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Improvement in ROV Horizontal Plane Cruising Using Adaptive Method

M. Hosseini
Elec. Eng. Dept.
Imam Khomeini Univ.
Nowshar, Iran
Email: seied64@yahoo.com

S. Seyedtabaii
Elec. Eng. Dept.
Shahed University
Tehran, Iran
Email: stabaii@shahed.ac.ir

Abstract—**Control of underwater remotely Operated Vehicles (ROVs) is challenging due to its highly nonlinear nature, strong coupling among variables and disturbances. Performance improvement is expected if adaptive methods are used to observe time varying model factors resulting from working point condition alteration. In this respect, feedback linearization and model reference adaptive control (MRAC) algorithms are integrated to form a control strategy for administering the horizontal plane cursing of the vehicle. The algorithm achievement is compared with what conventional PID controllers render in term of transient and steady state behavior. Extensive simulations conducted confirm the promising favorable results of the arrangement.**

Keywords-ROV Control, Feedback Linearization, adaptive control law, MRAC.

I. INTRODUCTION

Nowadays, remotely operated vehicles (ROVs) are the basic elements in missions for marine science, underwater gas and oil exploration, extraction, monitoring and salvage operations [1]. ROV is generally directed from the surface using a Surface Control Unit (SCU) where a human pilot administers the vehicle through a link cord which provides both its power and communication data. However, demand for an autonomous system is increasing due to its lower operational cost compared to manned vessels.

Precise execution of tasks such as auto-depth tuning, path tracking, station-keeping and auto-heading requires feedback control. ROV control, however, confronts three basic challenges: (1) Parametric uncertainties (2) Measurement noise and (3) disturbance resulted from underwater current and waves.

Practically, most of the industrial underwater robots use Proportional Integral Derivative (PID) controller due to its simplicities. An example of PID control of ROV has been detailed in [1].

However, precise functioning requires advanced measures and provisions to cope with system disturbances, nonlinearities and measurement errors. In this regard, employing adaptive methods have been reported in [2] [3]. Using fuzzy technique is the subject of investigation in [4]. Sliding mode control (SMC) has been examined for ROV path tracking in [5] [1]. Adaptive SMC has also been analyzed in [2]. In [6] a Model-Free High Order Sliding Mode Control is proposed. Adaptive neuro-fuzzy sliding mode algorithm is another technique for accurate achievement of the tasks that has been suggested in [7]. Application of adaptive fuzzy sliding mode is also detailed in [8].

In this paper, improvement in transient behavior of ROV during missions in horizontal plane is investigated. By employing feedback linearization, nominal nonlinearity and coupling among variables are bypassed and separate linear dynamical equations are derived for surge, sway and heading operations. The uncertainty and disturbances are administered using Model Reference Adaptive Control (MRAC). MRAC is also considered for enforcing the required transient behavior. Stability proof is presented which establishes the required conditions for guarantying asymptotical stability.

This paper is organized as follows. In Section II the dynamical model of ROV is briefly described. Control design consisting of feedback linearization, MRAC and its stability proof are covered in Section III. Simulation results are illustrated in Section IV and lastly conclusion comes in section V.

II. ROV DYNAMICS

A typical ROV has been shown in Fig. 1. It is equipped with 4 thrusters. T_{x1} and T_{x2} govern the surge movement, the sway motion is functioned by T_y, Tz conducts the heave operation and yaw rotation is performed by T_{x1}-T_{x2}.

The time-varying, coupled, nonlinear and uncertain in parameters dynamic model of ROV with respect to the local body-fixed reference frame, in matrix form, is given by [6],

$$\begin{aligned} &J\dot{X}_b + C(X_b)X_b + D(X_b)X_b + g(X_E) = F + F_d \\ &F^T = [F^x \quad F^y \quad F^z \quad T^k \quad T^m \quad T^n] \\ &X_b^T = [u \quad v \quad w \quad p \quad q \quad r] \end{aligned} \tag{1}$$

The body-fixed frame is bonded to ROV where its center is normally at the centre of gravity. In (1), X_b is the body frame state vector expressing linear (surge, sway and heave)

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velocities and angular (roll, pitch and yaw) rates shown in Fig. 1. F is the vector of forces and torques generated by the thrusters and F_d is a vector expressing the environment disturbances.

