CONTROL OF AUTONOMOUS UNDERWATER VEHICLES

a thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology

in

Electrical Engineering

by

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CERTIFICATE

This is to certify that the thesis entitled, " **Control of Autonomous Underwater Vehicles** " submitted by **Mahendra Pratap Singh** and **Bilas Chowdhury** in partial fulfillment of the requirements for the award of **Bachelor of Technology Degree** in **Electrical Engineering** at the **National Institute of Technology, Rourkela** is an authentic work carried out by them under my supervision.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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ABSTRACT

In this thesis an overview of Autonomous Underwater Vehicles (AUV) is presented which covers the advancements in AUV technology in last two decades, different components of AUV and the applications of AUVs. A glimpse on AUV research in India is presented.

A nonlinear model of AUV is obtained through kinematics and dynamics equation which is linearized about an operating point to get linearized depth plane model. A two loop controller (PI control) is used to control the pitch and in turn the depth of the AUV.

After having developed, simulated and analyzed the pitch and depth controller for a single AUV, we focus our attention towards developing formation control of three AUVs. The formation control for multiple Autonomous Underwater Vehicles (AUVs) is considered in spatial motions. The objective is to drive a leader AUV along a desired trajectory, and make the follower robots keep a desired formation with respect to the leader's configuration in 3-dimensional spaces (leader-follower formation control).

Also, an obstacle avoidance scheme, using pitch and depth control, is used to avoid static obstacles in the path of AUV.

The results of the above three control objectives such as tracking control of AUV, controller for avoiding obstacles and formation control of multiple AUVs are presented and discussed in the thesis.

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Chapter 1

Introduction

History and classification of AUV

About 70% of the Earth's surface is covered with water which is like an empire of natural resources. In order to utilize these resources, mankind depends on developing underwater vehicles and employing them [1]. The idea of submersible vehicles originated a long time back. The first American submarine was titled "Turtle" built in 1975. In 1879 the Reverend George W. Garrett designed the "Resurgam" which is considered to be world's first practical powered submarine. There have been many more submersibles developed and used for different operations in past decade. Torpedoes, which are considered as first autonomous underwater vehicles, also developed along with these submarines.

There are various types of underwater vehicles which can be categorized into two categories namely manned and unmanned systems. In manned system, we have military submarines and non-military submersibles operated for underwater investigations and assessment.

Unmanned submersibles can also be further classified into different categories. The simplest and most easily described are those submersibles that are towed behind a ship. They act as platforms for various sensor suites attached to the vehicle frame. Second type is called Remotely Operated Vehicle (ROV) which is a tethered vehicle. The tether supplies power and communication to the ROV and it is controlled directly by a remote operator. Third type is an Unmanned Untethered Vehicle (UUV). These vehicles have their own onboard power but are controlled by a remote operator through a communication link. An Autonomous Underwater Vehicle (AUV) is an undersea system which has its own power and controlled by an onboard computer while doing a pre-defined task [2] [16].

AUVs are compact, self-contained, low-drag profile crafts powered (in most cases, but not all) by a single underwater DC power thruster. The vehicle uses on-board computers, power packs and vehicle payloads for automatic control, navigation and guidance. They can be equipped with state-of-the-art scientific sensors to measure oceanic properties, or specialized biological and chemical pay-loads to detect marine life when in motion. As is common in most developments today, AUVs have been operated in a semi-autonomous mode under human supervision, which requires them to be tracked, monitored, or even halted during a mission so as to change the mission plan. However, there have been successful attempts at true autonomy [3].

The first AUVs were built in the 1970s, put into commercial use in the 1990s, and today are mostly used for scientific, commercial, and military mapping and survey tasks (Blidberg2001). Developed in cooperation between Kongsberg Maritime and the Norwegian Defense Research Establishment, the HUGIN series represents the most commercially successful AUV series on the world market today (Hagen et al. 2003) [1].

Currently, the challenges for AUV address the navigation, communication, autonomy, and endurance issues. Autonomy is the main aspect of AUVs which deals with the electronics and control design. In this work, the main concentration is on the autonomy. During a mission, an AUV may undergo different maneuvering scenarios such as a complete turn at the end of a survey line, a severe turn during obstacle avoidance or frequent depth changes while following a rugged seabed terrain [4]. Different control schemes are used for different operations. First, a pitch and depth controller is used to maintain the AUV at a particular height above the sea floor. Second, a tracking and formation control is achieved so that a group of AUVs move on pre-defined path while maintaining a desired distance and angular separation between them. Next, an obstacle avoidance scheme, which uses forward look sonar to detect obstacles, is presented to avoid static obstacles in the path. A small paragraph is dedicated to AUVs in India and future of AUVs.

AUV in India

A good research is going on in development of AUV in India.

Some of the Indian students residing worldwide have found the Indian Underwater Robotics Society (IURS). It brought the composite technology of Autonomous Underwater Vehicles to India. BhAUV is the first Indian robot designed by this group. It was competed in the 2005. Now, IURS has designed a completely new low-cost AUV “Jal” that includes a passive sonar system, computer vision, navigational sensors. [19]

Maya, a small autonomous underwater vehicle was developed by the National Institute of Oceanography (NIO), Goa (another CSIR lab) in September 2009 to sense physical, biological, and chemical properties of the ocean and collect relevant scientific data. [22]

Researchers at Central Mechanical Engineering Research Institute (CMERI) - the apex R&D institute for mechanical engineering under the Council of Scientific and Industrial Research (CSIR) – have developed India’s first indigenous autonomous underwater vehicle (AUV). The mega system can fulfill tasks such as seafloor mapping, coastal surveillance, mine countermeasure, and oceanographic measurements during adverse weather conditions. [20]

A technological dream name “VARUN” whose main theme was to meet up the challenge of the modern technology, made by students of Delhi Technological Universities (DTU), won the contest named “Autonomous Underwater Vehicle Competition” held by AUVSI every year. The team secured the 14th position in the International AUVSI competition held at SSC Transdec, San Diego in the year 2009. The fourth generation team is developing a completely new prototype using better technologies and hopes to fare much better this year. [21]

In February 2011, a group of scientists performed sea trials of AUV in south-east India off Chennai coast.

Objectives

i. To get a linearized pitch and depth model of AUV to control the depth inside sea.

ii. Use leader-follower approach to perform formation control of multiple AUVs in spatial motion in both horizontal plane and 3D.

iii. Modeling of forward-look sonar to detect the static obstacles in the path of AUV and use of pitch depth control to avoid these sensed obstacles.

Organization of thesis

This thesis is divided into six chapters.

Second chapter deals with applications of AUVs, AUV technology, its main components, sensor. Also, a glimpse on AUV research in India is presented.

Third chapter deals with the modeling of AUV which includes the kinematics and dynamics equations. These equations are used in further chapters for controlling purpose.

Fourth chapter deals with the depth control of AUV. In this chapter a linearized model of AUV is obtained by making use of kinematics and dynamics described in previous chapter. This linearized model is used to control the depth by PI and P control.

Fifth chapter deals with the formation control of AUVs. Leader-follower approach is used where an AUV of formation is designated as follower which tracks the desired path. The remaining AUVs are designated as followers which follow the leader by maintaining a desired distance and angular orientation.

Sixth chapter deals with the obstacle avoidance. Here, sonar is used to detect the obstacles in the path of AUV by measuring range and height of the obstacle. These data are used by controller to plan a new path and make AUV to follow this by changing depth of AUV.

Chapter 2

Autonomous Underwater Vehicle

As the name suggests, AUV is an autonomous (no external input) robot which travels underwater. It is a part of unmanned underwater vehicles which includes AUV's partner called remotely operated underwater vehicle, ROV. The first AUV was developed at the Applied Physics Laboratory at the University of Washington as early as 1957 by Stan Murphy, Bob Francois and later on, Terry Ewart. The "Special Purpose Underwater Research Vehicle", or SPURV, was used to study diffusion, acoustic transmission, and submarine wakes.

Applications of AUVs

Until relatively recently, AUVs have been used for a limited number of tasks dictated by the technology available. With the development of more advanced processing capabilities and high yield power supplies, AUVs are now being used for more and more tasks with roles and missions constantly evolving.

i. Commercial: The oil and gas industry uses AUVs to make detailed maps of the seafloor before they start building subsea infrastructure; pipelines and subsea completions can be installed in the most cost effective manner with minimum disruption to the environment. The AUV allows survey companies to conduct precise surveys or areas where traditional bathymetric surveys would be less effective or too costly. Also, post-lay pipe surveys are now possible.

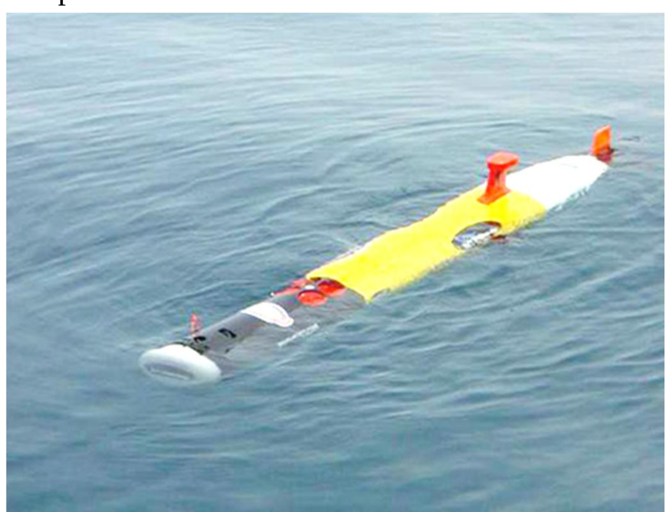

Fig. 2.1: REMUS AUV [image courtesy of AUV fest 2008: Partnership runs deep Navy/NOAA, oceanexplorer.noaa.gov]

ii. Military: A typical military mission for an AUV is to map an area to determine if there are any mines, or to monitor a protected area (such as a harbor) for new unidentified objects. AUVs are also employed in anti-submarine warfare, to aid in the detection of manned submarines.

iii. Research: Scientists use AUVs to study lakes, the ocean, and the ocean floor. A variety of sensors can be affixed to AUVs to measure the concentration of various elements or compounds, the absorption or reflection of light, and the presence of microscopic life. [5]

AUV Technology

The first AUVs were built in the 1970s, put into commercial use in the 1990s, and today are mostly used for scientific, commercial, and military mapping and survey tasks. During this span of time different technologies have introduced and the existing one are modified and advanced which has made AUVs to perform more and specific tasks. The main components in AUV technology comprises of autonomy, energy, navigation, sensors, and communication.

Autonomy: Many of the tasks being assigned to today's AUVs required only a list of preprogrammed instructions to accomplish a task. For this reason, there has not been a significant level of development, recently, that is focused on AUV autonomy. Over the past, issues such as intelligent systems architectures design, mission planning, and perception and situation assessment were investigated and now also research is going on in this field.
Energy: Endurance of AUVs has increased from a few hours to 10s of hours. Some systems now contemplate missions of days and, and a very few of year which is at the expense of sensing capability as well as very limited speeds. In the majority of early AUVs, Lead Acid batteries were used for energy systems. Some uses Silver Zinc batteries but it is very costly. Recent advances in NiMH batteries have provided new opportunities and this technology is being used in many of the current systems. Currently the ALTEX program is underway to utilize

Aluminum/Oxygen “semi-cell” technology to allow an AUV to transit under the Arctic ice. Also the Solar energy is now being used to power AUV.

