Robust-save energy controller on an autonomous underwater vehicle with obstacles avoidance

Vina Putranti & Zool H. Ismail
Centre for Artificial Intelligence & Robotics, Universiti Teknologi Malaysia (UTM), Kuala Lumpur, Malaysia
[E-mail: vinawep@gmail.com, zool@utm.my]

Received 8 May 2017 ; Revised 30 October 2017

This paper presents a robust-save energy control and obstacles avoidance technique for an Autonomous Underwater Vehicle (AUV). A super twisting sliding mode which consists of discontinues and continuous function is engaged as a robust control. A discontinuous function is useful to switch between two different systems; thus, the disturbance's effect can be minimized. However, it is resulting a high-infinite frequency which degrades the robustness of an AUV, hence, a continuous function is useful to smoothness the switching movement. Instead of line trajectory, a region shape based on region-tracking control is included to save the energy usage, whilst, the calculation of repulsive force between an AUV and obstacles is used to avoid the collision. To observe the performance, some simulations on a 6-DOF-AUV are presented. During the obstacles avoidance, it is shown that the proposed control allows the AUV to produce 0.6 m less error without oscillation, obtain 80 s faster time of error convergence and save 9.3 % of energy consumption compared to modified Function-based Augmented Proposal Derivative (PFAPD). Overall, the proposed method contributes to a robust, energy saving and obstacles avoidances control for an AUV under disturbance’s effect.

[Keywords: super twisting sliding mode control; region boundary technique; obstacle avoidance; autonomous underwater vehicle]

Introduction

Autonomous Underwater Vehicle (AUV) is developed with the aim to diminish the complexity of undersea project due to the health issue of human involved in a long term undersea mission	extsuperscript{1}. A trajectory-tracking, such as to detect a damage pipe, is an example on the use of an AUV. Developing an advance robust controller for a trajectory-tracking mission is a challenging task as the nonlinearity of underwater environment	extsuperscript{2}. Beside unpredictable perturbations which enable to move the AUV from desired position and increase the use of energy consumption, the problem comes out when some obstacles are appeared in the middle of prescribed trajectory	extsuperscript{3}. Thus, it is a challenging task to develop an advance robust controller with a save energy control and obstacles avoidance technique.

Wide range controllers of AUV have been proposed either for a tracking-trajectory mission or obstacle avoidance. Li et al. proposed adaptive control which was combined with inequality region function based on potential energy for an ODIN AUV	extsuperscript{4}. An AUV was placed on an initial positon and required to reach a certain region. After that, an AUV which was inside the region moved through a pipe whose size was scaled down from 3.8 (m) to 2 (m) of diameter. It is shown that an AUV converged to desired region and passed the pipe trajectory without collision. Repoulias and Papadopoulos utilized partial state-feedback linearization, backstepping and non-linear damping techniques to control an AUV under desired horizontal and circular lane	extsuperscript{5}. Information such as desired position as well as velocity are given as a reference data. It is shown
that the error smoothly converged with a smooth transient response although oscillation was produced in the beginning. 

Then, Elmokadem et al. proposed Sliding Mode Control (SMC) for a REMUS AUV under a constant and a sinusoidal perturbation. The trajectory was determined in a straight and circular line and it is shown that the AUV tracked the trajectory well although the oscillations of error convergence were produced in the beginning. A chattering was also existed here, thus, \textit{signum} function was replaced by \textit{saturation} function to reduce the chattering. However, it degraded the robustness of an AUV. An idea to increase the robustness as well as save the energy spent was carried out by Ismail and Putranti. A super twisting SMC was used by an AUV in a region trajectory-tracking mission. Compared to SMC, the proposed control required shorter time of error convergence, faster in handling perturbations, less chattering and energy consumption. However, the obstacle issue was not considered both by Elmokadem et al. and Ismail and Putranti.

Obstacle avoidance technique for underwater vehicle’s mission was brought by Suhu and Subudhi [8]. In this paper, a repulsive force between AUV and obstacles was calculated, thus, the obstacles could be avoided. Hou and Cheah proposed multi-layers’ region technique. The AUVs required to move from initial position to a certain region and an obstacle was introduced in between initial position and desired region to disturb the AUVs’ movement. It is shown that the AUVs passed the obstacle in a safe way. However, the perturbation was not included in the simulation. Slightly similar to Hou and Cheah, Ismail et al. used region boundary-based control and an edge segmentation scheme as an obstacle and collision avoidance for multi AUVs. The result showed that the AUVs could track the desired trajectory and pass an obstacle which was located on the trajectory line. The perturbation was also not included in the simulation.

