



MOTION CONTROL STRATEGY OF AN UNDERWATER GLIDER IN THE PRESENCE OF EXTERNAL DISTURBANCES

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ABSTRACT

This paper describes motion control strategy of an underwater glider in the presence of external disturbances based on state feedback and full order observer feedback. In this paper, we will be concerned only with the phugoid motion in the vertical plane. A control strategy for the glider was implemented with fast and stable convergence. Simulation results show that the open loop system is controllable and observable. The results suggest the use of a well-known guidance for fast tracking and stability control.

Keywords: control strategy, underwater gliders, linear quadratic regulator, simulation.

INTRODUCTION

Underwater gliders are a type of autonomous underwater vehicle (AUV) that moves by modifying their buoyancy and centre of mass through an internal moving mass. Therefore, motion control is achieved by varying these two parameters, which are typically controlled through feedback. To speed up convergence and improve performance, a feed forward component may be used. However, an underwater glider is subjected to various environmental disturbances such as current disturbance. For example, water current at the surface can slide the glider from its pre-set trajectory, which requires additional control effort to bring it back to desired path [1-3].

In order to reduce the energy consumed on path correction during steady gliding, it is very important to stabilize the desired path. However, little work has been done on gliding motion stability involving current disturbances which can easily shift the glider from its desired trajectory. However, little work has been done on gliding motion stability involving current disturbances which can easily shift the glider from its desired trajectory.

Leonard [4] and Nina [5] proposed LQR and a PID controller respectively for motion control, but both of these approaches were based on linearized dynamic model of a glider and the application was limited to equilibrium conditions. Bhatta [6] proposed a nonlinear controller involving torque and buoyancy control which is based on the assumption of equilibrium condition. Noh *et al* [7] made a performance comparison between LQR and PID controller for glider pitch control using SISO controller and the effect of external disturbances was neglected.

This paper compares and contrasts the use of a linear and nonlinear LQR observer to estimate the system states for an open loop and closed loop system. A dynamic model is used to design full state feedback observer and a Jacobian linearization approach is used to check the stability and controllability of the model.

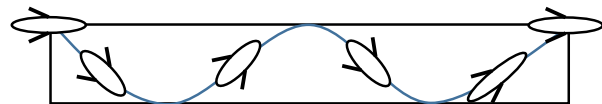


Figure-1. Underwater glider saw tooth profile.

UNDERWATER GLIDER MOTION CONTROL MECHANISM

In this section, we describe the mathematical model of underwater glider using longitudinal plane dynamics. The glider is considered as an ellipsoidal rigid body with uniformly distributed mass. The wings and rudder are fixed and lateral disturbances are neglected. The forces on the glider are gravity, hydrodynamic forces, lift, drag and pitching moment. Buoyancy and added mass effects are also considered in the mathematical modelling such as presented by [8]. The motion of underwater glider is controlled by varying buoyancy and internal moving masses about its centre of gravity. Figure-1 shows the motion profile of the underwater glider. The longitudinal frame of the body is the x-axis while the z-axis is at right angles to the x-axis

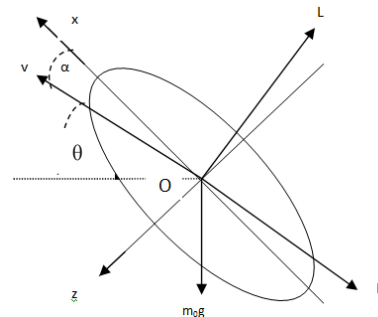


Figure-2. Underwater glider frame assignment.

The relationship between gravity W and buoyancy B is: $W = m_0 g$, and $B = \rho g \Delta$ where g is gravity, ρ is water density and Δ is volume of the glider body.



The glider is designed to be positively buoyant ($B > W$) such that it will surface automatically. The centre of buoyancy is considered in the origin O due to symmetry of the glider.

Considering the assumptions of Graver[1] and Zhang [9] that movable mass is fixed at origin O and stationary masses are uniformly distributed, such that the centre of buoyancy will coincide with the centre of gravity.

