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Experiments in Supervisory Control of a Computerized Vehicle for Inspecting Curved Surfaces

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EXPERIMENTS IN SUPERVISORY CONTROL OF A COMPUTERIZED VEHICLE FOR INSPECTING CURVED SURFACES

by

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ABSTRACT

This report describes the design of and experiments using a computerized vehicle for inspecting curved surfaces.

The objective of this report is to clarify the adaptability of supervisory control concepts to undersea inspection.

The experimental vehicle is designed to simulate the motion of an undersea inspection submersible. The control system makes possible three kinds of actual vehicle motion control: manual, automatic approaching and automatic surface following.

By experiments the difficulty of manual control is clarified and the advantage of the combined manual and automatic control system (supervisory control) is verified. Conclusions are as follows:

1) Pure time delay and exponential lag dynamics cause the operator difficulty.

2) A camera-oriented reference coordinate frame for the controls is better than a vehicle-oriented frame with manual control.

3) Automatic following is better than manual.

ACKNOWLEDGMENTS

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RELATED REPORTS

Sofyanos, Thomas N. and Thomas B. Sheridan. AN ASSESSMENT OF UNDERSEA TELEOPERATORS. MITSG 80-11. 313 pp. $8.00.

Brooks, Thurston L. and Thomas B. Sheridan. SUPERMAN: A SYSTEM FOR SUPERVISORY MANIPULATION AND THE STUDY OF HUMAN/COMPUTER INTERACTIONS. MITSG 79-20. 280 pp. $6.00.

MIT/Marine Industry Collegium. TELEOPERATORS UNDER THE SEA: OPPORTUNITY BRIEF #14. MITSG 79-15. 21 pp. $3.50

Carmichael, A. Douglas, Stewart D. Jessup and Glen Keller. A SMALL ROBOT SUBMARINE FOR OCEANOGRAPHIC APPLICATIONS. MITSG 76-15. 8 pp. $1.00.

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Chapter 1 Introduction

1-1. Purpose

The world's oceans cover approximately 70 percent of the globe, and of that 70 percent the continental shelves cover less than 8 percent. As a promising resource supplier the ocean is being explored and developed. The number of offshore structures is being increased rapidly with the march of ocean developers.

Unmanned untethered submersibles for inspection tasks

Inspection of undersea pipelines and offshore structures are conducted by divers or manned submersibles or unmanned submersibles. As an inspector the diver's advantage is in maneuverability, tactile sending and cognition. But the divers are losing their economic advantage because of the necessity of blood decompression and redundant back-up systems for their safety. Further, the diver's working depth is at most 1,000 feet even with the most advanced supporting systems. Manned submersibles are massive (and costly) because of the necessity of providing space for a pilot and an observer. Many unmanned tethered submersibles have been developed, but the restricted mobility caused by tether drag and tangle has not been solved yet. These problems and disadvantages suggest unmanned untethered submersibles for inspection tasks.

The data communication between an unmanned untethered submersible and an operator is conducted by a sonic link. The speed of sound in water is approximately 1,600 meters per second, it means that an acoustic signal will take a delay time of one second for every 1,600 meters of depth. The low bandwidth of a sonic channel restricts transmittable information. By a sonic link information is transmitted approximately 30 K bits per second under good conditions, much less under poor conditions. This means that a video picture composed of 128x128 points with 4 levels of gray scale would take 2 second for the entire "message" to be received and assembled on the surface.(1)

Manual Control

In the past, teleoperator systems necessarily used direct manual control. A human operator was always included in the closed-loop system as a controller.

Two basic models of a human operator have been developed. The crossover model of McRuer (1965) describes the operator's transfer function using frequency domain concepts.(2) The optimal control model of Kleiman (1971) describes the operator's function as a controller by using stochastic optimal control concepts.(3)

Both models show that a human operator has an inherent limitation (time delay etc.) as a controller. It is obvious that if the feedback "message" from a submersible is poor and the total control system has a significant time delay, control will deteriorate easily. An unmanned untethered inspection submersible communicating with an operator through a sonic link must be supported by a computer intermediary.

Supervisory Control

In 1967 Ferrell and Sheridan proposed that a hierachial man-computer system based on the human supervisor-subordinate relationship could be used in deep space to solve some of the control problems involving time delays. Under supervisory control the human operator directs the subordinate computer by planning the action and directions it should take, teaching it how to achieve the desired functions, monitoring its performance, intervening whenever it gets into trouble, and trusting it to accomplish the tasks without continuous assistance.(4)

Figure 1-1 shows the supervisory control concept applied to the system which has a time delay and a severely restricted data transmission rate. The remote computer is the actual direct controller of the vehicle and the camera. The local computer controls or monitors the remote computer. The information transmitted between them is modified and condensed as much as possible. The operator's control task is simplified by the assistance of the local computer so that the operator can concentrate on inspection tasks. Now the operator's role is converted from a master-slave controller to a "supervisor" of a semi-autonomous system.

When the operator chooses an automatic control mode, the remote computer takes care of the motion of the vehicle and the camera. When the automatic control mode is no more suitable (because of trouble or an irregular situation), the control mode is changed to the manual control mode automatically.

Fig. 1-2 shows the position of supervisory control within the classification of controls. Clearly, supervisory control is not perfect autonomous control, but it combines the best attributes of both machine and man to achieve the desired goal. "Two heads are better than one," especially, if they possess complementary capabilities.

1-2. Background

In 1967 Ferrell and Sheridan proposed supervisory control to handle the system which includes poor

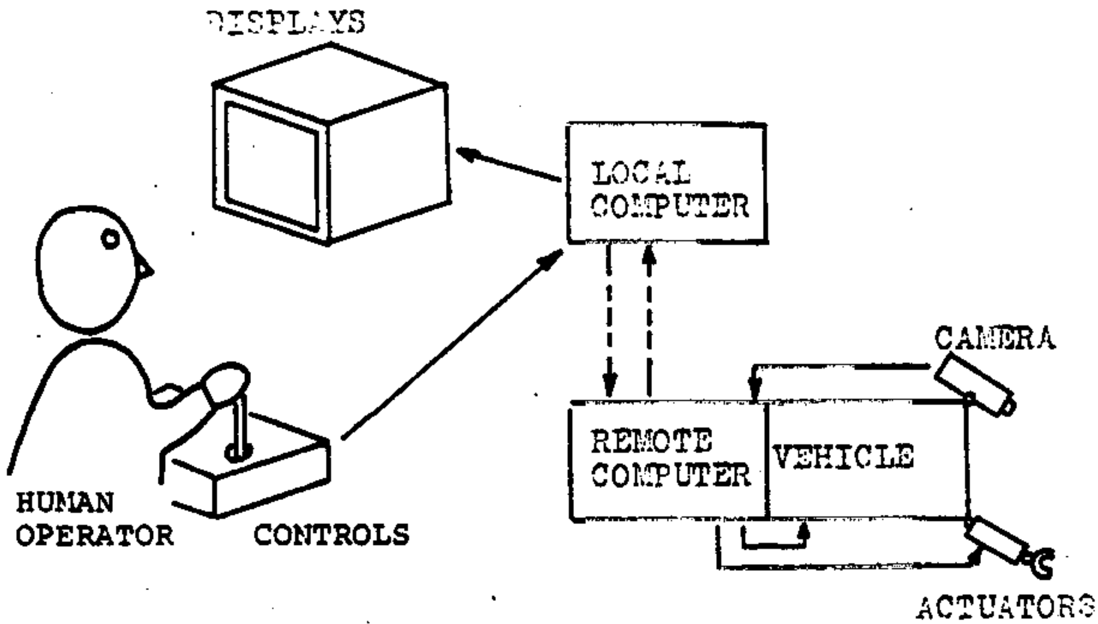


Fig. 1-1 Supervisory Control of a Teleoperator
(Adapted from Ref.(5) and Modified)

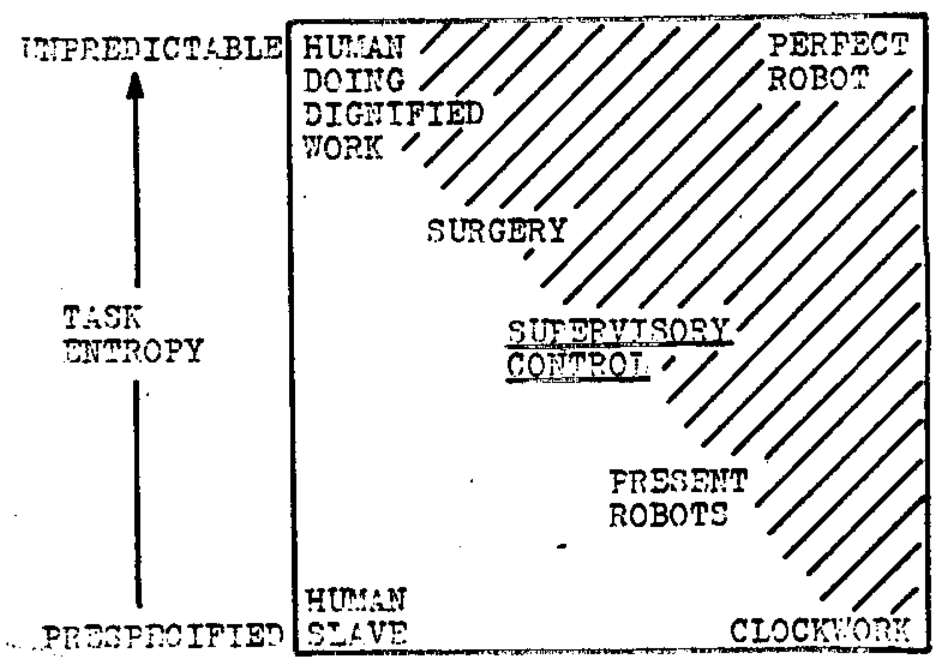


Fig. 1-2 Task Predictability vs. Degree of Automation [Adapted from Ref (5)]

feedback signals and a several seconds time delay.(5) After their proposal supervisory control concepts were expanded and applied to various areas in the Man Machine Systems Laboratory at M.I.T. Sheridan and Verplank in 1978 summarized various kinds of supervisory control applied to undersea teleoperators.(4) Brooks and Sheridan in 1978 further developed supervisory manipulation.(1) Yoerger in 1978 expanded a supervisory control concept to multi-dimensional aircraft control.(6)

The basic design of the multi-purpose inspection vehicle was developed in 1979 by the author and Takahashi. Takahashi in 1979 first constructed the vehicle as the simulator of undersea inspection tasks.(7) The vehicle was rebuilt as the experimental vehicle of this report.