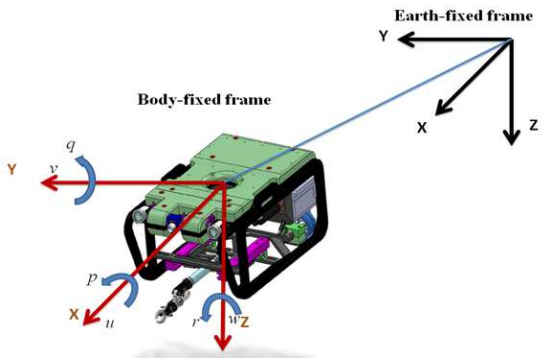

Figure 1. Body and Earth frames coordinates of an underwater vehicle [6]

The other parameters J, $C(X_b)$, $D(X_b)$ and $g(X_E)$ are defined as below,

$$M = diag\begin{bmatrix} m - F_{\dot{u}}^{x} \\ m - F_{\dot{v}}^{y} \\ m - F_{\dot{w}}^{z} \\ I_{xx} - T_{\dot{p}}^{k} \\ I_{yy} - T_{\dot{q}}^{m} \\ I_{zz} - T_{\dot{r}}^{n} \end{bmatrix} \qquad D(V) = -diag\begin{bmatrix} F_{u}^{x} + F_{u|u|}^{x}\,|u| \\ F_{v}^{y} + F_{v|v|}^{y}\,|v| \\ F_{w}^{z} + F_{w|w|}^{z}\,|w| \\ T_{p}^{k} + T_{p|p|}^{k}\,|p| \\ T_{q}^{m} + T_{q|q|}^{m}\,|q| \\ T_{r}^{n} + T_{r|r|}^{n}\,|r| \end{bmatrix}$$

$$c(V) = \begin{bmatrix} 0 & 0 & 0 & 0 & M(3)w & -M(2)v \\ 0 & 0 & 0 & -M(3)w & 0 & M(1)u \\ 0 & 0 & 0 & M(2)v & -M(1)u & 0 \\ 0 & M(3)w & -M(2)v & 0 & M(1)u & -M(5)q \\ -M(3)w & 0 & M(1)u & -M(6)r & 0 & M(5)q \\ M(2)v & -M(1)u & 0 & M(5)q & -M(4)p & 0 \end{bmatrix}$$

$$g(X_E) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -(y_G - y_B)\cos\theta\cos\varphi + (z_G - z_B)\cos\theta\cos\varphi \\ (z_G - z_B)\sin\theta + (x_G - x_B)\cos\theta\cos\varphi \\ -(x_G - x_B)\cos\theta\cos\varphi - (y_G - y_B)\sin\theta \end{bmatrix} mgx$$

Beside, the vector $X_E=[x, y, z. \phi, \theta, \psi]$ describes the Earth frame state variables: the vehicle x, y and z position and roll, pitch and yaw angles. The relation between speed in the body and Earth frames is expressed by,

$$\dot{X}_E = J(X_E)X_b$$

where $J(X_E)$ is the transformation matrix converting variables from the body fixed frame to the Earth-fixed frame. The equation of motions describing the ROV cruising in the horizontal plane is given by:

$$\begin{aligned} \dot{p}_n &= u\cos\psi - v\sin\psi \\ \dot{p}_e &= u\sin\psi + v\cos\psi \\ \dot{\psi} &= r \\ \dot{u} &= \frac{1}{M(1)}\left[F^x + M(2)vr - D(1)u\right] \\ \dot{v} &= \frac{1}{M(2)}\left[F^y + M(1)ur - D(2)v\right] \\ \dot{r} &= \frac{1}{M(6)}\left[T^n - M(2)vu + M(1)uv + -D(6)r\right] \end{aligned}$$

In state space form, the dynamical equations are expressed by:

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= h(x) \end{aligned} \qquad (2)$$

$$x = \begin{bmatrix} p_n \\ p_e \\ \psi \\ u \\ v \\ r \end{bmatrix}, \qquad u = \begin{bmatrix} F^x \\ F^y \\ T^n \end{bmatrix}, \qquad y = h(x) = \begin{bmatrix} p_n \\ p_e \\ \psi \end{bmatrix}$$

