Observer-based controller Design for Remotely Operated Vehicle ROV

Adel Khadhraoui[1], Lotfi Beji[1], Samir Otmane[1] and Azgal Abichou[2]

[1]*University of Evry, IBISC Laboratory, EA 4526, 40 rue du Pelvoux, 91020 Evry, France*

[2]*Polytechnic School of Tunisia, LIM Laboratory, BP743, 2078 La Marsa, Tunisia*

Keywords: Observer, Controller, Estimation, Lyapunov theory, Stabilization, ROV.

Abstract: This paper presents a method to design an observer-based controller that simultaneously solves global estimation of state and asymptotic stabilization of an underactuated remotely operated vehicle moving in the in three-dimensional. The vehicle does not have a sway and roll actuator and has only position and orientation measurements available. The control development is based on Lyapunov's direct method for nonlinear system.

1 INTRODUCTION

In many works on the control of dynamical systems, the state vector is assumed to be measured. However, on a practical level, this assumption is not always true. Indeed, for technical or economical reasons, it is difficult or impossible to measure all the state variables of the system. Hence, the need to fully know the state variables of the system is often a necessity in the phases of modeling and identification, diagnosis and control systems. All these problems require knowledge of the state vector, not accessible to measurement data, which makes the design of an observer a primordial task in control theory.

The problem of observation has been studied by a number of researchers these last years The linear case has been solved by Kalman and Luenberger, but the nonlinear case is still an active domain of research. The high-gain observer approach which is closely related to triangular structure has been developed by (Gauthier et al., 1992),(Gauthier and Kupka, 1994) and is derived from the uniform observability of nonlinear systems. Other methods have been developed: Kazantzis and Karavaris (Kazantzis and Kravaris, 1997), the backstepping observer which uses the Lyapunov auxiliary theorem and a direct coordinate transformation in design in (Li and Qian, 2006) and (Arcak, 2002). Switching or multi-model observers based on Linear Matrix Inequality techniques are used for the observation of LPV, quasi-LPV or Takagi-Sugeno fuzzy systems (Takagi and Sugenou, 1985), (Dounia et al., 2012), (Chang and Chen, 2013). The adaptive observer was proposed in (Pourgholi and Majd, 2012), parameter and state estimation problem in the presence of the perturbation. In (F. Rezazadegan and Chatraei, 2013), an adaptative control law for 6 DOF model is drived for the trajectory tracking problem of underactuated underwater vehicle in the presence of parametric uncertainty. The famous Kalman filter algorithm, which assumes white and Gaussian disturbances and noises has been successfully applied to the estimation of state variables of nonlinear system in numerous engineering applications. Applications such as State and parameter estimation of aircraft and Unmanned Aerial Vehicles (UAV's) (Langelaan, 2006), (Rigatos, 2012), are all examples of aerospace applications for the Kalman filter. In (Berghuis and Nijmeijer, 1993) the authors propose a nonlinear observer-based controller strategy for robot manipulators based on passivity theory. The controller and observer are designed to use the structure of each other and semi-global exponential stability of the observer error and controller error dynamics are proven. In (Shen et al., 2011), (Li et al., 2011), (Li et al., 2013), the problem of finite-time observers has been considered and global finite-time observer are designed for nonlinear system which are uniformly observable and globally Lipschitz. In (Fridman et al., 2008), a higher-order sliding-mode observer is proposed to estimate exactly the observable states and asymptotically the unobservable ones in multi-input-multi-output nonlinear system with unknown inputs and stable internal dynamics. In this paper, we propose to control Remotely Operated Vehicles (ROV's) for exploration in sub-sea historical sites. The main contribution in this paper is to design

Khadhraoui A., Beji L., Otmane S. and Abichou A..
Observer-based controller Design for Remotely Operated Vehicle ROV.
DOI: 10.5220/0005019102000207
In *Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2014), pages 200-207
ISBN: 978-989-758-039-0

a nonlinear observer to estimate the linear and angular velocity of the ROV. The remainder of this paper is organized as following. In Section 2 the kinematic and dynamic model of the ROV are presented. The design observer for estimating the linear and angular velocity in the presence of constants disturbance is synthesized in Section 3. In Section 4 a feedback law is proposed to stabilize the system of the ROV at the origin. The theoretical results are illustrated by simulations in section 5.

2 ROV MODEL DESCRIPTION

The ROV has a close frame structure and is equipped with two cameras which allow us the Tele-exploration in mixed-reality sites (see Figure 1). This vehicle is actuated with two reversible horizontal thrusters F_{1x} and F_{2x} for surge and yaw motion, and a reversible vertical thruster F_{3z} for heave motion. A 150 meters cable provides electric power to the thrusters and enables communication between the vehicle sensors and the surface equipment (see Figure 1).

2.1 Coordinate Frame

Underwater vehicle models are conventionally represented by a six degrees of freedom nonlinear set of first order differential equations of motion. Two reference frames are used to describe the vehicles states, R_0 for inertial frame, and R_v for local body-fixed frame with its origin coincident with the vehicles center of buoyancy, and the 3 principle axes in the vehicles surge, sway and heave directions (see Figure 1).

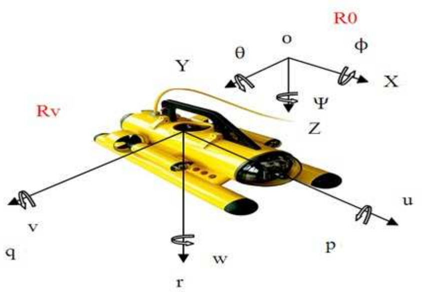

Figure 1: Body-fixed frame and earth-fixed frame for ROV.