The picture quality of a monitor T.V. under constrained bandwidth is undergoing research in the Man-Machine Systems Laboratory. Ranadive in 1979 presented his research about the practical tradeoffs among resolution, frame rate and grayscale under limited bandwidth data channels.(8) His result will be merged into the supervisory controlled inspection task simulator in the near future.

1-3. Requirements

Simulation of an undersea inspection vehicle

To clarify the adaptability of supervisory control to an undersea inspection submersible the "on-floor" simulator is designed and demonstrated. Inspection tasks have been identified as follows:

a) inspection of pipelines and offshore structures conducted with a T.V. camera;

b) detection of visual defects such as cracks and broken or missing structural members.

Requirements of a simulator have been identified as follows:

a) The vehicle should carry a T.V. camera, while a T.V. display is presented as an information monitor.

b) Various possible vehicle dynamics should be simulated in the host computer to simulate constraints on vehicle motion.

c) Various control modes should be tested, where the modes can be changed by an operator without interrupting the simulation.

Object-following inspection vehicle

To complete the automatic object-following vehicle system an automatic control mode is defined as follows:

a) An automatic control mode should be executed by an operator's simple action (pushing a button).

b) A T.V. camera direction should be kept perpendicular to the inspected surfaces.

c) The distance between the T.V. camera and surfaces should be kept constant.

d) When automatic control is violated, the vehicle should stop and the control mode should change to manual control.

1-4. Organization of the thesis

In Chapter 1 inspection tasks by supervisory control are defined. Chapter 2 is devoted to the description of the vehicle configuration, especially, the design of sensors. In Chapter 3 computer control techniques for both system hardware and control software are presented. In Chapter 4 an evaluation of the system is made. Comparisons between purely manual control and combined manual-computer control are used as a basis for determining the applicability of supervisory control to inspection tasks. In Chapter 5 are discussions of results and conclusions.

Chapter 2 Experimental Vehicle Design

To meet the requirements stated in Chapter 1 an experimental vehicle was designed and created. The following three design factors were considered: 1) vehicle structure as a simulator; 2) sensors; 3) driving system. Fig. 2-1 shows the experimental vehicle. Table 2-1 shows specifications of the experimental vehicle.

2-1. Vehicle configuration as a simulator

As a simulator of an undersea inspection submersible a camera position and its direction are critical factors. By means of the experimental vehicle a three-dimensional camera position is obtained independently. Panning and tilting of the camera are also possible independently.

The camera is set on a dovetail slider which is installed in a camera supporting track structure. The height of the camera can be changed by the vertical motion of the dovetail along a camera supporting track.

Three wheels attached to a platform are driven independently and the directions of the wheels are kept the same so that the platform can be moved to any horizontal location without rotation.

The camera supporting track structure is set on the rotating table which in turn is installed on the

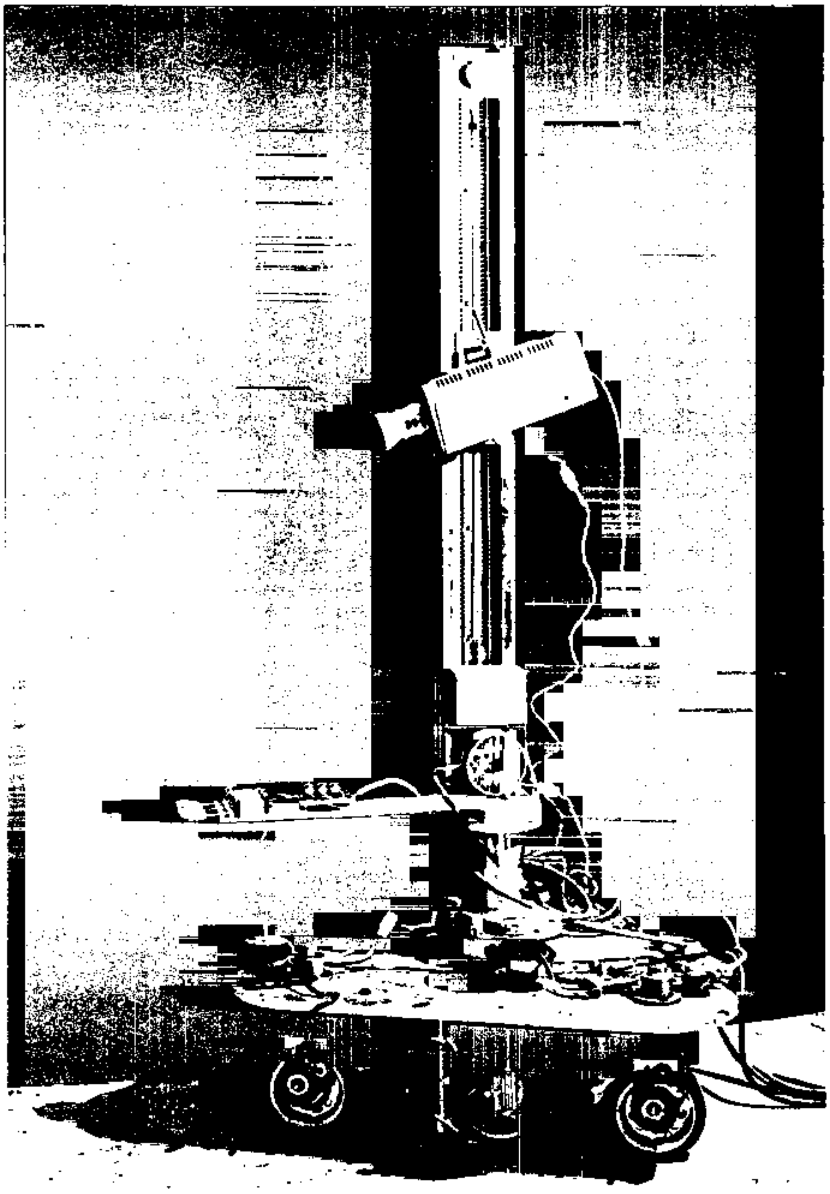


Fig.2-1 Experimental Vehicle

	Range	Rate
Translation	-------	0-6 cm/sec
Steering	±90 deg	0-30 deg/sec
Camera up & down	60 cm	0-5 cm/sec
Camera Panning	±180 deg	0-9 deg/sec
Camera Tilting	±45 deg	0-6 deg/sec
Weight	20 kg	
Size	125 cm(H), 60 cm(W), 60 cm(D)	
Power	AC 115 V	

Table 2-1 Experimental Vehicle Specifications

basic vehicle platform. Panning motion of the camera is obtained by the rotating motion of the table.

Between the dovetail and a camera body a tilting mechanism is installed.

2-2. Sensors

To satisfy the requirements of an automatic object following vehicle stated in Chapter 1, sensors should have the following characteristics:

a) to detect the camera direction;

b) to detect the distance between the camera and a surface.

Another role c) is added to investigate various control methods of an experimental vehicle:

c) to detect the radius of a surface with the assumption that a surface is a part of a cylinder.

Fig. 2-2 shows sensors developed between the surface and the vehicle by contacting directly the surface. Rollers are attached to the tips of sensors. The rollers are forced by springs to remain in contact with the surface. Three mechanical sensors are installed with the same directions as the camera direction. The displacements of the sensors are converted to voltages, which are used as input signals to the computer.

Video camera direction

If tactile sensors are installed with the same orientation as a video camera, the camera orientation relative to a surface is detected by two sensors. When two displacement input signals are the same, the camera direction is perpendicular to the surface (in the plane of the sensors and the camera). The difference between the two signals shows how the camera direction is different from the perpendicular.

Distance between a camera and a surface

The displacement of a central sensor in a row of three detects the distance directly.

