THE COMPARISON OF UNMANNED UNDERWATER VEHICLES' CONTROL STRATEGIES

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Abstract

The need for unmanned underwater vehicle services is increasing steadily in recent years. In order to complete their task satisfactorily these type of vehicles need control algorithms with very good performances for their guidance. This is especially true for a special kind of unmanned underwater vehicles which don't have real time connection with the operator. This type of vehicles are called autonomous underwater vehicles. This paper makes a comparison of two common type of control algorithms (sliding mode control and PID) which use different type of thrusters. Thrusters with propellers driven constant speed electric drives and variable speed electric drives have been considered.

Keywords: sliding mode control, PID, unmanned underwater vehicles, thrusters.

Presenting Author's Biography

Primož Podržaj. He was born in Ljubljana, Slovenia in 1972. He received BSc, MSc and PhD from the Faculty of Mechanical Engineering, University of Ljubljana in 1996, 2000 and 2004 respectively. He is currently working as the teaching assistant in the same institution. His main research interest is Control theory, but he is also working in the are of Resistance Spot Welding Control and Intelligent Space.

1 Introduction

The need of unmanned underwater vehicles (UUV) has become apparent as the world pays great attention on environmental and resources issues as well as scientific and military tasks. UUVs are used extensively in different kinds of applications such as scientific inspection of deep sea, exploitation of underwater resources, long range survey, oceanographic mapping, underwater pipelines tracking and so on. In general UUVs can be divided in two categories:

- **R**emotely **O**perated **V**ehicles (ROVs)
  As the name suggests, ROVs are unoccupied underwater vehicles (robots). They are linked to the ship by a tether (sometimes referred to as an umbilical cable), a group of cables that carry electrical power, video and data signals back and forth between the operator and the vehicle. High power applications will often use hydraulics in addition to electrical cabling. Most ROVs are equipped with at least a video camera and lights. Additional equipment is commonly added to expand the vehicle's capabilities. These may include sonars, magnetometers, a still camera, a manipulator or cutting arm, water samplers, and instruments that measure water clarity, light penetration and temperature. A new generation of ROVs has an interchangeable toolsled for different payloads and is therefore very versatile. Examples of such systems are the deep-water vehicles Tiburon [2, 3] and Victor 6000 [4] and the mid-water vehicle ROMEO [5].

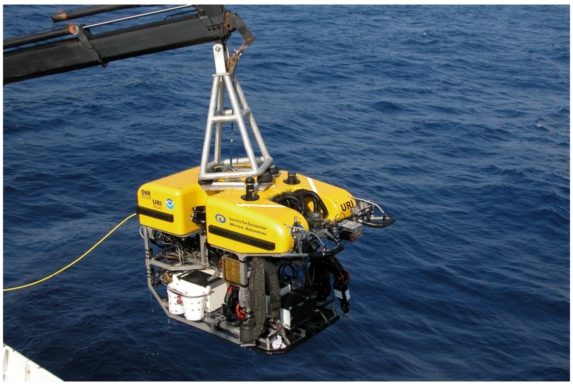

Fig. 1 A science ROV being launched from an oceanographic research vessel [1].

- **A**utonomous **U**nderwater **V**ehicles (AUVs)
  AUVs could be defined as untethered underwater vehicles (robots). In general they are very small and represent the new up and coming technology in deep ocean research. The main feature of the AUVs is their autonomy. The main disadvantage compared to ROVs is that the whole energy needed for their operation has to be stored in the vehicle. This fact limits their operating time. They are however preferred choice for a specific modes of operation. A vehicle might for example be programmed to stop thrusting and float passively at a specific depth or density layer in the sea, or to actively loiter near a desired location. AUVs may also be programmed to swim at a constant pressure or altitude or to vary their depth and/or heading as they move through the water, so that undulating sea saw survey patterns covering both vertical and/or horizontal swaths may be formed. AUVs are also well suited to perform long linear transects, sea sawing through the water as they go, or traveling at a constant pressure. They also provide a highly productive means of performing seafloor surveys using acoustic or optical imaging systems.