Reviewing the advantages and the disadvantages of previous work, this paper proposes a super twisting sliding mode-region based control with obstacles avoidances for an AUV’s tracking-trajectory. The perturbation effect will be considered in the simulation process. The paper is organized as follow: Section II studies about kinematic and dynamic model of a 6 DOF AUV. Section III describes the objectives and some assumptions of this paper, Section IV gives deep explanations about the proposed control, while analysis of simulation and conclusion are explained in Section V and VI.

System Model of 6 DOF AUVs

This section studies the kinematic and the dynamic analysis of a 6 DOF AUV. A 6 DOF AUV explains about two types of geometric transformation, namely, translation and rotations. The translation consists of sway, surge and heave movements, while rotation consists of roll, pitch and yaw movements. Introduces the origin $C$, which is located on the center of mass of the AUV, and two types of references, called body-fixed reference and earth-fixed reference. The illustration of a 6 DOF AUV is shown in Figure 1.

The relationship between inertial position of AUV and its velocity is explained by kinematic model. It uses Jacobian matrix to approximate a small displacement in different spaces. Define vector of position, velocity and force in linear and angular motion of an AUVs in Eq. (1)\textsuperscript{11}.

$$\eta = [\eta_1; \eta_2]^T = [x, y, z; \phi, \theta, \psi]^T$$
$$\nu = [\nu_1; \nu_2]^T = [u, v, w; p, q, r]^T$$
$$\tau = [\tau_1; \tau_2]^T = [X, Y, Z; K, M, N]^T \hspace{1cm} (1)$$

where, $\eta$ indicates the linear and angular position, $\nu$ indicates the linear and angular velocity, while $\tau$ indicates the linear and angular force. The kinematic model of the AUV, which is formulated by combining rotational joint and Jacobian matrix, is given in Eq. (2).

$$\dot{\eta} = \begin{bmatrix} J_1(\eta_2) & 0_{3x3} \\ 0_{3x3} & J_2(\eta_2) \end{bmatrix} \nu \hspace{1cm} (2)$$

On the other hand, the dynamic model studies about the effect of force, produced by the AUV,
while it is on its motion. The estimation of external force is included in this model. The dynamic model of the AUV is given in Eq. (3)\(^1\).

\[
M \ddot{v} + C(v)\dot{v} + D(v)\dot{v} + g(\eta_2) = \tau
\]  

(3)

where, \(M \in \mathbb{R}^{6x6}\) represents the inertia matrix of rigid body including the added mass term. \(C \in \mathbb{R}^{6x6}\) is the matrix of the coriolis and centripetal forces of rigid body including the added mass term. \(D \in \mathbb{R}^{6x6}\) denotes the hydrodynamic damping and lift force. \(g(\eta_2) \in \mathbb{R}^{6x1}\) is the gravitational force and moment. While, \(\tau \in \mathbb{R}^{6x1}\) are vector of disturbances and generalized forces acting on the vehicle.

**Objectives**

The objectives of this paper are explained as follow,

1. To formulate a robust controller which saves the energy consumption and reduces the external perturbation’s effect
2. To formulate a controller which allows an AUV to avoid some solid obstacles that located on the middle of prescribed trajectory

All the objectives can be obtained by following these assumptions,

**Assumption 1** : The value external perturbation are determined and bounded.

**Assumption 2** : The location and size of solid obstacles are known.

**Proposed Controller**

This chapter discusses a robust-saved energy control for an AUV which combines between super twisting sliding mode and region based control. A repulsive force is used to avoid the obstacles which are located on the desired tracking trajectory.

**A. Region-Based Control**

To reduce the energy usage, this paper engages moving region trajectory instead of line trajectory. Given the inequality function of desired region as shown in Eq. (4)\(^4\).

\[
f_i(\Delta \eta_i) \leq 0
\]  

(4)

where \(\Delta \eta_i = (\eta - \eta_o) \in \mathbb{R}^3\). \(\eta_o = [x_o, y_o, z_o]^T\) is a time varying and known as the reference point of region with \(i = 1, 2, \ldots, N\) number of desired region. The illustration of spherical region can be seen in Figure 2.