Navigation: Early AUVs used dead reckoning for their navigation. Acoustic transponder navigation systems provides greater accuracy but at a significant cost. In the past few years, many AUVs have taken advantage of Global Positioning Systems (GPS). It is possible to obtain an accurate position when the vehicle surfaces.

Sensors: An AUV is simply a platform on which to mount sensors to acquire data from the ocean environment. Recently, it has been recognized that we must develop entirely new sensors based on the constraints imposed by AUVs i.e. sensors specifically for AUVs; smarter, lower power, highly reliable, smaller in size, and etc. With the new processors, it has been possible to obtain very high resolution images over longer and longer ranges.

Communication: In the underwater environment, acoustic communications is probably the most viable communication system. Other technologies, such as laser communication at short range and relatively noise free communications over larger ranges using RF current field density are also used. There has been a significant advance in acoustic communications such that relatively low error rate communications is possible over ranges of kms at bit rate of a few kbps. [2][5]

Other aspects like hydrodynamics and control systems, user interface, modeling etc. also constitute a good part in AUV technology.

Main components of AUV

Most of the AUVs are modular in structure consisting of a cylindrical main body blended with a nose cone at its front and a tapered tail section at its rear, giving it a hydrodynamically efficient streamlined shape. [4]

The pressure hull provides the majority of the buoyancy for the vehicle and space for dry components such as batteries and control electronics [4]. The tail cone is like a torpedo tail, and is designed to reduce the drag caused by the pressure drop at the end of the vehicle body. The nose section consists of scientific sensors like forward look sonar which helps in navigation. The main section encompasses of electronic circuitry, batteries, Rate GYRO which is used to measure the

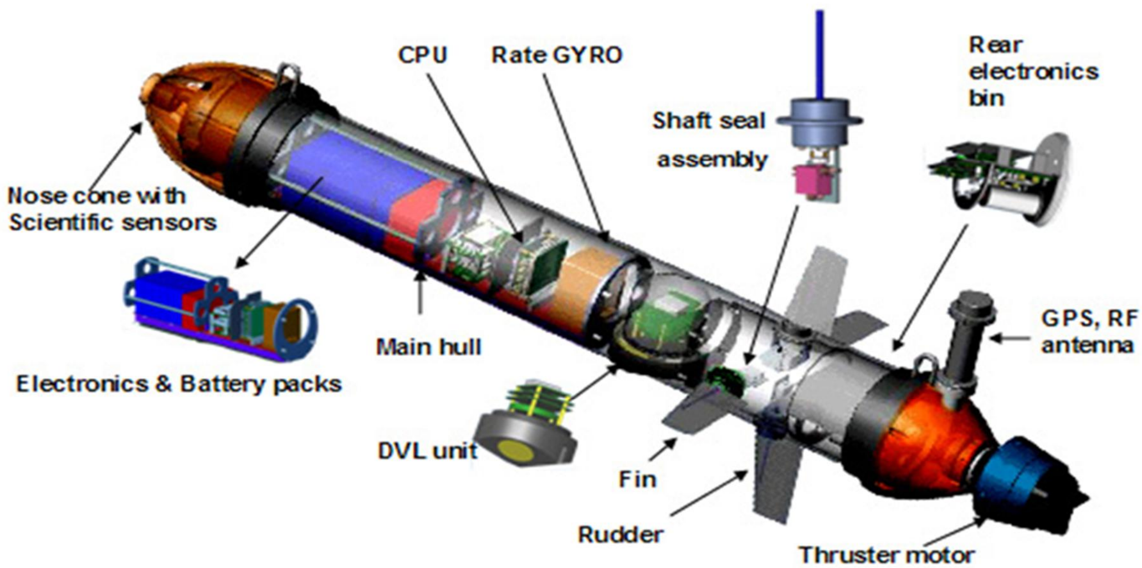

Fig. 2.2: Exploded view of AUV. [22]

yaw of the vehicle, main CPU, and Doppler Velocity Log (DVL) sensor that allows the vehicle to know the approximate distance it travelled in three orthogonal axes. Fins help in swimming. Rudder is the vertical and movable control surface, which is hinged to the fin and primarily controls the yawing movement of the vehicle. At the rear, there are thruster motor which provides the necessary thrust to move in forward direction and GPS antenna used to locate the exact position of AUV.

AUV Sensors

Different types of sensors are used depending upon the application of AUV e.g. whether we want to know the temperature, depth, concentration, or high resolution photos or all.

Temperature Sensors: Generally Platinum Resistance Thermometers (PRTs), which are suitable for use in all anticipated environments, are used. Combinations of PRTs with thermistors are also suitable for use in all anticipated temperature extremes.

Pressure Transducers: Most strain gauge type pressure sensors are temperature sensitive and hence the data quality is affected by all temperature changes, not just the extremes. This problem can be overcome by the inclusion of a temperature sensor diffused into the silicon of the strain sensing element [18]. The completed sensor is then thermally characterized, which allows a performance of better than 10mBar accuracy (for a 60 Bar transducer) over the full working range of temperatures. [5]

Conductivity Sensors: Standard designs use an epoxy molded body bonded to a stainless steel base.

Optical Sensors: Sensors such as transmissometers and fluorimeters operate by emitting a light beam (pulsed for the fluorimeters) through optical filters and into the sea water via a window set in the face of the sensor housing which has to be relatively thick to withstand high pressures. [6] [18]

Multibeam sonar: This allows the sounder to provide continuous swath bathymetry. Deep-water, high altitude systems utilize low acoustic frequencies (~12 kHz) and have large, heavy transducer arrays to achieve the necessary range. The Multibeam sonar is comprised of a wet end and a dry end. The wet end consists of the transmit and receive transducer arrays together with any closely associated electronics. It is mounted within the flooded section of the AUV. The dry end, which is mounted inside the pressure hull, consists of the sonar processing electronics and any additional equipment required for sonar control and data logging.

Side scan sonar: It transmits beams of acoustic energy from the side of the tow fish and across the seabed. For these reasons, it is normally towed from ships. Unlike a ship, the AUV can operate close to the seabed, and consequently, the sonar transducers are mounted on the hull rather than towed. [7][10]

The sonar transmits one pulse at a time and waits for the sound to be reflected back. The imaging range is determined by how long the sonar waits before transmitting the next acoustic pulse. The image is thus built up one line of data at a time. Operation of the sonar is controlled via an interface (such as RS232) to the AUV computer. Sonar data will available to the AUV computer over an Ethernet connection.

Limitations on the different sensors limit the operation of AUV e.g. if depth, temperature, etc. change then the existing sensors may not work.

Chapter 3

Modeling

To get a mathematical model of the vehicle, we divide modeling task into two categories; Kinematics which relates only geometrical aspects of motion and Dynamics which is the analysis of forces causing the motion.

Since six independent co-ordinates are necessary to determine the position and orientation of a rigid body, AUV has six degree of freedom, (6 DOF).

Notation used:

DOF	Motion	Forces	Linear and angular velocity	Position
1	Motion in x-direction(surge)	X	*u*	*x*
2	Motion in y-direction(sway)	Y	*v*	*y*
3	Motion in z-direction(heave)	Z	*w*	*z*
4	Rotation about x- axis(roll)	K	*p*	ϕ
5	Rotation about y-axis(pitch)	M	*q*	θ
6	Rotation about z-axis(yaw)	N	*r*	Ψ

Table 3.1: Notation used for AUV modeling. [8]

The first three coordinates and their time derivatives are used to represent the position and translation motion along x, y, and z axes, while the last three coordinates and their time derivatives are used to describe the orientation and rotational motion.

Kinematics

For analyzing the motion of the vehicle in 6DOF, we choose two co-ordinate frames. The moving reference frame is fixed to the vehicle called as body-fixed reference frame. Motion of the body-fixed frame is described relative to an inertial frame. For marine vehicles, it is usually assumed that the acceleration of a point on the surface of Earth can be neglected. Thus, an Earth fixed frame can be considered to be an inertial frame. This suggests that the linear and angular velocities of the vehicle should be expressed in body-fixed frame while position and orientation should be described with respect to inertial frame. [8]. In a very general form, the motion of vehicle in 6DOF can be described by the following vectors:

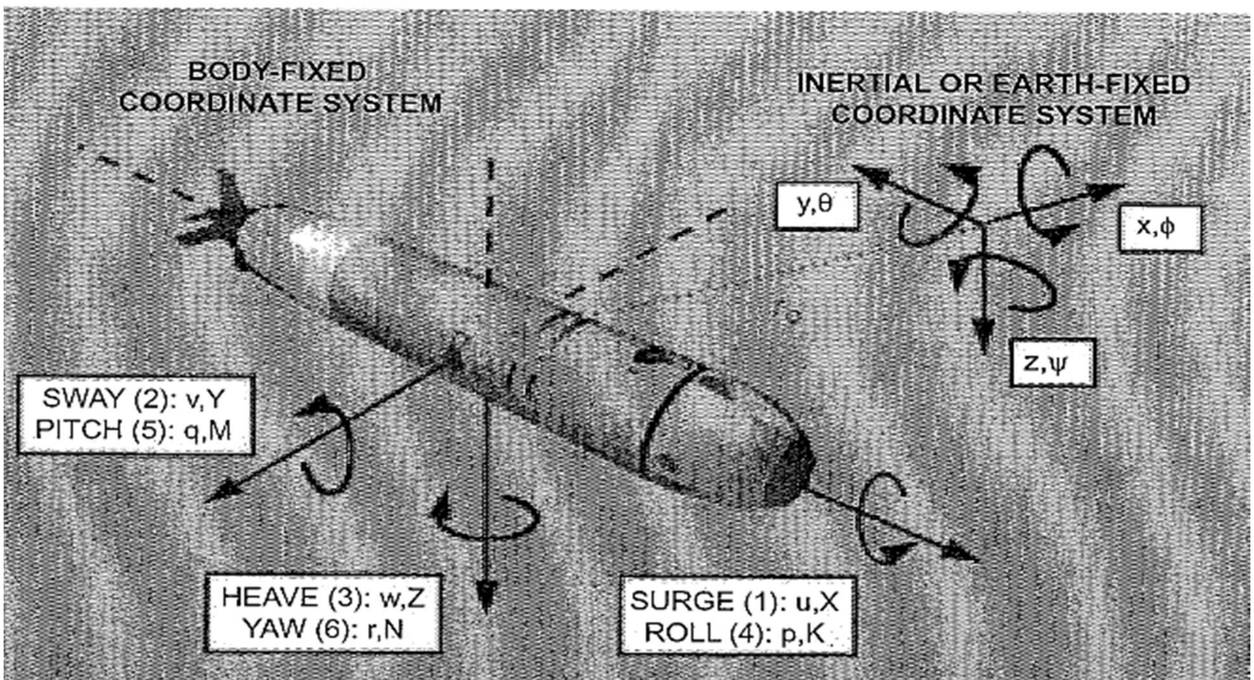

Fig. 3.1: Body-fixed and inertial reference frames. [9]

