# GENERAL PURPOSE DIGITAL SIMULATION OF UNDERWATER VEHICLES

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## ABSTRACT

This paper is a summary of a real time simulation of a remotely-manned underwater vehicle control system in the Man-Machine System Laboratory at MIT. A non-linear model which is able to simulate the tight maneuvering of the vehicle is presented. This paper also categorizes various automatic control tasks of the vehicle .

## INTRODUCTION

Because of the ocean's natural resources, recently much engineering attention has been focused on underwater technology. This has included the design and development of a series of remotely-manned underwater vehicles for depths too deep for human divers. These vehicles have been used for the inspection and repair of underwater structures and the exploration of the ocean environment.

This report emphasizes :

1) Dynamic behavior of underwater vehicles.
2) Analysis and design of some basic servo controllers for underwater vehicles.
3) Use of servo controllers in some complicated tasks like following the cotour of the ocean bottom.

## MODELLING

Our model uses two orthogonal coordinate systems. One remaines fixed at the water surface while the other travels with the submarine to act as a local reference system.

The position of the vehicle can be specified by reference to the axis OXYZ (on the surface of the water), and to use the rectangular coordinates Xc,Yc,Zc. the usual approach for orientation of the vehicle is to start with cxyz parallel to OXYZ and bring the vehicle from this reference orientation to its actual one by:

1) a " swing " around z axis, $\psi$ ,
2) a " tilt " around yaxis, $\theta$ ,
3) a " heel " around x axis, $\phi$ .

Therefore, the vehicle may be located in space by:

A) Three position coordinates Xc,Yc,Zc.
B) Three angular coordinates $\phi$ , $\theta$ and $\psi$.

From Newton's law,

```
Tx-DRx-B*SIN(θ)          =M*[u+q*w-r*v-
Xg*(q**2+r**2)+Yg*(p*q-r)+Zg*(p*r+q)]

Ty-DRy-B*COS(θ)*SIN(ϕ)=M*[v+r*u-p*w-
Yg*(r**2+p**2)+Zg*(q*r-p)+Xg*(p*q+r)]

Tz-DRz-B*COS(θ)*COS(ϕ)=M*[w+p*v-u*q-
Zg*(p**2+q**2)+Xg*(r*p-q)+Yg*(q*r+p)]

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Mx-DRxx=Ix*p+(Iz-Iy)*q*r+M*[Yg*(w+p*v-u*q)
-Zg*(u+u*r-w*p)]

My-DRyy=Iy*q+(Ix-Iz)*r*p+M*[Zg*(u+q*w-r*v)
-Xg*(w+p*v-u*q)]

Mz-DRzz=Iz*r+(Iy-Ix)*p*q+M*[Xg*(v+r*u-p*w)
-Yg*(u+q*w-r*v)]
```

where

$u\hat{i}+v\hat{j}+w\hat{k}$ = velocity of the vehicle with respect to the attached frame.

$p\hat{i}+q\hat{j}+r\hat{k}$ = angular velocity of the vehicle with respect to the attached frame.

$DRx\hat{i}+DRy\hat{j}+DRz\hat{k}$ = drag force acting on

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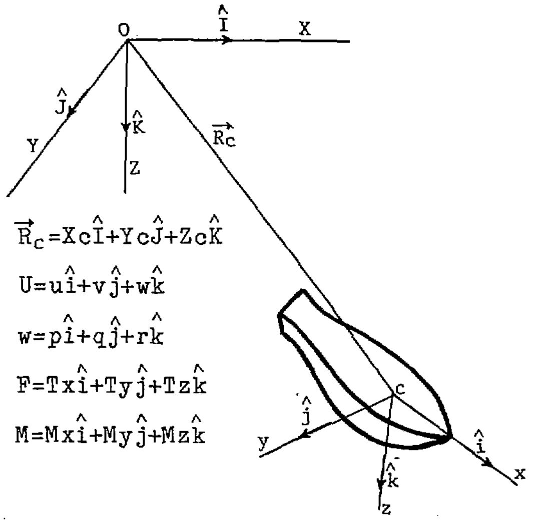

Fig.1 Coordinate systems

the body.
$DRxx\hat{i}+DRyy\hat{j}+DRzz\hat{k}$= drag moment acting around the body.
M,Ix,Iy,Iz = mass and principal moment of inertia around C.
B= bouyancy force.
$Tx\hat{i}+Ty\hat{j}+Tz\hat{k}$= thrust force acting on the body of the vehicle.
$Mx\hat{i}+My\hat{j}+Mz\hat{k}$= thrust moment produced by the thrusters.
$Xg\hat{i}+Yg\hat{j}+Zg\hat{k}$= vector distance of the center of the gravity from c.