R in Figure 2 denotes the radius of sphere. Then, it is required to specify the potential energy from Eq. (4) as shown in Eq. (5)\(^4\).

\[
P_i (\Delta \eta_i) = \frac{k_p}{2} [\max_i(0, f_i(\Delta \eta_i))]^2
\]

\[
= \begin{cases} 
\frac{k_p}{2} f_i^2(\Delta \eta_i) & , if f_i(\Delta \eta_i) \leq 0 \\
0 & , if f_i(\Delta \eta_i) > 0 
\end{cases}
\]  

(5)

where \(k_p \in \mathbb{R}^{N \times N}\) denotes positive constants with \(i = 1, 2, \ldots, N\) number of desired region. Partial derivatives of Eq. (5) with respect to \(\eta\) will produce the region error as shown in Eq. (6)\(^4\).

\[
\sum_{i=1}^{N} k_{pi} \max_i(0, f_i(\Delta \eta_i)) \frac{\partial f_i(\Delta \eta_i)}{\partial \eta} \leq \Delta R_e
\]  

(6)

where, \(R_e\) is the region error of an AUV. Propose the reference vector based on the region error as Eq. (7).

\[
\dot{\eta}_r = J^{-1}(\dot{\eta}_d - \Delta \eta) - \alpha J^{-1} \Delta R_e
\]  

(7)

where \(\alpha\) is a constant and \(J^{-1}\) is inverse of Jacobian matrix.

**B. Super Twisting Sliding Mode-Region Based Control**

Given the equation of super twisting sliding mode control which consists of discontinuous and continuous system in Eq. (8)\(^7\).

\[
\tau_{st} = \int -K sgn (s) - \kappa |s|^{0.5} sgn (s)
\]  

(8)

where, \(s\) is a sliding vector, \(K\) is a gain of discontinuous system, \(\kappa\) denotes a gain of continuous system and \(sgn\) is a signum function. The value of \(K > \frac{d}{\Gamma_M}\) and \(\kappa^2 \geq \frac{4d(\Gamma_M + d)}{\Gamma_M \Gamma_m (K + d)^2}\), where, \(d\) is arbitrary chosen as a positive real number of disturbance, \(\Gamma_m\) and \(\Gamma_M\) are constants with \(\Gamma_m = K - d_o\) and \(\Gamma_M = K + d_o\), with \(d_o\) denotes
initial of $d$. The signum value is equal to -1, 0 and 1 if the sliding surface is less than zero, equal to zero and greater than zero, respectively.

The next step is defining a sliding vector which is given in Eq. (9).

\[ s = \dot{\eta} - \dot{\eta}_r \]  

(9)

where, \( \dot{\eta} \) is actual velocity of an AUV and \( \dot{\eta}_r \) is reference vector given in Eq. (7). Differentiate Eq. (9) with respect to time, hence,

\[ \ddot{s} = \ddot{\eta} - \ddot{\eta}_r \]  

(10)

where, \( \ddot{\eta} \) is the acceleration of an AUV and \( \ddot{\eta}_r \) is obtained by differentiate Eq. (7) with respect to time as follow:

\[ \ddot{\eta}_r = J^{-1}(\ddot{\eta}_d - \Delta \eta) + J^{-1}(\ddot{\eta}_d - \Delta \eta) - \alpha J(-\Delta RE - \alpha J^{-1}(\Delta RE)) \]  

(10)

The next step is multiplying Eq. (10) with \( M \), determine \( \ddot{s} \) equal to zero and substitute Eq. (3) as follow,

\[ M \ddot{s} = M \dot{\eta} - M \dot{\eta}_r \]

\[ M \ddot{s} = J^{-1} \tau - M \dot{\eta}_r - C \dot{\eta} - D \dot{\eta} - g \]

\[ J^{-1} \tau - (C \dot{\eta} + D \dot{\eta} + g) = M \dot{\eta}_r \]

\[ \tau_{reg} = J(M \dot{\eta}_r + C \dot{\eta} + D \dot{\eta} + g) \]  

