Ullah et al. 2018. *Int. J. Vehicle Structures & Systems*, 10(2), 137-141
ISSN: 0975-3060 (Print), 0975-3540 (Online)
doi: 10.4273/ijvss.10.2.12

International Journal of Vehicle Structures & Systems
Available online at www.maftree.org/eja

Pitch and Depth Control of Underwater Glider using LQG and LQR via Kalman Filter

B. Ullah[a], M. Ovinis[a,c], M.B. Baharom[a], S.S.A. Ali[b] and M.Y. Javaid[a]

[a]*Dept. of Mech. Engg., Universiti Teknologi Petronas, Malaysia*
[b]*Dept. of Electrical Engg., Universiti Teknologi Petronas, Malaysia*
[c]*Corresponding Author, Email: mark_ovinis@utp.edu.my*

ABSTRACT:

Underwater gliders are adversely affected by ocean currents because of their low speed, which is compounded by an inability to make quick corrective manoeuvres due to limited control surface and weak buoyancy driven propulsion system. In this paper, Linear Quadratic Regulator (LQR) and Linear Quadratic Gaussian (LQG) robust controllers are presented for pitch and depth control of an underwater glider. The LQR and LQG robust control schemes are implemented using MATLAB/Simulink. A Kalman filter was designed to estimate the pitch of the glider. Based on the simulation results, both controllers are compared to show the robustness in the presence of noise. The LQG controller results shows good control effort in presence of external noise and the stability of the controller performance is guaranteed.

KEYWORDS:

Underwater glider; Linear quadratic regulator; Linear quadratic Gaussian; Longitudinal stability; Kalman filter

CITATION:

B. Ullah, M. Ovinis, M.B. Baharom, S.S.A. Ali and M.Y. Javaid. 2018. Pitch and Depth Control of Underwater Glider using LQG and LQR via Kalman Filter, *Int. J. Vehicle Structures & Systems*, 10(2), 137-141. doi:10.4273/ijvss.10.2.12.

1. Introduction

Underwater gliders can autonomously glide, covering large horizontal distances at low power consumption. The glider design consists of an elliptical hull with a couple of wings which may be fixed such as in Slocum [1] glider or movable such as in Alex [2], depending upon requirements of manoeuvrability. A rudder is fixed at the end but in some hybrid underwater vehicles, the rudder is movable such as a robotic fish [3]. An internal moving mass (typically an internal battery) is used to vary the pitch while a ballast tank is used to vary the buoyancy [4, 5]. Two types of ballasts are used inside gliders. In the first type, oil is pumped into and out from one bladder to the other one inside the hull [6]. The other type of glider uses a ballast tank of piston cylinder and the water is pumped in and out of the glider [4]. The vehicle buoyancy is made either positive or negative due to pumping out oil from one bladder to the other. Control inputs for a glider are internal actuator moving mass, position of the moving linear mass and secondary moving mass for roll control.

Gliders are usually modelled as a multi body system with a combination of internal moving masses, wings and hull. There have been many control schemes to control the pitch and depth of the glider, such as linear [7] and nonlinear control [8]. A buoyancy driven underwater glider with controllable wing was modelled by [2]. Among the control schemes that were implemented to control the motion of underwater glider are PID, state feedback; Linear Quadratic Regulator (LQR), adaptive fuzzy sliding mode controller and neuro-fuzzy system [9-12]. Robust controllers are required to track the desired trajectory with improved performance when controlling pitch and depth of a glider in a variable environment, which is subjected to underwater disturbances and sensor noise (usually modelled as stochastic white noise). Linear Quadratic Gaussian Control (LQG) compensates Gaussian white noise disturbances acting on the system [13]. In our previous work [14], we have determined the hydrodynamic coefficients of the UTP underwater glider and modelled its dynamics.

In this paper, the pitch and depth control of the glider is presented. With the varying surface of water level with tides during sea trails, level of water during pressure sensor calibration can be different [15]. As a result, there are some variations that occurred in estimating the actual depth, so Kalman filter is used for estimating actual depth by considering Gaussian white noise. The controller designed for pitch and depth of the glider is to maintain the desired pitch and depth at desired value which can be achieved by reducing the error signal. An optimal state feedback controller has been designed and simulation work is performed using MATLAB/Simulink.