2.2 ROV Equations of Motion

The mathematical model of a ROV in 6 DOF can be described by:

$$\left.\begin{aligned} \dot{\eta}_1 &= J_1(\eta_2)\nu_1, \dot{\eta}_2 = J_2(\eta_2)\nu_2 \\ M\dot{\nu} &= -C(\nu)\nu - D(\nu)\nu - g(\eta) + \tau \end{aligned}\right\} \quad (1)$$

where $\eta = [\eta_1\ \eta_2]^T$ with $\eta_1 = [x\ y\ z]^T$ and $\eta_2 = [\phi\ \theta\ \psi]^T$ is the position and orientation vector in earth-fixed frame, $\nu = [\nu_1\ \nu_2]^T$ with $\nu_1 = [u\ v\ w]^T$ and $\nu_2 = [p\ q\ r]^T$ is the velocity and angular rate vector in body-fixed frame, the symmetric positive definite inertia matrix $M = M_v + M_a$ includes the inertia M_v of the vehicle as a rigid body and the added inertia M_a due to the acceleration of the wave, the skew symmetrical matrix $C(\nu)$ is the matrix of Coriolis and centripetal, the hydrodynamic damping term $D(\nu) = D_L + D_Q(\nu)$ (positive definite diagonal matrix) takes into account the dissipation of energy due to the friction exerted by the fluid surrounding AUV, where $D_Q(\nu)$ and D_L are the quadratic and linear drag matrices, respectively. The terms $g(\eta)$ is the restoring force vector, τ is the input torque vector, and the transformation matrices $J_1(\eta_2)$ and $J_2(\eta_2)$ are as following:

$$J_1(\eta_2) = \begin{pmatrix} c\theta c\psi & s\theta s\phi c\psi - s\psi c\phi & s\theta c\phi c\psi + s\psi s\phi \\ c\theta s\psi & s\theta s\phi s\psi + c\psi c\phi & s\theta c\phi s\psi - c\psi s\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{pmatrix}$$

$$J_2(\eta_2) = \begin{pmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & \frac{s\phi}{c\theta} & \frac{c\phi}{c\theta} \end{pmatrix}$$

$$J(\eta_2) = \begin{pmatrix} J_1(\eta_2) & 0 \\ 0 & J_2(\eta_2) \end{pmatrix}$$

where $c(.) = \cos(.)$, $s(.) = \sin(.)$, $t(.) = \tan(.)$.

Remark 2.1. *For the sake of simplicity, external disturbances such as ocean current are not taken into consideration. The detailed definition of each element in (1) and the influence of external environment can be found in (Fossen, 1994). For the ROV one excludes an attitude in pitch equal to* $\frac{\pi}{2}$.

Assumption 2.2. *1) ROV has an (xz) and (yz) two planes of symmetry, surge is decoupled from pitch modes.*

2) The center of gravity is vertically aligned with the center of buoyancy, i.e.,$[0, 0, -z_g]^T$.

The autonomous underwater vehicle (ROV) is a complex nonlinear system described by twelve state variables and three controls. The full model can be found in (Khadhraoui et al., 2013). The kino-dynamic model of the ROV in low speed can be written in the form presented below:

$$\left.\begin{aligned} \dot{\eta}_1 &= J_1(\eta_2)\nu_1, \dot{\eta}_2 = J_2(\eta_2)\nu_2 \\ M\dot{\nu} &= -D_L\nu - g(\eta) + \tau \end{aligned}\right\} \quad (2)$$

Thus, the general mathematical model of the ROV in surge, sway, heave and heading motion is given by:

$$\left.\begin{array}{rcl}
\dot{u} &=& \frac{m_{55}}{m_{11}m_{55}-m_{15}^2}[d_u u+(F_W-F_B))s\theta+\tau_u] \\
&-& \frac{1}{m_{22}}[d_q q+z_g F_B s\theta] \\
\dot{v} &=& \frac{m_{44}}{m_{22}m_{44}-m_{24}^2}[d_v v+(F_W-F_B)c\theta s\phi] \\
\dot{w} &=& \frac{1}{m_{33}}[d_w w-(F_W-F_B)c\theta c\phi+\tau_w] \\
\dot{p} &=& \frac{1}{m_{44}}[d_p p-z_g F_B c\theta s\phi] \\
\dot{q} &=& \frac{m_{11}}{m_{11}m_{55}-m_{15}^2}[d_q q+z_g F_B s\theta] \\
&-& \frac{m_{15}}{m_{11}m_{55}-m_{15}^2}[d_u u+(F_W-F_B))s\theta+\tau_u] \\
\dot{r} &=& \frac{1}{m_{66}}[d_r r+\tau_r] \\
\dot{x} &=& c\theta c\psi u+(s\theta s\phi c\psi-s\psi c\phi)v \\
&+& (s\theta c\phi c\psi+s\psi s\phi)w \\
\dot{y} &=& c\theta s\psi u+(s\theta s\phi s\psi+c\psi c\phi)v \\
&+& (s\theta c\phi s\psi-c\psi s\phi)w \\
\dot{z} &=& -s\theta u+c\theta s\phi v+c\theta c\phi w \\
\dot{\phi} &=& p+s\phi\tan\theta q+c\phi\tan\theta r \\
\dot{\theta} &=& c\phi q-s\phi r \\
\dot{\psi} &=& \frac{s\phi}{c\theta}q+\frac{c\phi}{c\theta}r
\end{array}\right\} \quad (3)$$

where d_u, d_v, d_w, d_p, d_q and q_d are the drag parameters of the ROV. The submerged weight F_W, and the buoyancy force F_B, are given by

$$F_W = m.g,\ F_B = \rho.\nabla.g$$

where g is the gravitational constant, ρ is the density of the fluid and ∇ is the volume of the ROV.