(11)

Then, including Jacobian matrix of region boundary error to formulate an energy saving potential control as shown in Eq. (12).

\[ \tau_{reg} = J(M \dot{\eta}_r + C \dot{\eta} + D \dot{\eta} + g) - J \Delta RE \]  

(12)

Combine Eq. (8) and Eq. (12), yielding a robust-saved energy control as shown in Eq. (13).

\[ \tau = \tau_{st} + \tau_{reg} \]

\[ \tau = \int(-K \text{sgn}(\dot{\eta} - \dot{\eta}_r)) - \kappa|J(\dot{\eta} - \dot{\eta}_r)|^{0.5} \text{sgn}(\dot{\eta} - \dot{\eta}_r) + J(M \dot{\eta}_r + C \dot{\eta} + D \dot{\eta} + g) - J \Delta RE \]  

(13)

Eq. (13) shows the formula of super-twisting sliding mode control based on region boundary technique.

C. Repulsive Force

Repulsive force is used to avoid some obstacles which disturb the AUV’s movement in the tracking trajectory mission. This method is widely used as obstacle avoidance technique as it is easy to be applied. Given the repulsive force function in Eq. (14),

\[
\tau_{rep} = - \sum_{i=1}^{N_{obs}} g_{obs}(\eta, \eta_{obs_i}) = -K_0(\eta - \eta_{obs_i})^{(r_{obs_i}^2 - d^2)}
\]  

(14)

where, \( \nabla R \) represents the gradient of repulsive force, \( K_0 \in \mathbb{R}^3 \) is the gain which arbitrary chosen less than zero, \( \eta \in \mathbb{R}^3 \) denotes the AUV’s position, \( \eta_{obs} \in \mathbb{R}^3 \) denotes the obstacle’s position with \( i = 1, 2, \ldots, N \) number of obstacle, \( r_{obs} \) represents the distance between the \( i \) obstacle and the AUV and \( d \) is safe distance between them. The repulsive force will produce a maximum value when the position of AUV is equal to the position of obstacles. Hence, parameter \( d \) is involved, so that the value of \( \tau_{rep} \) will be maximum before the crash accident. The value of \( \tau_{rep} \) converge to zero once \( \eta - \eta_{obs_i} > d \).

The final equation of robust-saved energy control with obstacle avoidance is shown in Eq. (15).

\[ \tau = \tau_{st} + \tau_{reg} + \tau_{rep} \]  

(15)

Eq. (15) ensures a robustness of an AUV from a certain value of disturbance, save the energy controller and avoid the obstacles along the desired trajectory. The stability analysis of proposed control is presented in Appendix A.

Simulation Results

This chapter illustrates some simulations to observe the effectiveness of proposed control. An Omni-Directional Intelligent Navigator (ODIN) of a 6 DOF holonomic AUV which was developed by the University of Hawaii are carried in the simulation. For the simulation process, the AUV is located on an initial position at \([0, 14.5, 0]^T\) (m) and it requires to move to a start sign at \([1.5, 13.5, -1]^T\) (m). From a start sign, it tracks a 20 (m) length of spherical region trajectory and finish at \([21.5, 13.5, -1]^T\) (m). The inequality function of spherical trajectory is given in Eq. (16).

\[ f_1(\Delta \eta_1) = (x - x_o)^2 + (y - y_o)^2 + (z - z_o)^2 - R^2 \leq 0 \]  

(16)