The state variables of the model can be calculated with respect to the inertia frame by the matrix transformations:

$$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix}=\begin{bmatrix}1 & \mathrm{SIN}(\phi)*\mathrm{TAN}(\theta) & \mathrm{COS}(\phi)*\mathrm{TAN}(\theta)\\ 0 & \mathrm{COS}(\phi) & -\mathrm{SIN}(\phi)\\ 0 & \mathrm{SIN}(\phi)*\mathrm{SEC}(\theta) & \mathrm{COS}(\phi)*\mathrm{SEC}(\theta)\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix}$$

$$\begin{bmatrix}\dot{X}c\\ \dot{Y}c\\ \dot{Z}c\end{bmatrix}=A\begin{bmatrix}u\\ v\\ w\end{bmatrix}$$

where A is

$$\begin{bmatrix}\mathrm{COS}(\psi)*\mathrm{COS}(\theta) & \mathrm{COS}(\psi)*\mathrm{SIN}(\theta)*\mathrm{SIN}(\phi) & \mathrm{COS}(\psi)*\mathrm{SIN}(\theta)*\mathrm{COS}(\phi)\\ & -\mathrm{SIN}(\psi)*\mathrm{COS}(\phi) & +\mathrm{SIN}(\psi)*\mathrm{SIN}(\phi)\\ \mathrm{SIN}(\psi)*\mathrm{COS}(\theta) & \mathrm{SIN}(\psi)*\mathrm{SIN}(\theta)*\mathrm{SIN}(\phi) & \mathrm{SIN}(\psi)*\mathrm{SIN}(\theta)*\mathrm{COS}(\phi)\\ & +\mathrm{COS}(\psi)*\mathrm{COS}(\phi) & -\mathrm{COS}(\psi)*\mathrm{SIN}(\phi)\\ -\mathrm{SIN}(\theta) & \mathrm{COS}(\theta)*\mathrm{SIN}(\phi) & \mathrm{COS}(\theta)*\mathrm{COS}(\phi)\end{bmatrix}$$

$Xc\hat{I}+Yc\hat{J}+Zc\hat{K}$ = velocity of the vehicle with respect to the inertia frame.

## SERVO CONTROLLERS

We wish to design three basic servo controllers for the vehicle: 1) an orientation controller, 2) a position controller, and 3) a speed controller. With the help of the above controllers the operator can reposition the vehicle to some arbitrary point in 3-dimensional space with any orientation or follow a trajectory.

The functions of the orientation controller are:
1) To overcome the rotational disturbances imposed on the body of the vehicle.
2) To bring the vehicle to the desired orientation as fast as possible. (The power of the thrusters and their time constants pose some limitation on this).

The "Estimator and Control Law" method was used to design the orientation controller. The estimator receives three different angles from three different inclinometers and produces all states of the model such as angular velocities. The estimator is corrected every sampling time by comparing its output with the actual measured angles.

With the help of the "Control law" method, which uses the state variables generated by the estimator, the orientation controller loop can be closed.

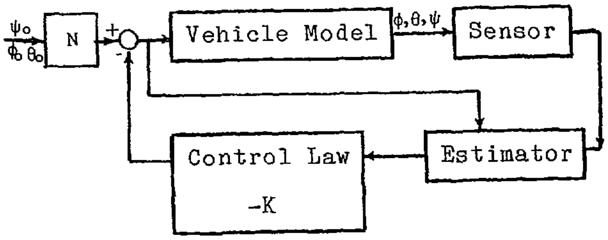

Fig.2 Estimator mechanization

The same idea is used for the velocity controller and the position controller. The velocity estimator receives three different translational velocities, and produces all the variables needed for the feedback loop. The inputs to the position estimator are collected from several sonar systems on board and on the vehicle. The position controller observer also produces all state variables needed for the feedback loop.