Having accurate ROV-observer motion information, namely the position information η_1, η_2 and velocity information ν_1, ν_2 is crucial for the controller to work properly. Unfortunately, among these parameters only the 3-dimension position information η_1 and attitudes information η_2 are available from the vehicles sensor system and underwater acoustic positioning system; the velocity could not be measured directly. Also, the position information obtained through the measurement is uncertain due to noise and other imperfections. To handle this problem, estimation is applied to the measurements.

3 OBSERVER DESIGN

In the sequel, we consider that the measurements are the position vector η_1 and the orientation vector η_2, and our objective is to estimate the linear and angular velocities from these measurement.

3.1 Nominal Case

Proposition 3.1. *Let us consider the system (2). Then, there exist a diagonal positive definite constant matrix L_1 (control gain matrix) and a matrix depending on the state $L_2(\eta)$ for which system (2) admits the following asymptotic observer:*

$$\left.\begin{array}{rcl}
\dot{\widehat{\eta}} &=& J(\eta_2)\widehat{\nu}-L_1(\eta-\widehat{\eta}) \\
M\dot{\widehat{\nu}} &=& -D_L\widehat{\nu}-g(\eta)+\tau-L_2(\eta)(\eta-\widehat{\eta})
\end{array}\right\} \quad (4)$$

Proof. According to the system dynamics (2) and the given observer (4), the error dynamics becomes:

$$\left.\begin{array}{rcl}
\dot{\widetilde{\eta}} &=& J(\eta_2)\widetilde{\nu}-L_1\widetilde{\eta} \\
M\dot{\widetilde{\nu}} &=& -D_L\widetilde{\nu}-L_2(\eta)\widetilde{\eta}
\end{array}\right\} \quad (5)$$

where $\widetilde{\eta} = \eta-\widehat{\eta}$ and $\widetilde{\nu} = \nu-\widehat{\nu}$.
We consider the following Lyapunov function:

$$V_1 = \frac{1}{2}(\widetilde{\eta}^T\widetilde{\eta}+\widetilde{\nu}^T\widetilde{\nu}) \quad (6)$$

The time derivative of V_1 can be expressed as:

$$\dot{V}_1 = -\widetilde{\eta}^T L_1\widetilde{\eta}-\widetilde{\nu}^T M^{-1}D_L\widetilde{\nu}+\widetilde{\eta}^T J(\eta_2)\widetilde{\nu}-\widetilde{\nu}^T M^{-1}L_2(\eta)\widetilde{\eta} \quad (7)$$

If we take

$$L_2(\eta) = MJ(\eta_2)$$

Then, equation (7) become

$$\dot{V}_1 = -\widetilde{\eta}^T L_1\widetilde{\eta}-\widetilde{\nu}^T M^{-1}D_L\widetilde{\nu} \quad (8)$$

then,

$$\dot{V}_1 \leq -\lambda_1 \parallel\widetilde{\eta}\parallel -\lambda_2 \parallel\widetilde{\nu}\parallel \quad (9)$$

where λ_1 and λ_2 are the minimum eigenvalues of L_1 and $M^{-1}D_L$, respectively.
By using the Lyapunov theory, we conclude that system (5) is asymptotically stable. then, the proposed observer allows us to estimate all the state vector asymptotically.

3.2 Perturbed Case

In the presence of environmental constants disturbances Θ, the dynamics of the ROV can be written

$$M\dot{\nu} = -D_L\nu-g(\eta)+\Theta+\tau \quad (10)$$

and we define the dynamic observer at the forme

$$M\dot{\widehat{\nu}} = -D_L\widehat{\nu}-g(\eta)+\widehat{\Theta}+\tau \quad (11)$$

where Γ is the diagonal positive definite matrix and $\widehat{\Theta}$ is an estimate of Θ verify $\dot{\widehat{\Theta}} = \Gamma\widetilde{\nu}$. We consider the following Lyapunov function candidate

$$W_\Theta = \tfrac{1}{2}\widetilde{\nu}^T M\widetilde{\nu} + \tfrac{1}{2}\widetilde{\Theta}^T\Gamma^{-1}\widetilde{\Theta} \quad (12)$$

The time derivative of W_Θ can be expressed as follows

$$\dot{W_\Theta} = -D_L\widetilde{\nu}^2 \quad (13)$$

By using La Salle invariance principle (Khalil, 2002), we conclude that $\widetilde{\nu}$ is globally asymptotically stable.