Radius of a cylindrical surface

If three points are given, the circle on which three points lie is determined. When the coordinates of three points (x1, y1), (x2, y2), and (x3, y3) are given, the y coordinate of the center of a determined circle is:

$$y = \frac{(x2-x1)(x3^2-x1^2+y3^2-y1^2)-(x3-x1)(x2^2-x1^2+y2^2-y1^2)}{2[(x3-x1)(y1-y2)+(y3-y1)(x2-x1)]}$$

When the origin point of a new coordinate is taken at (x2,0), the new coordinates of three points are

(x1,y1), (0,y2) and (x3,y3)

If the directions of sensors are fixed parallel to the y axis, y1, y2 and y3 are the displacements of sensors and x1 and x3 are x coordinates of sensor positions. Let x1=-A and x3=A, where A is the distance between the two sensors. Now three given points are expressed as (-A, y1), (0, y2) and (A, y3). The y coordinate of the circle is:

$$Y=\frac{2A^2+y1^2+y3^2-2y2^2}{2(y1+y3-2y2)}$$

The directions of the sensors are kept perpendicular to the surface so that Y+y2 is the radius (R) of the curvature of the inspected surface.

$$R = Y+y2$$

Fig. 2-3 shows the relationship between R and sensor displacements.

Small errors caused by the differences between A and the actual touching points on the sensor rollers are neglected.

2-3. Driving system

The experimental vehicle has five degrees of freedom: three for translation, two for panning and tilting. All motion is generated by stepping motors that exactly reflect the signals from the computer to each degree of freedom.

Fig. 2-2 Sensors

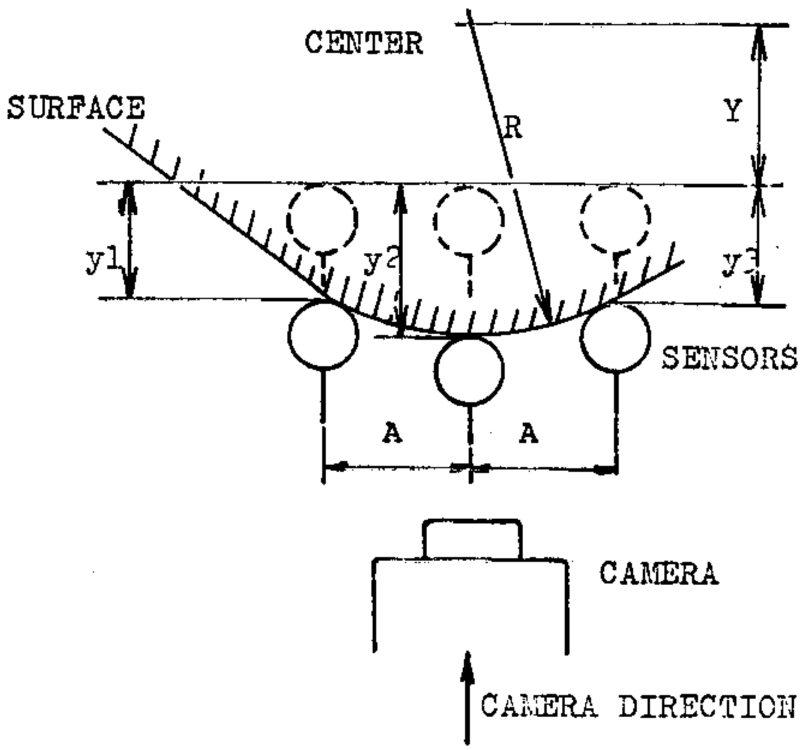


Fig. 2-3 Relationship between Radius and Sensor Displacements

Panning and steering motion is controlled by position feedback to obtain precise and reliable two-dimensional vehicle positions and camera directions.

Chapter 3 Control System

3-1. Hardware

Fig. 3-1 shows the configuration of the control system.

Keyboard

A keyboard is used to select the computer program and to input experimental specifications (speed, control gain etc.). While an operator is controlling the vehicle the keyboard is unnecessary for vehicle control.

Special console box

A special console box consists of two joysticks, four control mode selection buttons and alarm or direction indicator lamps. In Fig. 3-2 the console box is shown.

Joysticks are used to control the vehicle manually. Fig. 3-3 shows the relationship between joystick control and vehicle and camera motion.

By mode selection buttons an operator can choose a control mode (manual, automatic, etc.).

Pulse generator

A pulse generator converts analog signals from the AN5400 to sequential pulses to input into the current amplifiers for stepping motors.