$\eta = [\ \eta_1^T\ \ \eta_2^T]^T$ $\qquad \eta_1 = [x\ \ y\ \ z]^T$ $\qquad \eta_2 = [\phi\ \ \theta\ \ \Psi]^T$

$v = [\ v_1^T\ \ v_2^T]^T$ $\qquad v_1 = [u\ \ v\ \ w]^T$ $\qquad v_2 = [p\ \ q\ \ r]^T$

$\tau = [\ \tau_1^T\ \ \tau_2^T]^T$ $\qquad \tau_1 = [X\ \ Y\ \ Z]^T$ $\qquad \tau_2 = [K\ \ M\ \ N]^T$ [8]

Where η describes the position and orientation of the vehicle with respect to the earth-fixed reference frame, ν the translational and rotational velocities with respect to the body-fixed reference frame, and τ the total forces and moments acting on the vehicle with respect to the body-fixed reference frame. [8]

Vehicle's path relative to the earth-fixed coordinate system is given

$$\dot{\eta}_1 = J_1(\eta_2)\, \nu_1 \qquad [8] \quad (3.1)$$

where $J_1(\eta_2)$ is the transformation matrix as follows:

$$J_1(\eta_2) = \begin{bmatrix} c\Psi c\theta & -s\Psi c\phi + c\Psi s\theta s\phi & s\Psi s\phi + c\Psi c\phi s\theta \\ s\Psi c\theta & c\Psi c\phi + s\phi s\theta s\Psi & -c\Psi s\phi + s\theta s\Psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \qquad [8]$$

here, $c\bullet$ means cosine($\bullet$) and $s\bullet$ means sine($\bullet$).

The body-fixed angular vector ν_2 and the Euler rate vector $\dot{\eta}_2$ are related through transformation matrix $J_2(\eta_2)$ by the relation

$$\dot{\eta}_2 = J_2(\eta_2)\, \nu_2 \qquad [8]\ (3.2)$$

and

$$J_2(\eta_2) = \begin{bmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi / c\theta & c\phi / c\theta \end{bmatrix} \qquad [8]$$

here, too , $c\bullet$ means cosine($\bullet$), $s\bullet$ means sine($\bullet$), and $t\bullet$ means tangent($\bullet$).

Dynamics

Dynamics is further divided into translational motion and rotational motion of the vehicle. The translational equation of motion is given as below:

$$m(\dot{v}_0 + \omega * v_0 + \dot{\omega} * r_g + \omega * (\omega * r_g)) = f_0$$

and the rotational equation of motion is as follows:

$$I_0 \dot{\omega} + \omega * (I_0 \omega) + m r_g * (\dot{v}_0 + \omega * v_0) = m_0 \; [8]$$

where m is the mass of the body (vehicle) and I_0 is the moment of inertia.

The above two equations are generally written in component form according to the SNAME (1950) notation, that is:

$f_0 = \tau_1 = [X \; Y \; Z]^T$ external forces

$m_0 = \tau_2 = [K \; M \; N]^T$ moment of external forces

$v_0 = v_1 = [u \; v \; w]^T$ linear velocity

$\omega = v_2 = [p \; q \; r]^T$ angular velocity

$r_g = [x_g \; y_g \; z_g]^T$ center of gravity

Applying this notation to the above equations, we have:

$$m\,(\dot{u} - vr + wq - x_g\,(q^2 + r^2) + y_g\,(pq - \dot{r}) + z_g\,(pr + \dot{q})) = X$$

$$m\,(\dot{v} - wp + ur - y_g\,(r^2 + p^2) + z_g\,(qr - \dot{p}) + x_g\,(qp + \dot{r})) = Y$$

$$m\,(\dot{w} - uq + vp - z_g\,(p^2 + q^2) + x_g\,(rp - \dot{q}) + y_g\,(rq + \dot{p})) = Z$$

$$I_x \dot{p} + (I_z - I_y)\,qr - (\dot{r} + pq)\,I_{xz} + (r^2 - q^2)\,I_{yz} + (pr - \dot{q})\,I_{xy} + m[y_g\,(\dot{w} - uq + vq) - z_g\,(\dot{v} - wp + ur)] = K$$

$$I_y\dot{q} + (I_x - I_z)\,rp - (\dot{p} + qr)\,I_{xy} + (p^2 - r^2)\,I_{xz} + (qp - \dot{r})\,I_{yz} + \mathrm{m}[z_g\,(\dot{u} - vr + wq) - x_g\,(\dot{w} - uq + vp)] = \mathrm{M}$$

$$I_z\dot{r} + (I_y - I_x)\,pq - (\dot{q} + rp)\,I_{yz} + (q^2 - p^2)\,I_{xy} + (rq - \dot{p})\,I_{xz} + \mathrm{m}[x_g\,(\dot{v} - wp + ur) - y_g\,(\dot{u} - vr + wq)] = \mathrm{N}$$

The first three equations represent translational motions and the last three rotational motions. [8]

The center of buoyancy is taken to be same as the center of body-fixed frame so that I_0 has only diagonal elements i.e. I_0 = [I_x 0 0; 0 I_y 0; 0 0 I_z]. The off diagonal elements are neglected so that the above equations can be further simplified by drooping off diagonal elements of inertia tensor

Unless the vehicle is specially ballasted y_g is in fact negligible and the equations can further be reduced by drooping out y_g term.

External forces and moments are given by

$$\sum F_{ext} = F_{hydrostatic} + F_{lift} + F_{drag} + F_{control}$$

which can be found out in terms of vehicle parameters. [9]

Chapter 4

Pitch and Depth Control

The objective is to maintain the AUV at a particular height above the seafloor. This is achieved by changing the pitch of the vehicle. A two loop controller is used for this purpose. The inner loop controller, PD controller controls the pitch and the outer loop controller, P controller controls the depth of the vehicle.

Linearized kinematics and dynamics

First, the kinematics and dynamics equations are simplified by drooping out the terms other than body relative surge velocity u, heave velocity w, pitch rate q, and the earth relative forward position x, depth z, and pitch angle θ. Next, this simplified model is linearized about an operating point [9]. The final model is simulated in Simulink and vehicle's behavior is observed. Using equations (3.1) and (3.2) and drooping out the undesired terms, we get the kinematics of the AUV for pitch and depth control as follows:

$$\dot{x} = \cos(\theta u) + \sin(\theta w)$$

$$\dot{z} = -\sin(\theta u) + \sin(\theta w)$$

$$\dot{\theta} = q \quad [9]$$

We linearizes these equations by assuming that there are small perturbation around a steady point. Let u_1 be the steady state forward velocity around which u is linearized. Heave and pitch rate are linearized about zero. Using Maclaurin expansion of the trigonometric terms and neglecting higher order terms, the linearized kinematic equations are

$$\dot{x} = u + \theta w$$

$$\dot{z} = -u_1\theta + w$$

$$\dot{\theta} = q \quad [9]$$

Similarly for dynamics equations, all the unrelated terms are set to zero and out of plane vehicle motion equations are neglected. The dynamics equations are:

$$m(\dot{u} + wq - x_g q^2 + z_g \dot{q}) = \mathrm{X}$$

$$m(\dot{w} - uq - z_g q^2 - x_g \dot{q}) = \mathrm{Z}$$

$$I_y \dot{q} + m[z_g(\dot{u} + wq) - x_g(\dot{w} - uq)] = \mathrm{M}$$

Now, using the linearization, the above equations are reduced to

$$m(\dot{u} + z_g \dot{q}) = \mathrm{X}$$

$$m(\dot{w} - x_g \dot{q} - u_1 q) = \mathrm{Z}$$

$$I_y \dot{q} + m[z_g \dot{u} - x_g(\dot{w} - u_1 q)] = \mathrm{M} \quad [9]$$

X, Z, and M values are found in terms of vehicle parameters e.g. added mass due to fin lift, body lift, moment, drag, etc. so that the above equations transform to the following equations

$$(m - Z_{\dot{w}})\,\dot{w} - (mx_g + Z_{\dot{q}})\,\dot{q} - Z_w w - (mu_1 + Z_q)q = Z_{f_s} f_s$$

$$-(mx_g + M_{\dot{w}})\,\dot{w} + (I_y - M_{\dot{q}})\,\dot{q} - M_w w + (mx_g u_1 - M_q)q - M_\theta \theta = M_{f_s} f_s \,[9]$$

where, $M_{\dot{w}}$, $M_{\dot{q}}$, $Z_{\dot{w}}$, $Z_{\dot{q}}$, are the added mass, Z_{f_s} is the fin lift, f_s is stern plane angle.

If heave velocity is less, we can neglect it with respect to other terms so that the kinematics and dynamics equations can be written into following matrix form:

$$\begin{bmatrix} I_y - M_{\dot{q}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} -M_q & 0 & M_\theta \theta \\ 0 & 0 & u_1 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} M_{f_s} \\ 0 \\ 0 \end{bmatrix}$$

Transfer functions

From the above matrix representation, the transfer function for the inner pitch loop is found as

$$G_\theta(s) = \frac{\theta(s)}{f_s(s)} = \frac{\frac{M_{fs}}{Iy - M_{\dot{q}}}}{s^2 - \frac{M_q}{\mathrm{Iy} - M_{\dot{q}}}s - \frac{M_\theta}{\mathrm{Iy} - M_{\dot{q}}}}$$

Pitch control is done by PD controller with general transfer function given by

$$\frac{f_s(s)}{e_\theta(s)} = -K_p(T_d s + 1)$$

where, e_θ(error in pitch) = θ_{des}(desired pitch) – θ(actual pitch). K_p is the proportional gain, T_d is the derivative time constant. Here '-' sign is due to the difference in sign convention between stern plane angle and vehicle pitch angle.

Outer depth loop transfer function relates the θ_{des} to z. As inner pitch loop is very fast compared to outer depth loop, we can assume that θ_{des} is nearly equal to θ so that the transfer function becomes

$$G_z(s) = \frac{z(s)}{\theta(s)} = \frac{-u_1}{s}$$

For depth control, a proportional controller (P control) is used whose gain, $\Delta = \frac{\theta(s)}{e_z(s)}$; where e_z is the error in depth of the vehicle.

Substituting the data given for REMUS AUV as given in [9], we get

$$G_\theta(s) = \frac{-3.18}{s^2 + 1.09s + 0.52}$$

Open loop poles are -0.55 ± j0.47. Choosing 5% overshoot or damping ratio, $\xi = 0.69$ and T_d = 0.210, we got from the root locus plot the value of natural frequency, ω_n = 5.77 rad/sec and gain K_p = 10.3 and Δ = - 0.772.