Remark 3.2. *As the terms $\widehat{\Theta}$ contains the vector uncertainty ν, it is sufficient to replace the expression $\widetilde{\nu} = \nu - \widehat{\nu}$ in the expression of $\dot{\widehat{\Theta}}$*

$$\widehat{\Theta}(t) = \widehat{\Theta}(t_0) + \Gamma\int_{t_0}^{t}(\nu - \widehat{\nu})(\sigma)d\sigma$$

like that $\nu = J^{-1}(\eta_2)\dot{\eta}$, then

$$\widehat{\Theta}(t) = \widehat{\Theta}(t_0) + \Gamma\int_{t_0}^{t}(J^{-1}(\eta_2)\dot{\eta} - \widehat{\nu})(\sigma)d\sigma$$

which gives

$$\widehat{\Theta}(t) = \widehat{\Theta}(t_0) + \Gamma\int_{\eta(t_0)}^{\eta(t)} J^{-1}(\sigma')d\sigma' - \Gamma\int_{t_0}^{t}\widehat{\nu}(\sigma)d\sigma$$

4 OUTPUT-FEEDBACK OBSERVER

This section describes the design of the control-based observer. Based on the estimated states, we will try to stabilize the kino-dynamic model:

$$\left.\begin{array}{rcl} \dot{\eta} &=& J(\eta_2)\nu \\ M\dot{\nu} &=& -D_L\nu - g(\eta) + \tau \\ \dot{\widetilde{\eta}} &=& J(\eta_2)\widetilde{\nu} - L_1\widetilde{\eta} \\ M\dot{\widetilde{\nu}} &=& -D_L\widetilde{\nu} - L_2(\eta)\widetilde{\eta} \end{array}\right\} \quad (14)$$

The control laws required for the stabilization task are given in the following proposition.

Proposition 4.1. *Let k_u, k_w and k_r three nonnegative reel numbers, considered large enough. Then, with the action of the following feedback laws*

$$\left.\begin{array}{rcl} \tau_u &=& \frac{-(m_{15}^2 - m_{11}m_{55})k_u}{m_{55}}[\widehat{u} + k_q\widehat{q} + k_x x + k_\theta\theta] \\ \tau_w &=& -m_{33}k_w[\widehat{w} + k_z z] + \varpi_{\tau_w} \\ \tau_r &=& -m_{66}k_r[\widehat{r} + k_\psi\psi] \end{array}\right\} \quad (15)$$

where ϖ_{τ_w} is a constant parameter will be specified later. $k_x, k_z, k_\theta, k_\psi$ and k_q are positives constants. The system (14) is locally asymptotically stable at the origin.

Proof. For an under-atuated system, the position vector can be partitioned to actuated and non-actuated states as

$$\eta = [\eta^a \ \eta^u]^T \quad (16)$$

where, $\eta^a = [x \ z \ \theta \ \psi]^T$ is the actuated states of the ROV and $\eta^u = [y \ \phi]^T$ is the non-actuated states.

Step 1) Stability analysis of actuated state:
The corresponding linearized around zero of the actuated system is given by:

$$\left.\begin{array}{rcl} \dot{u} &=& -\alpha_1 u + \alpha_2 q + \alpha_3\theta + \tau_u \\ \dot{x} &=& u \\ \dot{w} &=& -\gamma_1 w + \gamma_2 + \tau_w \\ \dot{z} &=& w \\ \dot{q} &=& \beta_1 u - \beta_2 q + \beta_3\theta + \beta\tau_u \\ \dot{\theta} &=& q \\ \dot{r} &=& -\rho r + \tau_r \\ \dot{\psi} &=& r \end{array}\right\} \quad (17)$$

where $\alpha_i =, \beta_i, \gamma_i, \gamma_i, \pi_i$ and ρ are positive constants depends on the ROV fixed parameters.
We consider the following Lyapunov function candidate

$$\begin{array}{rcl} V_2 &=& \frac{1}{2}\{x^2 + (u+x)^2 + \theta^2 + (q+\theta)^2 \\ &+& z^2 + (z+w)^2 + \psi^2 + (\psi + r)^2\} \end{array} \quad (18)$$

The time derivative of V_2 can be expressed as:

$$\begin{array}{rcl} \dot{V_2} &=& xu + (x+u)(u - \alpha_1 u + \alpha_2 q - \alpha_u\theta + \tau_u) \\ &+& \theta q + (q+\theta)(q - \beta_1 q + \beta_2 + \alpha_q\theta + \beta\tau_u) \\ &+& zw + (z+w)(w - \gamma_1 w - \gamma_2 + \tau_w)) \\ &+& \psi r + (\psi + r)(r - \rho r + \tau_r) \end{array} \quad (19)$$

by using (15) given in the proposition and we take $\varpi_{\tau_w} = \gamma_2$, equation (19) becomes:

$$\begin{array}{rcl} \dot{V_2} &=& (x+u)[(1-\alpha_1)u - k_u\widehat{u} + \alpha_2 q - k_u k_q\widehat{q}] \\ &+& (x+u)[(\alpha_u - k_u k_\theta)\theta - k_u k_x x] + xu \\ &+& (q+\theta)[(1-\beta_1)q - kk_q\widehat{q} + \beta_2 u - k\widehat{u}] \\ &+& (q+\theta)[(\alpha_q - kk_\theta)\theta - kk_x x] + \theta q \\ &+& (z+w)[(1-\gamma_1)w - k_w\widehat{w} - k_w k_z z] + zw \\ &+& (\psi + r)[(1-\rho)r - k_r\widehat{r} - k_r k_\psi\psi] + \psi r \end{array} \quad (20)$$

where $k = \beta k_u$. We consider the coordinate:

$$u = \widetilde{u} + \widehat{u}, q = \widetilde{q} + \widehat{q}, w = \widetilde{w} + \widehat{w}, r = \widetilde{r} + \widehat{r}$$