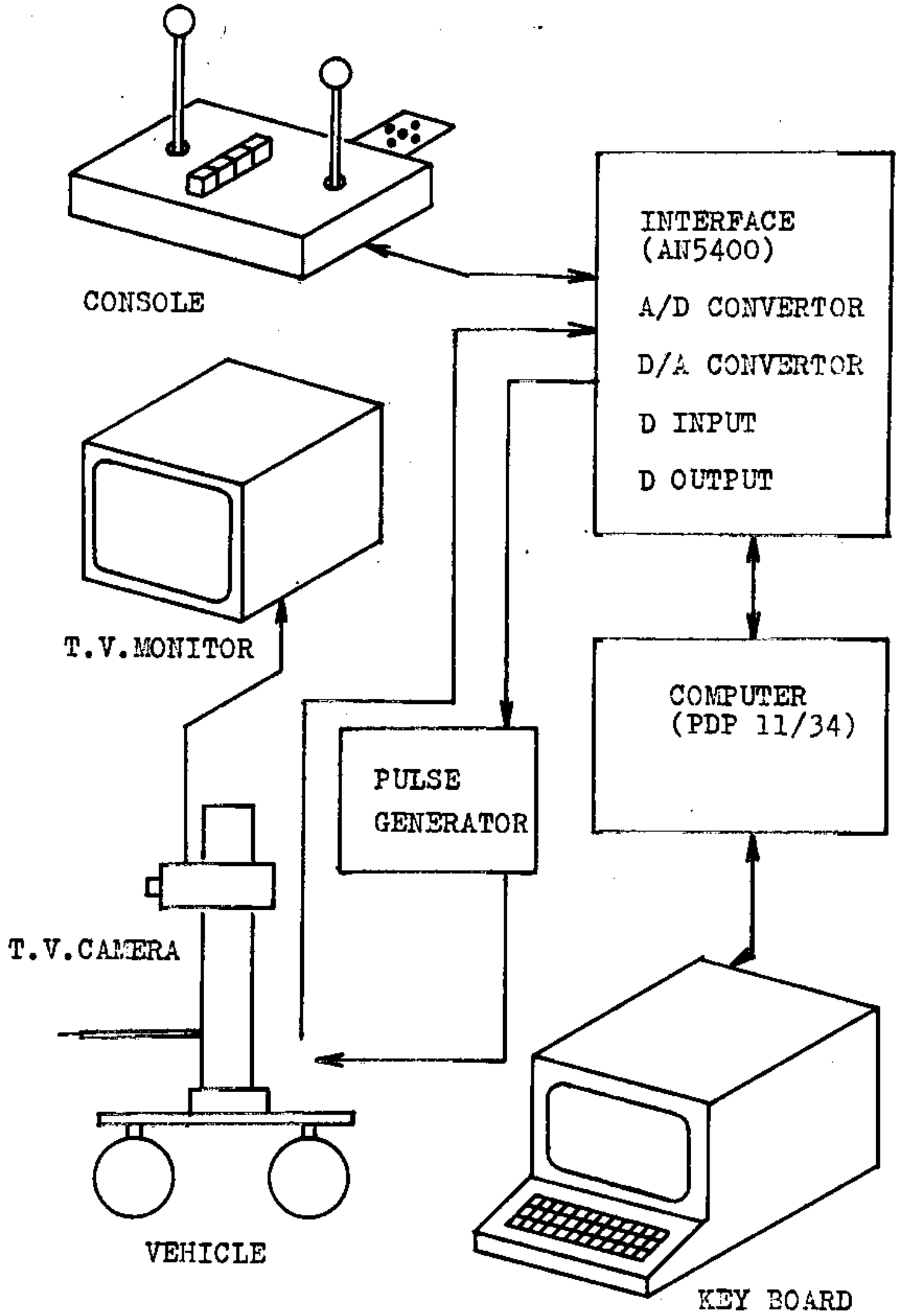


Fig. 3-1 Control System Configuration

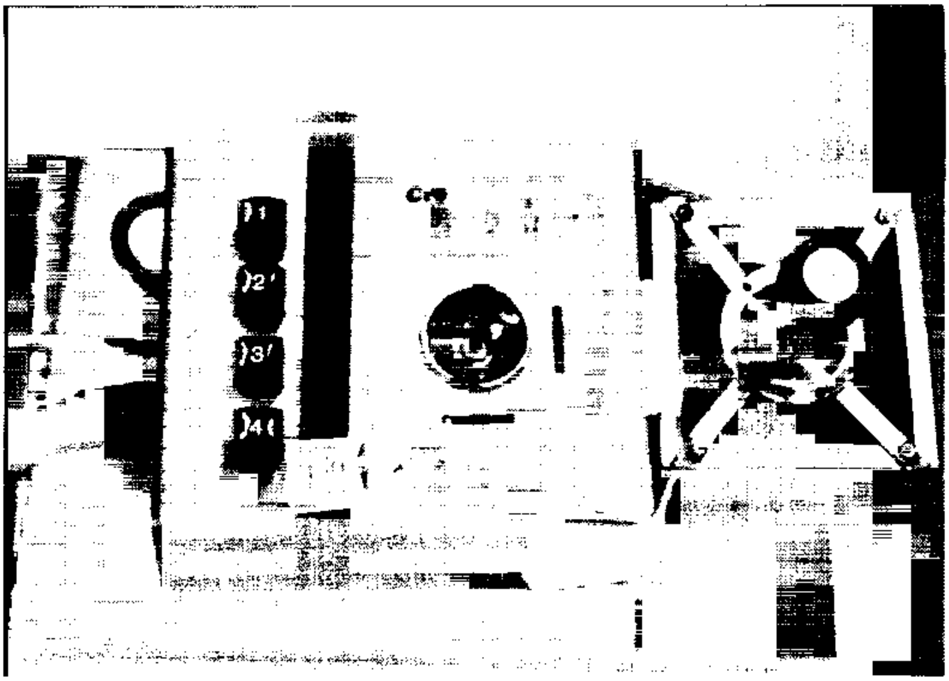


Fig. 3-2 Console Box

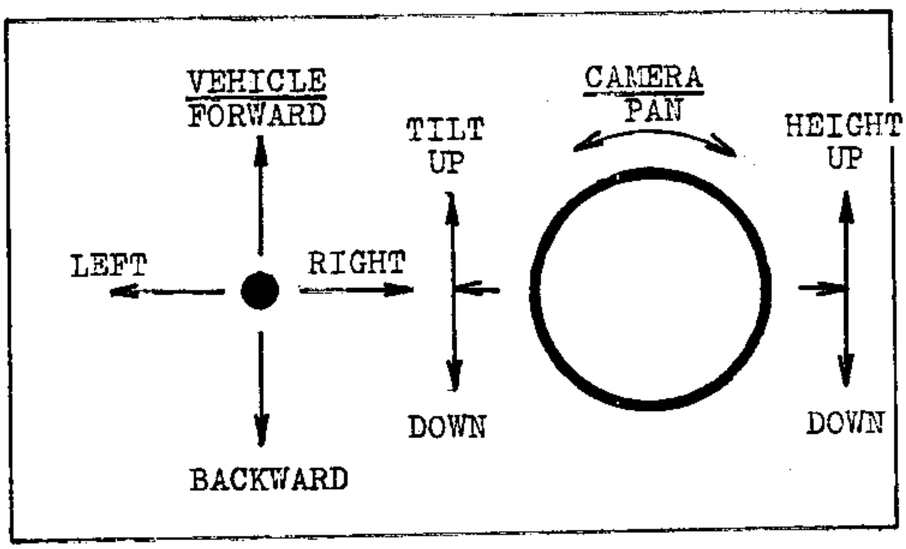


Fig. 3-3 Joystick Control

Sensor output signals and position feedback signals

Three sensor output signals and position feedback signals for panning and steering are connected to the A/D convertors of the AN5400.

Video picture

The camera on the vehicle and a T.V. monitor are connected directly. An operator can inspect the object's surfaces by means of the video picture of a T.V. monitor.

Computer and computer interface

Every signal from the console and the vehicle is fed into the computer interface (AN5400) which consists of A/D Convertors (32 channels), D/A Convertors (32 channels), Digital Output (32 bits) and Digital Input (32 bits). The computer (PDP 11/34) is the only "brain" of the system. Every calculation and decision is done by this computer, and all output signals are sent to a pulse generator or to the console through the computer interface (AN5400).

3-2. Software

The program to control the computer interface (AN5400) is written in assembly language.* Vehicle control programs are written in Fortran IV. For the

*The programs for AN5400 were completed by Dr. K. Tani (Department of Mechanical Engineeering, M.I.T.)

convenience of experiments, the programs are separated into the following categories:

a) programs to simulate the direct manual control of an undersea inspection submersible, including the vehicle dynamics;

b) programs to simulate the supervisory control of an undersea inspection submersible.

Manual control

Each motion of an undersea inspection submersible is simulated by a pure time delay plus a first-order exponential lag. A pure time delay is mainly caused by the elapsed time by acoustic data transmission. A first-order time lag is caused by the inertia of the submersible plus its motion through viscous fluid.

In this program a delay time and the time constants of the first-order lags can be chosen before executing a program.

Camera or vehicle-oriented coordinates

The proper coordinate system should be chosen so that it is always clear to the operator which operations are required to make the vehicle move as he wants. Namely, the operator should not have to think about details of the coordinate system, just about what he wants to accomplish.

In the manual control mode there are two kinds of correspondence between joystick manipulation and actual vehicle motion.

a) The coordinates of the joystick correspond to the coordinates fixed on the vehicle. In this case, the forward direction is defined as the forward direction of the vehicle.

b) The coordinates of the joystick correspond to the coordinates fixed on the camera. In this case, the forward direction is defined as "into the picture" instead of forward relative to the vehicle.

Camera and vehicle-oriented coordinates are easily transformed into each other. For example, where velocity is concerned only a 3 x 3 transformation matrix need be used.

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}_{\text{Vehicle}} = \begin{bmatrix} \cos A & -\sin A & 0 \\ \sin A & \cos A & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}_{\text{Camera}}$$

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}_{\text{Camera}} = \begin{bmatrix} \cos A & \sin A & 0 \\ -\sin A & \cos A & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}_{\text{Vehicle}}$$

Where $\dot{x}$, $\dot{y}$ and $\dot{z}$ are velocity components. A is the angle between the camera-oriented coordinate frame and the vehicle-oriented coordinate frame.

Fig. 3-4 shows the relationship between two frames. Programs to simulate both the camera and the vehicle-oriented coordinate systems were prepared.

<u>Approach of the vehicle to a surface</u>

Before entering the automatic object-following mode, the sensors must contact the surface to be inspected. After contact the vehicle position and the camera direction must be normalized to enter the automatic mode smoothly. Both manual and automatic approach modes are available.

<u>Manual approach</u>

At first an operator controls the vehicle to bring it close to the object. When one of any three sensors touches the surface, the vehicle stops automatically and alarm lamps intermittently go on and off.

When the operator pushes the button (2), the lamps become direction indicators and the operator can control the vehicle again. Table 3-1 shows the direction indications of the lamps.

When only the center lamp is on, the approach mode is completed.

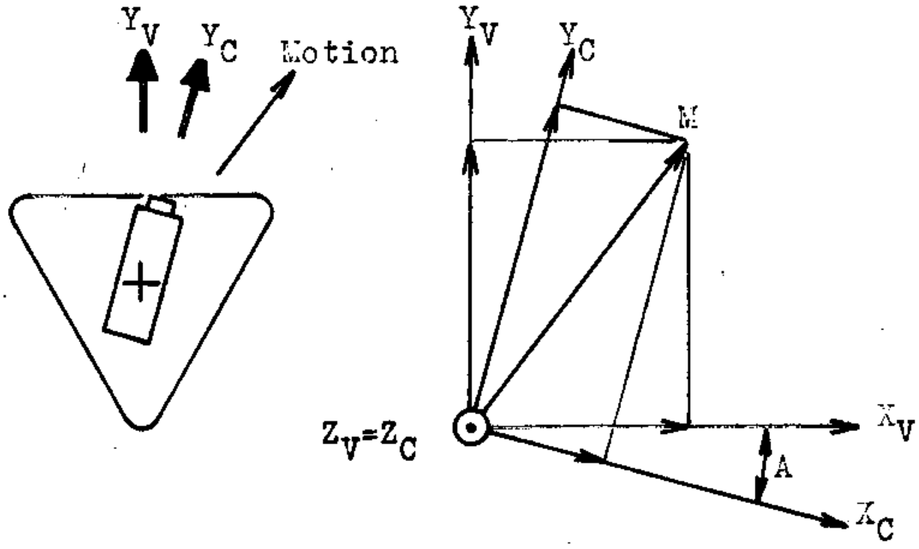


Fig. 3-4 Relationship between Camera and Vehicle Coordinates

INDICATOR LAMPS	● ○ ● ○ ○	● ○ ○ ● ○	● ● ○ ○ ○	○ ○ ● ○ ●	○ ○ ○ ● ●
CAMERA DIRECTION	O.K.	T.R.	T.L.	O.K.	T.R.
VEHICLE POSITION	G.F.	G.F.	G.F.	G.B.	G.B.
INDICATOR LAMPS	○ ● ○ ○ ●	○ ○ ● ● ○	○ ● ● ○ ○	○ ○ ● ○ ○	● --ON ○ --OFF
CAMERA DIRECTION	T.L.	T.R.	T.L.	O.K.	
VEHICLE POSITION	G.B.	O.K.	O.K.	O.K.	

T.R.--Turn Right, T.L.--Turn Left,
G.F.--Go Forward, G.B.--Go Backward

Table 3-1 Direction Indicator Lamps

Automatic approach

In the automatic approach mode, the computer controls the vehicle as indicated by the lamps. When the sensors do not touch the object the indicator shows "go forward." Therefore, after some rough direction control, the operator can push the button (2) to enter the approach mode. The normalization of the vehicle position and the camera direction is completed by the computer.

Object-following mode

Two programs to simulate each control method were developed.

a) pure feedback control;

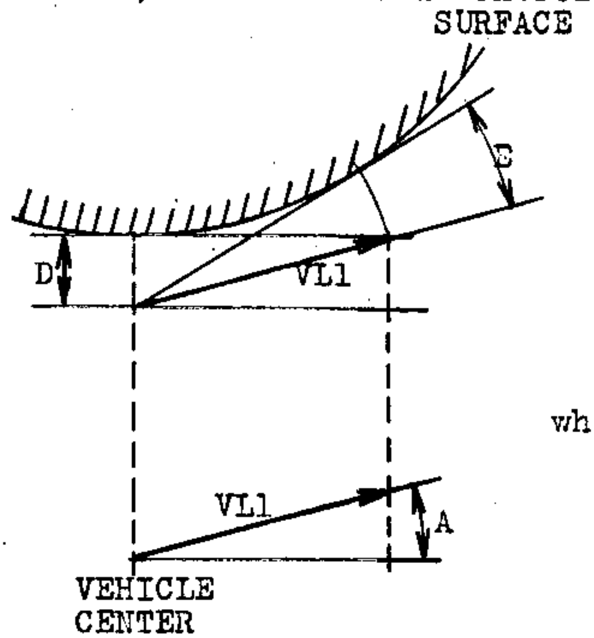
b) modified feedback control.