The added masses are assumed to be equal ($m_1=m_3$). The gravity and buoyancy forces in terms of m_0 control the pitch of the glider from origin O to maximum length of buoyancy tank. The net buoyancy mass is m_0 . $m_0=m_G-m_w$. Where m_G is the total mass of the glider which is the sum of uniform hull mass m_h , fixed point mass to balance the center of gravity. The mass of the displaced water is m_w , ballast mass is m_b which is used to control buoyancy, fixed moving mass \bar{m} for pitch control along the nose x-axis. $m_G = m_h + m_w + m_b + \bar{m}$. The schematic diagram for uniformly distribution of internal masses is shown in Figure-3.

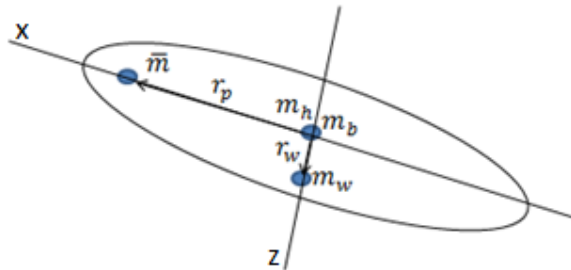


Figure-3. Internal mass distribution of glider.

Let J_2 be the moment of inertia in e_2 direction passing through the centre of gravity of the glider. The pitch angle is θ and the gliding angle is θ_g . The angle of attack is α . The relation between the pitch angle and gliding angle is

$$\theta = \theta_g + \alpha \quad (1)$$

Hydrodynamic forces

The lift L, Drag D and hydrodynamic moment M for underwater glider with wings and rudder are dependent on the angle of attack and velocity of the gliders. Lift of the glider is varying linearly with angle of attack while drag of the glider is parabolic function of angle of attack as follows:

$$L = (K_{I0} + K_I \alpha) V^2 \quad (2)$$

$$D = (K_{D0} + K_D \alpha^2) V^2 \quad (3)$$

$$M = (K_{M0} + K_M \alpha + K_{\omega} \omega) V^2 \quad (4)$$

where V represents the magnitude of the velocity and K_{L0} , K_L , K_{D0} , K_D , K_{M0} and K_M are hydrodynamic coefficients. ω_2 is the angular velocity of the pitch and K_{q2} is the pitching damping coefficient [8]. The hydrodynamic coefficients are determined for UTP glider in [10] for various angle of attacks and for constant fluid speed and shown in Table-1.

Table-1. Hydrodynamic parameters.

Parameters	Values
K_{D0}	0.3293
K_D	3.562
K_{L0}	0.2017
K_L	6.62
K_{M0}	0.01575
K_M	2.442

MATHEMATICAL MODEL

Zhang *et al* in [3] and Leonard and Bhatta in [8] used the equations of motion for underwater glider for buoyancy control as represented in equations 5-8 in polar coordinates. The velocity V represents the total velocity vector of the glider with respect to gliding angle γ . The simplified dynamic model for four states $[V, \theta_g, \alpha, \omega]$ of underwater glider is shown as:

$$\dot{V} = -\frac{1}{m}(m_0 g \sin \theta_g + D) \quad (5)$$

$$\dot{\theta}_g = \frac{1}{mV}(-m_0 g \cos \theta_g + L) \quad (6)$$

$$\dot{\alpha} = \omega_2 - \dot{\theta}_g \quad (7)$$

$$\dot{\omega}_2 = \frac{1}{J_2} (K_{M0} + K_M \alpha + K_{q2} \omega_2) V^2 \quad (8)$$

where J_2 is total inertia about y-axis, V & θ_g are the total velocity vector and gliding angle respectively.