III. CONTROL LAWS DESIGN

A. Feedback linearization

In order to obtain SISO forms for the three channels, feedback linearization method is employed. The relative degree of (2) with respect to the defined h(x) is two. Therefore by feedback linearization, equation (2) is transformed to the following linear system equation,

$$\begin{bmatrix} \dot{p}_n \\ \ddot{p}_n \\ \dot{p}_e \\ \ddot{p}_e \\ \dot{\psi} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_n \\ \dot{p}_n \\ p_e \\ \dot{p}_e \\ \psi \\ \dot{\psi} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$$

where v is a fraction of the control force, u, given as below,

$$u = \frac{1}{diag(L_g L_f h(x))}\left[v - L_f^2 h(x)\right] = Q^{-1}(-P + v)$$

$$v = \begin{bmatrix} v_1 & v_2 & v_3 \end{bmatrix}^T$$

L stands for the Lie derivative which is defined by,

$$L_f h(x) = \frac{dh(x)}{dx} f(x)$$

B. Model reference adaptive control (MRAC)

The v portion of the control force is equivalent to the acceleration command provided by the MRAC algorithm, namely,

$$\ddot{y}_{pi} = v_i, \qquad i = 1,2,3$$

for surge (i=1), sway (i=2) and heading (i=3). MRAC configuration has been depicted in Fig. 2.

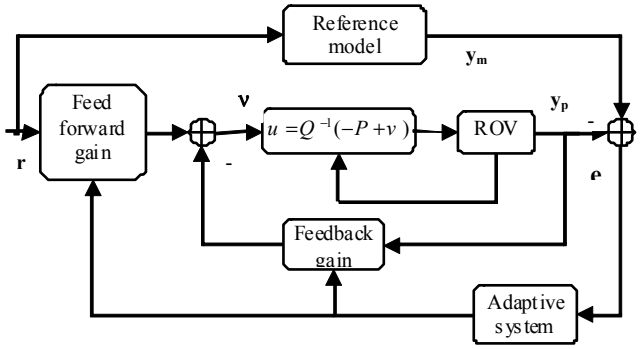

Figure 2. MRAC adaptive block diagram

Considering surge motion, as an example, a second order reference model is assigned as follows,

$$\ddot{y}_m + a_1\dot{y}_m + a_0 y_m = a_r r$$

where the parameters α_0, α_1 and b determine the type of the desired transient response. The adjustable control law is defined as given below,

$$v_1 = k_r r + k_0 y_p + k_1 \dot{y}_p \tag{3}$$

where k_r is the feed forward gain, r is the reference input, k_0 and $k_1$are the feedback gains. MRAC adjusts the parameters k_r, k_0, and k_1 so that the system output is forced to track the output of the reference model.

To enforce zero model reference tracking, the error function $e=y_m-y_p$ is introduced and the error dynamics is formed,

$$\begin{aligned}&\left(\ddot{y}_m - \ddot{y}_p\right) + a_1\dot{y}_m + k_1\dot{y}_p + a_0 y_m + k_0 y_p = r(a_r - k_r)\\ &\Rightarrow \ddot{e} + a_1\dot{e} + a_0 e = -(a_1+k_1)\dot{y}_p - (a_0+k_0)y_p + r(a_r - k_r)\end{aligned} \tag{4}$$

by taking

$$\delta_1 = -(a_1+k_1), \qquad \delta_0 = -(a_0+k_0), \qquad \delta_r = (a_r - k_r) \tag{5}$$

Equation (4) is rewritten in state space form as follows,

$$\begin{aligned}&\ddot{e} + a_1\dot{e} + a_0 e = \delta_1\dot{y}_p + \delta_0 y_p + \delta_r r \Rightarrow\\ &\dot{\varepsilon} = A\varepsilon + B\theta\end{aligned}$$

where

$$A = \begin{bmatrix} 0 & 0 \\ -a_0 & -a_1 \end{bmatrix}, \qquad B = \begin{bmatrix} 0 & 0 & 0 \\ y_p & \dot{y}_p & r \end{bmatrix}$$

$$\varepsilon = \begin{bmatrix} e & \dot{e} \end{bmatrix}^T, \theta = \begin{bmatrix} \delta_0 & \delta_1 & \delta_r \end{bmatrix}^T$$

C. Stability and control law

For maintaining the stability of the adaptive algorithm the following Lyapunov function is introduced,

$$V = \tfrac{1}{2}\left[\varepsilon^T P \varepsilon + \theta^T \Gamma \theta\right]$$

where P is a symmetric 2*2 and Γ is 3-dimensional diagonal positive definite matrixes as follows,

$$P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}, p_{12} = p_{21}, \quad \Gamma = diag(\lambda_0, \lambda_1, \lambda_r)$$

The time derivative of V is calculated as follows,

$$\begin{aligned}\dot{V} &= \varepsilon P \dot{\varepsilon} + \theta P \dot{\theta} = \varepsilon P\left[-A\varepsilon + B\theta\right] + \theta\Gamma\dot{\theta}\\ \dot{V} &= -\varepsilon P A \varepsilon + \varepsilon P B \theta + \theta\Gamma\dot{\theta}\end{aligned}$$