In the feedback control mode the vehicle locus correction signal is calculated from the present distance between the object and the vehicle. Namely, if the vehicle is far from the reference distance, the steering direction is corrected to bring the vehicle close to the object and vice versa.

In the modified feedback control mode the feedback signal is modified by the curvature of the inspected surfaces. The modifying value is determined by the radius of the curvature. Namely, the future distance between the vehicle and the object is estimated by knowing the curvature of the surfaces.

Fig. 3-5 shows how the correction signal is determined.

1) Pure Feedback Control



$\sin A = \frac{D}{VL1} \fallingdotseq A \quad (\because D \ll VL1)$

$\therefore A = \frac{D}{VL1}$

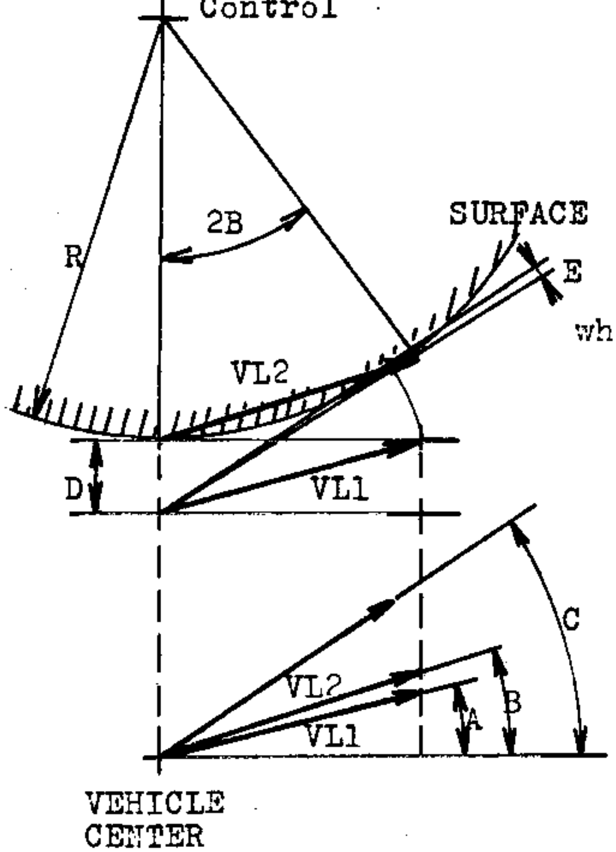
where, D: Sensor displacement from the origin position

VL1: Specific distance (refer to gain)

A: Angle by which steering should be corrected

E: Error

2) Modified Feedback Control



$\sin B = \frac{VL2}{2R} \fallingdotseq B \quad (\because VL2 \ll 2R)$

$\therefore B = \frac{VL2}{2R}$

$C = A + B = \frac{D}{VL1} + \frac{VL2}{2R}$

where, D: Sensor displacement from the origin position

VL1, VL2: Specific distance

R: Radius of curvature

C: Angle by which steering should be corrected

E: Error

Fig. 3-5 Steering Correction Signals

Chapter 4 Experiments and Results

To clarify the advantages or disadvantages of supervisory control of an inspection vehicle, comparisons of supervisory and manual control were made. Unfortunately, the video picture under a limited frame rate could not be implemented. Therefore, research on the quality of control as related to the uncertainty of sizes of inspected parts could not be completed. Experiments were focused on vehicle control tasks which would be required to operate an unmanned submersible.

4-1. Considerations

Experiments were organized to reveal the problems which would occur in practical operation of a vehicle such as that simulated.

A difficulty of control is caused by a significant time delay and a first-order exponential time lag. By manual control the operator can conquer these problems. Though a human operator is a good controller, when the time delay and lag are excessive his controlability will decrease rapidly and finally control will be impossible.

The primary experiments were made to evaluate the capability of the human operator. The evaluation was based on the time required to complete given inspection tasks.

The only way to escape from the cited difficulties is to control the vehicle automatically. The vehicle control system demonstration was organized to show the maximum capability of the experimental vehicle. In Fig. 4-1 a demonstration plan is shown.

4-2. Equipment for experimental demonstration

Details of the system are explained in other chapters. In Fig. 4-2 the experimental layout is shown. Fig. 4-3 shows the specific surface used in the primary experiments. In Fig. 4-4 the object which was followed by the experimental vehicle is shown.

4-3. Results

In the primary experiments the capability of one human operator was examined. Results are shown in Fig. 4-5, Fig. 4-6 and Fig. 4-7. The salient results are as follows:

a) The camera-oriented coordinate system is easier than the vehicle-oriented coordinate system for an operator.

b) The difficulty of control increases in proportion to the size of a time delay and a viscoinertial lag