Equations (5) - (8) are nonlinear equations. For steady glides, the parameters in equations (5) - (8) are determined by using equilibrium values at $\omega_{ze} = 0$. The state variables at equilibrium have the following relationships as calculated in [3].

$$\theta_e = \tan^{-1}(\frac{-K_{De}}{K_{Le}}), \alpha_e = (\frac{-K_{M0}}{K_M})$$

$$\omega_{2e} = 0, V_e = \left(\frac{m_0 g}{\sqrt{K_{D_e}^2 + K_{L_e}^2}} \right)^{1/2}$$

Where $K_{De} = K_{D0} + K_D \alpha_e^2$, $K_{Le} = K_{L0} + K_L \alpha_e$



Controller design

In this section the performance of motion control of underwater glider is checked by applying the mathematical model and equilibrium values in previous section to two different controllers. The velocity of the glider is analysed by super imposing the vehicle relative velocity with estimated and measured ocean current. The ocean current is imposed in the dynamic model and in controller in the form of external noise.

A generalized system given in state space form can be stated as

$$\dot{x}(t) = Ax(t) + Bu(t) + B_v v(t) \quad (9)$$

$$y(t) = Cx(t) \quad (10)$$

Two types of controllers are analyzed for this system. The system is considered to be linearized where $u(t)$ is the input signal which is the force required to regulate the ballast tank and $v(t)$ is a disturbance signal.

LQR design

Linear Quadratic Regulator (LQR) is designed based on the glider dynamic model in vertical plane. Nonlinear equations of motion are linearized and then the closed loop system with LQR controller for stabilization is simulated. LQR stabilizes control law that can be minimized using a cost function which can be defined as:

$$J_{LQR} = \int_0^{\infty} x(t)^T Q x(t) + \rho u(t)^T R u(t) dt \quad (11)$$

Q and R are weighing matrices for state variables and controller for input variables. It is assumed that all the glider states are measurable and available for state feedback. The gain (matrix) K is determined by first solving the algebraic Riccati equation K.

$$PA + A^T P - PBQ_u^{-1} B^T P + Q_x = 0$$

P is positive semi definite function and K can be calculated from LQR Matlab command. Q_u and Q_x are calculated from diagonal matrices making all other element to zero. K_r is calculated from the system model. As there are sensors used to calculate the depth of glider so there may have chances of uncertainty that will raise the steady state error. In order to bring the steady state error to zero, an integral action has been augmented in the state feedback system matrix. This method is similar to PID controller. The controller can compensate for small output deviations from the reference signal. The augmented matrix is described as:

$$\begin{bmatrix} \dot{x}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ z(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ I \end{bmatrix} r(t) \quad (12)$$

Due to augmented matrix, the new control law is:

$$u(t) = -Kx(t) \quad (13)$$

The value of K increases if ρ is increased. Let Q is a 4-by-4 matrix and R is constant. The value of Q is set to:

$$Q = C^T C \quad (14)$$

By implementing the values of Q and R, the matrix K is computed as follows:

$$K = [-0.0699 \quad 0.0516 \quad 0.0172 \quad 0.0250] \quad (15)$$

The block diagram of state feedback system is shown in Figure-4.

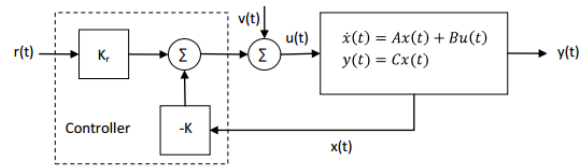


Figure-4. Block diagram for state feedback design

Assume that all states of the system are measured, the control law for augmented matrix in equation (12) can be written as

$$u = -Kx(t) + K_r r(t) \quad (16)$$

The closed loop poles are determined by considering the closed loop system characteristic polynomial. The closed loop system is described by:

$$\dot{x}(t) = (A - BK)x(t) + BK_r r(t) + B_v v(t) \quad (17)$$

In equation (17), $A - BK$ is system matrix and corresponding polynomial characteristic equation which

decides the closed loop poles is $\det(sI - A + BK) = 0$. In equation 17, the constant K_r does not affect the stability of the system however it affects the steady state solution. The constant gain K_r is calculated in the following equation.

$$K_r = \frac{1}{C(-A + BK)^{-1} B} \quad (18)$$

OBSERVER DESIGN

To estimate the desired value of pitch angle which is selected as the output of the system, a linear full state observer is designed. The block diagram of the linear observer is shown in Figure-5.