The time derivative of V_2 becomes:

$$\begin{aligned}
\dot{V}_2 &= -k_1u^2 - k_2x^2 - k_3q^2 - k_4\theta^2 - k_5w^2 - k_6z^2 \\
&- k_7r^2 - k_8\psi^2 + \varpi_1 xu + \varpi_2\theta q + \varpi_3 xq + \varpi_4\theta u \\
&+ \varpi_5\theta x + \varpi_6 uq + \varpi_7 zw + \varpi_8\psi r + k_w(z+w)\widetilde{w} \\
&+ k_r(\psi+r)\widetilde{r}(x+u+\theta+q)(k_u\widetilde{u}+k_uk_q\widetilde{q})
\end{aligned} \tag{21}$$

where
$k_1 = k_u - 1 + \alpha_1$, $k_2 = k_uk_x$, $k_3 = kk_q - 1 + \beta_2$

$k_4 = kk_\theta$, $k_5 = k_w - (1-\gamma_1)$, $k_6 = k_wk_z$

$k_7 = k_r - (1-\rho)$, $k_8 = k_rk_\psi$

$\varpi_1 = 2 - \alpha_1 - k_u(1+k_x)$, $\varpi_2 = 2 - \beta_2 - k(k_q + k_\theta)$

$\varpi_3 = \beta_1 - k_u(\beta + k_\theta)$, $\varpi_4 = \alpha_2 - k_u(k_q + \beta k_x)$

$\varpi_5 = \beta_1 + \alpha_2 - k_u(\beta + k_q)$, $\varpi_6 = -k_u(\beta k_x + k_\theta)$

$\varpi_7 = 2 - \gamma_1 - k_w(1+k_z)$, $\varpi_8 = 2 - \rho - k_r(1+k_\psi)$

In the above expression, we remark that the last terms have uncertain signs. For the analysis we will use the Young's inequality (see Appendix C for the details), with the quantities ε_i as positive constants, we obtain:

$$\begin{aligned}
\dot{V}_2 &\leq -(k_1-\varepsilon_1)u^2 - (k_2-\varepsilon_2)x^2 - (k_3-\varepsilon_3)q^2 \\
&- (k_4-\varepsilon_4)\theta^2 - (k_5-\varepsilon_5)w^2 - (k_6-\varepsilon_6)z^2 \\
&- (k_7-\varepsilon_7)r^2 - (k_8-\varepsilon_8)\psi^2 + k_w(z+w)\widetilde{w} \\
&+ k_r(\psi+r)\widetilde{r} + (x+u)(k_u\widetilde{u}+k_uk_q\widetilde{q}) \\
&+ (\theta+q)(k\widetilde{u}+kk_q\widetilde{q})
\end{aligned} \tag{22}$$

We consider the following Lyapunov function candidate

$$V_3 = V_1 + V_2 \tag{23}$$

Taking account of (8) and (22), the time derivative of V_3 can be expressed as:

$$\begin{aligned}
\dot{V}_3 &\leq -(k_1-\varepsilon_1)u^2 - (k_2-\varepsilon_2)x^2 - (k_3-\varepsilon_3)q^2 \\
&- (k_4-\varepsilon_4)\theta^2 - (k_5-\varepsilon_5)w^2 - (k_6-\varepsilon_6)z^2 \\
&- (k_7-\varepsilon_7)r^2 - (k_8-\varepsilon_8)\psi^2 - \widetilde{\eta}^T L_1\widetilde{\eta} \\
&- \widetilde{\nu}^T M^{-1} D_L\widetilde{\nu} + (x+u)(k_u\widetilde{u}+k_uk_q\widetilde{q}) \\
&+ (\theta+q)(k\widetilde{u}+kk_q\widetilde{q})k_w(z+w)\widetilde{w} \\
&+ k_r(\psi+r)\widetilde{r}
\end{aligned} \tag{24}$$

Reusing the Young's inequality, with the quantities ε_i and ε'_i as positive constants, we obtain:

$$\begin{aligned}
\dot{V}_3 &\leq -(k_1-\varepsilon_1)u^2 - (k_2-\varepsilon_2)x^2 - (k_3-\varepsilon_3)q^2 \\
&- (k_4-\varepsilon_4)\theta^2 - (k_5-\varepsilon_5)w^2 - (k_6-\varepsilon_6)z^2 \\
&- (k_7-\varepsilon_7)r^2 - (k_8-\varepsilon_8)\psi^2 - (\lambda_2-\varepsilon'_1)\widetilde{u}^2 \\
&- (\lambda_1-\varepsilon'_2)\widetilde{x}^2 - (\lambda_2-\varepsilon'_3)\widetilde{q}^2 - (\lambda_1-\varepsilon'_4)\widetilde{\theta}^2 \\
&- (\lambda_2-\varepsilon'_5)\widetilde{w}^2 - (\lambda_1-\varepsilon'_6)\widetilde{z}^2 - (\lambda_2-\varepsilon'_7)\widetilde{r}^2 \\
&- (\lambda_1-\varepsilon'_8)\widetilde{\psi}^2
\end{aligned} \tag{25}$$

If we choose

$$\forall i, j : k_i - \varepsilon_i > 0, \lambda_j - \varepsilon'_i > 0$$

Then, $\dot{V}_3 < 0$. By using Lyapunov theory, we conclude that system (10) is asymptotically stable.

