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Optimal Autopilot and Guidance of the ROV: SAGA

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Abstract: In this study, an optimal autopilot algorithm is developed for 3D motion of SAGA which is an unmanned underwater survey vehicle. Firstly, a nonlinear mathematical model for SAGA is obtained. The structure of the mathematical model of the vehicle comes from a Newton-Euler formulation. The resultant nonlinear system is then controlled by PID controllers. These PID controllers are designed for 3D motion which is realized by a suitable combination of right, left and vertical thrusters. The optimal control problem is that the vehicle is supposed to reach the desired position and rotation with desired velocity by consuming minimum energy. This problem is solved with a genetic algorithm. All of this study is performed in a Matlab/Simulink environment.

Keywords: Autopilot, guidance, genetic algorithm, mathematical modelling, PID controller, unmanned underwater vehicle.

1. INTRODUCTION

Unmanned underwater vehicles are frequently used both in civilian and military areas. They are the most important tools to investigate underwater. The unmanned underwater survey vehicle (SAGA) used in this study is a remotely operated underwater survey vehicle specifically developed for the purpose of investigation of underwater and equipped with a camera and a two dimensional sonar (see Figure1), in addition to several other custom specific sensors as can be seen in http://www.desistek.com.tr (2015). It is very easy to obtain navigational data and high resolution video, as regards to underwater operation, from this vehicle.

Fig. 1. Underwater survey vehicle SAGA

The control of the vehicle is very important in almost all the applications of these kinds of vehicles; because vehicles have complex dynamics and there are difficulties owing to underwater environment. There are many control techniques to design autopilots for unmanned underwater vehicles (UUV). Speed autopilots are designed by P or PI control techniques as is done in Caccia and Veruggio (2000). Also, position autopilots are designed by similar controllers (Zanoli and Conte (2003)). More complicated autopilots are designed with PID techniques and sliding mode control techniques as in Lee, Sohn, Byun and Kim (2009). Optimal kinematic control for an autonomous underwater vehicle and a particular set of optimal motions which trace helical paths is discussed in Biggs and Holderbaum (2009). A new optimal control method based on the energy equations of the controlled system is presented in Fukushima, Arslan and Hagiwara (2009). This method is applied on an underactuated underwater vehicle. The configuration optimization of an underwater vehicle is studied and the maneuver requirements of the optimization problem are obtained by the solution of an optimal control problem in Seong, Ruzzene, Scorceletti and Bottosso (2010). Optimal control is applied on an underwater sensor network for cooperative target tracking in Baumgartner, Ferrari and Rao (2009).

In this study, the surge and heave speed of the vehicle and the yaw angle are controlled by using PID controllers. They are the real autopilots of the vehicle. The optimal autopilot algorithm is designed to perform 3D motion. The vehicle can reach the desired position along many different tracking routes and with many different speeds. Different forces are produced from thrusters for each different route. The vehicle has limited energy either because of having a battery, or instantaneous power utilization is limited. It is aimed that the vehicle consumes energy economically while the design objectives are satisfied. The optimal autopilot(s) stands on a level between the guidance and the real autopilots.

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Depending on the guidance requirements a reference constructed by interpolation of the already calculated optimal inputs is generated for the real autopilots to drive the system (sub-optimally). In this way, the vehicle is supposed to reach the desired position and the yaw angle with desired velocity by consuming minimum energy.

2. MATHEMATICAL MODEL

The notation used for the mathematical model of the underwater vehicle is shown in table 1. The motion of the unmanned underwater vehicle is expressed in 6 degrees of freedom. For underwater vehicles, the 6 different motion variables are defined as surge, sway, heave, and roll, pitch and yaw, as is done in Fossen (1994).

The basic structure of mathematical model of an unmanned underwater vehicle is obtained as shown below as suggested by Fossen (1994).

$$M(\dot{v}) + C(v)v + D(v)v + g(\eta) = u \quad (1)$$

$$\dot{\eta} = J(\eta)v \quad (2)$$

M: Total mass of the vehicle,
C: Total Centrifugal and Coriolis forces
M_{RB}: The rigid body mass of the vehicle,
M_A: Added inertia matrix,
C_{RB}: Rigid body centripetal and Coriolis matrix,
C_A: Hydrodynamic Centripetal and Coriolis matrix,
D: Damping matrix,
g: Restoring forces and moments,
τ: Input vector,
v: The linear and angular velocity vector of the vehicle,
η: The position and attitude vector of the vehicle,
J: Transformation matrix.