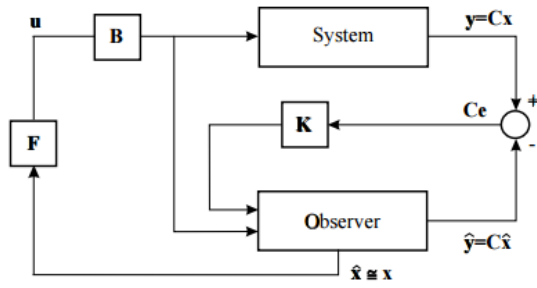


Figure-5. Observer design block diagram.

The real state matrix of the system from equations (5) -(8) is

$$X = [V \quad \gamma \quad \alpha \quad \omega_2] \quad (19)$$

The estimated state matrix is

$$\hat{X} = [\hat{V} \quad \hat{\gamma} \quad \hat{\alpha} \quad \hat{\omega}_2] \quad (20)$$

Consider a linear time invariant continuous system from Zhang *et al* [7].

$$\dot{\hat{X}} = A\hat{X} + B\hat{U} + L_0(\theta - \hat{\theta}) \quad (21)$$

$$\hat{\theta} = C\hat{X} \quad (22)$$

L_0 is observer gain matrix and the matrices A, B and C are the linearized system matrices which are obtained through Jacobean linearization is given by:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 \\ a_{21} & a_{22} & a_{23} & 0 \\ a_{31} & a_{32} & a_{33} & 1 \\ a_{41} & 0 & \frac{K_M Y(1)^2}{J_2} & \frac{K_{Q2} Y(1)^2}{J_2} \end{bmatrix}$$

Where

$$a_{11} = -\frac{1}{m}(2Y(1)(K_{D0} + K_D Y(3)^2)), a_{12} = \frac{-m_0 g \cos(Y(2))}{m}$$

$$a_{13} = -\frac{2K_D Y(1)^2 Y(3)}{m}, a_{21} = \frac{(2Y(1)(K_{L0} + K_L Y(3)))}{mY(1)}$$

$$a_{22} = \frac{m_0 g \sin(Y(2))}{mY(1)}, a_{23} = \frac{K_L Y(1)^2}{mY(1)}$$

$$a_{31} = -\frac{(2Y(1)(K_{L0} + K_L Y(3)))}{mY(1)}, a_{32} = \frac{-m_0 g \sin(Y(2))}{mY(1)}$$

$$a_{33} = -\frac{K_L Y(1)^2}{mY(1)}, a_{41} = \frac{2Y(1)(K_{M0} + K_M Y(3))}{J_2}$$

$$B = \begin{bmatrix} 0 & 1 & 0 & \frac{-K_M V^2}{J_2} \end{bmatrix}^T \quad C = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

The state space matrices are used for LQR and observer design and the results for gliding angle at different buoyancy rates are compared in the next section. The parameter of the observer for gliding angle and velocity are obtained by tuning the Qs and Rs matrices of LQR in Matlab/Simulink.

The eigenvalues of observer are obtained by following the robust approach of pole placement design. The observer gain is designed with eigenvalues of -1.7, -1.1, -0.918+2.19i, -0.918-2.19i which show that the system has two real roots and two imaginary roots and is marginally stable. Figure-6 shows the gliding angle at various pump rates by using designed observer. It shows that the pitch initial value has been set to -35° using LQR and at higher pump rate the convergence is fast. On the other hand, the lower value has slower response. According to the calculations of controllability and observability, the rank is 4 which is equal to the number of state variables. Thus glider dynamic system is controllable and observable.

SIMULATION RESULTS

In order to verify the effectiveness of full state observer, the gliding angle and velocity of the glider is checked by adding a disturbance as a measurement noise $v(t)$ with normal random signal with mean $\mu=0$ and standard deviation $\sigma=0.01$ was added to the input for gliding angle and velocity. The results are compared with disturbance and without disturbance. Figure-7 shows the gliding angle at various buoyancy rates. The glider stabilizes quickly after 20 s at higher buoyancy rates.

