100 degree F) water temperature. Consequently, the greatest attention, in regards to fouling, is being directed towards the intake tunnel. Inspection procedures will be to look at the walls of the risers and the tunnel. The tunnel is at its lowest at 240 feet below sea level and gradually rises up to about 160 below mean sea level, or 46 feet below the water surface. Water depth at the end of the tunnel is roughly 46 feet at the intake tunnel. Our plan is to use a vehicle for inspection. Divers can be used but they are restricted to 100 feet depth without a decompression chamber on site.

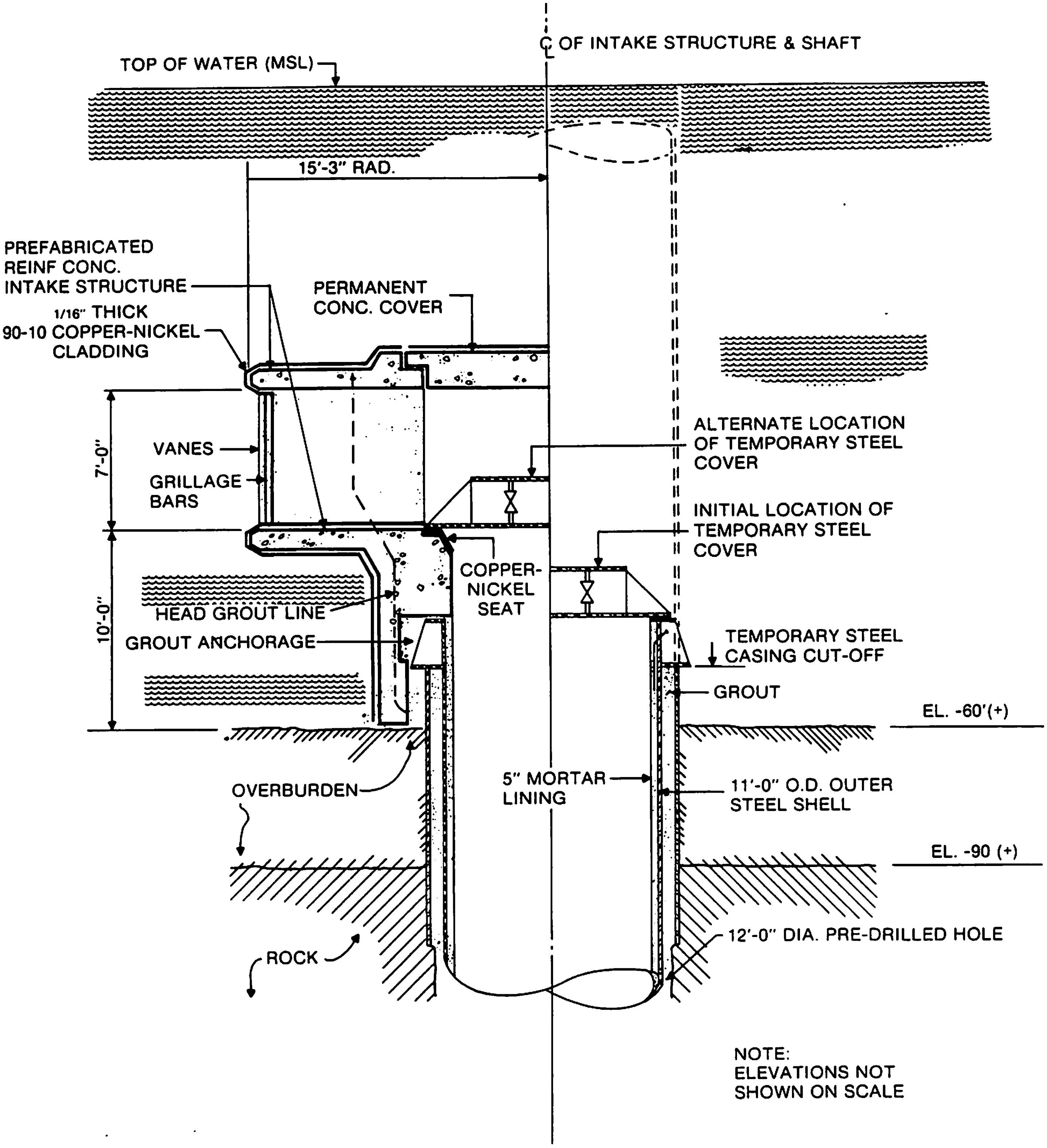


INTAKE TUNNEL & SHAFTS

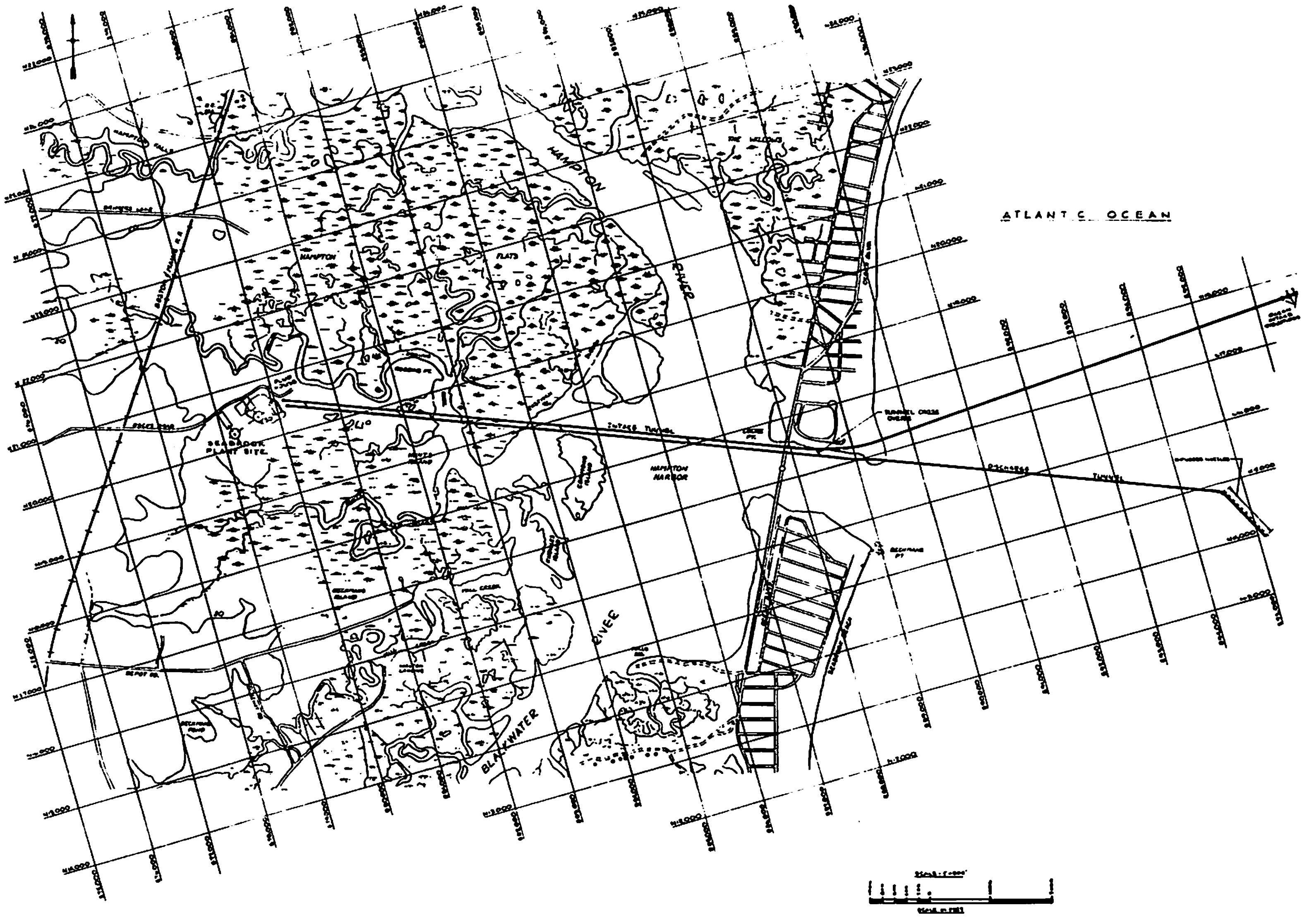


PROFILE OF DISCHARGE TUNNEL & SHAFTS

PUBLIC SERVICE COMPANY OF NEW HAMPSHIRE SEABROOK STATION - UNITS 1 & 2 FINAL SAFETY ANALYSIS REPORT	PROFILE OF INTAKE AND DISCHARGE TUNNELS CIRCULATING WATER SYSTEM
	227 FIGURE 1



PUBLIC SERVICE COMPANY OF NEW HAMPSHIRE SEABROOK STATION - UNITS 1 & 2 FINAL SAFETY ANALYSIS REPORT	OCEAN INTAKE STRUCTURE TYPICAL SECTION THRU TOP OF INTAKE SHAFT AND HEAD	
	228	FIGURE 2



PUBLIC SERVICE COMPANY OF NEW HAMPSHIRE SEABROOK STATION - UNITS 1 & 2 FINAL SAFETY ANALYSIS REPORT	CIRCULATING WATER SYSTEM TUNNELS GENERAL PLAN	
	9763-F-101112	FIGURE 3

An ROV on a tether can be used, we believe, effectively 500 to 1000 feet into the tunnel. The tunnels are completely concrete lined. The concrete intake structures are completely clad with copper-nickel to inhibit fouling. A tethered vehicle would be restricted by its cable in the distance to which it could penetrate the tunnel. An untethered vehicle offers the best potential inspection tool; particularly if it is smart.

