International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2015): 6.391

Design and Control of Autonomous Unerwater Vehicle for Depth Control Using LQR Controller

Reshmi K R G[1], Priya P S[2]

[1]M.Tech Scholar (Control System), Department of Electricaland Electronics, Lourdes Matha College of Science and Technology, Kuttichal, Thiruvananthapuram-695574, Kerala, India

[2]Assistant Professor, Department of Electrical and Electronics, Lourdes Matha College of Science and Technology, Kuttichal, Thiruvananthapuram-695574, Kerala, India

Abstract: ***Autonomous underwater vehicle (AUV)is a non-linear dynamic system which is modelled with six degree of freedom equation. Due to hydrodynamic forces these equations are complex nonlinear and highly coupled, hence impractical for implementing controllers. Here, a reduced order subsystem derived from dive plane parameter for depth control has been linearized and is used for controlling scheme. The controlling techniques used here is a linear quadratic regulator (LQR) .the objective is to determine a control strategy to deliver better performance for depth control.***

Keywords: Autonomous underwater vehicle (AUV), depth control, LQR,MATLAB,SIMULINK

1. Introduction

An AUV is a programmable robotic submarine which can drift, drive or glide without real time control, without any human, depending on the system. They are manuoeuvrable in 3 dimension and can be programmed to flat passively or to actively near desired location or to swim at different depth. From the practical point of view it is important to design and investigate AUVs with six degree of freedom (6-DOF). The automatic control of underwater vehicle represents a difficult design problem due to the nature of the dynamics of the system to be controlled.

Autonomous underwater vehicle is complex nonlinear system due to hydrodynamic uncertainties involved in it. AUV maneuvering and control is crucial task. Any automatic controller design for an AUV must satisfy two conflicting requirements, it has to be sophisticated enough to perform its mission in the realm of complicated and ever-changing vehicle or environmental interactions. It has to be simple enough so that on-line implementation is possible by the on-board vehicle computer at a sufficiently high sample rate.

A varied number of technique have been proposed for the depth control of AUV. A model of AUV for dive plane dynamics has been derived and a LQR based controller has been designed and their performance is analysed using MATLAB and Simulink.

2. Literature Survey

In the last decades there was a strong movement towards the development of underwater vehicle. One of the safest way to explore the underwater is using small unmanned underwater vehicles to carryout various missions and measurements, among others, can be done without risking human live’s. Autonomous underwater vehicles (AUVs) and remotely operating vehicles (ROVs) are the types of underwater vehicles. There are numerous applications for AUV and ROV, including underwater structure inspection, oceanographic surveys, operations in hazardous environments, and military applications. In order to fulfil these objectives, the vehicles must be provided with a set of controllers assuring the desired type of autonomous operation and offering some aid to the operator, for vehicles which can be teleoperated.

Hundreds of different AUVs have been designed over the past 50 or so years, but only a few companies sell vehicles in any significant numbers, Vehicles range in size from man portable lightweight AUVs to large diameter vehicles of over 10 meters length. Large vehicle have advantages in terms of endurance and sensor payload capacity; smaller vehicles benefit significantly from lower logistics (for example: support vessel footprint; launch and recovery systems). Some manufacturers have benefited from domestic government sponsorship including Bluefin and Kongsberg.

The modelling of an AUV itself is a huge area of interest for researchers so as the controlling methods. Modelling of marine vehicles involves the study of statics and dynamics. Statics is concerned with the equilibrium of bodies at rest or moving with constant velocity, whereas dynamics is concerned with bodies having accelerated motion. The foundation of hydrostatic force analysis is the Archimedes’ principle. The study of dynamics can be divided into two parts: kinematics, which treats only geometrical aspect of motion, and kinetics, which is the analysis of the forces causing the motion [1]. The increasing needs for AUV have brought about corresponding demands of accurate control of AUV and consequently, models which control laws are based on. Abkowitz [2] addressed issues pertaining to the stability and motion control of marine vehicle. He derived the dynamics of marine vehicles, and also studied and analyzed the external forces and moments acting on the vehicles. Ship hydrodynamics, steering and maneuverability are well discussed. Fossen [1] has also described the modeling of marine vehicles. He described the details of vehicles’ kinematics and rigid body dynamics. Based on these, the compact forms of equations of vehicle motion were explained specifically. In addition, he divided the hydrodynamic forces and moments into two parts: radiationinduced forces and Froude-Kriloff and diffraction forces. Stem Description.