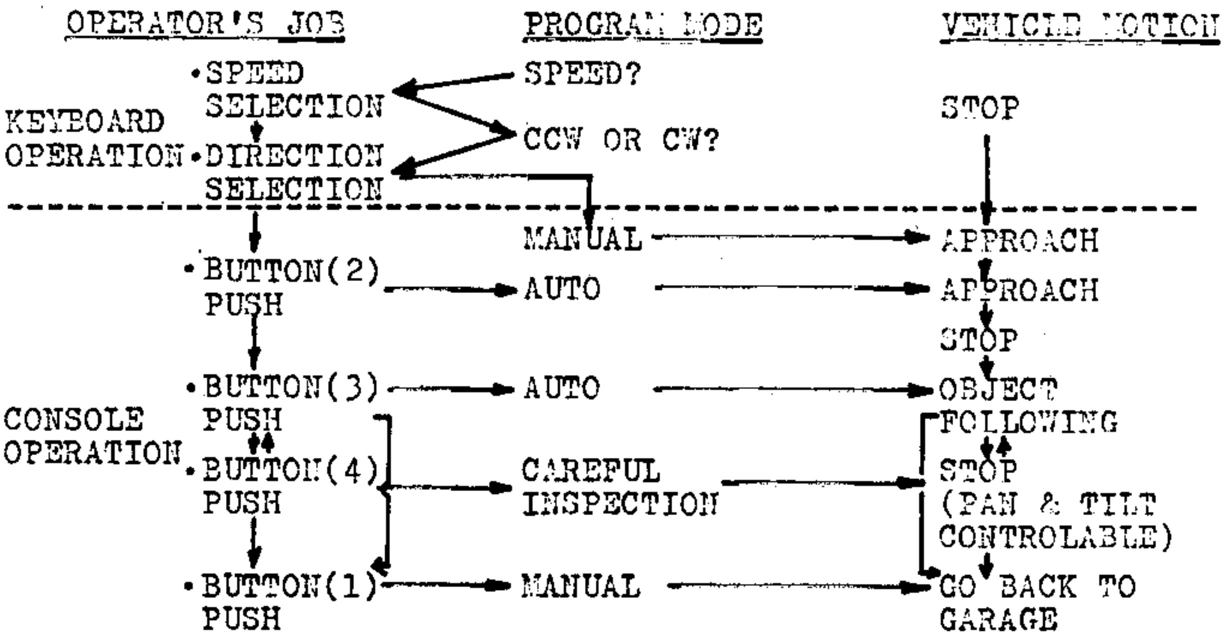


Fig.4-1 Demonstration Plan

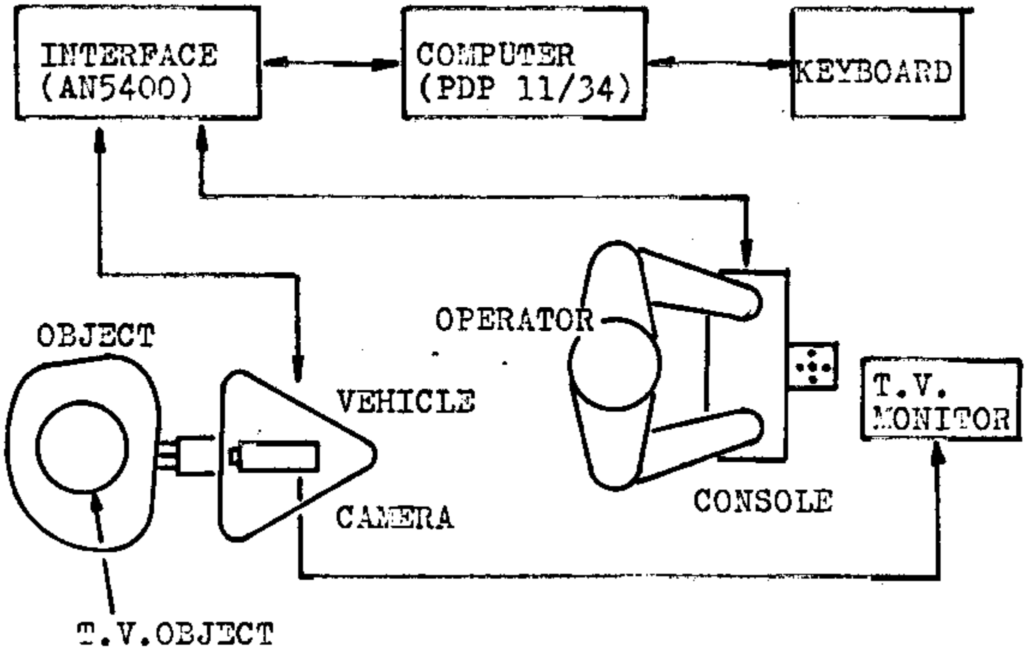


Fig. 4-2 Experimental Layout

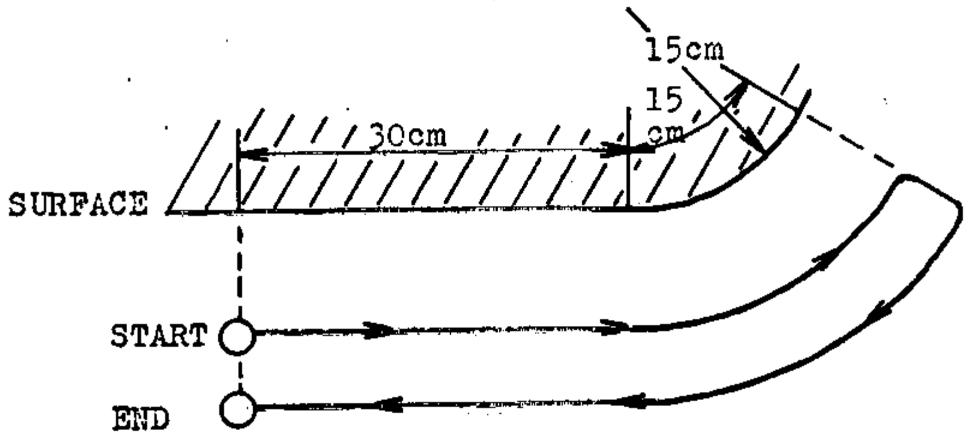


Fig. 4-3 Specific Surface for Primary Experiments

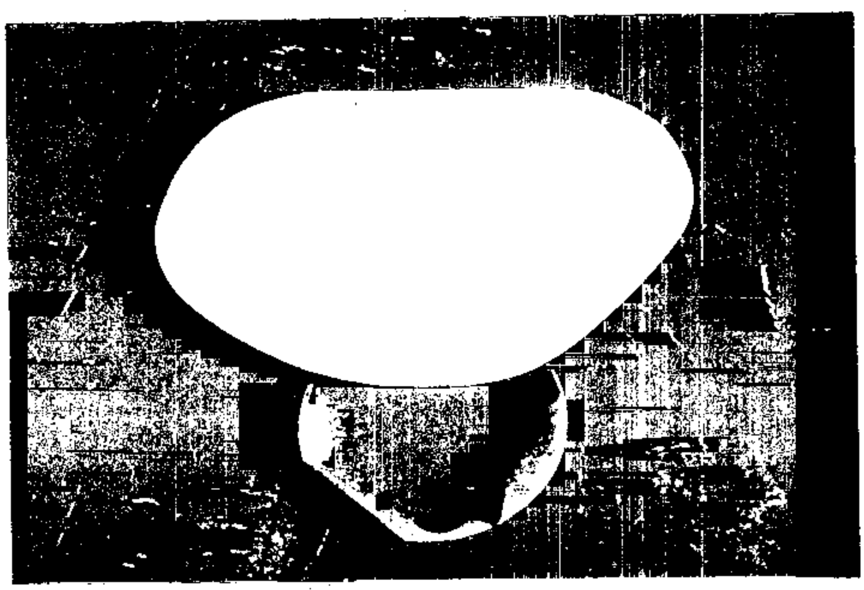
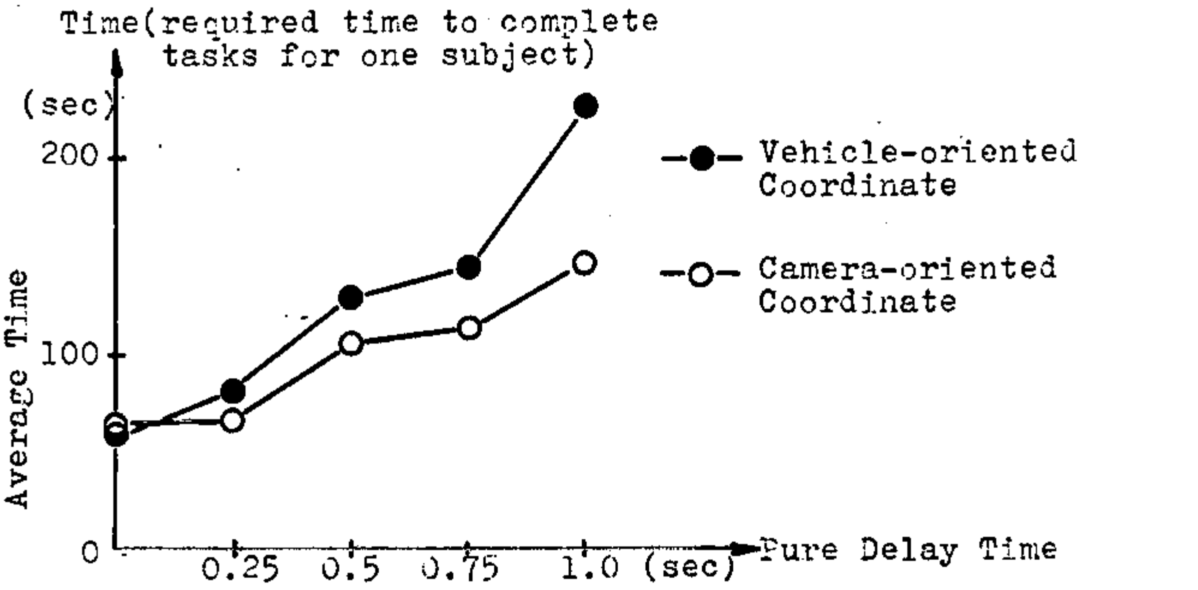
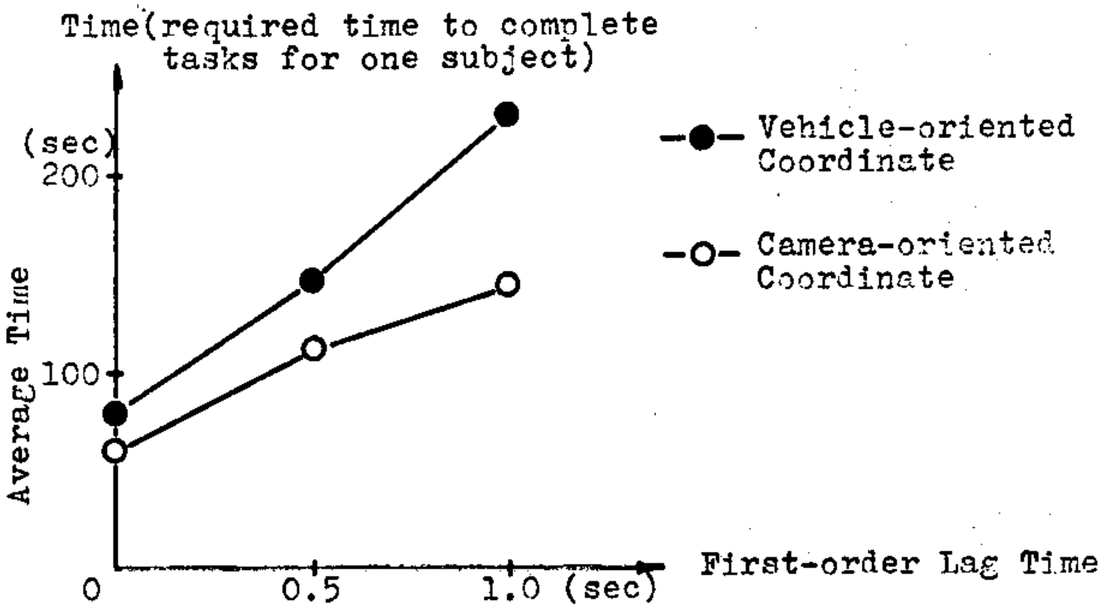


Fig. 4-4 Object for Demonstration



#Time Coefficient of First-order Exponential Lag:1.0sec

Fig. 4-5 Effect of Pure Delay Time with Manual Control



#Pure Delay Time: 1.0sec

Fig. 4-6 Effect of First-order Lag Time with Manual Control

*Detailed Data for Fig.4-5 and Fig.4-6 are shown in APPENDIX D.