Before the plant starts up and the tunnels are flooded, it is necessary to inspect the condition of the tunnels. If it is necessary to shut the plant down for only one day once the two units are operating, the loss in revenues will be approximately $1.4 million. After the tunnels are flooded, between six months to one year will pass before the plant is operational. Refueling of the plant occurs about every year and a half, during this time inspection of the tunnels is planned. One other method of inspection is to pump the water out of the tunnels, but this would cost from $0.25 to 0.5 million, merely to empty them.

The type of work an ROV would be required to perform in the tunnel includes video documentation, a sampling capability, still photography and the capability to hover or stop and inspect the concrete's condition. Also, it would be required to transit to the seaward end to inspect the chlorine nozzles. The overriding consideration is that these tasks must be performed inexpensively. The only need is to check for large scale spalling and biofouling.

The tunnels will be flooded in the fall or winter of 1983 and the first inspection is scheduled for the summer of 1984. The tunnels are not marked inside, therefore, the only navigation or positioning for a tethered ROV would be to measure the amount of cable paid out. No positioning system has yet been devised for an untethered vehicle.

OFFSHORE OIL AND GAS FIELD DEVELOPMENT
AND
APPLICATIONS OF UNDERWATER AUTONOMOUS VEHICLES

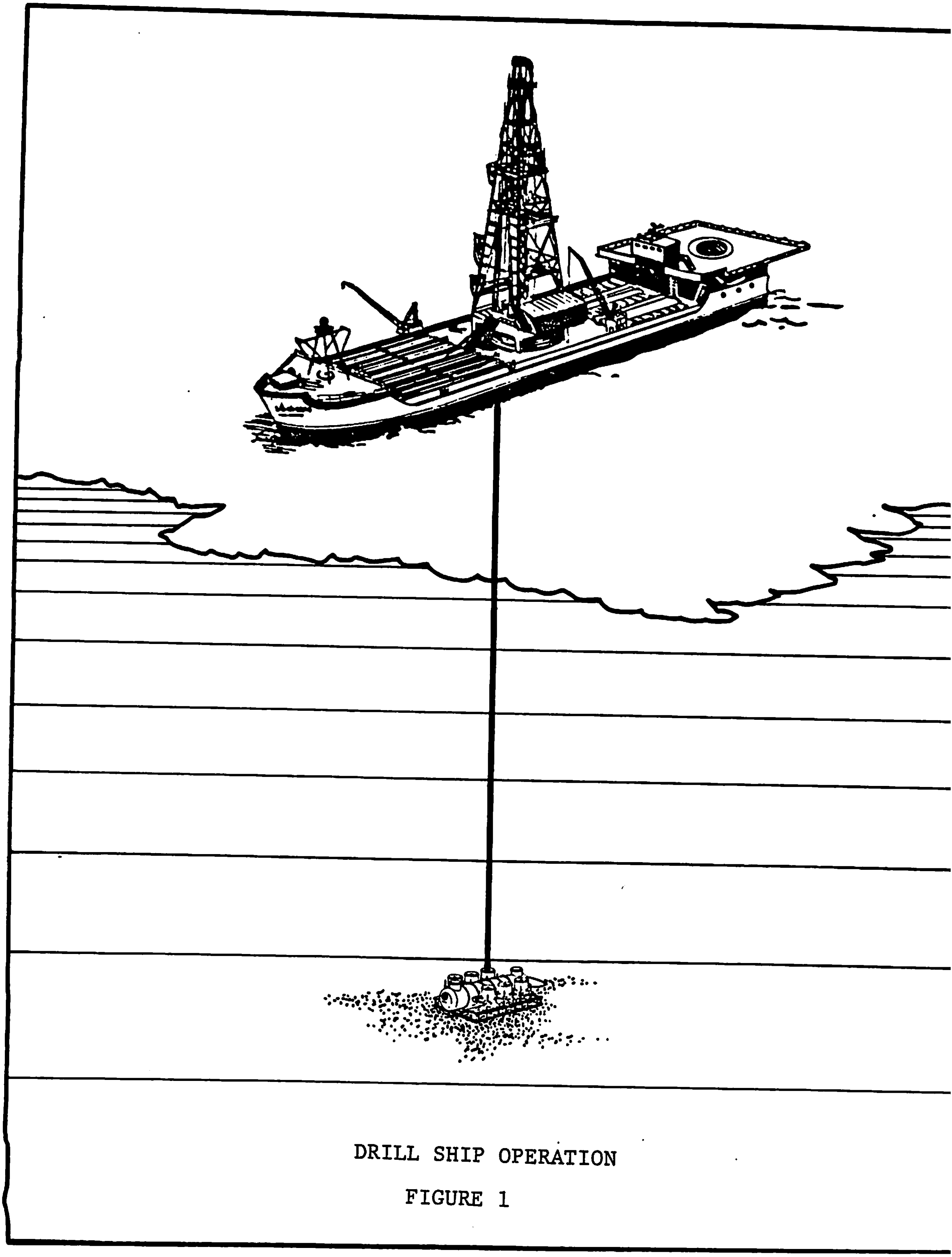
Frank Wang

Conoco Inc.