2. Kinematic model

Motion of a glider is characterized in body and inertial frame coordinates system. The body frame coordinates are mentioned in Table 1. The surge velocity is taken along x-axis while the sway velocity is taken along y-axis as shown in Fig 1.

Table 1: Body frame and earth frame

DOF	Description	Position (Earth-Fixed)	Velocities (Body-Fixed)	Forces & Moments (Body-fixed)
1	Surge (x-direction)	x	u	X
2	Sway (y-direction)	y	v	Y
3	Heave (z-direction)	z	w	Z
4	Roll motion (Rotation about x-axis)	Φ	p	K
5	Pitch motion (Rotation about y-axis)	ϴ	q	M
6	Yaw motion (Rotation about z-axis)	ψ	r	N

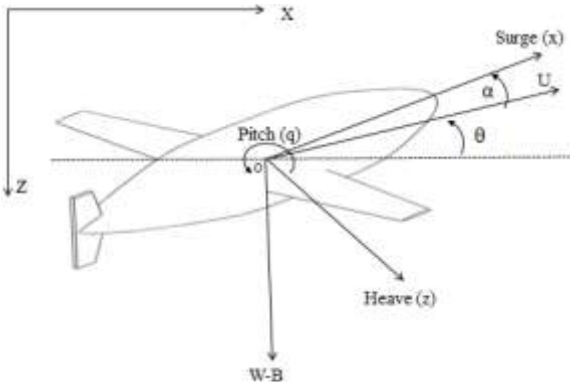

Fig. 1: Co-ordinates of the glider

The heave presents vertical velocity along z-axis. The position of glider in body reference is denoted as, $b = [x \quad y \quad z]^T$, where b is the position vector from the origin of the inertial frame to the origin of the body frame. The translational velocity and angular velocity vector is represented as, $v = [u \quad v \quad w]^T$. The position of the center of buoyancy (CB), r_b and the primary moving mass r_p and the variable ballast mass r_b are,

$$r_b = [0 \quad 0 \quad 0]^T \tag{1}$$

$$r_p = [r_{p^1} \quad 0 \quad r_{p^3}]^T \tag{2}$$

The linear velocity v,

$$v = [v_1 \quad 0 \quad v_3]^T \tag{3}$$

Angular velocity Ω in body frame co-ordinates are defined as,

$$\Omega = [\Omega_1 \quad \Omega_2 \quad \Omega_3] \tag{4}$$

The body reference frame is converted into inertial frame as follows,

$$R = \begin{bmatrix} c\psi c\theta & -s\psi c\theta + c\psi s\theta s\psi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\psi \\ -s\theta & c\theta s\psi & c\theta c\phi \end{bmatrix} \tag{5}$$

3. Dynamic model

In this section, the nonlinear coupling between vehicle's central moving fixed mass and variable ballast mass is described. The nonlinear dynamics equations and control law design is limited to vertical plane and adopted from [1]. The equations of motion are derived in inertial frame of reference and described in two coordinates, inertial frame and body frame (See Fig. 1). The hull is ellipsoidal with fixed wings. The position of the glider is estimated by using a well-developed dynamic model and by reducing measurement errors as modelled by Fossen [2]. In this model, the ocean currents such as environmental disturbances (wind, waves) which effect the glider position and motion are considered in the form of Gaussian white noise. In the dynamic model, the disturbances that are produced due ocean currents (wind waves) are added and approximated by applying principle of superposition. Some researchers used dynamic equations for gliders [3-4] but the environmental disturbances are considered only for linearized dynamic equations as follows,

$$X = m\begin{bmatrix} \dot{u} + wq - vr - x_G(q^2 + r^2) \\ + y_G(-\dot{r} + pq) + z_G(\dot{q} + pr) \end{bmatrix} \tag{6}$$

$$Y = m\begin{bmatrix} \dot{v} + wp - ur - y_G(r^2 + p^2) \\ + z_G(-\dot{p} + qr) + x_G(\dot{r} + qp) \end{bmatrix} \tag{7}$$

$$Z = m\begin{bmatrix} \dot{w} - (-vp + wq) - z_G(p^2 + q^2) \\ + x_G(rp - \dot{q}) + y_G(\dot{p} + rp) \end{bmatrix} \tag{8}$$