## BOTTOM FOLLOWING

Path following is an algorithm that enables the vehicle to follow a path under the water at small and constant distance from the ocean bottom contour. The operator takes the vehicle to a certain depth, then turns the vehicle in the horizontal surface to a desired orientation. (In other words, the operator assigns some yaw angle to the vehicle ). After the operator starts the path following program, the vehicle is able to follow the contour of the bottom at the assigned distance, at the specified yaw angle.

This algorithm enables the vehicle to follow any path without colliding with the ocean floor and maintain constant orientation. The algorithm uses the position controller to keep the distance between the vehicle and the bottom in the assigned distance; it also uses the velocity controller to achieve the desired speed along the path.

The vehicle is equipped with four sonar sensors,A,B,C and D in figure 3.

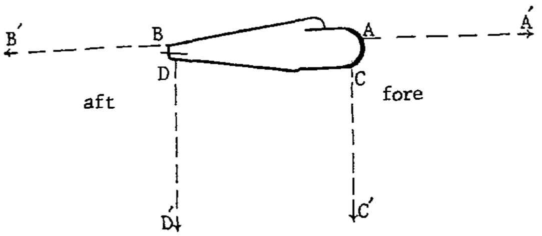

Fig. 3

A and B measure the forward and rearward distances, while C and D measure the distances between the vehicle and the ocean bottom.

The more knowledge about the environment is collected for the algorithm, the better the vehicle can follow the path. To insure that the vehicle recognizes the environment all paths can be divided to three categories:

1) Paths with slopes between $45^\circ$ and $90^\circ$
2) Paths with slopes between $-45^\circ$ and $45^\circ$

3) paths with slopes between $-90^\circ$ and $-45^\circ$

Dividing the bottom contour into three categories is essential for the vehicle to make automatic control decisions. If the measured distance from sonar A is smaller than the other sonars, then the vehicle is in an environment of type 1 and the closest part of the vehicle to its environment is point A.

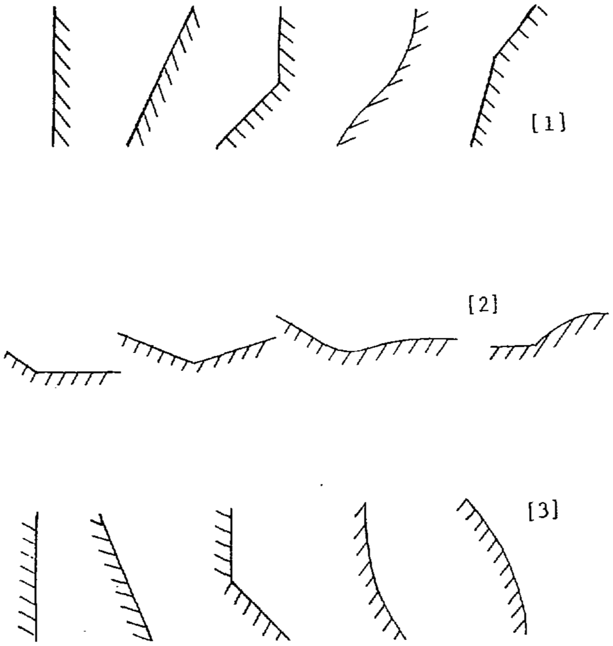

Fig.4 Three categories of environment contours.

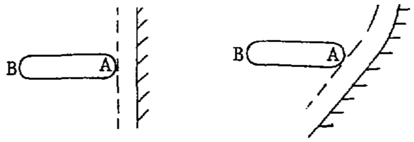

Fig.5 Vehicle moving in environment of type 1 .

In any path of type 1 there is always some danger that the vehicle will collide at its bow. If the measured distance from sonar B is smaller than that of the other sonar sensors, then the vehicle is in an environment of type 3 and point B is the closest part of the vehicle to its environment.