The field development of an offshore oil and gas production complex requires a great deal of engineering effort and capital expenditures. In addition to "money," it takes a lot of planning, risk-taking, judgement and hard work to make it happen.

Before any large expenditure of manpower and funds takes place, we must first be certain that hydrocarbons are present. This requires a detail mapping and seismic studies, with high resolution acoustic methods, for the intended area. After this, an estimate is made concerning whether or not the hydrocarbons are of commercial quantity. Secondly, an understanding of the environment is required. This includes water depth, the distance from shore, winds, waves, currents, temperature, ice and wild life inhabitance. These and other data are necessary to access the environmental impact of the envisioned development on the area. The only positive way to confirm the existence of hydrocarbons is by drilling on location. Normally it would take a few good exploratory wells to give us enough confidence to consider further development.

For unproven reservoirs we do not like to expose ourselves to a great deal of operational costs with high risk. Normally, a drill ship or floater is employed (Figure 1). These are hired by the oil company to perform the drilling. If the well proves commercial, it is safely capped and, at some point in the future, a production structure is installed, additional drilling is completed and then the production commences.



DRILL SHIP OPERATION

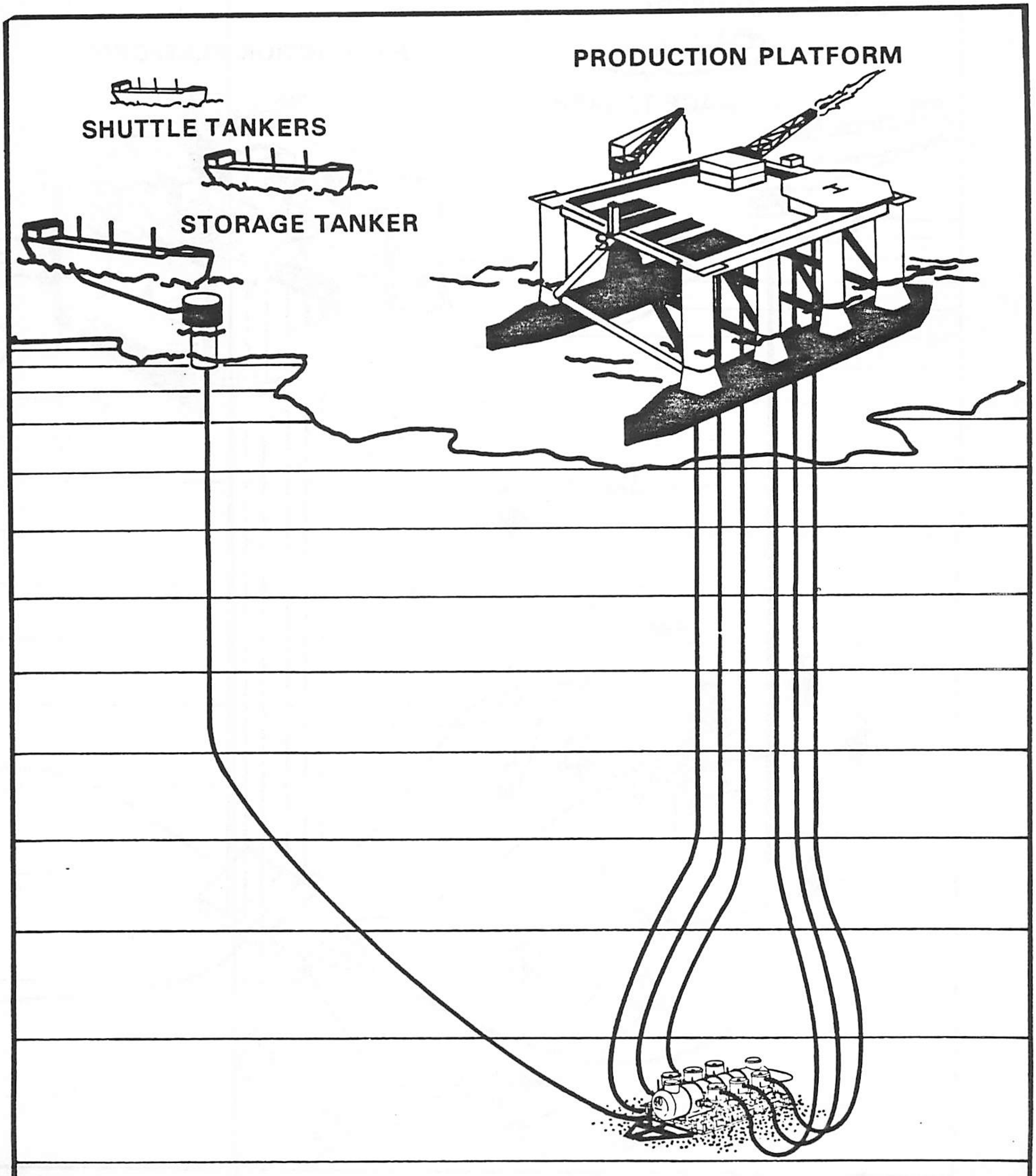
FIGURE 1

As an option, semi-submersibles can be used to house production facilities. After initial processing, the oil is pumped into a storage tanker and then offloaded and transported by shuttle tankers to the delivery port. This is often called early production system (Figure 2). Following this, depending upon how large the predicted production will be, efforts can be made to expand the early production system to a full production system for long term operation.

It is important to understand the soil and sea floor conditions in order to begin conceptualizing the construction plans for the offshore platforms. There are a variety of production platforms which can be used, they can be bottom-founded structures, or floating structures. The candidate materials can be steel, concrete or combinations of steel/concrete and other materials. In the Arctic, artificial islands made of sand and gravel or caissons made of steel or concrete can be used to house the production wells and facilities. Method of transporting the product such as sub-sea pipelines, storage tankers, shuttle tankers and other aspects must be considered. Favorable results from risk and economic analyses for the entire operation will determine whether this would be a "go" project. After the construction and drilling phase are completed the attention is shifted to the operation phase.