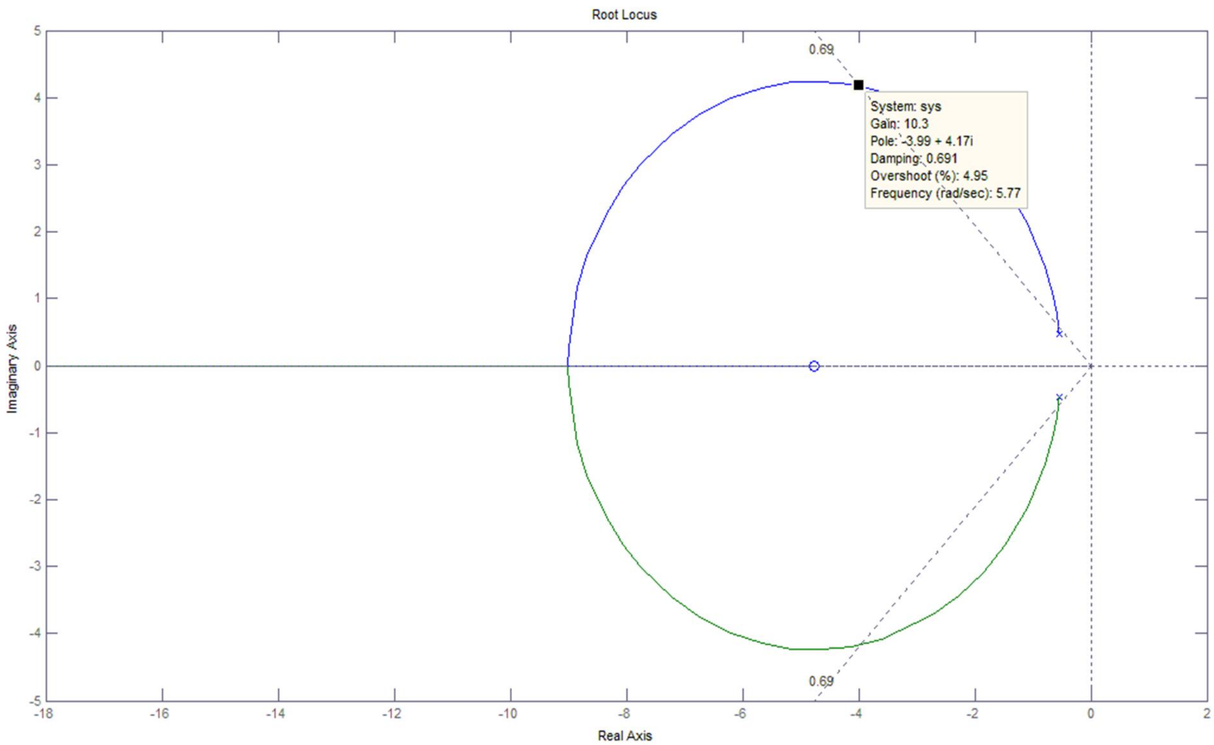

Fig. 4.1: Root locus plot

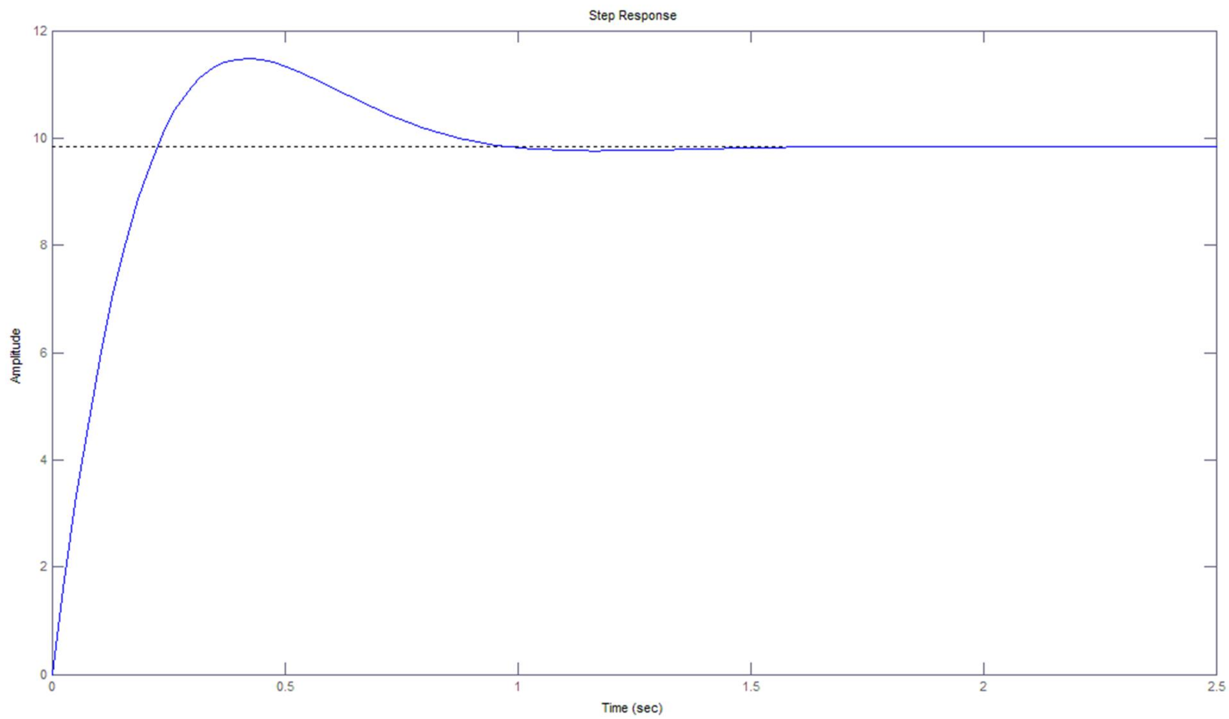

Fig. 4.2: Closed loop step response

Simulation results

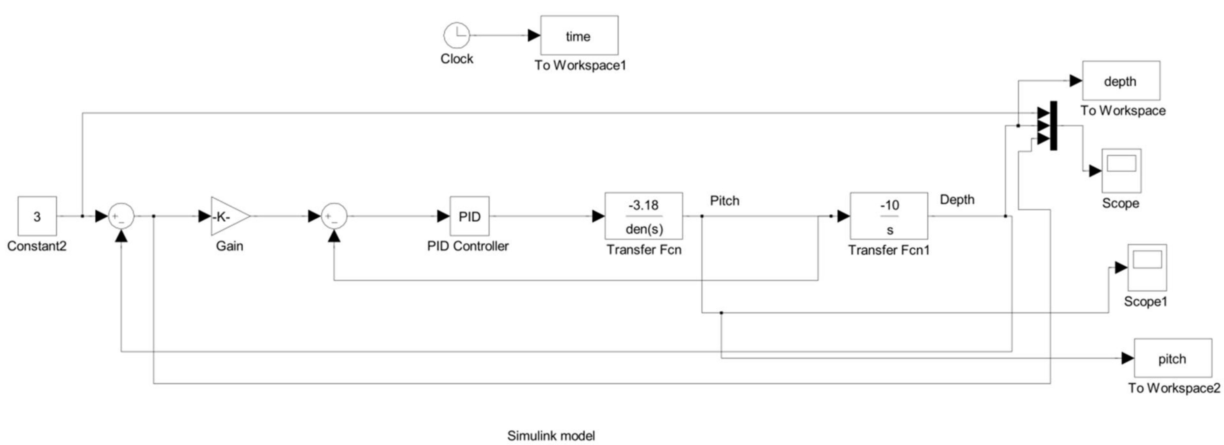

Fig. 4.3: Simulink model for pitch and depth control

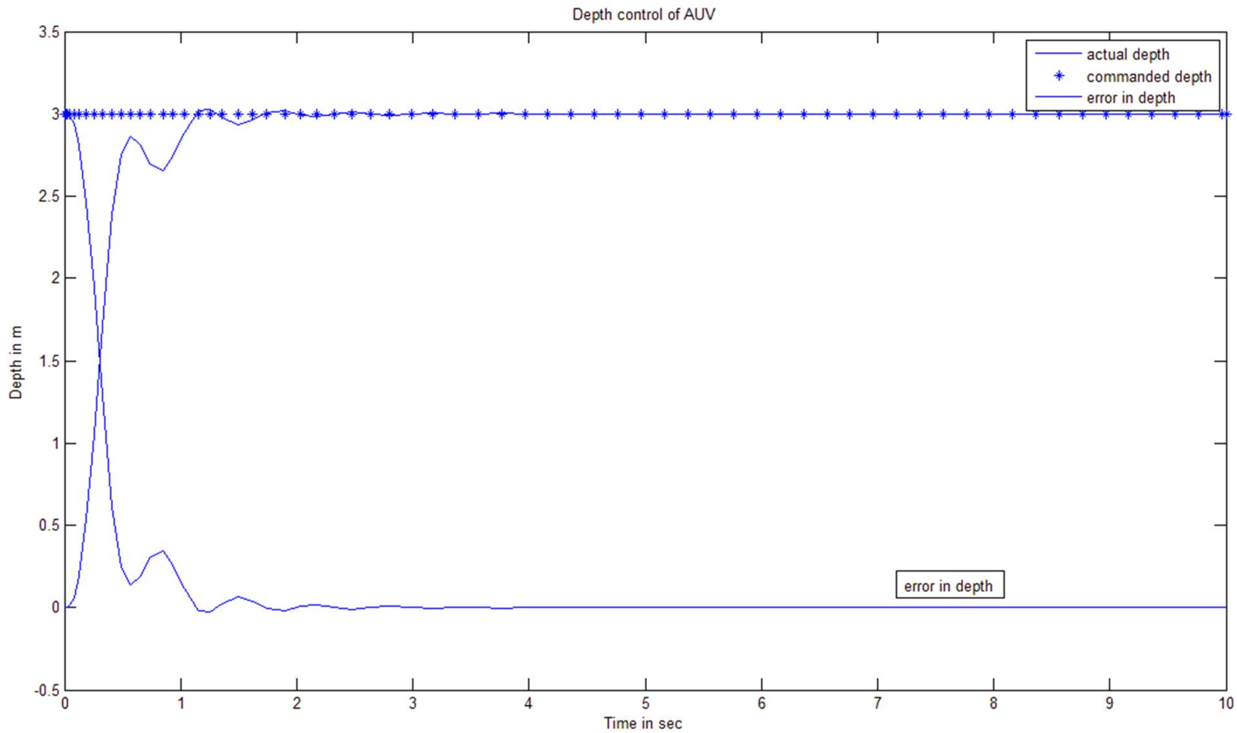

Fig. 4.4: Depth control of AUV

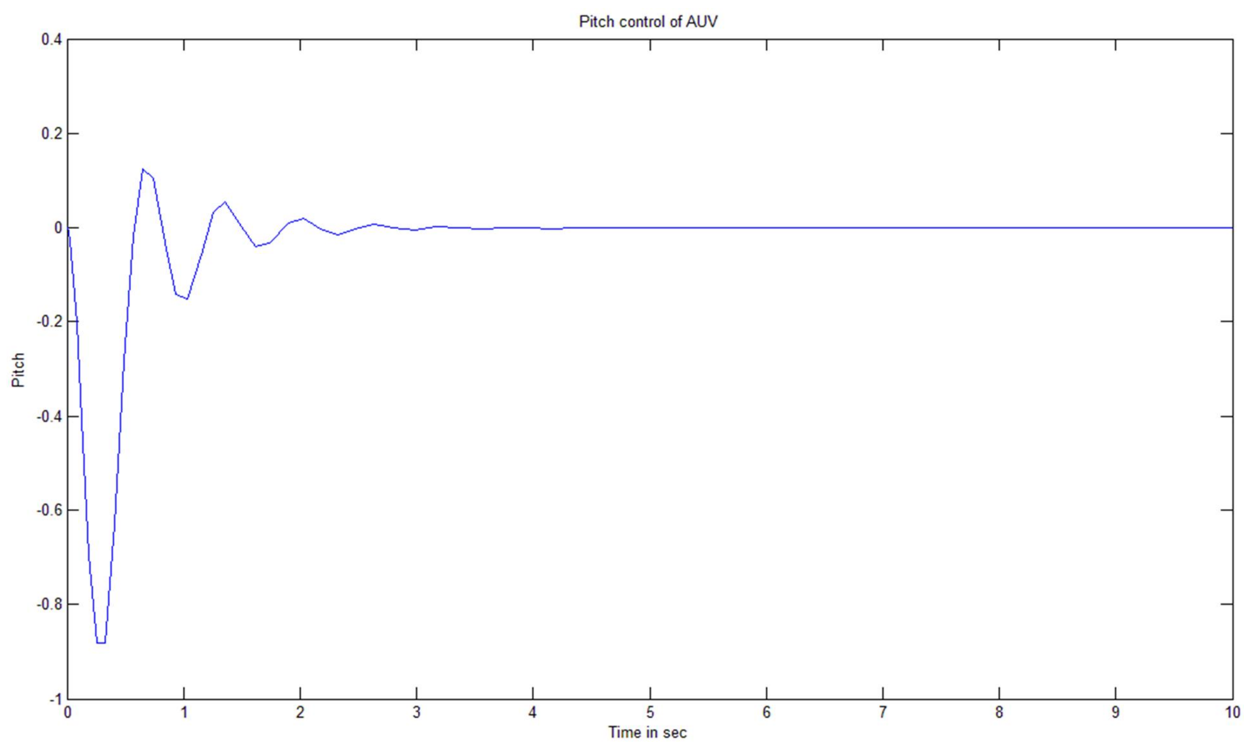

Fig. 4.5: Pitch control of AUV

From the waveforms it is clear that that the linearized pitch depth model of AUV gives satisfactory results as the actual depth is settling to commanded depth and also the pitch of the vehicle is settling to zero value as required.

State Feedback control

Here, we employed a state feedback controller with actuating signal, u = - Kx . where K is the gain matrix and x is the state matrix.

we have,

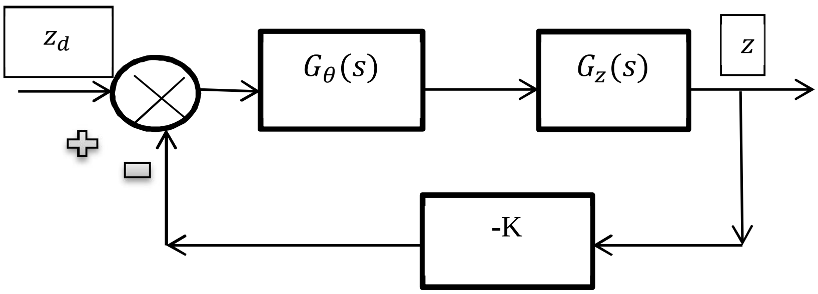

Fig. 4.6: State feedback control model

$G_\theta(s) = \frac{-3.18}{s^2 + 1.09s + 0.52}$

$G_z(s)$ = -10/s

which gives $G_\theta(s)*G_z(s) = \frac{31.8}{s^3 + 1.09s^2 + 0.52s}$

>>[A, B, C, D] = tf2ss([31.8],[1 1.09 .52 0]) gives

$$A = \begin{bmatrix} -1.09 & -.52 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad C = [0 \quad 0 \quad 31.8] \quad D = 0$$

Controllability matrix, $P_c = [B \ AB \ A^2B]$ is calculated and found out that it is non-zero signifying that the system is state controllable.

For damping ratio, ξ = 0.69 desired poles are -0.338±j 0.355, -10 (from root locus plot) which give desired characteristic equation: $s^3+10.676s^2+7s+2.4=0$

Since A matrix is not in CCF, we use a transformation $\bar{x}$ =Px which transform the system in CCF form so that P matrix is [0, 0, 1; 0, 1, 0; 1, 0, 0] and system co-efficient are (-1.09, -0.52, 0) which give the gain matrix K = [2.4-0, 7+0.52, 10.676+1.09]P or [11.766, 7.52, 2.4].

Chapter 5

Tracking and Formation Control

In this chapter the problem of leader-follower formation control for multiple Autonomous Underwater Vehicles (AUVs) in spatial motions is considered. The objective is to drive a leader robot along a desired trajectory, and make the follower robots keep a desired formation with respect to the leader's configuration in 3-dimensional spaces. [11]

Advantages of formation control

In many applications, a given task is too complex to be accomplished by a single robot; thus a multi-robot system working cooperatively is required to complete the job. Multi-robot systems are more robust as compared to the single-robot systems because a team of robots provides certain amount of redundancy, which is useful when some of the robots malfunction also less time is needed to complete the job e.g. the use of AUVs for offshore operations includes ocean sampling, mapping, minesweeping, ocean floor survey, and oceanographic data collection. Instead of a single specialized expensive AUV, it is beneficial to use comparatively simple and inexpensive AUVs to cooperatively increase the service area. One fundamental problem in multi-AUVs cooperation is formation control in an effort to design a structure for AUVs to keep a desired formation configuration while completing the assigned tasks. Some examples of formation in animals include bird flocking, fish schooling, and animal herding. [11] [12]

Approach

There are mainly three approaches toward formation control of autonomous vehicles, namely behavioral, virtual structure, and leader-follower.

In the behavioral approach, a weighted average of desired behavior (e.g. collision avoidance, formation keeping, target seeking) of each vehicle is used to obtain the control input for that one;

therefore, this approach allows decentralized implementation. The theoretical formalization and mathematical analysis of this approach is difficult and consequently it is not easy to guarantee the convergence of the formation to a desired configuration. [11] [13] [14]

The virtual structure approach considers the robot formation as a single virtual rigid structure so that the behavior of the robotic system is assimilable to that of a physical object. Desired trajectories are to the entire formation as a whole and not assigned to each single robot. In this case the behavior of the robot formation is predictable and consequently the control of the robot formation is straightforward. Nevertheless a large inter-robot communication bandwidth is required. [14]