Eqn. (6)-(8) are derived from Newton's Euler motion equations and rearranged by Fossen [2]. The values of external forces (X, Y, Z) and moments (K, M, N) are computed in Eqn. (12) in a matrix form as follows,

$$K = I_{xx}\dot{p} - (I_{yy} - I_{zz})qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] \tag{9}$$

$$M = I_{yy}\dot{q} + (I_{xx} - I_{zz})rp + (qr - \dot{p})I_{xy} + (p^2 - r^2)I_{xz} + (qp - \dot{r})I_{yz} + m[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)] \tag{10}$$

The external forces are the sum of hydrostatic, hydrodynamic and control forces. Eqns. (6-8) represent translational motions and Eqns. (9-11) represents rotational motions as follows,

$$N = I_{zz}\dot{r} + (I_{yy} - I_{xx})pq + (q^2 - p^2)I_{xy} - (\dot{q} + rp)I_{yz} + (rp - \dot{p})I_{xz} + m[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)] \tag{11}$$

The hydrostatic forces are, restoring forces, gravitational forces and moments as given by,

$$\begin{bmatrix} X \\ Y \\ Z \\ K \\ M \\ N \end{bmatrix} = \begin{bmatrix} (W - B)\sin\theta \\ (-W + B)\sin\varphi\cos\theta \\ (-W + B)\cos\varphi\cos\theta \\ (-y_G W + y_b B)\cos\varphi\cos\theta + (z_g W - z_b B)\sin\varphi\cos\theta \\ z_g W\sin\theta - z_b B\sin\theta + (x_g W - x_b B)\cos\theta\cos\varphi \\ (-x_g W + x_b B)\cos\theta\sin\varphi + (y_g W\sin\theta - y_b B\sin\theta) \end{bmatrix} \tag{12}$$

Here, W is the weight of the glider and the net buoyancy force B is given by,

$$B = \rho g V \tag{13}$$

In this Eqn., g is gravity force, ρ is the density of water and m is the mass of the glider. For UTP underwater glider, buoyancy force is designed to be slightly positive but in most of the cases, the glider is neutrally buoyant: (B=W). Eqns. (6 - 11) are written in more simplified form for vertical plane and all unrelated variables [r, p, and v], higher order terms are put to zero. The effect of drag components over pitch rate is also neglected.

The hydrodynamic forces and moments are,

$$m[\dot{u}+z_g\dot{q}]=X_u u-(W-B)\cos\theta \tag{14}$$

$$m[\dot{w}-x_g\dot{q}]=Z_w w+Z_q q-(W-B)\sin\theta+Z_{\delta s}\delta_s \tag{15}$$

$$I_{yy}\dot{q}+m[z_g\dot{u}-x_g\dot{w}]=M_w w+M_q q-z_g W\cos\theta+M_{\delta s}\delta_s \tag{16}$$

Xu, Zu, and Mt are glider parameters e.g. added masses, body lift, moment, drag, etc. After linearization, Eqns. (14 - 16) transform for pitch control model,

$$(m-z_w)\dot{w}-(mx_g+z_{\dot{q}})\dot{q}-z_w w-(mu_1+z_q)q=z_{\delta t}f_s \tag{17}$$

$$-(mx_g+M_{\dot{w}})\dot{w}+(I_y-M_{\dot{q}})\dot{q}-M_w w+(mx_g u_1-M_q)q-M_\theta\theta=M_t\delta_s \tag{18}$$

$$\dot{\theta}=q \tag{19}$$

Where M, Z and X are glider parameters e.g. $M_{\dot{w}}, M_{\dot{q}}, Z_{\dot{w}}, Z_{\dot{q}}$ are added masses due to body, wings, lift and drag forces. The stability derivatives are,

$$X_u=-\rho v S_h C_D$$
$$X_w=-\frac{1}{2}\rho(S_H(C_{L\alpha\alpha}+C_{D0H})+S_w(2C_{L\alpha\alpha})) \tag{20}$$