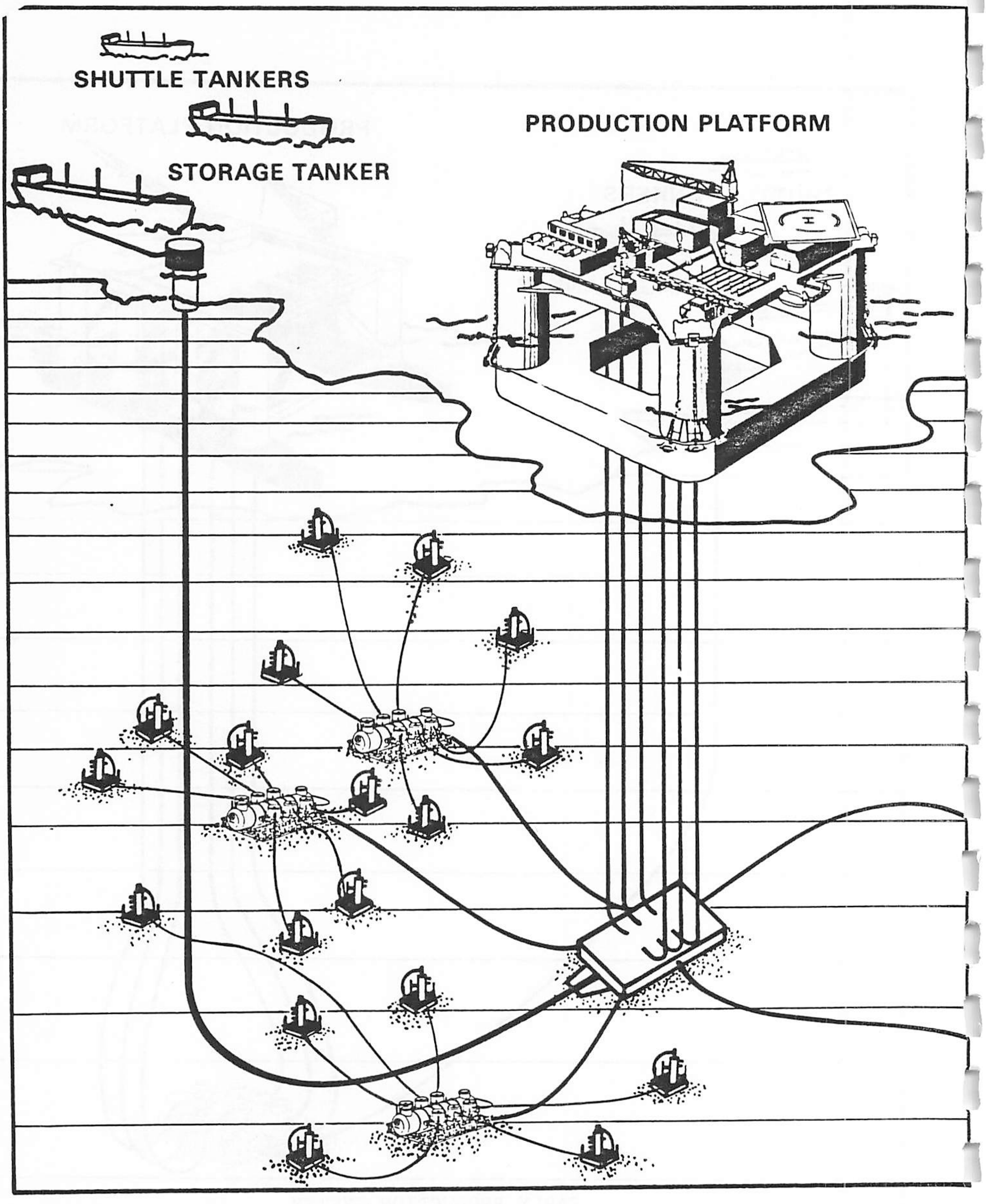
A typical offshore complex, including a steel jacket production structure, is shown in Figure 4. The steel piles are hammered into the seabed and sometimes groups of piles are used. The structure itself is called a "jacket." For smaller platforms, the deck (or surface platform) was welded directly to the piles; all the jacket did was to provide stability and hold the piles together. In the North Sea and on larger structures, the piles are stopped short and the underwater deck is welded directly to the jacket itself.

Figure 5 shows a concrete gravity structure. This gravity structure is very massive and provides oil storage capability underwater. They