By considering the following adaptive law

$$\dot{\theta} = -\frac{\varepsilon P B}{\Gamma} \tag{6}$$

$\dot{V}$ gets negative definite and asymptotical stability is established.

$$\dot{V} = -\varepsilon P A \varepsilon \le 0$$

Now the required values for the adaptive control parameters are determined from (6) as follows.

$$\begin{aligned}\dot{\delta}_0 &= -\frac{(p_{12}e + p_{22}\dot{e})}{\lambda_0} y_p\\ \dot{\delta}_1 &= -\frac{(p_{12}e + p_{22}\dot{e})}{\lambda_1} \dot{y}_p\\ \dot{\delta}_r &= -\frac{(p_{12}e + p_{22}\dot{e})}{\lambda_r} r\end{aligned} \tag{7}$$

By taking the derivative of each equations of (5) with respect to time while considering (7), the adaptive laws, the feedback gains k_0, k_1 and feedforward gain k_r are determined,

$$k_0 = \frac{1}{\lambda_0}\int_0^t \left(p_{12}e + P_{22}\dot{e}\right)y_p d\tau + k_0(0)$$
$$k_1 = \frac{1}{\lambda_1}\int_0^t \left(p_{12}e + p_{22}\dot{e}\right)y_p d\tau + k_1(0) \qquad (8)$$
$$k_r = \frac{1}{\mu}\int_0^t \left(p_{12}e + p_{22}\dot{e}\right)r d\tau + k_r(0)$$

The MRAC laws for y position and yaw channels can be designed in the same way.

D. PID control design

For the simplified model of yaw channel, PID control law is calculated. The PID control law is

$$u_1 = k_1 e + k_2\int_0^t e dt + k_3\dot{e}$$

where e is the error between the reference input and system output and k_1, k_2, k_3 are gains of the PID controller. Similarly, this is done for the control of y and position. Fig. 3 shows the block diagram of the system using PID controller.

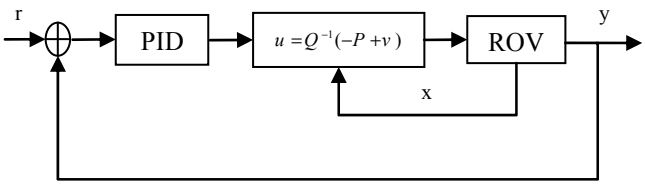

Figure 3. PID control system diagram.

IV. PATH FOLLOWING SIMULATIONS

Consider an ROV with the following parameters borrowed from the real ROV investigated in [6].

Moments of inertia:

$$I_{xx} = 1.32Kgm^2, \qquad I_{xy} = I_{yx} = 0Kgm^2$$
$$I_{yy} = 2.08Kgm^2, \qquad I_{yz} = I_{zy} = 0Kgm^2$$
$$I_{zz} = 2.32Kgm^2, \qquad I_{zx} = I_{xz} = 0Kgm^2$$

Hydrodynamic parameters:

$$\begin{bmatrix} X_u & Y_v & Z_w \end{bmatrix} = \begin{bmatrix} -72 & -77 & -95 \end{bmatrix} kgs^{-1}$$
$$\begin{bmatrix} X_{\dot{u}} & Y_{\dot{v}} & Z_{\dot{w}} \end{bmatrix} = \begin{bmatrix} -29 & -30 & -90 \end{bmatrix} kg$$
$$\begin{bmatrix} K_p & M_q & N_r \end{bmatrix} = \begin{bmatrix} -40 & -30 & -30 \end{bmatrix} kgs^{-1}$$
$$\begin{bmatrix} K_{\dot{p}} & M_{\dot{q}} & N_{\dot{r}} \end{bmatrix} = \begin{bmatrix} -5.2 & -7.2 & -3.3 \end{bmatrix} kg$$
$$X_{u|u|} = Y_{v|v|} = Z_{w|w|} = K_{p|p|} = M_{q|q|} = N_{r|r|} = 0$$

Centre of gravity and centre of buoyancy:

$$\begin{bmatrix} x_G & y_G & z_G \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix} m$$
$$\begin{bmatrix} x_B & y_B & z_B \end{bmatrix} = \begin{bmatrix} 0 & 0 & -0.1 \end{bmatrix} m$$

Robot parameters:

$$\rho = 1024kgm^3 \qquad m = 98.5kg \qquad g = 9.81ms^{-1}$$

The ROV thrusters' nonlinear functions are approximated by a power of three (u^3) function and input saturation at ±5 volt is imposed. Under these circumstances the max deliverable speed for the surge, sway and heave are approximately 1, 0.5 and 0.5 m/s, respectively.