Eqns. (17-19) can be further simplified when sway velocity is neglected and Eqns. for depth control are obtained as follows,

$$\begin{bmatrix} I_y-M_{\dot{q}} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix}+\begin{bmatrix} -M_q & 0 & M_\theta\theta \\ 0 & 0 & u_1 \\ -1 & 0 & 0 \end{bmatrix}\begin{bmatrix} q \\ z \\ \theta \end{bmatrix}=\begin{bmatrix} M_f \\ 0 \\ 0 \end{bmatrix} \tag{21}$$

The linearized model is used for plotting the response of pitch and depth of the glider using state feedback control and LQR in the presence of external noise in MATLAB/Simulink. The simulation is carried out for the UTP glider having length 1.03m and maximum diameter of 0.28m with 0.98m wings span and weight is 40kg. Eqns. (17-19) and matrix representation in Eqn. (21) are further used for pitch control using transfer function as follows,

$$G_{\theta(s)}=\frac{\theta(s)}{M_f(s)}=\frac{\frac{M_{fs}}{I_y-M_{\dot{q}}}}{s^2-\frac{M_q}{I_y-M_{\dot{q}}}s-\frac{M_\theta}{I_y-M_{\dot{q}}}} \tag{22}$$

The outer loop transfer function for depth control relates the θ_{des} to z. θ_{des} is assumed to be equal to θ, so the transfer function becomes;

$$G_z(s)=\frac{z(s)}{\theta(s)}=\frac{-u_1}{s} \tag{23}$$

Hydrodynamic parameters of UTP glider are mentioned in Table 2.

Table 2: Hydrodynamic parameters of UTP glider [14]

Parameter	Value	Parameter	Value
M_q	5.379	Z_q	-20.0968
I_{yy}	0.192	M_w	-6.0057
Z_w	85.2791		

4. Controller design

The state feedback controller is designed based on the pole placement technique. We assume that the glider's states are measurable and available for feedback. The controllability of the glider is checked, and it is observed that the glider is controllable for feedback. The poles of the closed system are placed at the desired depth of the glider by means of state feedback through a state feedback gain matrix. Robust pole placement technique is followed to determine the desired closed loop poles. The desired closed loop poles are taken as J = [-0.8, -0.9, -0.2, -0.3]. A generalized system given in state space form can be stated as,

$$\dot{x}(t)=Ax(t)+Bu(t)+B_v v(t) \tag{24}$$

$$y(t)=Cx(t) \tag{25}$$

Two types of controllers are used for this system. The system is linearized, where u(t) is the input signal which is the force required for regulating the ballast tank and v(t) is a disturbance signal. A Linear Quadratic Regulator (LQR) is designed and nonlinear equations of motions are linearized for vertical plan. The weighing matrices in LQR design are tuned and are used as inputs for controller. The algebraic Riccati Eqn. is used for calculating gain matrix [6],

$$PA+A^TP-PBQ_u^{-1}B^TP+Q_x=0 \tag{26}$$

P is positive semi definite function and K is calculated from LQR command in MATLAB. Q_u and Q_x are calculated from diagonal matrices making all other element to zero. K_r is calculated from the system model.

To drive the steady state error to zero, an integral action has been augmented in the state feedback system matrix. This method is similar to that of a PID controller. The controller can compensate for small output deviations from the reference signal. The augmented matrix is described as,

$$\begin{bmatrix} \dot{x}(t) \\ \dot{z}(t) \end{bmatrix}=\begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix}\begin{bmatrix} x(t) \\ z(t) \end{bmatrix}+\begin{bmatrix} B \\ 0 \end{bmatrix}u(t)+\begin{bmatrix} 0 \\ I \end{bmatrix}r(t) \tag{27}$$