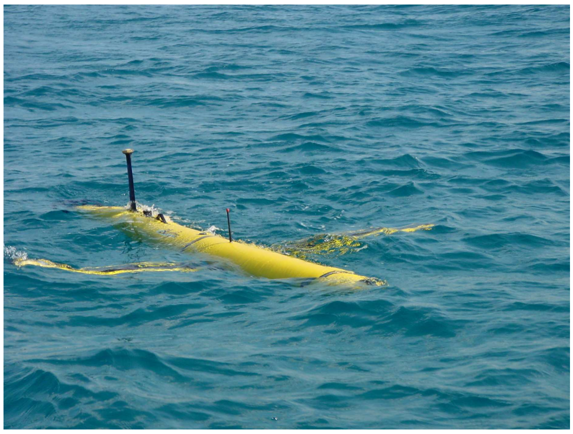

Fig. 2 An AUV (Bluefin-12) during engineering trials [6].

The dynamics of both ROVs and AUVs is highly nonlinear and the hydrodynamic coefficients of vehicles are difficult to be accurately estimated a priori because of the variations of these coefficients with different operating conditions. The performance of the control system is of great importance especially for the AUVs, because their guidance might rely on it. Consequently it is clear that a great effort is being made in order to improve the performance of the UUVs control system. Various control methodologies have been proposed to control the movement of UUV. Sliding mode control for example has been proposed by Yoerger and Slotine in 1984 [7], by Healey and Lienard in 1993 [8] and by Chatchanayuenyong and Parnichkun in 2006 [9]. The H_∞ approach was used by Fryxell et. al. in 1996 [10] and Conte and Serani in 1998 [11]. Neural network control was studied by Porto and Fogel in 1990 [12], by Lorenz and Yuh in 1996 [13] and by Li and Lee in 2005 [14]. Adaptive techniques were for example studied by Yuh in 1990 [15], by Fossen and Fjellstad in 1995 [16] and by Zhao et. al. in 2001 [17]. Fuzzy control was used by Smith et. al. in 1993 and 1994 [18, 19]. Even PID control approach was for example used by Perrier and Canudas-De-Wit in 1996 [20].

This article discuses the distinction of control algorithm performance based on the different type of thrusters used. If thrusters use variable speed electric motor to drive a propeller, a PID controller was used. If however constant speed electric motor is used to drive a propeller, sliding mode control seems to be a more appropriate choice.

2 Modeling

2.1 Vehicle modeling

The dynamic model of UUV can be derived from the general Newton-Euler motion equation of a rigid body in a fluid medium. Let $\mathbf{v}_{rel}$ be the six-dimensional speed column vector relative to the fluid, defined by

$$\mathbf{v}_{rel} = \left[\mathbf{v}_{1rel}^T, \mathbf{v}_{2rel}^T\right]^T = [u, v, w, p, q, r]^T \quad (1)$$

where u is the surge velocity, v the sway velocity, w the heave velocity, p the roll angular velocity, q the pitch angular velocity, and r the yaw angular velocity. All of them are shown in Fig. 3. If the fluid is irrotational,

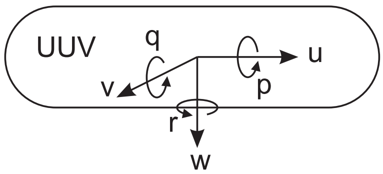

Fig. 3 Definition of body fixed coordinate system

inviscid, of uniform and constant density, and of infinite extent except for the rigid body itself, then the equation of motion can be expressed in spatial notation in the local reference frame as [21]

$$\begin{aligned}&\mathbf{M}\dot{\mathbf{v}}_{rel} + \mathbf{C}(\mathbf{v}_{2rel})\mathbf{v}_{rel} = -\mathbf{M}_A\dot{\mathbf{v}}_{rel}\\ &-\mathbf{C}_A(\mathbf{v}_{1rel}, \mathbf{v}_{2rel})\mathbf{v}_{rel} - \mathbf{D}_L\mathbf{v}_{rel}\\ &-\mathbf{D}_Q|\mathbf{v}_{rel}|\mathbf{v}_{rel} + g\mathbf{W}[\mathbf{k}_0^T, \mathbf{k}_0^T]^T + [\mathbf{F}^T, \mathbf{F}^T]^T\end{aligned} \quad (2)$$

The experimental identification of the complete model according to eq.2 is possible, but very complicated, because tow tank approach has to be used [22]. This approach is also not applicable for UUvs with variable and mission-dependent configuration. UUVs in general move at small speeds and their maneuvers often consist of plane surge motion or vertical translation. The coupling terms may therefore be neglected without serious loss of information. This means that that off-diagonal elements of the added mass matrix, the Coriolis and centripetal kinematics, and drag coupling terms are neglected. This approximation relies on the fact that[21]:

1. the off-diagonal elements of the added mass matrix of a rigid body having three symmetry planes are identically null [23]
2. the off-diagonal elements of the positive definite matrix are much smaller than their diagonal counterparts [24]
3. the hydrodynamic damping is negligible at low speeds

The resulting model structure for a single degree of freedom is [21]

$$m_\xi\dot{\xi} = -k_\xi\xi - k_{\xi|\xi|}\xi|\xi| + \phi_\xi + \nu_\xi \quad (3)$$

where m_ξ is the inertia relative to the considered degree of freedom, ξ is 1-D velocity, k_ξ and $k_{\xi|\xi|}$ are the linear and quadratic drag coefficients, ϕ_ξ is the applied force or torque and ν_ξ is the disturbance modeling otherwise unmodeled phenomena such as cable effects.

Although this equation is the most often used when control issues are studied the equation can further be modified. The actuator action ϕ_ξ is usually determined experimentally in a thrust tunnel. The drawback of such a method is the fact that the model neglects the propeller-propeller and/or propeller-hull interactions that occur during operating conditions. One possible solution is the introduction of thruster installation coefficient η_ξ, which represents the reduction in the efficiency of the thrusters. Eq. 3 can therefore be modified into the following form [21]:

$$m_\xi\dot{\xi} = -k_\xi\xi - k_{\xi|\xi|}\xi|\xi| + \eta_\xi\phi_\xi^n + \nu_\xi \quad (4)$$

where the nominal actuator action ϕ_ξ^n is assumed to be known. Even more detailed versions of eq. 3 are possible, but will not be presented here.

2.2 Thruster modeling

Recently there is a lot of research going on in the area of modeling and control of underwater vehicle thruster system [25, 26, 27, 28, 29].

The thruster force depends on the type of the electric-drive used. If it is a constant speed electric drive, the force can have only three values. Maximum values in two directions and zero value.

If the electric drive is however variable speed electric drive, its force can be calculated according to the following equation [21]

$$\tau = c_\tau\, n\,|n| - c_s\,|n|\,v_a \quad (5)$$

where n is the propeller revolution rate, v_a the velocity of the fluid through the propeller blade (velocity of advance) and c_τ and c_s the unknown constants. The saturation term $c_s\,|n|\,v_a$ can be neglected in many standard operations. If the thruster time constant is neglected, the propeller revolution rate can be directly related to the voltage U. Eq. 5 can therefore be modified to the following form [21]

$$\tau = c_U\, U\,|U| \quad (6)$$

where c_U is the unknown constant. The characteristic of variable speed electric drive is therefore nonlinear, but can easily be linearized by software or electronics. It's main advantage is that the whole range of forces between $-\tau_{max}$ and τ_{max} is applicable.

3 Control algorithms

This paper discusses the differences in control algorithm performance based on the thruster selection. Eq. 3 is usually written in slightly different form if the control of UUVs is studied. If displacement (in x-direction) is used instead of velocity the following equation can be obtained

$$m\ddot{x} + k_{\dot{x}}\dot{x} + k_{\dot{x}|\dot{x}|}\dot{x}|\dot{x}| = \phi_x + \nu_x \tag{7}$$

Simple algebraic manipulation results in

$$\ddot{x} = \frac{-k_{\dot{x}}\dot{x} - k_{\dot{x}|\dot{x}|}\dot{x}|\dot{x}| + \nu_x}{m} + \frac{\phi_x}{m} \tag{8}$$

Eq. 8 will be the starting point for control algorithm comparison. For simulation purposes we can chose some values for system parameters and discard disturbances. In our case the final equation can be written as

$$\ddot{x} = -\dot{x} - \dot{x}|\dot{x}| + \phi_x \tag{9}$$

and will be used as a basis for control algorithm comparison.