The properties of any controller should be good performance and robustness. Many types of control schemes have been used to design controllers for AUV. While many of the controllers are designed based on a series of SISO linear system models of an AUV, a few nonlinear control designs have also been implemented in order to achieve better performance and robustness against uncertainties in the modelling of AUV.PID controllers are the most widely used industrial controllers found today. Analysis methods of linear system are well known and established. Abundant tools are also able to determine the performance of linear controllers. PID controllers have all the advantages, which include faster rise time, reduce steady state error and damped oscillations. However, the dynamic models of the AUV are nonlinear. The theory of optimal control is concerned with operating a dynamic system at minimum cost. One of the main methods in this theory is the liner-quadratic regulator (LQR). The settings of LQR are found by using a mathematical algorithm that minimizes a cost function with supplied weighting factors. The linear quadratic state feedback regulator problem is solved by assuming that all states are available for feedback.

3. System Description

The navigation system provides information related to the target and the vehicle itself using onboard sensor such as inertial navigation system, compass, pressure transducers etc. This information is fed to the guidance system which by utilizing some guidance law generates reference heading.

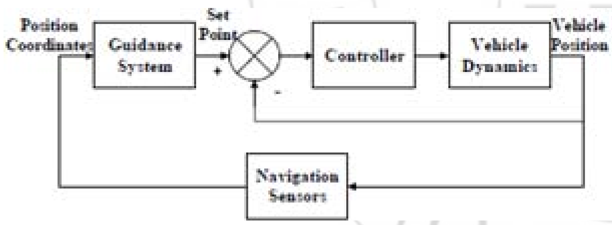

Figure 1: Navigation and guidance system

The control system is then responsible for keeping the vehicle on course as specified by the guidance system. A simple block diagram of an NGC system is shown in fig.1

The vehicle used in this study is called Hammerhead has a torpedo shaped body about three and a half meter long and approximately one-third of a meter in diameter. The control surfaces are the two rear rudders for steering and two front hydroplanes for diving. The rudder and hydroplanes are controlled by two separate on-board stepper motors and the signal to the stepper motors is sent through an umbilical attached to the rear end of the vehicle. The on-board sensors include inertial navigation system (INS), TCM2 compass, pressure sensor, global positioning system (GPS), and a shaft speed encoder. The data logged using the above mentioned sensors is summarised below:

INS heading, pitch, roll, linear and angular velocities
TCM2 Compass heading, pitch and roll
Pressure sensor depth of the vehicle
GPS co-ordinates of the vehicle on the surface, forward speed
Shaft speed
Encoder vehicle speed

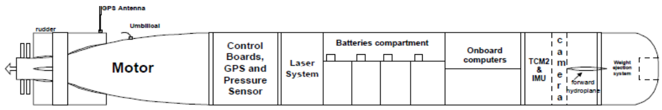

Figure 2: Sectional view of the hammerhead AUV

Fig. 2 depicts the sectional view of the Hammerhead AUV showing the hardware setup. The other end of the umbilical is attached to a control computer used to send and receive various signals. The rudder/ heading angle data pair is used to generate the yaw model while the hydroplane angle/depth is used to develop the depth channel model. Cross coupling effects between different channels such as yaw and roll of the vehicles.

4. System Modelling

Mathematical modelling of underwater vehicles is a widely researched area and unclassified information is available through the Internet and from other source of written publications. The generalized six-degree of freedom (6 DOF) equations of motion (EOM) for an underwater vehicle will be developed. The underlying assumptions are that: The vehicle behaves as a rigid body; the earth's rotation is negligible as far as acceleration components of the centre of mass are concerned and the hydrodynamic coefficients or parameters are constant. The assumptions mentioned above eliminate the consideration of forces acting between individual elements of mass and eliminate the forces due to the Earth's motion. The primary forces that act on the vehicle are of inertial, gravitational, hydrostatic and hydrodynamic origins. These primary forces are combined to build the hydrodynamic behaviour of the body.

The standard AUV vehicle notation of 6-DOF are tabulated below

Table 1: AUV notations

DOF	Motion	Forces and Moments	Linear and Angular velocities	Positions and Euler Angles
1	Surge	X	u	x
2	Sway	Y	v	y
3	Heave	Z	w	z
4	Roll	K	p	ϕ
5	Pitch	M	q	θ
6	Yaw	N	r	ψ

Out of the 6 DOFs the first 3 parameters represents linear motion and position and other three represents orientation and rotational equation of motion. The modelling of AUV consider the system as rigid body and assuming to be rigid, the equation of motions are derived by considering the reference frames.