The new control law for the augmented matrix is,

$$u(t)=-Kx(t) \tag{28}$$

K increases if ρ is increased. *Q(t)* is square symmetric matrix called state weighing matrix and *R(t)* is the square matrix known as control cost matrix. The values of *Q* are set to,

$$Q=C^TC \tag{29}$$

The state space matrices from the transfer function (22 - 23) are used in Simulink model Fig. 2 and the results for state feedback controller for pitch and depth are shown in Figs. 3 and 4 respectively. The weighing matrices *Q* and *R* are tuned, and the control gain matrix *K* has been calculated as,

$$K=\begin{bmatrix} -0.0699 & 0.0516 & 0.0172 & 0.0250 \end{bmatrix} \tag{30}$$

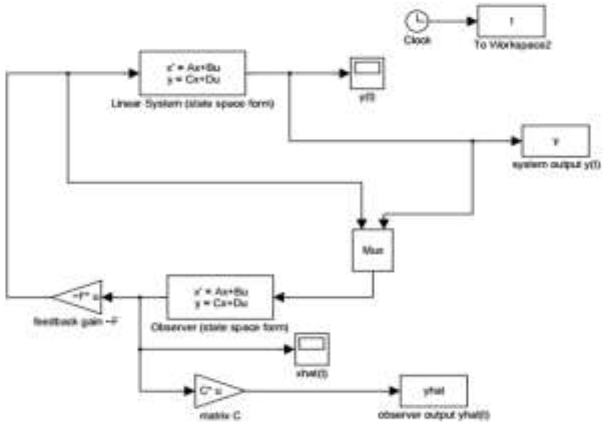

Fig. 2: Full state feedback with observer

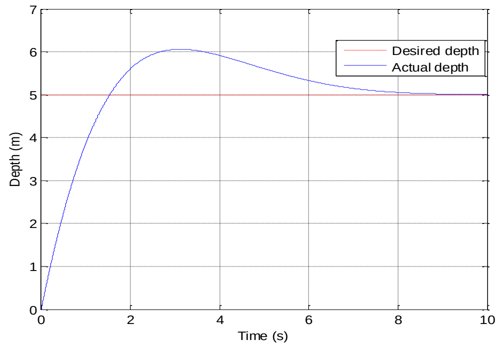

Fig. 3: Depth control of AUG

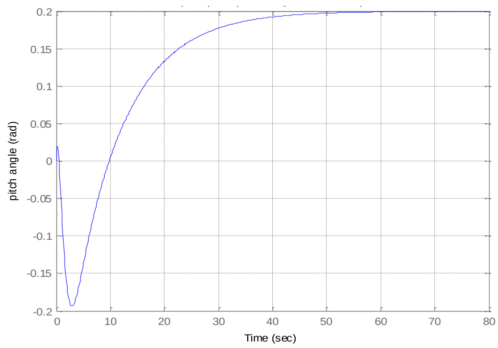

Fig. 4: Closed loop step response for pitch control with full state feedback control

5. Linear quadratic Gaussian controller

The LQG regulator consists of optimal state feedback gain and Kalman state estimator. It enables one to regulate performance and control effort and considers measurement of Gaussian white noise. The LQG regulator, Kalman filter and LQ-optimal gain K are shown in Fig. 5. Kalman filter regulator has the following state space Eqns.,

$$\frac{d}{dt}\hat{x} = [A - LC]\hat{x} - [(B - LD)K\hat{x} - Ly_v] \qquad (31)$$

$$u = -Kx$$

The filter is used to regulate the output **y** around zero subjected to external disturbances $y_v = y + v$. The plant state equations are of the form,

$$\dot{x} = Ax + Bu + Gw$$

$$y_v = Cx + Du + Hw + v \qquad (32)$$

Where *w* and *v* are modelled as Gaussian white noise.