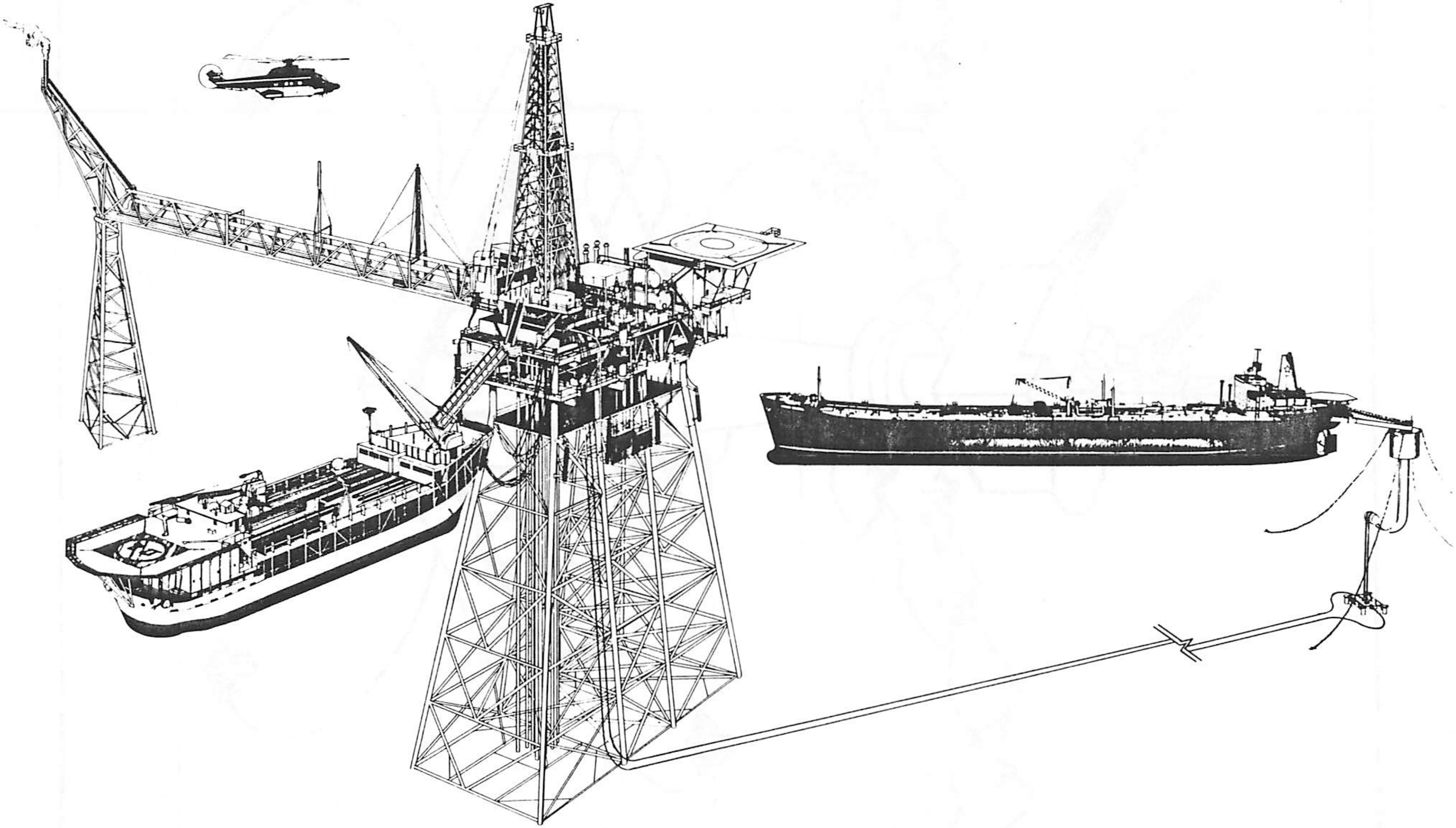
EARLY PRODUCTION SYSTEM

FIGURE 2



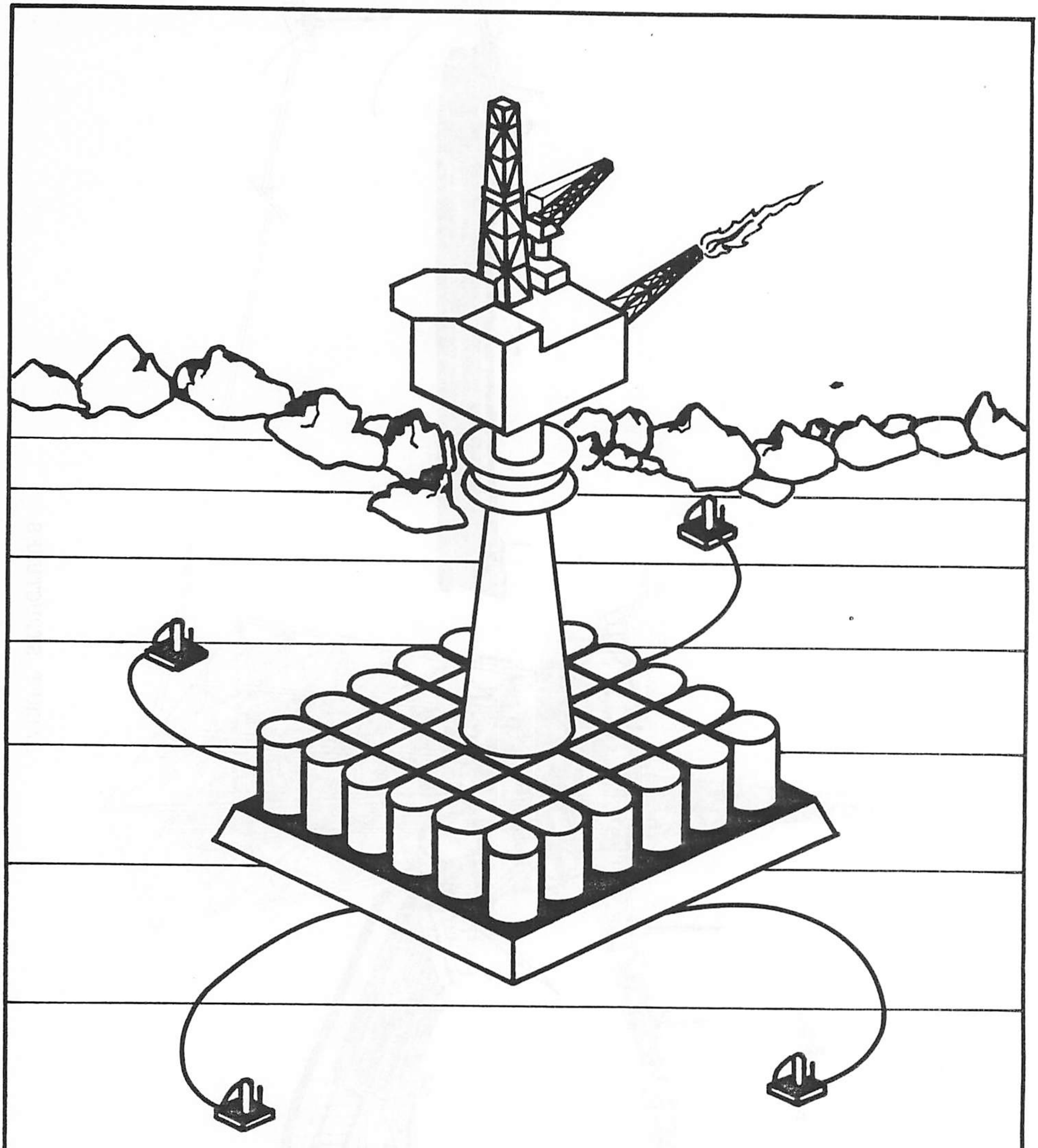
FLOATING PRODUCTION SYSTEM

FIGURE 3



JACKET STRUCTURES

FIGURE 4

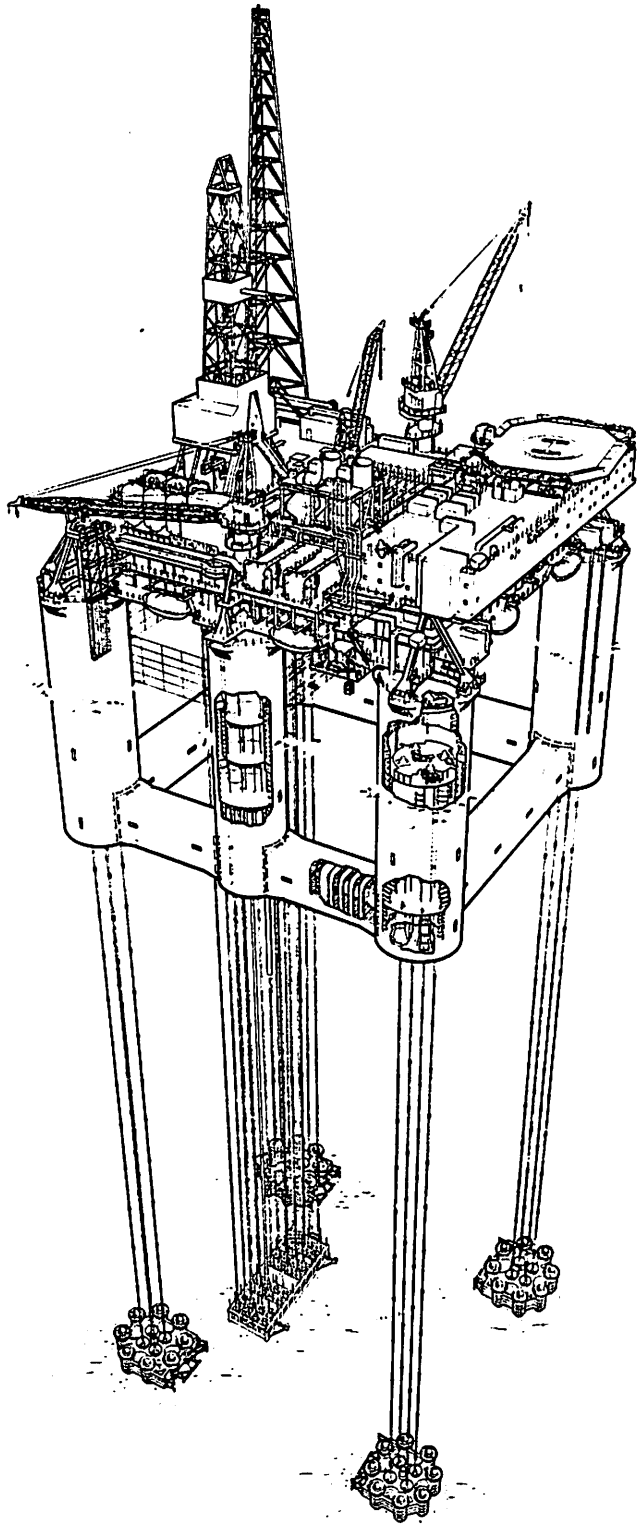


CONCRETE GRAVITY STRUCTURE

FIGURE 5

are anchored to the sea bottom by gravity. The structure is constructed onshore in a dike area and floated out to deeper water where it is ballasted down and then mated to the deck. The entire structure is then towed to the field and set in place. Areas in North Sea often provides good soil bearing capabilities at seabed. This allows the use of the gravity structure. This is not true for all parts of the world.

Another production structure is the Tension Leg Platform (TLP) (Figure 6). TLP is aimed to operate in deep water applications. The first TLP is under construction for the North Sea Hutton Field. It is 95.7 meters wide, 91.7 meters long and 67 meters in height, and has six legs. Operating draft is 33 meters. The hull is 22,000 tons of steel. The deck is the size of about two football fields and weigh 17,000 tons with equipment. There are three levels in the deck structure: a main deck, mes deck and weather deck. There are two accommodation modules which can house 340 people in total. Also included is a heliport and a drilling rig. The sub-sea drilling template is a structure which is anchored to the sea bottom by piles and provides a positive separation of the drilling string, the risers and pipelines. There are 28 drilling slots. The tension legs (tethers) are anchored to a foundation template - each would take about 1,000 tons of loads under operating conditions. There are eight piles around each of the four foundation templates. The piles are 72 inches in diameter, have 2.5 inches of wall thickness. In each of the four corner columns there are torque machines, load cells and tensioning machines to handle the tethers. Three of the four tethers for each of the corner columns are designed to stabilize the TLP for a 100 year storm. The fourth can be changed out for inspection at any time. The construction of the tethers are similar to a drill pipe. In view of the ALEXANDER KEILLAND case, we have included reserve buoyancy in the form of double shelled damage control sections in the water line region of each of the legs. All legs are connected by a tunnel through the pontoons.



TENSION LEG PLATFORM

FIGURE 6

Concerning underwater vehicles, almost every phase of the activity in deeper water applications will require their support. One area is riser installation wherein the adequacy of its attachment to the platform can be checked by underwater TV and photography to provide long-term records.

Pipeline installation is another area requiring remote vehicles services. Conventional diving is used extensively on pipeline work. Generally, during installation there is a survey boat in front of the lay barge which often deploys a vehicle to observe the sea bottom just ahead of the pipe. Although the pipeline route is extensively surveyed beforehand, the vehicle is used to be certain that there are no unpleasant surprises in front. After the pipe is installed the vehicle is used to inspect it for missing sections of concrete or other problems.

During pressure testing of the pipeline, dyes are often introduced into the pipe and pressure is applied internally. Vehicles can be used at this stage to inspect and locate any leakage. Vehicles may also be used in assisting as-built surveys to determine precise local conditions and where the pipe is located after it has been installed.