$$M\dot{v}+C(v)v+D(v)v+g(\eta)=\tau \quad (1)$$

$$\dot{\eta}=J(\eta)v \quad (2)$$

International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2015): 6.391

Where (1) is the vehicle dynamics and (2) is the kinematics.in the equations M is a 6X6 matrix representing inertia matrix that includes rigid bodymass matrix and an added mass matrix.C(v) is a 6X6 coriolis and centripetal matrix.D(v) is the hydrodynamic matrix ,g vector of gravitation and buoyancy , η is the postions and eulerangles,τ is the control vector. The reference frames considered for deriving the mathematical model are body fixed reference frame and earth fixed reference frame(fig 3) and transformation from one coordinate system to another is done using Euler angle transformation.[1]

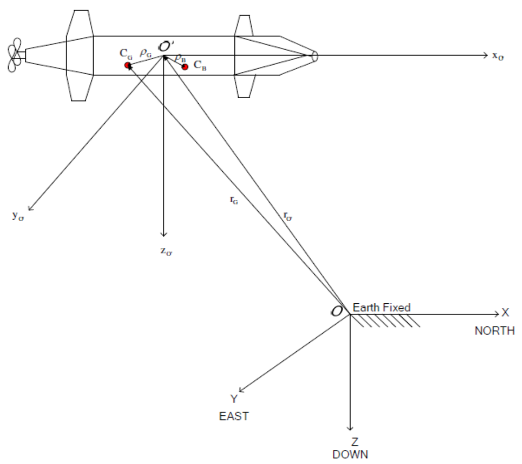

Figure 3: Earth fixed and body fixed reference frames

Kinematic and dynamic equation of motion makes the mathematical model of 6 DOF of AUV.
Kinematic equations of motions
From earth to body velocities

$$[V]_{earth} = \begin{bmatrix} [R] & 0 \\ 0 & [T] \end{bmatrix} [V]_{body} \quad (3)$$

From body to earth velocity

$$[V]_{body} = \begin{bmatrix} [R]^{T} & 0 \\ 0 & [T]^{-1} \end{bmatrix} [V]_{earth} \quad (4)$$

Dynamic equations of motion of the system can be generalized as

$$\Sigma F_{translational} = m(\dot{v}_0 + \omega\rho_G + \dot{\omega}\,\omega\rho_G + \omega\rho_G) \quad (5)$$

$$\Sigma M_{rotational} = I_0\,\dot{\omega} + \omega(I_0\omega) + m(\rho_G\,\dot{v}_0 + \rho_G) \quad (6)$$

Equation (3) to (6) formulate the 6 DOF equations of an AUV.

$$X = m\begin{bmatrix} \dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) \\ + z_G(pr + \dot{q}) \end{bmatrix} \quad (7)$$

$$Y = m[\dot{v} + ur - wp + x_G(pq + \dot{r}) - y_G(p^2 + r^2) + z_G(pr - \dot{q})] \quad (8)$$

$$Z = m[\dot{w} - uq + vp + x_G(pr - \dot{q}) + y_G(qr + \dot{p}) - z_G(p^2 + q^2)] \quad (9)$$

$$K = I_x\dot{p} + (I_z + I_Y)qr + I_{xy}(pr - \dot{q}) - I_{yz}(q^2 - r^2) - I_{xz}(pq + \dot{r}) + m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} + ur - wp)] \quad (10)$$

$$M = I_y\dot{q} + (I_x - I_z)pr - I_{xy}(qr + \dot{p}) + I_{yz}(pq - \dot{r}) + I_{xz}(p^2 - r^2) - m[x_G(\dot{w} - uq + vp) - z_G(\dot{u} - vr + wq)] \quad (11)$$

$$N = I_z\dot{r} + (I_y - I_x)pq - I_{xy}(p^2 - q^2) - I_{yz}(pr + \dot{q}) + I_{xy}(qr - \dot{p}) + m[x_G(\dot{v} + ur - wp) - y_G(\dot{u} - vr + wq)] \quad (12)$$

For depth control of AUV, The vehicle is assumed to be in vertical plane. For a vertical motion of vehicle the following assumptions are forward speed is constant, Sway and yaw can be neglected, in steady state θ_0 is a constant and (q_0=ϕ_0=0).