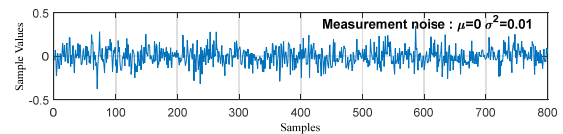
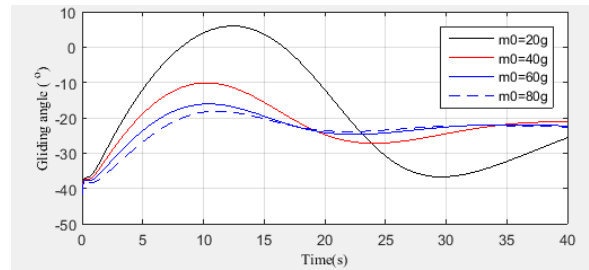


Figure-6. Input signal for measurement noise at 800 sample rates.

Figure-7. Open loop response of gliding angle θ_g with different pump rates.

As shown in the Figures-8 and 9, the high observer gain makes the system very sensitive.

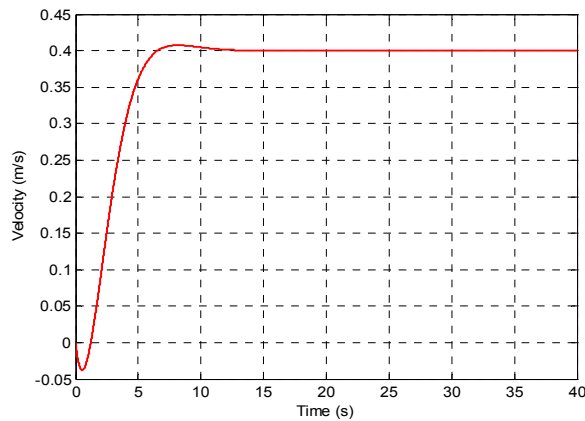


Figure-8. Velocity of the glider with full state feedback controller.

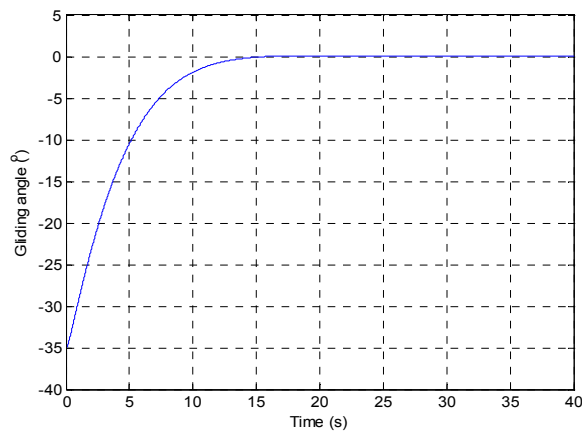


Figure-9. Response of the gliding angle using full state feedback

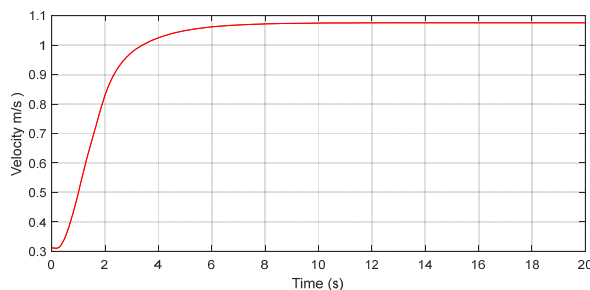


Figure-10. Response of velocity in the presence of noise.

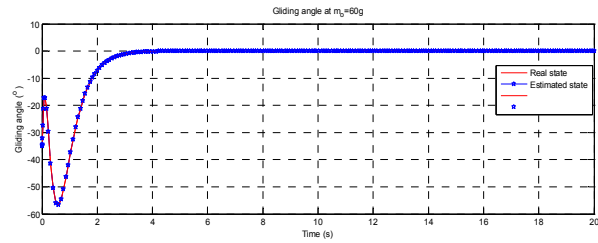


Figure-11. Response of the gliding angle using full state observer.