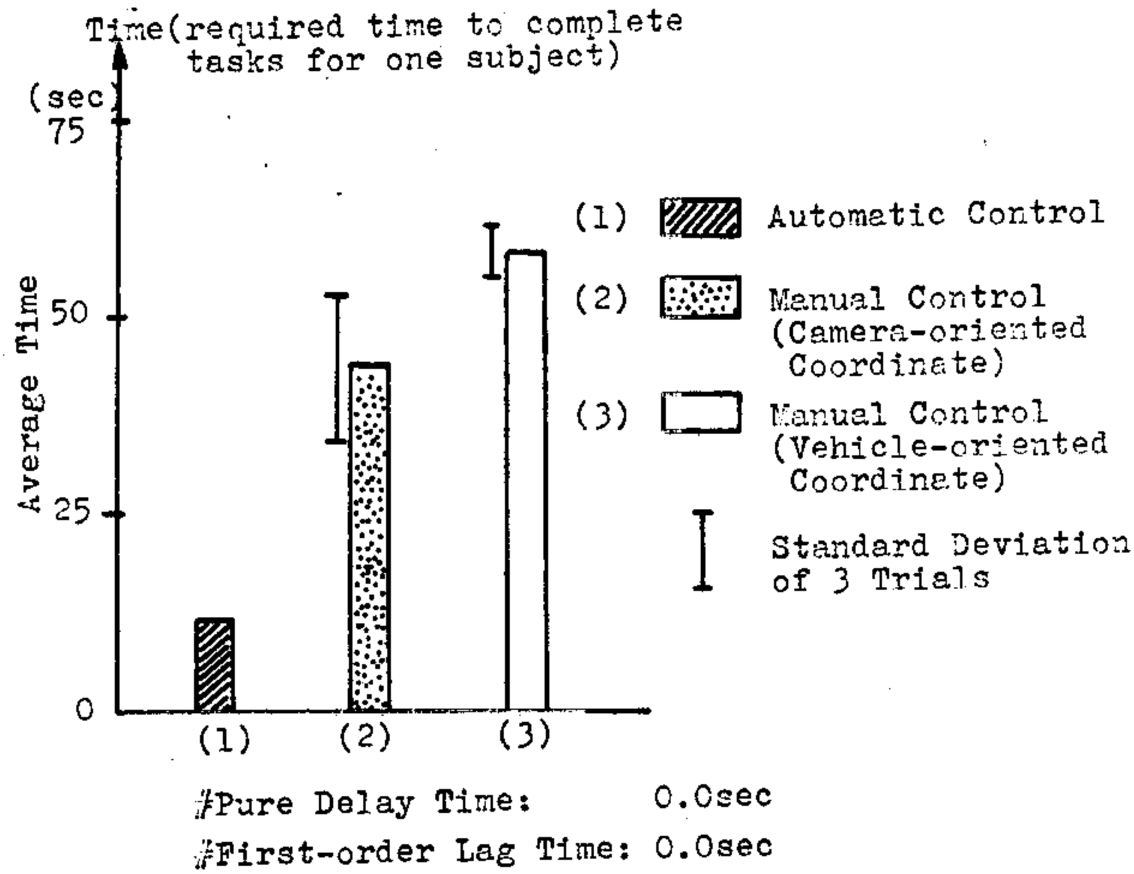


Fig.4-7 Comparison among Automatic Control and Two Modes of Manual Control

time constant.

c) Computer control is faster than manual control.

The capability of the supervisory controlled vehicle may be summarized as follows:

Automatic approaching

a) The vehicle can approach an object at approach speed of 1.5 cm/sec and can normalize its position with respect to camera direction automatically.
b) The maximum allowable deflection angle from the normal line of a surface is ± 15 degrees.
When the deflection angle is over ± 15 degrees automatic approaching must be assisted by the operator.
c) The required time for the normalization is 1-5 sec, 1 sec (when already perpendicular to the surface), 5 sec (when the deflection angle is ± 15 degrees).

Object-Following

a) Direction: both CCW and CW directions can be chosen by an operator;
b) Maximum speed:
1.8 cm/sec (with feedback control);
3.0 cm/sec (with modified feedback control);
c) Minimum radius of a surface: 10 cm;

If the radius of a curvature is under 10 cm, the vehicle stops automatically. In this case, the vehicle must be controlled by the operator.

Temporary stops

The vehicle can be stopped at any point at the operator's direction to inspect a surface carefully. In this mode panning, tilting and vertical translation of the camera are possible.

Continuous inspection

After the first round of inspection the camera position changes automatically and the vehicle can start the second round of inspection, perhaps at a different height.

Videotape

A videotape record was made to show various capabilities of the simulated vehicle under various control modes. The reader may refer to this paper for further details.

Chapter 5 Conclusions and Discussion

5-1. Conclusions

The human operator's capability to control an unmanned unthethered submersible was explored by means of a simulation.

The control of a system which includes a significant time delay and a significant first-order exponential time lag proved to be difficult for a human operator.

The coordinate framework chosen for manual control is important. The advantage of a camera-oriented coordinate frame was proven.

Even for a system which does not include a time delay, automatic inspection is faster than with manual control. However, very precise automatic control is clearly costly.

Supervisory control appears to be the most favorable choice.

5-2. Discussion

The computerized inspection vehicle control sytem concept appears to be powerful and promising. However, the cost was not considered in this report. For further evaluation of this approach a microcomputer control system should be tried instead of the general purpose minicomputer system used in these experiments.

The frame rate problem of low bandwidth communication was not considered in this report. This problem has been partially solved already. The next step in simulation research should implement a digitizer for experimental control of the video signal.

In this report automatic control is restricted to two dimensional objects. The problems of using an inspection vehicle to follow three-dimensional objects should be explored. To complete the three-dimensional object-following system use of sonic distance sensors such as these employed in the Polaroid camera should be considered.

APPENDIX A

FIRST-ORDER LAG APPROXIMATION

The motion equation of a submersible is as follows:

$$M \cdot \frac{dV}{dt} + [C] \cdot \vec{V} = [I] \cdot \vec{F}$$

Where M is the Mass of the submersible

$\vec{V}$ is Velocity

$[C]$ is the Coefficient matrix of viscosity

$[I]$ is Interference matrix

$\vec{F}$ is Thrust force of the vehicle

If the viscosity resistance has no directivity and the thrust force has no interference, the equation is simply written as follows:

$$M \cdot \frac{dV}{dt} + CV = F$$

The Laplace transform is obtained.

$$M \cdot V \cdot S + C \cdot V = F$$

$$\therefore \frac{V}{F} = \frac{\frac{1}{M}}{1+TS} \qquad \text{where} \quad T = \frac{C}{M}$$

For real submersible operation it is assumed that the displacement of a joystick corresponds proportionally to the thrust force of the submersible. Therefore, $F = P \cdot D$. where P is the gain and D is the displacement of the joystick.

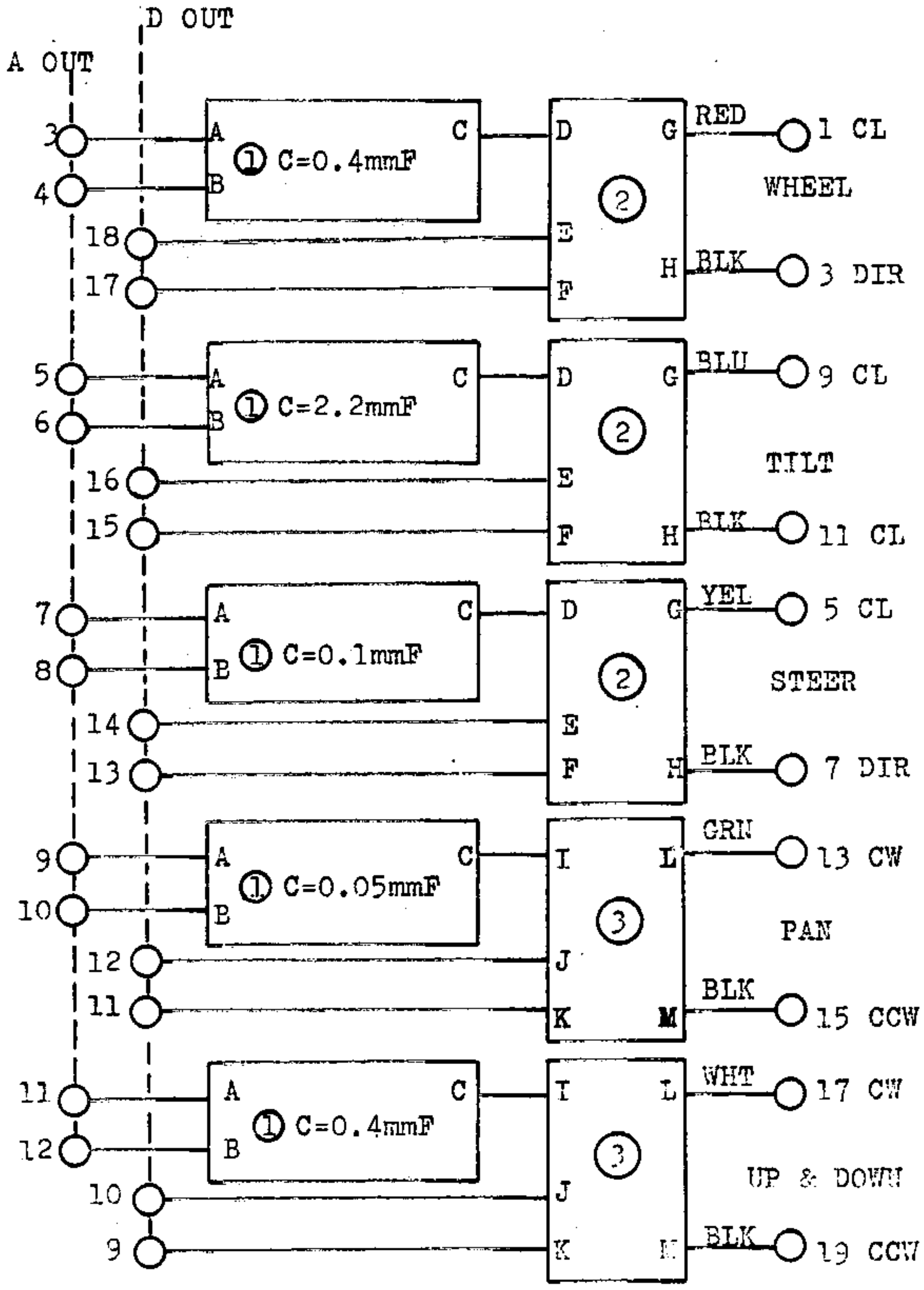
Finally, the relationship between the displacement of the joystick and the velocity of the vehicle is written as follows:

$$\frac{V}{D} = \frac{\frac{1}{P \cdot M}}{1 + TS} = \frac{K}{1 + TS} \quad \text{where, } K = \frac{1}{P \cdot M}$$