The mass matrix of the vehicle is the sum of the rigid body mass and added inertia matrices.

$$M = M_{RB} + M_A$$

In many ROV applications the vehicle usually moves at low speeds. If the vehicle also has three planes of symmetry, this suggests that we can neglect the contributions from the off-diagonal elements in the added inertia matrix M_A. Hence the following simple expressions for M_A and C_A are preferred for SAGA:

$$M_A = -\mathrm{diag}\{X_{\dot{u}}, Y_{\dot{v}}, Z_{w}, K_{\dot{p}}, M_{\dot{q}}, N_{\dot{r}}\}$$

$$C_A(v) = \begin{bmatrix} 0 & 0 & 0 & 0 & -Z_{\dot{w}}w & Y_{\dot{v}}v \\ 0 & 0 & 0 & Z_{\dot{w}}w & 0 & -X_{\dot{u}}u \\ 0 & 0 & 0 & -Y_{\dot{v}}v & X_{\dot{u}}u & 0 \\ 0 & -Z_{\dot{w}}w & Y_{\dot{v}}v & 0 & -N_{\dot{r}}r & M_{\dot{q}}q \\ Z_{\dot{w}}w & 0 & -X_{\dot{u}}u & N_{\dot{r}}r & 0 & 0 \\ -Y_{\dot{v}}v & X_{\dot{u}}u & 0 & -M_{\dot{q}}q & 0 & 0 \end{bmatrix}$$

The Coriolis and centripetal force matrix of SAGA is the sum of the rigid body and hydrodynamic Coriolis and centripetal matrices.

$$C = C_{RB}(v) + C_A(v)$$

The motion of the vehicle in 6 DOF can be described by the following vectors:

$$\vec{\eta} = [\,\eta_1^T, \eta_2^T\,]^T \qquad \eta_1^T = [x, y, z]^T \qquad \eta_2^T = [\phi, \theta, \psi]^T \quad (3)$$

$$\vec{v} = [\,v_1^T, v_2^T\,]^T \qquad \overrightarrow{v_1} = [u, v, w]^T \qquad \overrightarrow{v_2} = [p, q, r]^T \quad (4)$$

$$\vec{\tau} = u = [\tau_1^T, \tau_2^T\,]^T \qquad \overrightarrow{\tau_1} = [X, Y, Z]^T \qquad \overrightarrow{\tau_2} = [K, M, N]^T \quad (5)$$

In the nonlinear mathematical modelling of the vehicle, u is the column matrix which consists of moments and forces produced from thrusters. The vehicle has three thrusters, two of which are located horizontally, at the right and left sides of the vehicle (see Fig. 1). The last one is located vertically. The vertical thruster is positioned almost on the CG point of the vehicle. The motion in the x-axis (surge motion) and the rotation around the z-axis (yaw angle) are accomplished by horizontal thrusters. The motion in the z-axis (heave motion) and the rotation around the y-axis (pitch angle, very small) are managed by using the vertical thruster. In this study, the 3D motion is realized by a suitable combination of right, left and vertical thrusters. Each thruster model includes propeller, motor and water models as is done in Cody, Healey, Rock and Brown (1995).

The resultant thrust force and moments applied on the vehicle is expressed as follow.

$$\begin{vmatrix} \sum X \\ \sum Y \\ \sum Z \\ \sum K \\ \sum M \\ \sum N \end{vmatrix} = \begin{vmatrix} T_1 + T_2 \\ 0 \\ T_3 \\ 0 \\ T_3 r_3 \\ T_1 r_1 + T_2 r_2 \end{vmatrix} \quad (6)$$

where,

T_1: Right thruster force,
T_2: Left thruster force,
T_3: Vertical thruster force,
r_1: Distance between the right thruster and the center of gravity, 119.21 mm,
r_2: Distance between the left thruster and the center of gravity, −119.21 mm
r_3: Distance between the vertical thruster and the center of gravity, 217 mm.

3. CONTROLLER DESIGN

The surge speed, heave speed and yaw angle of the vehicle are controlled by using PID controllers. Since SAGA does not have actuators for sway and roll motions, it cannot