The simulation is carried out using close loop state feedback system with observer estimation. The adjustable input net buoyancy m_0 keep the value for the first 2.5 seconds at its initial peak value and then the pumping rate gradually decreases. The glider motion is controlled through the change of net buoyancy using linear actuators. Buoyancy of the gliders is checked at different values of pumping rate peak values i.e. (20g, 40g, 60g, 80g) with respect to linear actuator as shown in Figure 4. The other state variables such as gliding angle and angle of attack is changing as the pumping rate is changed. This idea is taken from SLOCUM glider in which the pitch is adjusted by changing the center of gravity.

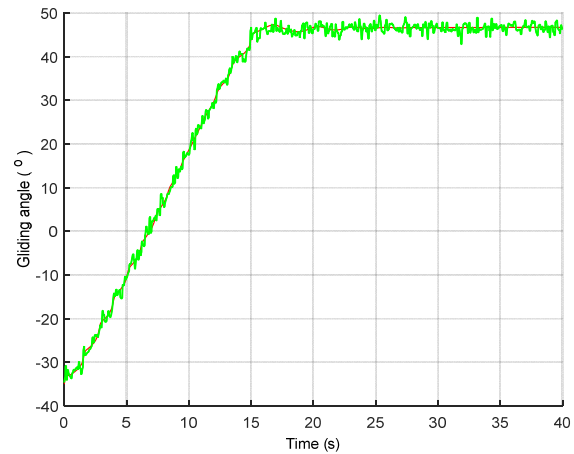


Figure-12. Closed loop response of gliding angle at standard deviation $\sigma=0.01$ and mean $\mu=0$.

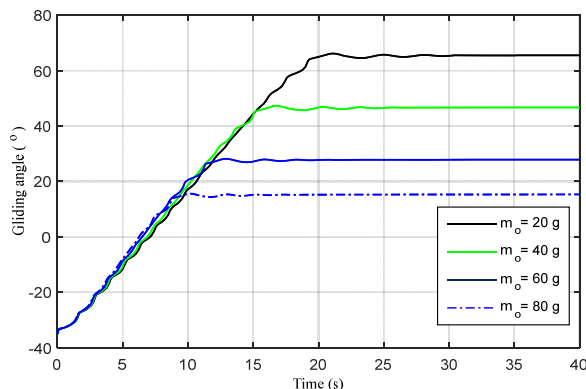
However, different researchers have used different pumping rate according to its desired trajectory which is mentioned in Table-2.

**Table-2.** Different underwater gliders with main specifications.

Gliders	Payload (kg)	Speed (m/s) Range (km)	Weight (kg)	Net buoyancy (g)
Slocum (battery)	3 - 4	0.4 1500	52	520
Spray [11]	3.5-51.8	0.25 7000	51	900
Seaglider [11]	25	0.25 4600	52	840
Deep-glider [11] [12]	25	0.25 8500	62	-
Slocum (thermal) [13]	2	0.4 40000	60	235
Liberdade XRAY glider [14]	850	0.514-1.54 1500	-	-

Major limitation and challenges

There are several things that must be given careful treatment. The main attempt is to choose a controller that can guarantee fast convergence and track the desired path with minimum overshoot value in the presence of external disturbance. An appropriate control strategy is required that will follow desired trajectory with minimum error for varying payloads.

**Figure-13.** Gliding angle at different pump rates at equilibrium.**CONCLUSION AND FUTURE WORK**

Observer based full state feedback controller was developed to investigate the dynamics of the system including ballast rate as an input and gliding angle was estimated through observer. Apart from this, the response of the angle of attack against the net buoyancy is also observed. Based on the observer based controller, further investigation can be carried out to estimate the pitch angle when response is taken from on-board sensors of underwater glider during the glide operation and then the real state and estimated state can be compared using nonlinear observer system. Furthermore, the analysis can be improved by implementing advanced controller techniques such as adaptive sliding mode controllers.

In future work, nonlinear observer based closed loop response by using a robust control technique will be examined.

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