3.1 Sliding mode control

If sliding mode control (SMC) is considered eq. 9 can be rewritten in the following form

$$\ddot{x} = f(\mathbf{x}) + u \tag{10}$$

Let's suppose that the desired state $\mathbf{x}_d = \mathbf{0}$. The sliding surface S can therefore be defined by the following equation [30]

$$s = \dot{x} + \lambda x \tag{11}$$

The control action u is defined by the following equation

$$u = \begin{cases} -\phi_{max} & \text{if } s > 0 \\ \phi_{max} & \text{if } s < 0 \end{cases} \tag{12}$$

It was supposed that $\phi_{max} = 2$. The model of the control system is shown in Fig. 4. The model of the system

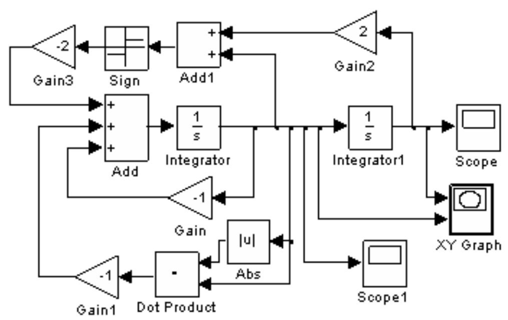

Fig. 4 The Matlab/Simulink model of the system

is in the lower part of Fig. 4. The upper part represents the controller. The constant λ was chosen to to be equal to $\lambda = 2$. The sliding surface is therefore defined with the following equation

$$\dot{x} = -2x \tag{13}$$

and marked with a dashed line in Fig. 5. Fig. 5 shows the transient response of the controlled system from the

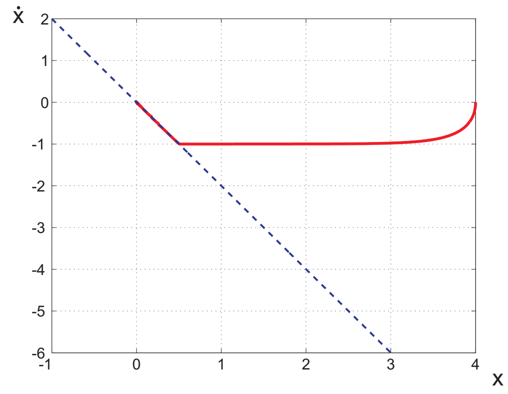

Fig. 5 The phase diagram of transient response (SMC)

initial value of $x(0) = 4$ to the desired value $x_d = 0$. The SMC controlled system trajectory reaches the sliding surface from any initial condition in a finite time and then slides along the surface towards x_d exponentially with a time constant equal to $\frac{1}{\lambda}$, as can be seen in Fig. 5. The transient response of the system (displacement x vs. time t). can be seen in Fig. 6. The system

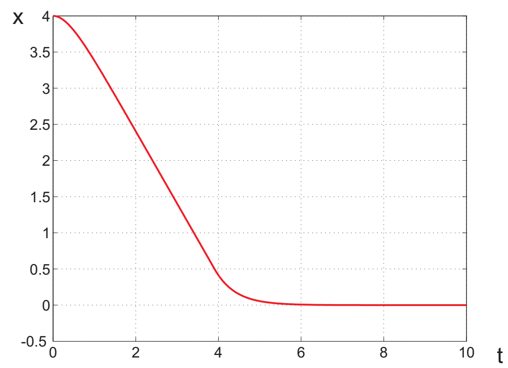

Fig. 6 Transient response (SMC)

reaches the sliding surface (the desired state $x_d = 0$) in approximately 5 seconds. The major drawback of SMC can however be seen in Fig. 7. It shows the control

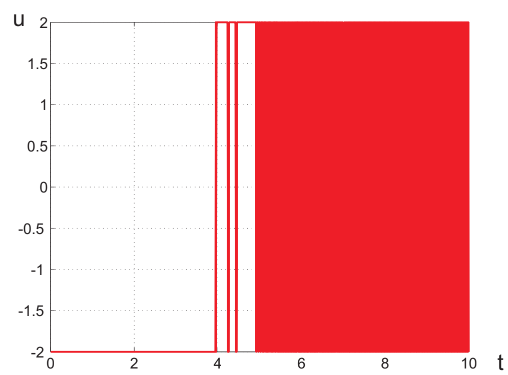

Fig. 7 Control input versus time (SMC)

signal versus time. It can be seen that a major control activity starts at approximately five seconds, when the sliding surface is reached. This phenomenon is called chattering and is very undesirable in practice, since beside involving high control activity may excite high frequency dynamics neglected in the course of modelling.