The performance of the designed controller is studied through extensive simulations. The test specifications are as follows:

1. A nonlinear system behavior is affected by the level of excitation. Consistency of response is evaluated by applying short and large steps as reference command.
2. Disturbances deviates systems from their desired working condition. Feedback is expected to manage such an unwanted effect. However, large value of disturbances may left unacceptable error. To test the capacity of the algorithm, the system is under constant disturbance of water current of 0.4m/s from 0 to 4 s at x direction and 0.2m/s at y direction after 4 s.
3. Control design is often based on nominal value of the parameters of the system. Surely perturbation has negative effect on the controller performance. To evaluate the uncertainty containment of the algorithm, test considering % 30 tolerances for the parameters of the system are conducted..

A sample of test performance in x direction has been depicted in Fig. 4.

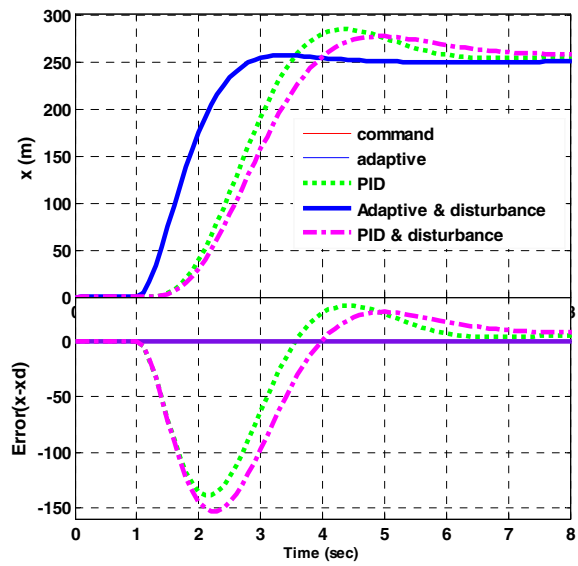

Figure 4. Control in the x direction.

As the figure clearly indicates, ROV follows the reference system perfectly. The adaptive control system is fast without any undesired overshoot. Under other test conditions more or less similar patterns have been acquired. However, this is not true for the PID to cope with the aforementioned test situations. It can be tuned to well behave under limited band of perturbation in comparison with the wide band of perturbation that MRAC can administer. This is also confirmed considering the tracking error portrayed at Fig. 4. The test performance in the y direction has been exhibited in Fig. 5. The same conclusion which is derived for the control in the x direction can be attributed to the y direction. The heading control of the MRAC system has also been depicted in Fig. 6. with similar adavantages.

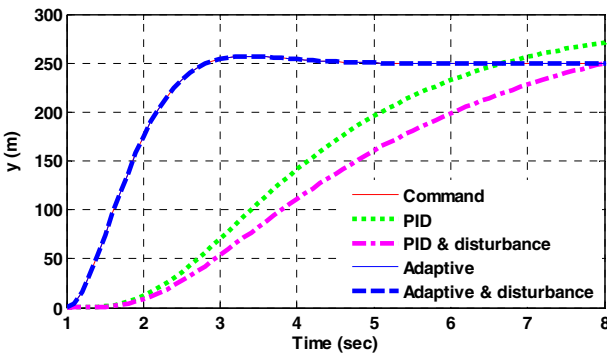

Figure 5. Control in the y direction.

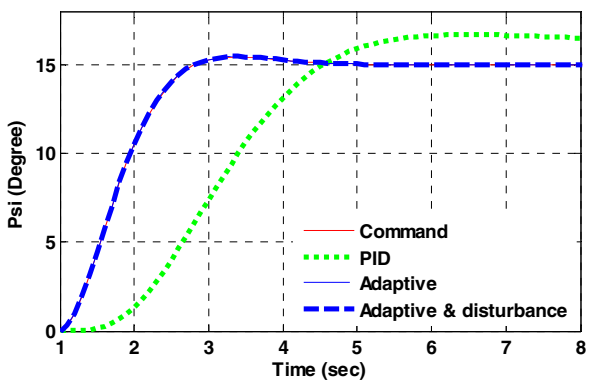

Figure 6. Heading output response

V. Conclusion

In this paper, the concept of ROV control under model uncertainty and disturbance using model reference adaptive control is discussed. The system is under disturbance and % 30 tolerances for the system parameters are imposed. The asymptotical stability proof is provided. Simulation results confirm the superiority of the MRAC versus the conventional PID. Zero model reference tracking is accomplished.

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