In the leader-follower approach, a robot of the formation, designated as the leader, moves along a predefined trajectory while the other robots, the followers, are to maintain a desired distance and orientation with respect to the leader. In this case, a global leader can be designated and the group behavior can be assigned based on the global leader's reference trajectory. [11]

As the bandwidth of underwater acoustic communication is severely constrained, which inhibits a large number of data exchange among the vehicles, leader-follower scheme is useful because only communication event required is to broadcast the necessary information of the leader to the follower.

In this chapter formation control is achieved using leader-follower approach and PD control.

Leader-follower formation control of AUVs in 2D (horizontal plane)

In leader-follower formation control, the leader AUV has to track the desired trajectory and the follower AUV tries to maintain a desired distance and angle relative to the leader. When all vehicles are in expected positions, the desired formation is established.

The leader-follower formation problem in horizontal plane can be given as follows: Given the position of the leader vehicle, the reference trajectory for the follower is set in such a way that its position is shifted by a distance d and an angle θ relative to the leader. Hence, the reference trajectory of the follower is generated as the leader cruises. [11]

AUV kinematics and dynamics: To study the planar motion, we define an inertial frame {I} and a body fixed frame {B}. The origin of {B} frame coincides with the AUV center of mass

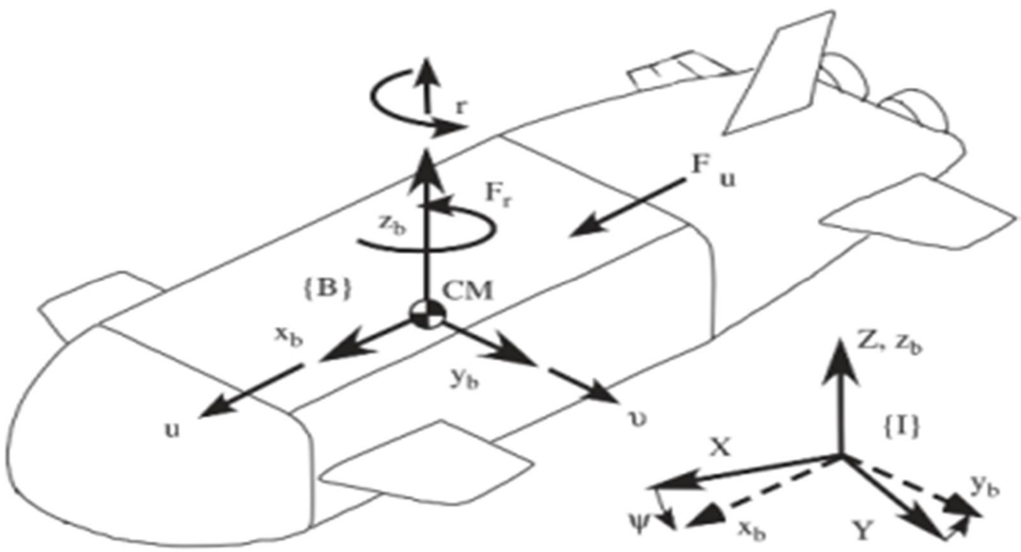

Fig. 5.1: AUV diagram showing inertial and body fixed frames. [15]

(CM) while its axes are along the principal axes of inertia of the vehicle. x_b is the longitudinal axis, y_b is the transverse axis, and z_b is the normal axis [15]. The kinematic equations of motion for an AUV on the horizontal X-Y plane can be written as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\Psi} \end{bmatrix} = \begin{bmatrix} \cos(\Psi) & -\sin(\Psi) & 0 \\ \sin(\Psi) & \cos(\Psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix}$$

where x and y represent the inertial coordinates of the CM of the vehicle and u and v are the (linear) surge (forward) and sway (side) velocities, respectively, defined in the body fixed frame. The orientation of the vehicle is described by angle Ψ measured from the inertial X-axis and r is the yaw (angular) velocity. Assuming that (i) the CM coincides with the center of buoyancy (CB) (ii) the mass distribution is homogeneous, (iii) the hydrodynamic drag terms of order higher than two are negligible, and (iv) heave, pitch and roll motions can be neglected, the dynamics is expressed by the following differential equations:

$$\dot{u} = \frac{m_{22}}{m_{11}} vr - \frac{X_u}{m_{11}} u - \frac{X_{u|u|}}{m_{11}} u|u| + \frac{1}{m_{11}} F_u$$

$$\dot{v} = -\frac{m_{11}}{m_{22}} ur - \frac{Y_v}{m_{22}} v - \frac{Y_{v|v|}}{m_{22}} v|v| + \frac{1}{m_{22}} F_v$$

$$\dot{r} = \frac{m_{11} - m_{22}}{m_{33}} uv - \frac{N_r}{m_{33}} r - \frac{N_{r|r|}}{m_{33}} r|r| \quad [15]$$

The variable F_u denotes the control force along the surge motion of the vehicle and variable F_v denotes the control force along the sway motion of the vehicle. Third equation is uncontrolled and the AUV is an underactuated dynamic system. The constants m_{11} and m_{22} are the combined rigid body and the added mass terms, and m_{33} is the combined rigid body and added moment of inertia about z_b axis. X_u, $X_{u|u|}$, Y_v, $Y_{v|v|}$, N_r, and $N_{r|r|}$ are the linear and quadratic drag terms coefficients. [15]

Reference path and controller design: we choose a reference circular inertial planar trajectory given as follows $x_R(t) = 8\sin(0.01t)$ m,

$y_R(t) = 8\cos(0.01t)$ m.