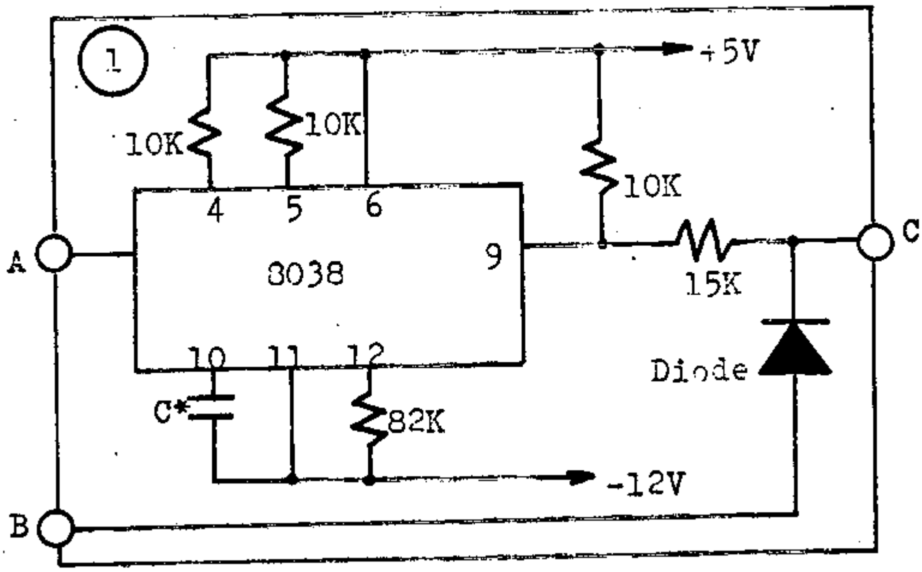
APPENDIX B

PULSE GENERATOR CIRCUIT SCHEMATIC

B-1 Pulse Generator System

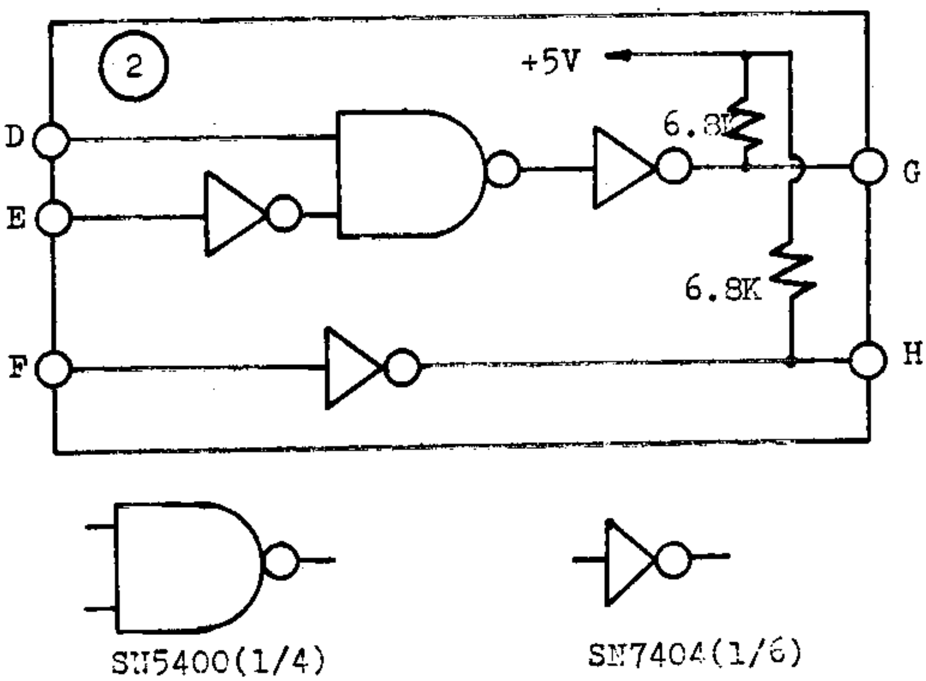


B-2 V/F Convertor Schematic

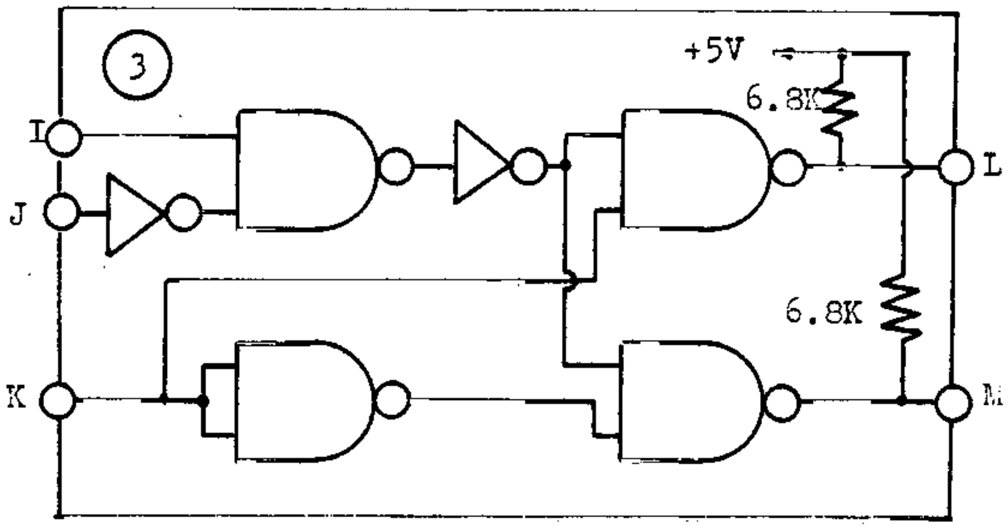


C*: Capacitor
Each capacitance is shown in B-1

B-3 Pulse Controller Schematic A



B-4 Pulse Controller Schematic B



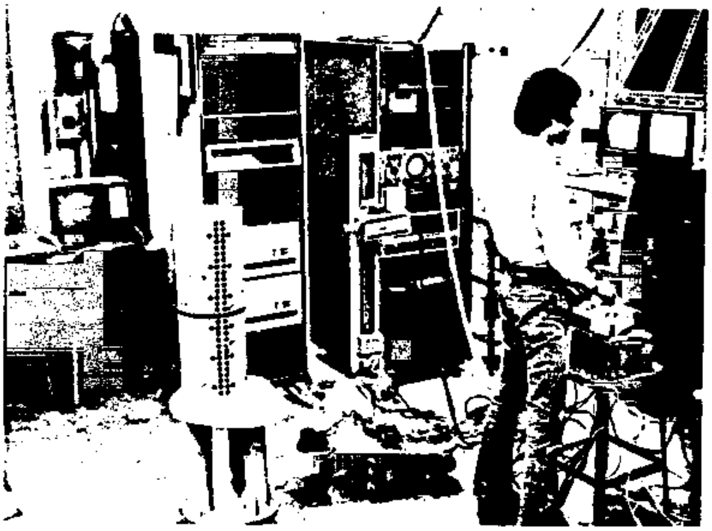
APPENDIX D
RESULTS OF PRIMARY EXPERIMENTS

Experimental Conditions			Results*	
Coordinate	D.T.** (sec)	L.T.*** (sec)	Mean Value (sec)	S.D.**** (sec)
Vehicle Oriented	0.0	0.0	58.3	2.9
		0.5	58.3	2.9
		1.0	60.0	5.0
	0.25	0.0	58.3	2.9
		0.5	58.3	2.9
		1.0	80.0	8.7
	0.5	0.0	51.7	2.9
		0.5	81.7	7.6
		1.0	133	19
	0.75	0.0	58.3	2.9
		0.5	122	17
		1.0	143	10
	1.0	0.0	80.0	5.0
		0.5	145	13
		1.0	233	55
Camera Oriented	0.0	0.0	44.3	9.3
		0.5	62.7	2.5
		1.0	65.0	5.0
	0.25	0.0	58.3	7.6
		0.5	56.7	10
		1.0	68.3	7.6
	0.5	0.0	70.0	5.0
		0.5	78.3	7.6
		1.0	105	15
	0.75	0.0	61.7	5.8
		0.5	102	10
		1.0	115	22
	1.0	0.0	61.7	7.6
		0.5	115	13
		1.0	147	5.8

* Required Time to Complete Tasks for One Subject
** D.T.: Pure Delay Time
*** L.T.: Time Coefficient of First-order Exponential Lag
****S.D.: Standard Deviation of 3 Trials

APPENDIX E

SIMULATOR VEHICLE LABORATORY



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