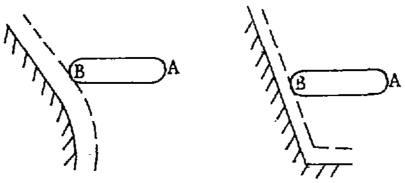

Fig.6 vehicle moving in environment of type 3 .

The following shows the logic to realize the environment.

$$\text{If } \begin{cases} AA' < BB' \\ AA' < CC' \\ AA' < DD' \end{cases} \longrightarrow \text{type 1}$$

$$\text{If } \begin{cases} CC' < AA' \\ CC' < BB' \\ \text{or} \\ CC' < AA' \\ CC' < BB' \end{cases} \longrightarrow \text{type 2}$$

$$\text{If } \begin{cases} BB' < AA' \\ BB' < CC' \\ BB' < DD' \end{cases} \longrightarrow \text{type 3}$$

If the vehicle is in an environment of type 1, the algorithm realizes that the measured distance from sonar A is the smallest measurement. Then the vehicle uses its horizontal thrusters to keep AA' in the assigned distance. The horizontal thrusters are run by the position controller.

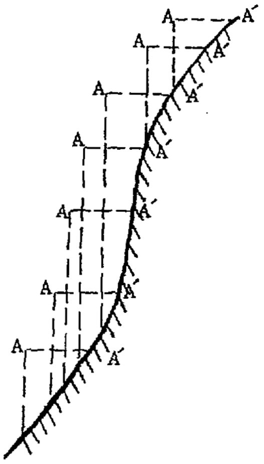

Fig. 7 In path of type 1 , AA' is kept in the assigned distance.

If the vehicle gets closer or farther from the bottom because of any disturbance (for example ocean currents), then the position controller will overcome the disturbance and will bring the vehicle to the desired distance.

One must use the vertical thrusts to vary the speed along a type 1 path such as that shown in figure 7 . The control algorithm uses the speed controller to run the vertical thrusters. Vertical movement of the vehicle by means of the vertical thrusters and speed controller causes the forward distance to change, which in turn can act like a disturbance for the position controller. This disturbance must be overcome by position controller. In other words, there can be some mutual forcing or cross-coupling by the control systems.

If the vehicle is in an environment of type 2 , the vertical thrusters are run by position controllers to keep CC' or DD' in the desired range. The horizontal thrusters are run by speed controller . Any horizontal movement causes some change in the vertical distance CC' or DD' , which can be overcome by the position controller. In an environment of type3 , the algorithm works the same as it does in type 1.

The entire underwater vehicle control system is being modelled in the Man-Machine System Laboratory at MIT on an 11/34 computer. Figure 8 shows this simulation configuration . An electric wheeled vehicle equipped with a camera is able to simulate the motion of the underwater vehicle in the laboratory. Alternatively, a Megatek stroke writing display can be used to show a continuously moving three-dimensional graphical simulation of the underwater vehicle.

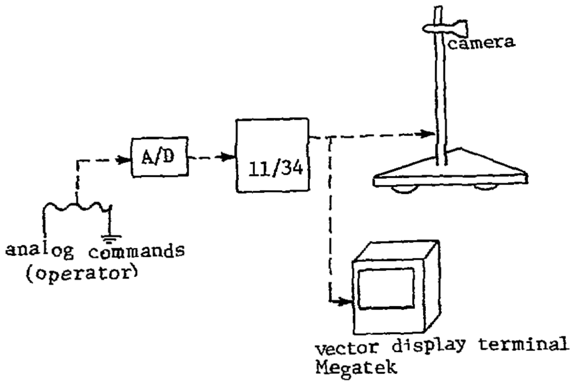

Fig. 8 Underwater simulation in the laboratory.

REFERENCES

R.E.D. Bishop "Mechanics of Marine vehicles" University of London , England, 1975 .

M.A. Abkowitz "Stability and Motion Control of Ocean Vehicles" , MIT Press, 1979 .

J. Welty "Momentum Transfer " John Wiley, 1976 .

G.E. Franklin "Digital Control" Addison-Wesley Publishing Co., 1980 .

R.C. Dorf " Modern Control System " Addison-Wesley Publishing Co. 1980 .