From this reference path, we find the error in position (= actual position – reference position). This error is then given to proportional derivative controller (PD controller) which generates necessary controlling signals. The output from controller is then feed to system (AUV) which reduces the error in position and thus, AUV tracks the desired trajectory. The reference path for follower AUV is the circle with same frequency but with different radius.

Simulation: Numerical data used in simulation:

Parameter	Symbol	Value	Unit
Mass	M	185	Kg
Rotational mass	I_Z	50	kgm^2
Added mass	$X_{\dot{u}}$	-30	Kg
Added mass	$Y_{\dot{v}}$	-80	Kg
Added mass	$N_{\dot{r}}$	-30	kgm^2
Surge linear drag	X_u	70	kg/s
Surge quadratic drag	$X_{u\|u\|}$	100	kg/m
Sway linear drag	Y_v	100	kg/s
Sway quadratic drag	$Y_{v\|v\|}$	200	kg/m
Yaw linear drag	N_r	50	kgm^2/s
Yaw quadratic drag	$N_{r\|r\|}$	100	kgm^2

Table 5.1: Rigid body and hydrodynamic parameters of the AUV studied by Pettersen and Egeland (1999). [15]

Also, m_{11} = m- $X_{\dot{u}}$ = 215 kg, m_{22} = m- $Y_{\dot{v}}$ = 265 kg, m_{33} = m- $N_{\dot{r}}$ = 80 kgm^2 [15]

Simulation result:

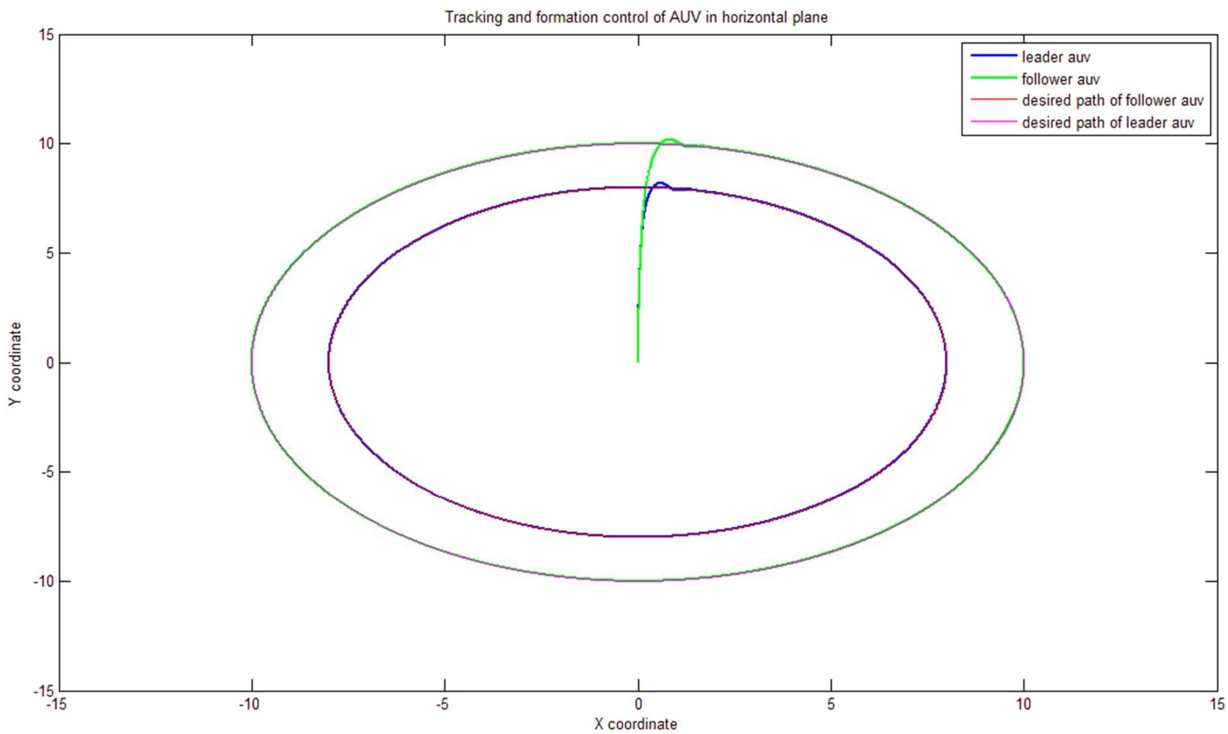

Fig. 5.2: Tracking and formation control of AUVs in horizontal plane

The leader AUV is tracking its desired path which is a circle of radius 8m and also the follower AUV is maintaining a constant distance of 2m from the leader AUV. Thus, the PD controller used is working satisfactorily.

Leader follower formation control of AUVs in 3D

Here we have considered motion in Z axis direction also i.e. AUVs are at different heights with respect to each other. Therefore, in kinematics model one more state z in incorporated and also in dynamics model a controlling force for z motion is added in simulation.

The equations of motion of an underwater vehicle in six degrees of freedom (6 DOF) with respect to body fixed frame can be written as:

$$M(\eta)\,\ddot{\eta} + C(\eta)\dot{\eta} + D(\eta)\eta + g = \tau$$

where, $\eta = [\,x\ y\ z\ \phi\ \Theta\ \Psi\,]^T$ is position and orientation in {I} and $\dot{\eta} = [u\ v\ w\ p\ q\ r]^T$ is linear and angular velocity in {B}. M = diag{ m_{11}, $m_{22,\ldots\ldots}$, m_{66} } and C are the rigid body mass matrix and the coriolis and centripetal matrix, which includes the added mass matrix and the added coriolis and centripetal matrix, respectively. D = diag{d_{11}, d_{22},….,d_{66} } is the resultant matrix of linear and quadratic drag (damping matrix) and g is the resultant vector of gravity and buoyancy. τ is the vector of forces and moments acting on the robot in the body-fixed frame.

Here we are considering 4DOF i.e. control in x, y, z, and Ψ direction.

The mass matrix in this case is changed to the matrix given below

$$m = [m_{11}\ 0\ 0\ 0;\ 0\ m_{22}\ 0\ 0;\ 0\ 0\ m_{33}\ 0;\ 0\ 0\ 0\ m_{44}]$$

where, m_{11} = 99 kg, m_{22} = 108.5 kg, m_{33} = 126.5 kg, m_{44} = 29.1 kg

and damping matrix is given by

$$D = [\ d_{11}\ 0\ 0\ 0;\ 0\ d_{22}\ 0\ 0;\ 0\ 0\ d_{33}\ 0;\ 0\ 0\ 0\ d_{44}\ ]$$

where, d_{11} = 10+227.18$|u|$ kg/s, d_{22} = 405.41$|v|$ kg/s, d_{33} = 10+227.18$|w|$ kg/s, d_{44} = 1.603+12.937$|r|$ kg/s. [11]

The effects of coriolis force matrix C(η) and gravitation matrix g are neglected for simplicity.

Reference trajectory for leader is a straight line given as

$$x_R(t) = 40t + 10$$

$$y_R(t) = 30t - 5 \quad \text{in } z = 10 \text{ plane.}$$

Trajectories for followers are also straight lines but in different planes i.e. AUVs are at different heights (in z = 20 and z = 30 planes). Again PD controller is used to control the paths of AUVs.

Simulation results:

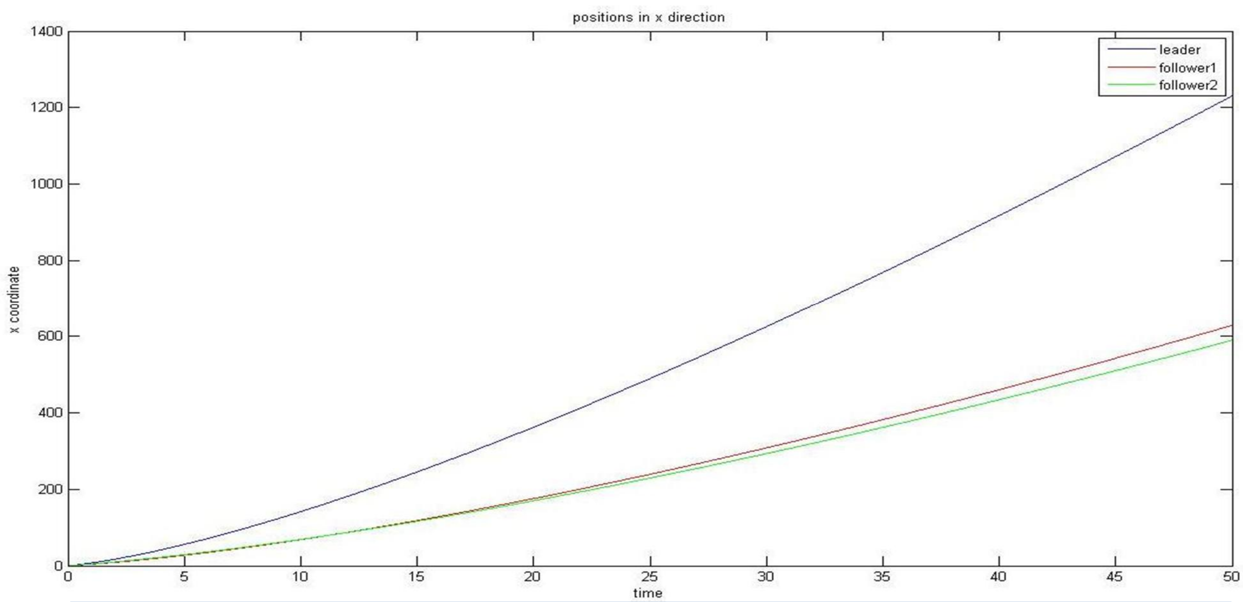

Fig. 5.3: Tracking and formation control of AUVs in 3D (positions in x direction)