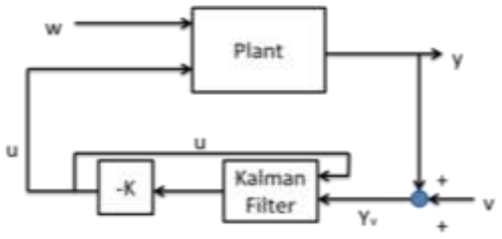

Fig. 5: Kalman filter block diagram

LQG optimal control regulation is measured by the quadratic cost function as:

$$J(u) = \int_0^\infty \{x^T Qx + 2x^T Nx + u^T Ru\} \qquad (33)$$

A state estimator $\hat{x}$ is derived such that $u = -k\hat{x}$ remains optimal for output feedback response. The sate estimator is generated by Kalman filter in the presence of external noise,

$$\frac{d}{dt}\hat{x} = A\hat{x} + Bu + L(y_v - C\hat{x} - Du) \qquad (34)$$

With input u and measurement noise y_v, the noise covariance data E(wwT) = Qn, E(vvT) = Rn, E(wvT) = Nn determines the Kalman gain L through algebraic Riccati Eqn., which deals with Gaussian white noise. The asymptotic covariance is minimized by the estimator error $x - \hat{x}$.

The response of Gaussian white noise with specified mean and variance is shown in Fig. 6. The simulation result in Fig. 7 shows the pitch of the glider without noise. Fig. 8 compares the measurement error for pitch angle using different controllers. The result shows that the noise level has been successfully filtered out and reduced to zero at first 2.5 seconds (dashed line).

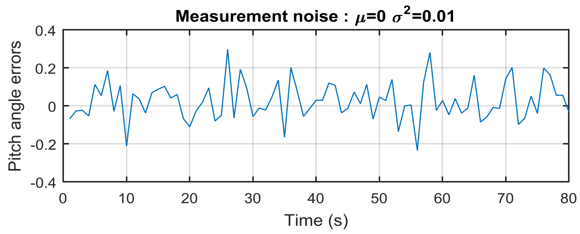

Fig. 6: Pitch angle with steady shift error using Gaussian white noise

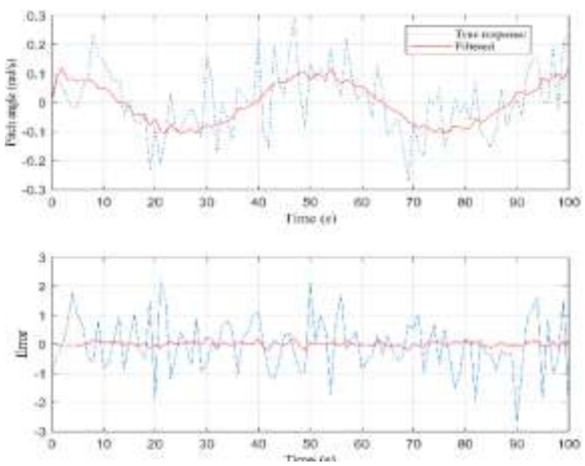

Fig. 7: Pitch angle response using Kalman filter

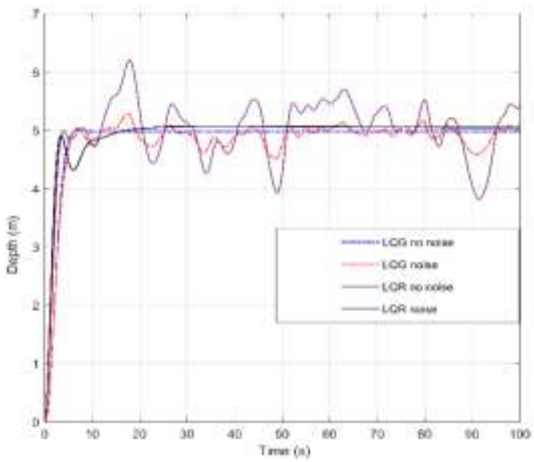

Fig. 8: Comparison between LQG and LQR with and without noise for depth control of underwater glider

6. Conclusion

The simulation results show that by manipulating noise covariance matrices, both LQR and LQG give satisfactory results for depth control. However, the uncertainty of depth increases in the presence of noise when LQR controller is used. LQG shows relatively better response in terms of overshoot and settling time.

ACKNOWLEDGMENTS:

Authors are thankful to Universiti Teknologi PETRONAS for providing the resources required for this research work.

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