Once the platform has been installed, there are a variety of maintenance tasks for a vehicle to perform: joint cleaning (for inspection), marine growth cleaning to reduce current and wave loads, inspection of anode conditions and member thickness measuring. Another task of importance is to observe and/or measure the rate of sediment erosion around and under the platform.

One of the major reasons for using a remote vehicle is safety. Any system that will remove a man from the water and can do the job with efficiency is preferred. This is a particular concern under ice.

As the oil exploration and production extended to deeper waters, the underwater vehicles plays an increasingly inportant role. Currently, there is much interest in platforms for depths between 1,000 and 1,500 feet. Such depths are beyond the current diving range and a diver alternative must be forthcoming. This is particularly critical in the lowering of equipment or pile sections to be bottom where insitu intervention of some type must be available to guide the crane operator and for safe operation. Finally, and extremely important, is the role of documentation. Often two divers may disagree on what they saw. In many instances their observations of the same phenomenon will vary. The ideal situation is to deploy a device which will permit the engineers on surface to view the scene and make their own observations, measurements and documentations.

There are several areas where added features on the present vehicle designs can ease the operations. In case of welding inspection for a complex joint, one can design a vehicle with a latching device to secure the vehicle to the structure and allow the engineers on the surface to see and direct the joint cleaning, inspection and document operations. Another, is for inspection, maintenance and even operation of sub-sea oil wells. Ideally, the engineer would like to have the ability to see and operate these wells through a remotely controlled vehicle from an office on surface where all the drawings and data is at his finger tips.

In conclusion, it is believed that the importance of the underwater autonomous vehicles will definitely increase as the operating water depth increases. With proper development, it can make the work safer, more efficient and extend the feasibility of deep water operations.

SUMMARY AND TRENDS

Robert W. Corell
Marine Systems Engineering Laboratory
University of New Hampshire

The progress which has taken place since the first Autonomous Underwater Vehicle (AUV) workshop was held, some three years ago, has been dramatic. Throughout the three meetings certain topics have become dominant, and it is instructive to review the progress which has been made in these areas alone.

Control and Guidance

In the first of these meetings George Russell of Heriot-Watt University presented a paper which opened our eyes to the serious problems which will be confronted in control and guidance. At that time, much of the thinking in the AUV control area was quite elementary and the problem was not well understood. During the past several days we have seen the level of understanding to have increased dramatically. There are now full computer simulations in many of the vehicles, full non-linear with linear perturbation models available for design and perturbation tests.

Trends in this area will move beyond this. As Doug Humphries demonstrated, as the vehicle speed increases there will be other control problems. Or as we seek to become more precise in working inside large structures, such as power plants, the control problems we initially thought of as difficult pale almost to insignificance. Control will continue to be an important aspect, but it appears that the technology is available in a number of other areas which we can adapt to our problems; hence, we are freed with a return to basics in the control and guidance area.