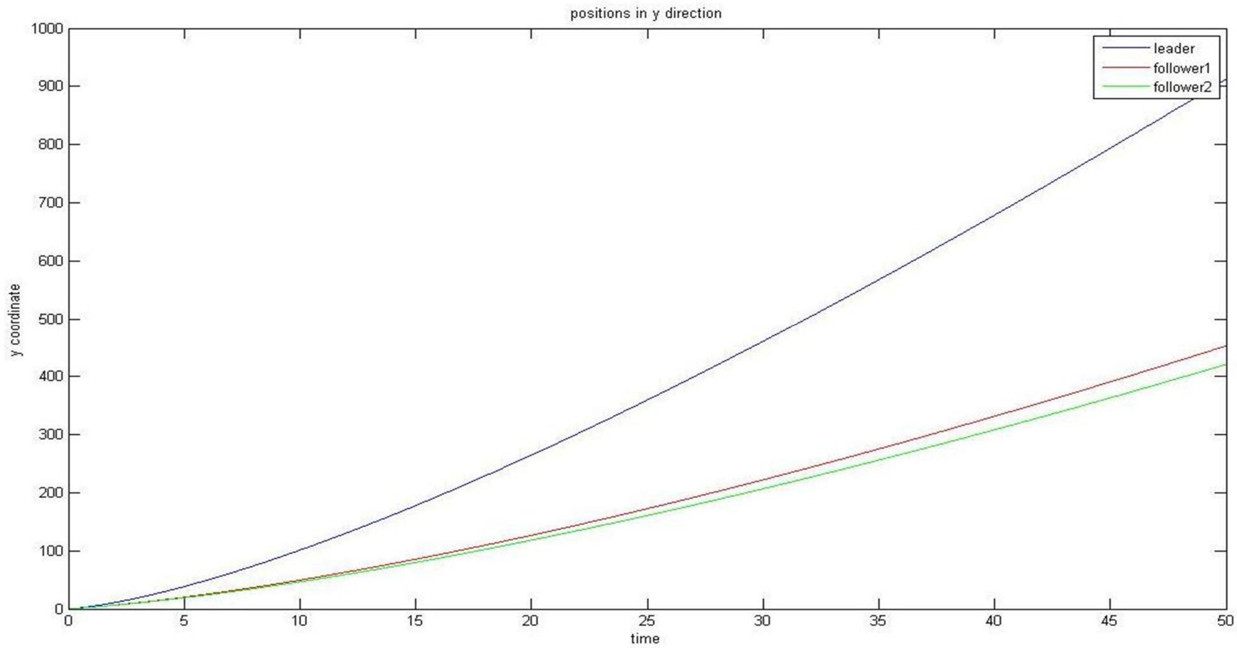

Fig. 5.4: Tracking and formation control of AUVs in 3D (positions in y direction)

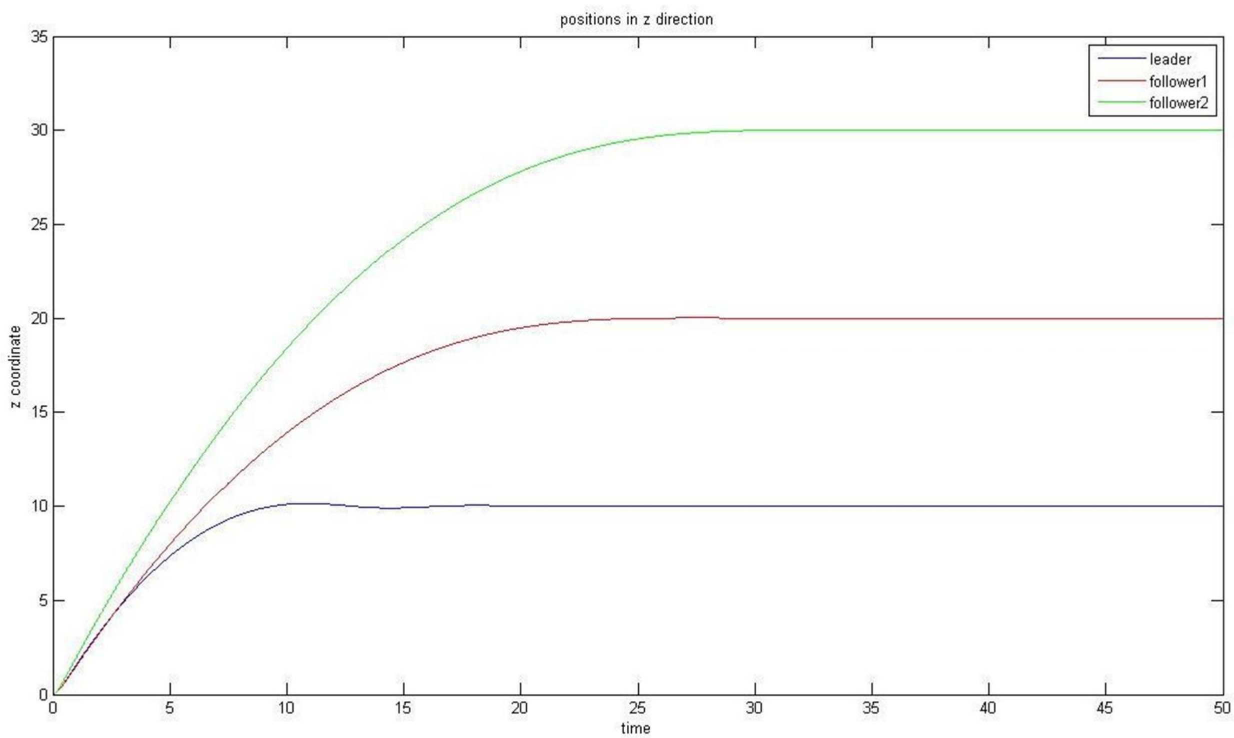

Fig. 5.5: Tracking and formation control of AUVs in 3D (positions in z direction)

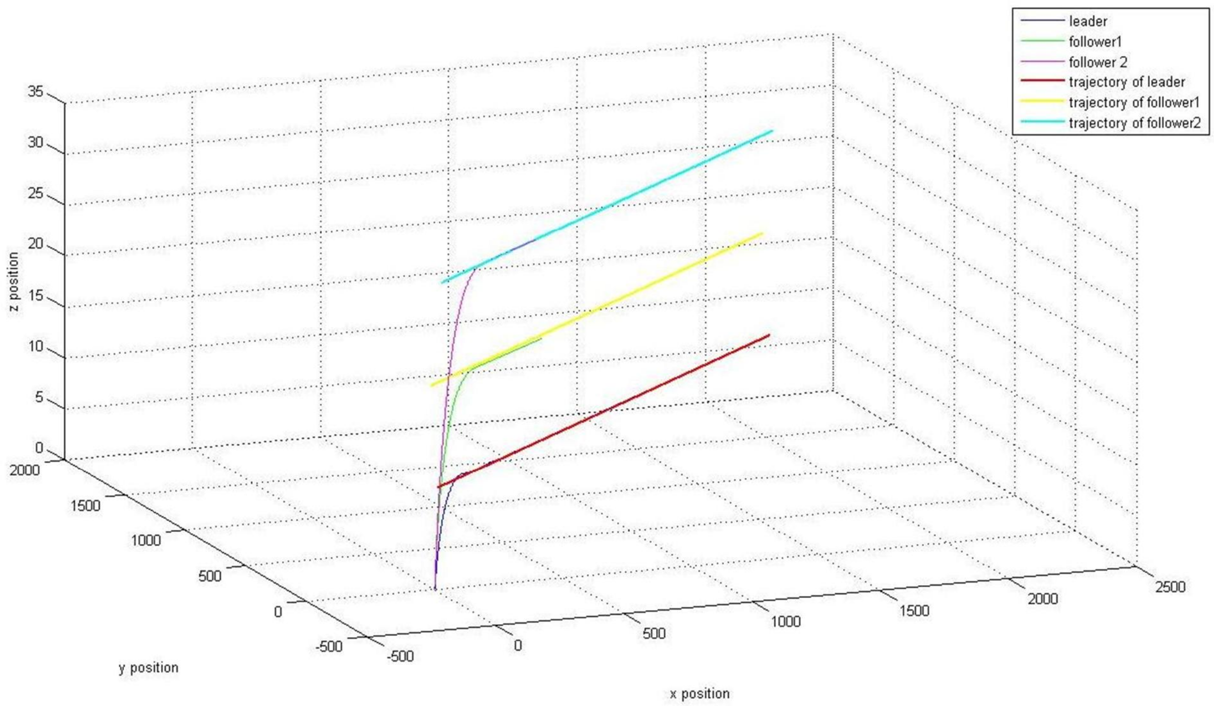

Fig. 5.6: Tracking and formation control of AUVs in 3D

From the waveforms, we have that the leader AUV is tracking its desired path which is a straight line in z =10 plane and follower1 is maintaining a distance of 10m from leader and follower2 is maintaining a distance of 20 m from leader which means that the proposed PD controller is operating properly. Thus, the tracking and leader follower formation control is achieved in 3D.

Chapter 6

Obstacle Avoidance

Obstacle detection and avoidance is an important aspect of autonomy in AUVs. Like roads on land, oceans are also crowded with lot of unwanted traffic. To bypass this traffic successfully, obstacle avoidance systems are incorporated in AUVs so that they can easily pass through obstacles without any harm and on same time carry on their mission (monitoring for example).

Approach

In this chapter, an obstacle avoidance scheme is used which is based on the pitch and depth control of AUV. The forward look sonar detects the obstacle in the path of the vehicle. If there is an obstacle then the obstacle avoidance algorithm is activated. The normal obstacles encountered inside sea are coral reefs and sea walls. AUV is required to pass over these reefs and/or walls. This can be achieved by increasing the pitch angle of AUV so that its depth (height) above the sea floor increases or decreases i.e. the AUV pitches up or pitches down and obstacles are avoided. [17]

The modeling of AUV remains the same as described in chapter 2. For obstacle avoidance, four states are considered namely heave, pitch rate, pitch angle and depth unlike the pitch and depth control where heave was not considered.

Forward look sonar detects the obstacle and gives a measure of its height and range. The important aspect is to plan a new path which will be traversed by the vehicle and then make a controller that will execute this planned path. Also, when the obstacle has passed, the vehicle should come to its original path.

Here, an only specific type of obstacle is considered as shown in fig. 6.1. The sonar will sense this obstacle and will give data about its range

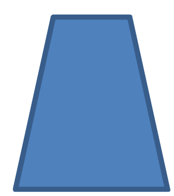

Fig. 6.1: Shape of obstacle considered for obstacle avoidance

and height. Now a new path is to be calculated so that the vehicle does not hit the obstacle. Obviously, the new path should be parallel to the boundary of the obstacle. Thus, first AUV will pitch up to the height of obstacle while maintaining a particular distance from the obstacle. After reaching the top of obstacle, AUV move over the top at a safe altitude and when the downward slope part encountered, it pitches down and moves toward the bottom of the obstacle. When the obstacle is passed, the obstacle avoidance algorithm is completed and AUV returns to its previous path. [17]

Simulation results

For simulation of the above algorithm, first we model the sea floor. In sea floor modeling, we put an obstacle at some distance from origin. Next step is to model the forward-look sonar. Here, the sonar considered for simulation is of 35m range and 24° forward zone. With the help of data given by sonar, we calculate the slope of upward motion (upward path) which is the ratio of height to range. This new path calculated is fed to the controller which controls the vehicle by changing pitch and depth to go through this part. The same process is repeated when AUV moves downward. During the flat portion of the obstacle, AUV is maintained at a particular altitude as slope is zero.