From all the equations and standard notation and considering the specification of the vehicle considered the equation of the vehicle, drooping out unwanted terms and considering the heave velocity is being very small and is neglected the state space equation of the system will be

$$\begin{bmatrix} I_y - M_{\dot{q}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} -M_q & 0 & M_\theta\theta \\ 0 & 0 & u1 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} M_{fs} \\ 0 \\ 0 \end{bmatrix} \quad (13)$$

By substituting the standard values and from state space matrix, the transfer function will be

$$G_\theta(s) = \frac{-3.18}{s^2 + 1.09s + 0.52} \quad (14)$$

Now the controller is implemented on (14) which is a reduced order equation from dive plane dynamics and linearized model for depth control

5. LQR Controller Design

A reduced order system with dive plane dynamics has been derived and is linearized for implementing the control stratorgy. The control strategy is the Linear Quadratic Regulator (LQR), which will provide a better response for the depth control performance of the system for a particular working condition. The LQR algorithm reduces the amount of work done by the control engineer to optimize the controller. However the engineers still needs to specify the cost function parameters and compare the result with specified design goal.

The LQR is essentially an automated way of finding an appropriate state feedback controller.

Linear quadratic regulator (LQR) is a well-known control techinique,which provide practical feedback gain [12].LQR is commonly used technique to find the best state feedback control matrix for a closed loop system. LQR control can been implemented for depth control of AUV based on the mathematical model. Conventional controller will give higher overshoot and due to improper tuning the control is not optimal. A LQR is comparatively steady in behaviour.

$$\dot{x} = Ax + Bu \tag{15}$$

Where,

$$A = \begin{bmatrix} -1.09 & -0.52 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 3.18 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 \end{bmatrix} \tag{16}$$

For a LQR controller, it is assumed that all n states are available for the controller. The design of LQR means to design a feedback matrix K.the objective is considered as J where J is minimized in such a way that response will be stable.

J can be written as

$$J = \int_0^\infty (x^T Qx + u^T Ru)dt \tag{17}$$

The control law is

$$U=-Kx \tag{18}$$

LQR design for the system: the symmetric matrices Q and R are considered as follows.

$$Q = C^T C \tag{19}$$

R=1

Q and R deciding weights. Q and R matrices are symmetric diagonal matrices.

Q,R $\geq$ 0; Q is related to J

Also P is needed for optimal feedback gainK. Closed loop poles are moved for ideal performance of the system
P is the positive matrix solved by riccati equation

$$0 = PA + A^T P + Q - PBR^{-1}B^T P \tag{21}$$

K can be given by matrix algebraic Riccati equation as

$$K = -R^{-1}B^T P \tag{22}$$

The control law is calculated using (22)

$$U=-Kx \tag{23}$$

6. Simulations and Results

The AUV model is derived for 6-DOF and the controller LQR is implemented and simulated using MATLAB Simulink model and simulation graphs are obtained.

The response are taken for closed loop system for easy and proper evaluation of system.the system is simulated using MATLAB Simulink and model is shown in fig 4

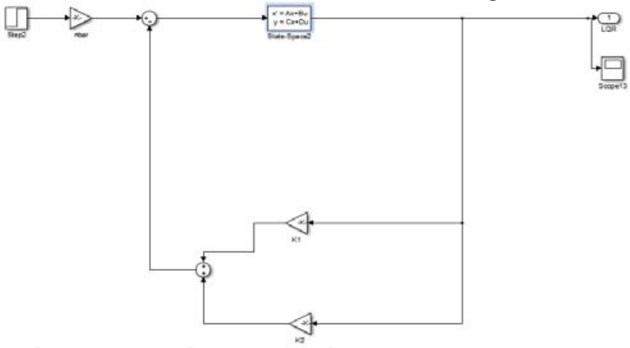

Figure 4: Model of LQR simulation

The system step response with and without LQR controller are shown in fig.5

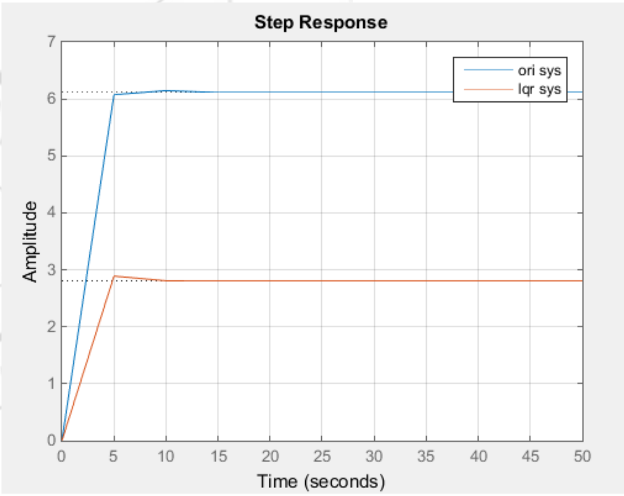

Figure 5: Step response of system with and without LQR

From the fig 5 it is clear that the system step response of the original system is high. By implementing LQR on the system the step response is improved for system.