Step 2) Stability analysis of non- actuated state:

Here, the roll angle and the sway direction are non-actuated states and their equations of motion are given by:

$$\left.\begin{aligned}
\dot{v} &= \tfrac{1}{m_{22}}[d_v v + (F_W - F_B)c\theta s\phi] \\
\dot{p} &= \tfrac{1}{m_{44}}[d_p p + z_g F_B c\theta s\phi] \\
\dot{y} &= c\theta s\psi u + (s\theta s\phi s\psi + c\psi c\phi)v \\
&+ (s\theta c\phi s\psi - c\psi s\phi)w \\
\dot{\phi} &= p + s\phi\tan\theta q + c\phi\tan\theta r
\end{aligned}\right\} \tag{26}$$

Therefore (26) can be linearized at zero its equilibrium point and it becomes:

$$\left.\begin{aligned}
\dot{v} &= \tfrac{1}{m_{22}}[d_v v + (F_W - F_B)\phi] \\
\dot{p} &= \tfrac{1}{m_{44}}[d_p p - z_g F_B\phi] \\
\dot{y} &= v \\
\dot{\phi} &= p
\end{aligned}\right\} \tag{27}$$

The second time derivative below, can be computed. We obtain $\ddot{\phi} = \frac{d_p}{m_{44}}\dot{\phi} - \frac{z_gF_B}{m_{44}}\phi$, then the asymptotic stability of ϕ and their derivative can be asserted by the identifying of these derivative to a stable polynomial from. Moreover, p converge exponentially to zero.

$$\begin{aligned}
\dot{v} &= \tfrac{d_v}{m_{22}}v \\
\dot{y} &= v
\end{aligned} \tag{28}$$

where $m_{22} > 0$ and $d_v < 0$. We can demonstrate that v converge exponentially to zero and y is constants.

5 SIMULATIONS

In this section, we give a numerical simulation to illustrate our theoretical results. Before starting, we will present the system parameter values (IS units). The added masses and hydrodynamic coefficients are calculated from the CAD-geometry and presented in Table 1. The ROV is assumed to be moving at low speed and the nonlinear system of the ROV is used. The initial conditions of the system are

$$[\nu,\eta](0) = [0.2,0,0,0,0,0,-0.5,0.1,0.3,0.1,0,-0.1]$$

and those of the observer are

$$[\widehat{\nu},\widehat{\eta}](0) = [-0.3,0.1,0,0.1,-0.2,0,0,0,0,0,0.1,0.2]$$

The result simulations for the observer part are given in figures 2 and 3. We see that all the state estimation errors converge to zero and thus, we conclude that the estimate vector $[\widehat{\eta},\widehat{\nu}]$ converge to the state system $[\eta,\nu]$.

According to proposition 2, the gain controllers used for simulation are:

$$k_u = k_w = k_r = 10,\ k_x = k_\theta = k_q = kz = k_\psi = 1$$

The simulation results for the controller part are given in figures 4- 7. We see that the inertial positions and the Euler angles converge in a small neighborhood of zero. Figure 8 shown the control force τ_u, τ_w and the control torque τ_r needed for stabilizing. It is clear that the total ROV model (14) is locally asymptotically stable at the origin using only three control inputs (15).

Table 1: Rigid Body and Hydrodynamics Parameters.

Parameter	Symbol	Value
mass	m	10.84
moment of inertia	I_{xx}, I_{yy}, I_{zz}	$0.065, 0.216, 0.2$
Added mass in surge	$X_{\dot u}$	-1.0810
Added mass in sway	$Y_{\dot v}$	-0.3848
Added mass in heave	$Z_{\dot w}$	-0.3.848
Added inertia in roll	$K_{\dot p}$	0
Added inertia in yaw	$N_{\dot r}$	-0.0075
Added inertia in pitch	$M_{\dot q}$	-0.0075
Surge linear drag	d_u	0.9613
sway linear drag	d_v	2.4674
heave linear drag	d_w	2.4674
yaw linear drag	d_r	5.3014×10^{-3}
Surge linear drag	d_q	5.3014×10^{-3}
Added inertia	$X_{\dot q}$	1.0885
Added inertia	$Y_{\dot p}$	0.3848
center of mass	G	(0,0,-0.16)
center of buoyancy	b	(0,0,0)

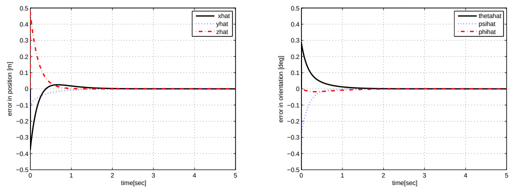

Figure 2: Errors in position and orientation.

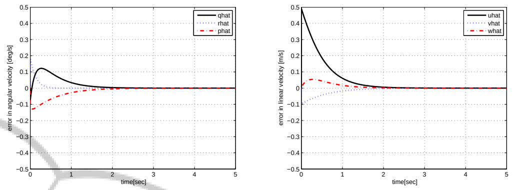

Figure 3: Errors in linear and angular velocity.

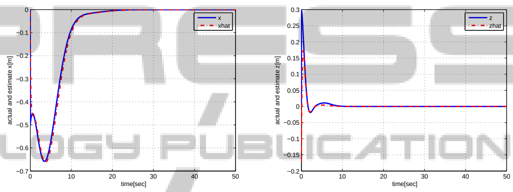

Figure 4: Actual and estimate position.

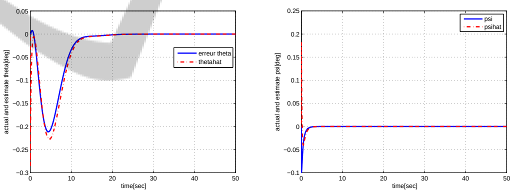

Figure 5: Actual and estimate orientation.

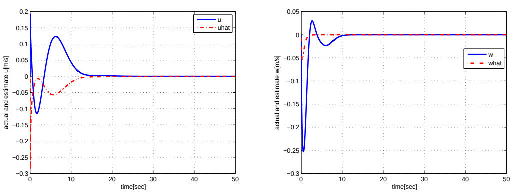

Figure 6: Actual and estimate linear velocity.