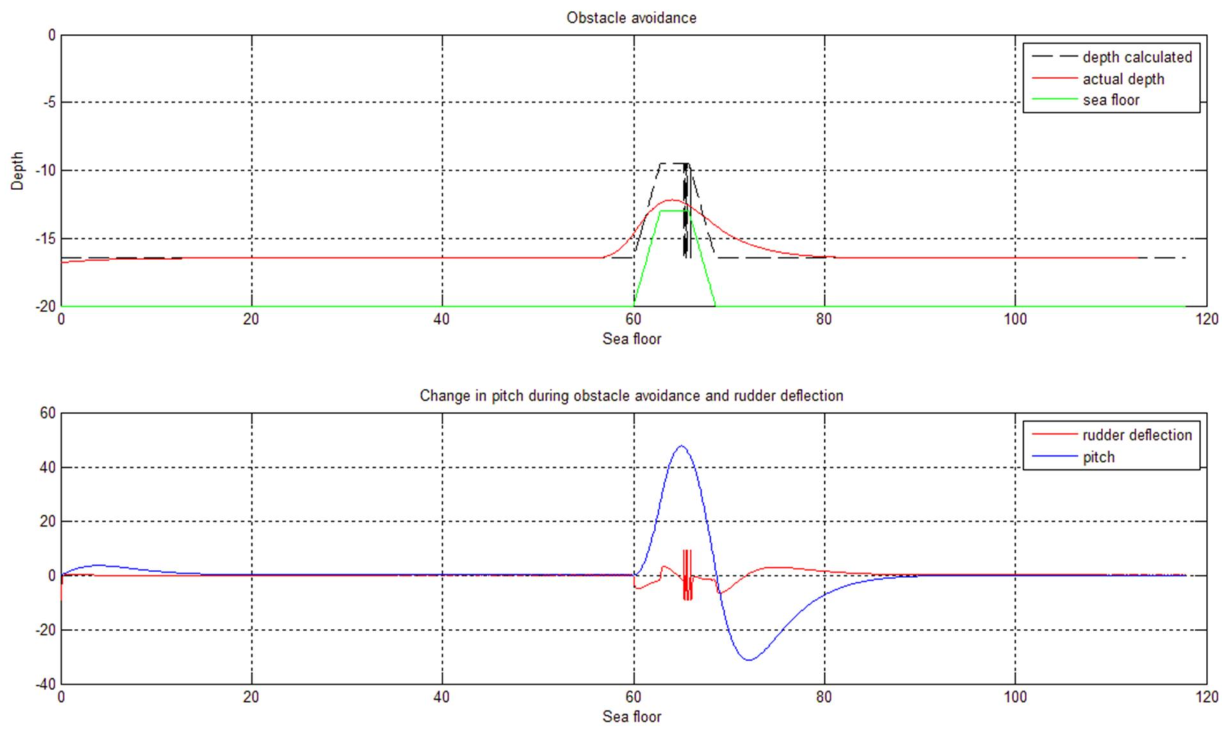

Fig. 6.2: Obstacle avoidance by varying pitch and depth (by using pitch and depth control)

The problem with this approach is that it does not consider the blind spot situation which can harm the vehicle. A new and more reliable approach to obstacle avoidance is the potential field method.

Chapter 7

Appendix

MATLAB code for formation control in 2D

```
5/8/11 1:27 AM     C:\Users\Manticore\Documents\MATLAB\auv.m                    1 of 1

function xdot = auv(t,x)
m11 = 215;
m22 = 265;
m33 = 80;
Xu = 70;
Yv = 100;
Nr = 50;
Xuu = 100;
Yvv = 200;
Nrr = 100;

xr = 8*sin(0.01*t); xr1 = 10*sin(0.01*t);
yr = 8*cos(0.01*t); yr1 = 10*cos(0.01*t);
dxr = 0.08*cos(0.01*t); dxr1 = 0.1*cos(0.01*t);
dyr = -0.08*sin(0.01*t); dyr1 = -0.1*sin(0.01*t);

ex = xr-x(1); ex1 = xr1-x(7);
ey = yr-x(2); ey1 = yr1-x(8);
dex = dxr-x(4); dex1 = dxr1-x(9);
dey = dyr-x(5); dey1 = dyr1-x(10);

Kpx = 100;
Kpy = 150;
Kdx = 50;
Kdy = 40;

Fx = Kpx*ex+Kdx*dex; Fx1 = Kpx*ex1+Kdx*dex1;
Fy = Kpy*ey+Kdy*dey; Fy1 = Kpy*ey1+Kdy*dey1;

xdot(1) = x(4);
xdot(2) = x(5);
xdot(3) = x(6);
xdot(4) = (m22/m11)*x(5)*x(6)-(Xu/m11)*x(4)-(Xuu/m11)*x(4)^2+(1/m11)*Fx;
xdot(5) = -(m11/m22)*x(4)*x(6)-(Yv/m22)*x(5)-(Yvv/m22)*x(5)^2+(1/m22)*Fy;
xdot(6) = ((m11-m22)/m33)*x(4)*x(5)-(Nr/m33)*x(6)-(Nrr/m33)*x(6)^2;
xdot(7) = x(9);
xdot(8) = x(10);
xdot(9) = (m22/m11)*x(10)*x(6)-(Xu/m11)*x(9)-(Xuu/m11)*x(9)^2+(1/m11)*Fx1;
xdot(10) = -(m11/m22)*x(9)*x(6)-(Yv/m22)*x(10)-(Yvv/m22)*x(10)^2+(1/m22)*Fy1;
xdot = [xdot(1);xdot(2);xdot(3);xdot(4);xdot(5);xdot(6);xdot(7);xdot(8);xdot(9);xdot↙
(10)];
```

```
clear all

x0 = [0,0,0,0,0,0,0,0,0,0];
tspan = 0:0.1:1000;
[t,x] = ode45('auv',tspan,x0);

xr = 8*sin(0.01*t); xr1 = 10*sin(0.01*t);
yr = 8*cos(0.01*t); yr1 = 10*cos(0.01*t);
plot(x(:,1),x(:,2),'LineWidth',2)
hold on
plot(x(:,7),x(:,8),'g','LineWidth',2)
hold on
plot(xr,yr,'r')
hold on
plot(xr1,yr1,'m')
```

MATLAB code for formation control in 3D


```
function xdot=fct3(t,x)

%%%%%%states%%%%%%
a = [x(1);x(2);x(3);x(4)];
da = [x(5);x(6);x(7);x(8)];
da1 = [x(12);x(13);x(14);x(8)];
da2 = [x(18);x(19);x(20);x(8)];
%%%%%%%%specifications%%%%%%
m11=99; m22=108.5; m33=126.5; m44=29.1;
M = [m11 0 0 0
     0 m22 0 0
     0 0 m33 0
     0 0 0 m44];

d11=10+227.18*x(5); d22=405.42*x(6); d33=10+227.18*x(7); d44=1.603+12.937*x(8);
d111=10+227.18*x(12); d221=405.42*x(13); d331=10+227.18*x(14);
d112=10+227.18*x(18); d222=405.42*x(19); d332=10+227.18*x(20);

D = [d11 0 0 0
     0 d22 0 0
     0 0 d33 0
     0 0 0 d44];
D1 = [d111 0 0 0
      0 d221 0 0
      0 0 d331 0
      0 0 0 d44];
D2 = [d112 0 0 0
      0 d222 0 0
      0 0 d332 0
      0 0 0 d44];

xr = 40*t+10; xr1 = 40*t-10; xr2 = 40*t+30;
yr = 30*t-5; yr1 = 30*t+5; yr2 = 30*t+5;
zr = 10; zr1 = 20; zr2 = 30;

e1 = xr-x(1); e4 = xr1-x(9); e7 = xr2-x(15);
e2 = yr-x(2); e5 = yr1-x(10); e8 = yr2-x(16);
e3 = zr-x(3); e6 = zr1-x(11); e9 = zr2-x(17);
de1 = 40-x(5); de4 = 40-x(12); de7 = 40-x(18);
de2 = 30-x(6); de5 = 30-x(13); de8 = 30-x(19);
de3 = -x(7); de6 = -x(14); de9 = -x(20);

Kp1 = 300; Kp11 = 50; Kp12 = 40;
Kd1 = 150; Kd11 =100; Kd12 = 100;
Kp2 = 400; Kp21 = 60; Kp22 = 50;
Kd2 = 200; Kd21 = 100; Kd22 = 100;
Kp3 = 100; Kp31 = 50; Kp32 = 50;
Kd3 = 40; Kd31 = 100; Kd32 = 100;

T1 = Kp1*e1+Kd1*de1;
T2 = Kp2*e2+Kd2*de2;
T3 = Kp3*e3+Kd3*de3;
```

```
T4 = Kp11*e4+Kd11*de4;
T5 = Kp21*e5+Kd21*de5;
T6 = Kp31*e6+Kd31*de6;
T7 = Kp12*e7+Kd12*de7;
T8 = Kp22*e8+Kd22*de8;
T9 = Kp32*e9+Kd32*de9;

T = [T1;T2;T3;0]; F1 = [T4;T5;T6;0]; F2 = [T7;T8;T9;0];

Vdot = inv(M)*(T-D*da);
V1dot = inv(M)*(F1-D1*da1);
V2dot = inv(M)*(F2-D2*da2);

xdot(1) = x(5);
xdot(2) = x(6);
xdot(3) = x(7);
xdot(4) = x(8);
xdot(5) = Vdot(1);
xdot(6) = Vdot(2);
xdot(7) = Vdot(3);
xdot(8) = Vdot(4);
xdot(9) = x(12);
xdot(10) = x(13);
xdot(11) = x(14);
xdot(12) = V1dot(1);
xdot(13) = V1dot(2);
xdot(14) = V1dot(3);
xdot(15) = x(18);
xdot(16) = x(19);
xdot(17) = x(20);
xdot(18) = V2dot(1);
xdot(19) = V2dot(2);
xdot(20) = V2dot(3);
xdot = [xdot(1);xdot(2);xdot(3);xdot(4);xdot(5);xdot(6);xdot(7);xdot(8);xdot(9);xdot↙
(10);xdot(11);xdot(12);xdot(13);xdot(14);xdot(15);xdot(16);xdot(17);xdot(18);xdot(19);↙
xdot(20)];
```

```
clear all

x0 = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0];
tspan = 0:0.01:50;
[t,x] = ode45('fct3',tspan,x0);

figure(1)
plot(t,x(:,1),t,x(:,9),'r',t,x(:,15),'g')
figure(2)
plot(t,x(:,2),t,x(:,10),'r',t,x(:,16),'g')
figure(3)
plot(t,x(:,3),t,x(:,11),'r',t,x(:,17),'g')
figure(4)
t = 0:0.01:50;
xr = 40*t+10;
yr = 30*t-5;
xr1 = 40*t-10;
yr1 = 30*t+5;
xr2 = 40*t+30;
yr2 = 30*t+5;
for i = 1:1:5001
    zr(i) = 10;
end
for j= 1:1:5001
    zr1(j) = 20;
    zr2(j) = 30;
end
plot3(x(:,1),x(:,2),x(:,3))
hold on
plot3(x(:,9),x(:,10),x(:,11),'g')
hold on
plot3(x(:,15),x(:,16),x(:,17),'m')
hold on
plot3(xr(:),yr(:),zr(:),'r','LineWidth',2)
hold on
plot3(xr1(:),yr1(:),zr1(:),'y','LineWidth',2)
hold on
plot3(xr2(:),yr2(:),zr2(:),'c','LineWidth',2)
grid on
```

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