Navigation

In the 1980 Symposium, there was much discussion about navigation, but there were only a few systems functioning in free-swimming vehicles. Today there are navigation systems that have been tested, although they are in the prototype stage. It is a certainty that we can use some of the existing navigation systems, such as those used on ALVIN and others. There was much discussion concerning long- and short-baseline and dead reckoning systems. This area will continue to command our attention and we will witness more full field evaluation of navigation systems and an increase in hybrids. There is, at present, no ideal navigation system; each application will require a close look at this problem. Each one is "site-and-mission" specific. In many cases technology will have to be developed to meet the needs and problems. Navigation within an offshore structure and under-ice will require that we develop and/or adapt technology to the specific requirements of AUVs.

Microcomputer Systems

The changes in this area over the past three years have been dramatic. In 1980, the discussion centered on Z-80s, 6100s and systems that had a few tens of Kbits of memory at most; generally single processor systems. In the last four days, almost all of the systems mentioned were multi-processors with tens of Kbits of memory and in some cases, hundreds of Kbits of memory. Likewise, have we moved from the simple languages of three or four years ago to much higher levels of language. New terms such as modularity, standardization, documentation have now appeared. Three years ago these were not demanding problems. Then, we were fully involved in merely getting things to move in order to demonstrate that free-swimmers had some role to play.

The trends are toward multi-processing and networking, and through the use of acoustic channels to "topside" computer systems of higher performance. We will undoubtedly see the appearance of a number of systems varying from the 68000 class to its successors operating with megabits or even megabytes of memory. All of this will be pushed by the desire to place increasingly more intelligence into the systems. The balance in the microelectronics and microcomputer business has been driven by hardware, we are not likely to see that continue. The future will clearly be software dominated. Modularity will probably increase. Standardization of some kind will be seen,. And we will be faced with the problem of somehow generalizing things so that we do not develop specific pieces of hardware and software for every new system that comes along. Further, our area will be impacted significantly by the artificial intelligence-based systems and by knowledge-based systems (KBS).

Communications

In 1980, discussions centered on simple command and control and low baud rates. At that time, there was some thought of doing something vertically through the water column. The thought of conducting horizontal acoustic communications through the water column drew hours of conversation. Today, actual experiments have been performed with high baud rates both vertically and to a more limited extent, horizontally. Commercial companies are already offering products in the five to ten kilobit transmission range. We are seriously talking of pseudo real-time (or fast slow-scan) TV with frame rates of up to four fames per second.

Trends in this area will be to go to both high baud rates as well as the standard 300 baud for command and control. There will continue to be an interest in performing horizontal communication work through the acoustic channel and to face the realities of multi-path, reverberation and all the other standard problems which have for years plagued the acoustician. This is a key technology area since free-swimmers must have that "phantom" acoustic tether. The near future will see a hard push toward developing reliable acoustic tethers to maintain command and control at 300 baud between the vehicle and a topside communications site. This is an absolute necessity for the next generation of vehicles and that will dominate much of our thinking.

Vision Systems

In 1980 we were briefed on vision systems by one of the classical AI laboratories of this country. For us, it was a new idea. Most of us now recognize that this is the second key component of "free-swimmers". In virtually all of the vehicles we talk about, be they manned or unmanned, the real need is to place some "eyeballs" beneath the sea. The Navy recently conducted a study of their undersea needs and concluded that 40 to 50 percent of all their requirements need some vision capability. In 1980, these thoughts were conversation items of only academic interest. Our full efforts at that time were merely to bring free-swimmers into the limelight. Today there is serious work being conducted in acoustic transmission of TV bandwidth signals.

In the coming years we will witness the debut of operational free-swimmer TV, with one to four frame per second, low pixel density of perhaps 10,000 to 25,000 pixels per frame. There is already hardware in several laboratories which is ready for field testing. There will be a demand for more sophistication toward increasing resolution and frame rates. Experiments with the "frame-rate-resolution-product" will take place since that product is what governs the acoustic channel. Photographic techniques will not necessarily drop out of sight since the early days of low pixel density systems will restrict us primarily to reconnaissance. Photography and high resolution TV (with on-board tape) will supply the required graphic resolution.

Obstacle avoidance was a term not even mentioned in 1980. Today, we are speaking of sophisticated obstacle avoidance systems with some intelligence for on-board decision making.

Manipulation and Man-Machine

In 1980 there was talk of putting manipulators on free-swimmers, but it was a subject for future efforts. Today we have reached the planning and thinking stage. The need for manipulation has been recognized and there are now design activity. Just as sophisticated vision systems, manipulators are now being used on tethered ROVs. The same pattern will follow with untethered vehicles, somewhat later. Initially there will be simple manipulators on AUVs, which, will as time progresses, assume greater and greater sophistication.

Power

This subject constituted almost an entire session in 1980, and could be called the "lithium era". Virtually all of us were absorbed in the subject of high energy/density power systems. For some reason this subject has not dominated these proceedings.

The reason might be that we can do all of the development work and early operational work considered essential in this business using available power sources. This may be a future requirement, but it does not seem to be as critical at present as it was once thought to be. In the future, power will probably return to the conversation. In some respects, it is our Achilles heel. Power needs are driven by propulsion requirements, manipulation demands and photographic requirements, not by microcomputer needs. There is little doubt of the need for improved power sources, but what happens in this field will probably be borrowed from elsewhere. Because of its expense, it is unlikely that we can perform the development work.

Artificial Intelligence (AI)/Computer Sciences

These subjects were clearly recognized in 1980 as being an important part of this business. But for many of us it dawned rather abruptly that we were working in the AI world. Also, for many of us who came into the free-swimming arena from other activities, we realized that the things we should be thinking about had been thought about by others for a considerable period of time in the AI community. In the past three years, AI has gone from an ivory tower concept to one that is impacting many fields; not the least of which is ours. We are now thinking seriously about it. We are troubled by it. We are learning the vocabulary. There are a few places where people are beginning to seriously implement and to make plans for putting higher levels of intelligence on their vehicles. But, as the session with Dick Blidberg suggests, there is a great deal to do before this is a major component. But we will be driven by it as we look for ways to increase the intelligence level of our vehicle systems. We will continue to be challenged by the concepts of "knowledge engineering".

Testbed Vehicles

In 1980, there were only a handful of these vehicles, and most were university or government laboratory systems. Today the numbers have doubled. Not only are the government and university laboratories involved, but industry is involved as well. The industrial vehicles are at the prototype stage, but show the possibility of producing product lines. The present stage is at a balance point; not quite ready to advance further.

It seems, based on our discussions, that operational AUVs are going to be before us in the near future. The level of interest at this Symposium is a good indication of that possibility. Research vehicles will continue to be a dominant part of this business over the next few years. Operational vehicles, if they do appear, will be relatively simple and taking on tasks that are not unduly complicated. This will also be a shakedown period. The dangers that faced the submarine community in the mid-1960s are something we should consider. On the other hand, the economic facts of life in the mid-1980s are different than those of the sixties, hence, we might not see the glut in AUVs that we saw in manned submersibles of the mid-sixties.