6 CONCLUSIONS

In this paper, an observer based controller is designed in order to estimate the state dynamics and to stabilize the whole closed loop system. The controller observer is designed based on the Lyapunov technics for nonlinear systems. The particularity of this work is that the considered system is not in triangular form and its dynamics are also coupled. The simulation result has demonstrated the effectiveness of our observer based

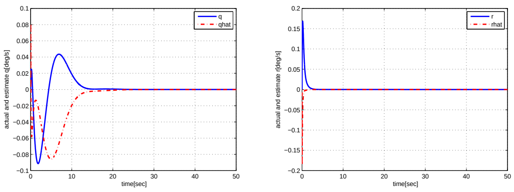

Figure 7: Actual and estimate angular velocity.

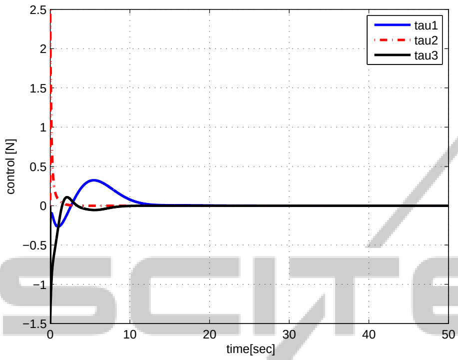

Figure 8: Control surge force, heave force and yaw torque.

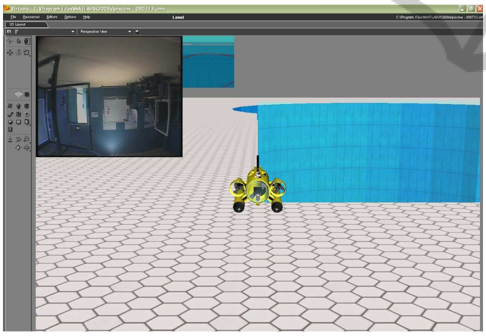

Figure 9: The ROV in virtual subsea.

controller.

In future papers, we will try to test the proposed work on a simulator while it progresses in a virtual subsea environment (Fig.9).

ACKNOWLEDGEMENTS

This work is supported by the European Digital Ocean project under grant FP7 262160.

REFERENCES

Arcak, M. (2002). Observer-based backstepping with weak nonlinear damping. In *American Control Conference*, volume 5, pages 3478–3483.

Berghuis, H. and Nijmeijer, H. (1993). A passivity approach to controller-observer design for robots. *IEEE Transactions on Robotics and Automation*, 9:740–754.

Chang, W.-J. and Chen, P.-H. (2013). Stabilization for truck-trailer mobile robot system via discrete lpv t-s fuzzy models. In *Intelligent Autonomous Systems 12*, volume 193, pages 209–217.

Dounia, S., Mohammed, C., Salim, L., and ThierryMarie, G. (2012). Robust h_∞ static output feedback stabilization of t-s fuzzy systems subject to actuator saturation. *International Journal of Control, Automation and Systems*, 10(3):613–622.

F. Rezazadegan, K. S. and Chatraei, A. (2013). Design of an adaptive nonlinear controller for an autonomous underwater vehicle. 2:1–8.

Fossen, T. I. (1994). *Guidence and Control of Ocean Vehicules*. Chichester: Wiley.

Fridman, L., Shtessel, Y., Edwards, C., and Yan, X.-G. (2008). Higher-order sliding-mode observer for state estimation and input reconstruction in nonlinear systems. *International Journal of Robust and Nonlinear Control*, 18(4-5).

Gauthier, J.-P., Hammouri, H., and Othman, S. (1992). A simple observer for nonlinear systems applications to bioreactors. *IEEE Transactions on Automatic Control*, 37:875–880.

Gauthier, J. P. and Kupka, I. A. K. (1994). Observability and observers for nonlinear systems. *SIAM J. Control Optim.*, 32:975–994.

Kazantzis, N. and Kravaris, C. (1997). Nonlinear observer design using lyapunov's auxiliary theorem. In *the 36th IEEE Conference on Decision and Control*, volume 5, pages 4802–4807.

Khadhraoui, A. Beji, L., Otmane, S., and Abichou, A. (2013). Explicit homogenous time varying stabilizing control of a submarine rov. In *International Conference on Informatics in Control, Automation and Robotics, (ICINCO 2013)*, volume 6, pages 26–32.

Khalil, H. K. (2002). *Nonlinear Systms*. Prentice Hall, third edition.

Langelaan, J. W. (2006). State Estimation for Autonomous Flight in Cluttered Environments. phd, Stanford University, Stanford, CA 94305.

Li, J. and Qian, C. (2006). Global finite-time stabilization by dynamic output feedback for a class of continuous nonlinear systems. *IEEE Transactions on Automatic Control*, 51:879–884.

Li, Y., Xia, X., and Shen, Y. (2011). A high-gain-based global finite-time nonlinear observer. In *9th IEEE International Conference on Control and Automation (ICCA)*, pages 483–488.

Li, Y., Xia, X., and Shen, Y. (2013). A high-gain-based global finite-time nonlinear observer. *International Journal of Control*, 86:759–767.

Pourgholi, M. and Majd, V. J. (2012). Robust adaptive observer design for lipschitz class of nonlinear systems. 6(3):29 – 33.