The simulated closed loop step response for depth control system of AUV is shown in fig 6

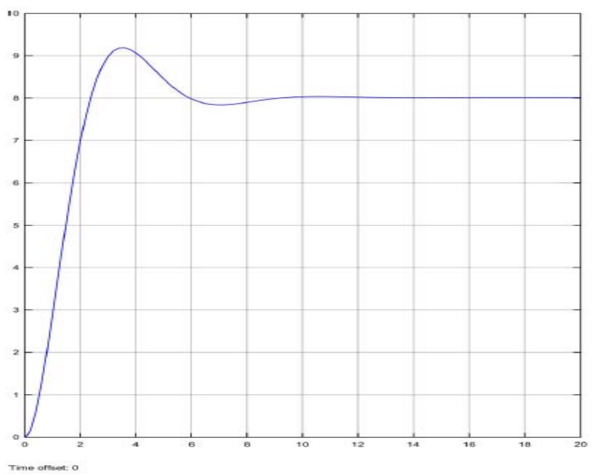

Figure 6: LQR controller depth response

The LQR will give an overshoot of 15% which is better compared to conventional controllers. Response time is bit slow, but from the result, it shows that LQR is remarkable than other conventional controllers.

7. Conclusion

LQR control can been implemented for depth control of AUV based on the mathematical model. Conventional controller will give higher overshoot and due to improper tuning the control is not optimal. A LQR is comparatively steady in behaviour. The AUV model is derived for 6-DOF and the controller LQR is implemented and simulated using MATLAB Simulink model and simulation graphs are obtained.

8. Future Scope

In addition to LQR other control methods like fuzzy LQR, slidingmode, fuzzyPID, etc. can also be implemented for the depth control of AUV system in future.

References

[1] H.Ying, Fuzzy Control &Modeling:Analytical foundations and applications. New York, IEEE Press, 2000
[2] AmrulFaruq, Shahrum Shah Bin Abdullah, M. Fauzi Nor Shah "Optimization of an Intelligent Controller for an Unmanned Underwater Vehicle" TELKOMNIKA, Vol.9, No.2, August 2011, pp. 245-256 ISSN: 1693-6930
[3] Mohammed Amjad,KashifIshaque,Saman Abdullah "An alternative approach to design a Fuzzy logic controller for an autonomous underwater vehicle"in proceedings of IEEE conference on cybernetics and intelligent system, January 2010
[4] NanangSyahroni, Young Bong Seo, Jae Weon Choi "Depth Control of Autonomous Underwater Vehicle Based on Open Control Platform" Proceedings of the 17th World Congress The International Federation of Automatic Control Seoul, Korea, July 6-11, 2008
[5] Neal M patel, Shawn E Gano, John E Renaud, Jay D. Martin, Michael A. Yukish,"Simulatiom model of an Autonomous under water vehicle for design optimization",45th AIAA/ASME/ASCE/ASC structures, structural dynamics &materials conference 19-22 April 2004,palm springs ,California
[6] Prezemyslaw Herman "Decoupled PD set-point controller for underwater vehicles" ocean engineering ELSEVIER FEBRUARY 2009
[7] S. D. Joshi, D. B. Talange "PERFORMANCE ANALYSIS: PID AND LQR CONTROLLER FOR REMUS AUTONOMOUS UNDERWATER VEHICLE (AUV) MODEL" IEEE Volume 3, Issue 2, July – September (2012), pp. 320-327
[8] Sujay D. Kadam, Kunal N. Tiwari," A simplified approach to tune PD controller for the depth control of an autonomous underwater vehicle", Communication, Computation and Networking Technologies ISBN:978-93-82880-09-7
[9] W.nazeam, R Suttan, J Chudley, "System identification, modelling and control of an autonomous underwater vehicle", In: Proceedings of the IFAC conference on control applications in marine systems, 2003
[10] Yang Shi , WeiqiQian "Adaptive Depth Control for Autonomous Underwater Vehicles Based on Feedforward Neural Networks", International Journal of Computer Science & Applications 2007 Technomathematics Research Foundation Vol. 4 Issue 3, pp 107-118

Author Profile

Reshmi K R G received her B.Tech degree in Electrical and Electronics from Kerala university in 2013.She is currently pursing second year M. Tech in Control Systems at Lourdes Matha College of Science and Technology.

Priya P S received her B.Tech degree in Electrical and Electronics from Bharathidasan university followed M.Tech in Control systems and Instrumentation from Sastrauniversity.She is currently working as Assistant Professor in Electrical and Electronics department at Lourdes Matha College of Science and Technology