3.2 PID control

PID control algorithm is the most commonly used type of control algorithm. Actually more than 90% of controllers are of PID type[31]. That's why it was chosen as a second type of control algorithm in our comparison study. It is usually used for continuous systems. Variable speed electric drive case is therefore applicable to this type of controller. The transfer function of the PID controller is equal to

$$P(s) = K \cdot \left(1 + \frac{1}{T_i\, s} + T_d\, s\right) \tag{14}$$

The parameters K, T_i and T_d have to be determined properly in order that the controlled system's performance is satisfactory. There are many PID tuning methods. One of the best known is the so called Ziegler-Nichols method. In order to determine parameters K, T_i and T_d we first need to determine the values of variables a and L from the step response of the open loop system (shown in Fig. 8) [31]. The parameters were

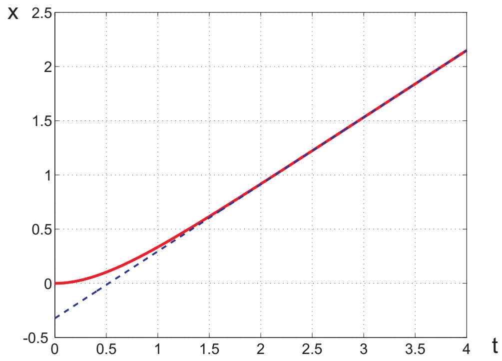

Fig. 8 Step response of the open loop system

found to be equal to:

$$\begin{aligned} a &= 0.32 \\ L &= 0.52 \end{aligned} \tag{15}$$

The parameters of the P, PI or PID type of controller can be determined according to Tab. 1. PID type of

Tab. 1 PID parameters according to Ziegler-Nichols [31]

Controller	K	T_i	T_d
P	1/a		
PI	0.9/a	3L	
PID	1.2/a	2L	L/2

controller was chosen in our case. The parameters K, T_i and T_d are therefore equal to:

$$\begin{aligned} K &= 3.72 \\ T_i &= 1.05 \\ T_d &= 0.26 \end{aligned} \tag{16}$$

The transient response of the resulting controlled system is shown in Fig. 9. Fig. 9 should be compared with

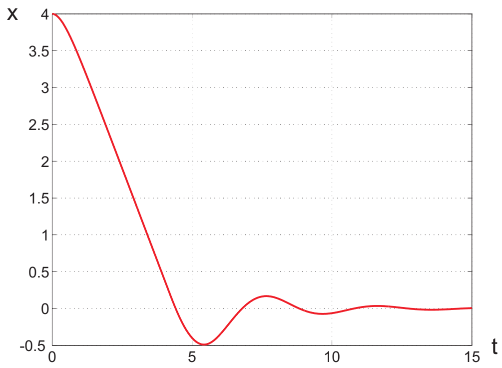

Fig. 9 Transient response (PID)

Fig. 6 in order to assess the performance of both type of control algorithms (SMC and PID). Although PID was used together with a more advanced variable speed electric drive, it can be seen that the settling time is much larger in this case. SMC also has no overshoot compared to PID. The major advantage of PID controller versus SMC one can however be seen if Fig. 10 is compared to Fig. 7. Both figures show control input

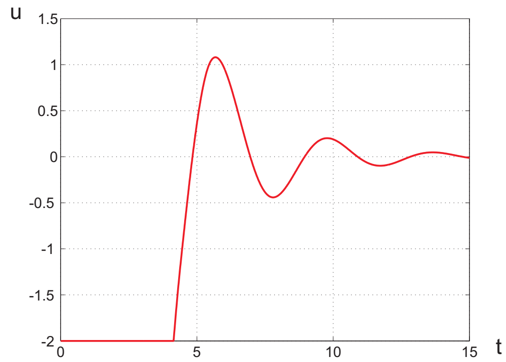

Fig. 10 Control input versus time (PID)

versus time. PID controller has much smaller activity compared to SMC.

4 Conclusion

It can be concluded that the SMC has better transient performance than PID one, although PID used advanced type of thrusters. It should also be emphasized that the SMC is not as sensitive to system parameter changes as PID is. The only major drawback of SMC is its high control activity after the sliding surface is reached. Sliding surface was actually a line in our case. If it was modified to a narrow area, the problem of high control activity would be overcome. But the system would not be as accurate as before. The ideal system would therefore be a combination of SMC for fast transient response and PID for high accuracy once the system is close to steady state. Possible combination of two control algorithms would however need further research.

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