Rigatos, G. G. (2012). Nonlinear kalman filters and particle filters for integrated navigation of unmanned aerial vehicles. *Robot. Auton. Syst.*, 60:978–995.

Shen, Y., Huang, Y., and Gu, J. (2011). Global finite-time observers for lipschitz nonlinear systems. *IEEE Transactions on Automatic Control*, 56:418–424.

Takagi, T. and Sugenou, M. (1985). Fuzzy identification of systems and its applications to modeling and control. 15:116–132.

APPENDIX A

Under the assumption 2.2, the inertia matrix takes the form (Fossen, 1994)

$$M = \begin{pmatrix} m_{11} & 0 & 0 & 0 & m_{15} & 0 \\ 0 & m_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & m_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{44} & 0 & 0 \\ m_{51} & 0 & 0 & 0 & m_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{66} \end{pmatrix}$$

where $m_{11} = m - X_{\dot{u}}, m_{22} = m - Y_{\dot{v}}, m_{33} = m - Z_{\dot{w}}$
$m_{44} = I_x - K_{\dot{p}} m_{55} = I_y - M_{\dot{q}}, m_{66} = I_z - N_{\dot{r}}$
$m_{15} = m_{51} = mz_G - X_{\dot{q}}$ and $m_{24} = m_{42} = -mz_G - Y_{\dot{p}}$.

APPENDIX B

These parameters of the linearized system 17 are given by:

$$\alpha_1 = \frac{m_{55} d_u}{m_{11} m_{55} - m_{15}^2}$$

$$\alpha_2 = \frac{m_{-15} d_q}{m_{11} m_{55} - m_{15}^2}$$

$$\alpha_3 = \frac{m_{55}(F_W - F_B) - m_{15} z_g F_B}{m_{11} m_{55} - m_{15}^2}$$

$$\beta_1 = \frac{m_{11} d_q}{m_{11} m_{55} - m_{15}^2}$$

$$\beta_2 = \frac{m_{-15} d_u}{m_{11} m_{55} - m_{15}^2}$$

$$\beta_3 = \frac{m_{11} z_g F_B - m_{15}(F_W - F_B)}{m_{11} m_{55} - m_{15}^2}$$

$$\gamma_1 = \frac{Z_w}{m_{33}},\ \gamma_2 = \frac{-(F_W - F_B)}{m_{33}}$$

$$\rho = \frac{d_r}{m_{66}}$$

APPENDIX C

Lemma 6.1. *(Young's inequality) For $a, b \geq 0$ and $p, q \geq 1$ such that $\frac{1}{p} + \frac{1}{q} = 1$, one has*

- $ab \leq \frac{a^p}{p} + \frac{b^q}{q}$
- *If* $p = q = 2$, *then*, $ab \leq \frac{a^2}{2\varepsilon} + \frac{\varepsilon b^2}{2}, \forall \varepsilon > 0$

To prove (22) we use Young's inequality to conclude that for any $\varepsilon_i' > 0$,

$$\begin{array}{rcl} \varpi_1 xu & \leq & \frac{\varpi_1^2}{4\varepsilon_1'} \mid x \mid^2 + \varepsilon_1' \mid u \mid^2 \\ \varpi_2 \theta q & \leq & \frac{\varpi_2^2}{4\varepsilon_2'} \mid \theta \mid^2 + \varepsilon_2' \mid q \mid^2 \\ \varpi_3 x\theta & \leq & \frac{\varpi_3^2}{4\varepsilon_3'} \mid x \mid^2 + \varepsilon_3' \mid \theta \mid^2 \\ \varpi_4 xq & \leq & \frac{\varpi_4^2}{4\varepsilon_4'} \mid x \mid^2 + \varepsilon_4' \mid q \mid^2 \\ \varpi_5 \theta u & \leq & \frac{\varpi_5^2}{4\varepsilon_5'} \mid \theta \mid^2 + \varepsilon_5' \mid u \mid^2 \\ \varpi_6 uq & \leq & \frac{\varpi_6^2}{4\varepsilon_6'} \mid u \mid^2 + \varepsilon_6' \mid q \mid^2 \\ \varpi_7 zw & \leq & \frac{\varpi_7^2}{4\varepsilon_7'} \mid z \mid^2 + \varepsilon_7' \mid w \mid^2 \\ \varpi_8 \psi r & \leq & \frac{\varpi_8^2}{4\varepsilon_8'} \mid \psi \mid^2 + \varepsilon_8' \mid r \mid^2 \end{array} \tag{29}$$

Then, the parameters of the function $\dot{V}_1$ in (22) are given by:

$$\begin{array}{rcl} \varepsilon_1 & = & \varepsilon_1' + \varepsilon_5' + \frac{\varpi_6^2}{4\varepsilon_6'} \\ \varepsilon_2 & = & \frac{\varpi_1^2}{4\varepsilon_1'} + \frac{\varpi_3^2}{4\varepsilon_3'} + \frac{\varpi_4^2}{4\varepsilon_4'} \\ \varepsilon_3 & = & \varepsilon_2' + \varepsilon_4' + \varepsilon_6' \\ \varepsilon_4 & = & \varepsilon_3' + \frac{\varpi_2^2}{4\varepsilon_2'} + \frac{\varpi_5^2}{4\varepsilon_5'} \\ \varepsilon_5 & = & \varepsilon_5',\ \varepsilon_6 = \frac{\varpi_1^2}{4\varepsilon_5'} \\ \varepsilon_7 & = & \varepsilon_7',\ \varepsilon_8 = \frac{\varpi_1^2}{4\varepsilon_7'} \end{array} \tag{30}$$