Missions/Applications

In 1980, our discussions on missions resembled a laundry list: many possibilities and a lot of "gee-whiz". There were even serious doubts that free-swimmers would ever make it into the real world. This does not seem true today. Today, we are still struggling to find that special place where these vehicles apply, but application areas are more focussed. In some of the deep ocean areas, free-swimmers are being contemplated. The ocean science community, for example, is also demonstrating an interest in free-swimmers. Places where the risk factor for other vehicle systems is too high (e.g., nuclear; under-ice) appear to be growth areas for free-swimmers and this also includes the military.

With regards to missions, we will see a tightening of our thoughts on the kinds of tasks these free-swimming vehicles will perform and, most likely, these will be very simple tasks initially.

Overall, this business has grown very rapidly. The pipe-dream stage of three or four years ago has passed, and we are at the stage where these vehicles are beginning to be taken seriously. But it will take time for them to find their way into the real business world where they will make money. So we will continue to go through an R&D/development and product development stage. It is difficult to speculate, with certainty, where the field will go, but the oil and gas industry will be a major factor. The military will continue to dominate a part of our business. Experience in remotely piloted aircraft have added to the military interest in free-swimming vehicles, including the increased interest in under-ice operations. It would seem that deep sea disposal and assessment of nuclear wastes on the sea floor may provide another driving force for these vehicles.

A great deal of energy will be placed on artificial intelligence or "knowledge" engineering. (One might term this "applied AI".) In the beginning, this will be placed in vehicles at a very elementary level. It will probably take a decade before we see the dreams talked about at this Symposium find their way into operational vehicles. This will, therefore, take hundreds of man-years of effort to take us from where we are now to that level of operation.

There is some speculation that there is one area to which we have not devoted much time, which is the field of the man-machine aspects. This is the interfacing of the operators with the vehicles themselves. If we do, in fact, develop slow-scan TV we are also going to obtain for ourselves some problems we have not fully considered. In the deep ocean, we will experience several seconds of acoustic time delay which will cause severe control loop problems. With man in that loop, the problems will need to be dealt with. This man-machine interface issue must be addressed at some stage; it appears that for a long time to come, free-swimmers will have man in the control loop.

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on
UNMANNED UNTETHERED SUBMERSIBLE VEHICLES

June 6-9, 1983
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AGENDA

THIRD INTERNATIONAL SYMPOSIUM ON UNMANNED UNTETHERED SUBMERSIBLE TECHNOLOGY

New England Center for Continuing Education
Durham, New Hampshire

June 6 - 9, 1983

SEA GRANT
University of New Hampshire
University of Maine
Sea Grant College Program

MONDAY, June 6, 1983

8:30 a.m. - 9:30 a.m.	Registration - (lobby)
9:30 a.m. (Berkshire Room)	WELCOME - Bob Corell, Dick Blidberg
10:00 a.m.	Break - (Windsor/Charles Room)
10:30 a.m. - 12:00 noon (Berkshire Room)	VEHICLE PROGRAM REVIEWS Patrick Borot - EPAULARD Vehicle CNEXO France George Russell Heriot-Watt University Scotland
12:00 noon	Lunch
1:30 p.m. - 3:00 p.m. (Berkshire Room)	VEHICLE PROGRAM REVIEWS Jim Ferguson - Dolphin Vehicle Internataionl Submarine Engineering Ltd. Canada Matt Sheehan Hamilton Standard
3:00 p.m.	Break - (Windsor Charles Room)
3:30 p.m. - 5:00 p.m. (Berkshire Room)	VEHICLE PROGRAM REVIEWS Jim Jalbert - EAVE-East Vehicle Marine Systems Engineering Lab. University of New Hampshire Eric Jackson - ARCS Vehicle International Submarine Engineering Ltd. Canada
5:30 p.m.	Social Hour - Portsmouth Yacht Club Newcastle, New Hampshire

TUESDAY, June 7, 1983

8:30 a.m. - 10:00 a.m. (Berkshire Room)	VEHICLE PROGRAM REVIEWS Ron Walrod Hydro Products Andre Galarne International Underwater Contractors
10:00 a.m.	Break - (Windsor Charles Room)
10:30 a.m. - 12:00 noon (Berkshire Room)	PROGRAM REVIEWS Chuck Thorpe Carnegie-Mellon University Dana Yoerger Massachusetts Institute of Technology Dick Blidberg Marine Systems Engineering Laboratory University of New Hampshire
12:00 noon - 1:30 p.m.	Lunch
1:30 p.m. - 3:00 p.m. (Berkshire Room)	PROGRAM REVIEWS Informal Program Reviews
3:00 p.m.	Break - (Windsor Charles Room)
3:30 p.m. - 4:30 p.m. (Berkshire Room)	TECHNOLOGY REVIEWS - Control/Guidance David Limbert/Haywood Hartwell Marine Systems Engineering Lab University of New Hampshire Doug Humphreys Aeronautical Research Associates of Princeton
4:30 p.m. (Berkshire Room)	RESOURCE SPEAKER - "Deep Ocean Power" Dr. Harold Couch Hamilton Standard

WEDNESDAY, June 8, 1983

8:30 a.m. - 10:00 a.m. (Berkshire Room)	TECHNOLOGY REVIEWS - Microcomputer Hardware/Software Steve Chappell Marine Systems Engineering Laboratory University of New Hampshire Brian Coles S.E.A., Inc. Dick Lord Marine Systems Engineering Lab. University of New Hampshire
10:00 a.m - 10:30 a.m.	Break - (Windsor/Charles Room)
10:30 a.m. - 11:30 noon (Berkshire Room)	TECHNOLOGY REVIEWS - Acoustics Jim Fish Acoustic Systems Inc. ________________________
11:30 noon - 1:30 p.m. (Mystic Room)	SYMPOSIUM LUNCH Speaker - Robert Ballard Woods Hole Oceanographic Institution
1:30 p.m. - 3:00 p.m.	Registration - (Lobby)
1:30 p.m. - 3:00 p.m. (Berkshire Room)	TECHNOLOGY REVIEWS - Image Bandwidth Compression Shel Walker/F.S. Hill University of Maine Mike Shevenell Marine Systems Engineering Lab. University of New Hampshire
3:00 p.m - 3:30 p.m.	Break - (Windsor/Charles Room)
3:30 p.m. (Berkshire Room)	RESOURCE SPEAKER Andre Galarne International Underwater Contractors, Inc.
5:30 p.m.	Social Hour - 1940 Room Elliott Alumni Center, UNH

THURSDAY, June 9, 1983

8:30 a.m. - 10:00 a.m. (Berkshire Room)	APPLICATION SPEAKERS Bruce Robison - Deep Ocean Science University of California Brian Thomas Gulf Oil Exploration & Production Company Mike Krabach Yankee Atomic Electric Company Frank Wang Conoco, Inc.
10:00 a.m. - 10:30 a.m.	Break - (outside Berkshire Room)
10:30 a.m. - 12:30 p.m. (Berkshire Room)	SUMMARY FORUM - Chairman Bob Corell