where, \([x_o, y_o, z_o]^T = [1.5, 13.5, -1]^T\) (m) and the radius of region or allowable error \( R = 0.2 \) (m). The initial velocity of an AUV is \([0,0,0]^T\) (ms\(^{-1}\)). Beside sinusoidal wave with
white Gaussian noise, some solid obstacles also disturb the AUV’s movement during the tracking mission. This paper uses the same sinusoidal wave as used by Elmokadem et al.\(^6\). The details information is described in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obstacle</td>
<td>( \eta_{obs} )</td>
<td>([10, 13.5, -1]^T ) (m)</td>
</tr>
<tr>
<td>Obstacle size</td>
<td>( \eta_{obs} )</td>
<td>0.4 (m) of radius</td>
</tr>
<tr>
<td>Obstacle size</td>
<td>( \eta_{obs} )</td>
<td>([10, 8, 13, -1]^T ) (m)</td>
</tr>
<tr>
<td>Obstacle size</td>
<td>( \eta_{obs} )</td>
<td>0.8 (m) of radius</td>
</tr>
<tr>
<td>Perturbation</td>
<td>Sinusoidal wave</td>
<td>Amplitude: 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Frequency: 5 (Hz)</td>
</tr>
<tr>
<td></td>
<td>Gaussian white noise</td>
<td>Variance: 0.000005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sample time: 1 (s)</td>
</tr>
<tr>
<td>Proposed control</td>
<td>( K )</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>( \kappa )</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>( \alpha )</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>( k_{p_1} )</td>
<td>( \text{diag}(1, 1, 1) )</td>
</tr>
<tr>
<td></td>
<td>( K_0 )</td>
<td>( \text{diag}(-0.01, -2, -0.1) )</td>
</tr>
<tr>
<td></td>
<td>( d )</td>
<td>( r_{DDH} + 0.1 ) (m)</td>
</tr>
</tbody>
</table>

A robust saved energy control with an obstacles avoidance technique is compared with an existing control, Potential Function-based Augmented Proposal Derivative (PFAPD), proposed by Suhu and Subudhi\(^8\). PFAPD is modified by adding \( g_\eta \) element to increase its performance. The AUV cannot accomplish the mission without adding \( g_\eta \).

The result of AUV under proposed control in an obstacle-rich environment is presented in Figure 3(a). It is shown that the AUV moved directly from initial position to start tracking region and avoided two obstacles which were introduced inside desired region. Collision was not happened and the AUV went back to desired region without oscillation. In contrast, Figure 3(b) showed that the AUV unbale to move directly to start tracking point and avoided the obstacles with some oscillations in the case of using modified PFAPD.

The error of proposed control and modified PFAPD in an obstacle-rich environment are shown in Figure 4(a) and 4(b), respectively. Figure 4(a) shows that the error position took 20 (s) to converge to allowable area without oscillation and it remained inside the boundary during the mission. Meanwhile, Figure 4(b) shows that some oscillations in about 100 (s) were produced by modified PFAPD before converged to zero. In the time of obstacles avoidance, the Y-axis of proposed control reached the maximum error at 1 (m) and converged to allowable error at 220 (s) of time, whilst, the maximum error of existing control is 1.6 (m) and it converged at 300 (s).

Fig. 3 – 3D view with obstacles of (a) proposed control, (b) modified of existing control
Figure 5 shows the result of force and moment in an obstacle-rich environment. More force and moment were needed by AUV to avoid the obstacles in both controls. It is shown in Figure 5(b) that the maximum value, ±48 (N), was spent by Y-force for modified PFAPD, while Figure 5(a) shows that the proposed control spent less than 30 (N).

Furthermore, the energy consumption is obtained by calculates force spent with a 2-norm function. The result of energy consumption in every case can be seen in Table 2. About 1248 (N) of energy was required by modified PFAPD to avoid the obstacles. On the other hand, the proposed control required about 105 (N) less energy to avoid the obstacles. Finally, the proposed control saved 9.3% energy in the case of an obstacle-rich environment.

### Table 2. Energy consumption

<table>
<thead>
<tr>
<th>Used Control</th>
<th>Energy Spent [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed control</td>
<td>1,142.7</td>
</tr>
<tr>
<td>Modified PFAPD</td>
<td>1,248.5</td>
</tr>
</tbody>
</table>

**Conclusion**

A super twisting sliding mode-region based control with obstacles avoidance technique have been proposed in this paper. Some simulation through MATLAB were conducted to see the effectiveness of proposed control. The results were compared with the existing control called Potential Function-based Proposal Derivative (PFPD). It is shown that a proposed control allows an AUV to avoid the obstacles, produces...
less error, and spent less energy requirement. Furthermore, the oscillations are not produced during all missions. The increasing use of AUV attracts researcher to develop a control which can coordinate multi-AUVs, thus, it is challenging to develop a control that allow multi-AUVs to track a certain trajectory as well as can reduce the perturbation effect and avoid solid obstacles in the future.

References