Design and Implementation of Electronic Control System for UTM-AUV

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Abstract: Parallel development of autonomous underwater vehicle (AUV) mechanical hardware and electronic control system can be effectively carried out if the control system can be independently developed from the mechanical hardware. Real time simulation using personal computer (PC) could be an alternative for fast development of control system. This paper describes an approach to design the electronic control system for UTM-AUV. Analysis of the designed control system has been done in real time simulation by using Real-Time Workshop. The generic real time has been selected as system target file to provide real time simulation environment. This concept used a stand-alone PC running the designed control system, which can be assumed as the actual AUV. At the same time another PC, which running the Simulink is connected to the stand-alone PC via TCP/IP connection to view the behavior of the control system.

Keyword
Control system design, Autonomous underwater vehicle and Real time simulation.

I. INTRODUCTION

Autonomous underwater vehicle (AUV) has become one of the most interested research areas for the past ten years in marine technology. The AUV is basically an extension of the ROV's technology. The main differences between ROV and AUV is that ROV is controlled by the pilot (human) from the mothership while the AUV is controlled by its on-board controller guided by build-in preprogrammed instructions.

Improvement has been made in control system such that the AUV can intelligently accomplish it mission without or little attention from human supervision. Therefore, the on-board electronic controller should be good enough to implement the control system and execute the instructions at high-speed rate. This will ensure the controller can provide the latest information about the AUV condition since the actual implementation is in real time.

Section II in this paper describes the general model for the dynamics of underwater vehicle moving in 6 degree-of-freedom (6 DOF). The nonlinear equations of motion are derived in terms of rigid body dynamic, hydrodynamics forces and moments, added mass and inertia, restoring forces and moments and hydrodynamics damping. The 6 DOF nonlinear equations of motion in their general representation, required that a large number of hydrodynamic derivatives are known. However, the number of unknown parameters can be reduced by using body symmetry considerations.

Section III describes the control system design based on dynamic equations obtained from section II. The selected control systems are decoupled control system and PI control system.

Section IV describes the implemention of real time simulation for the designed control system using Simulink and Real-time Workshop.

II. VEHICLE MODELING

The purpose of modeling the vehicle is to obtain accurate 6 DOF motion equations of the vehicles. These dynamic equations describe the velocity, the trajectory and the orientation of the vehicle after certain input are applied to the vehicles. Fossen in [1] used 6 independent coordinates to determine the position and orientation of a rigid body. Table 1 show the notation used in this paper for modeling the vehicle.

This paper used the model of NPS-AUV prototype at Naval Post Graduate School for modeling purpose. There is no information available for modeling the UTM-AUV prototype since the prototype still under construction. Furthermore, the UTM-AUV has similar characteristic with NPS-AUV.

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There are 2 coordinate frame normally used in analyzing the motion of the AUV in 6 DOF. The moving frame *XoYoZo* fixed to the vehicle and the reference frame *XYZ* (earth-fixed frame). The 6 DOF equation of motions for the AUV can be derive by using Newton-Euler formulation, which is based on Newton's Second Law.

$$f = m\ a \qquad (2.1)$$

Where f is the force, m is the mass and a is the acceleration.

From fig. 2.2, the translational motion of the AUV can be written as

$$f_c = m(\overset{o}{v}_c + \omega \times v_c) \qquad (2.2)$$

And the rotational motion can be written as

$$m_c = I_c \dot{\omega} + \omega \times (I_c\, \omega) \qquad (2.3)$$

Where

v_c = velocity of the center of gravity
ω = anggular velocity vector
I_c = Inertia tensor about the bodys center of gravity
f_c = forces referred to the body's center of gravity
m_c = moments referred to the body's center of gravity.

Derivation of the motion equations involves lot of mathematical calculation including matrix and vectors representation, thus will be not considered in this paper. Equation (2.2) and (2.3) can be written in component form according to SNAME (1950) notation, that is

$f_o = [X, Y, Z]^T$ external forces
$m_o = [K, M, N]^T$ moment of external forces
$v_o = [u, v, w]^T$ linear velocity of *XoYoZo*
$\omega = [p, q, r]^T$ angular velocity of *XoYoZo*
$r_G = [x_G, y_G, z_G]^T$ center of gravity

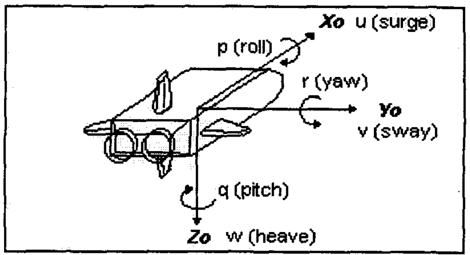

Fig 2.1: 6 different motion for AUV

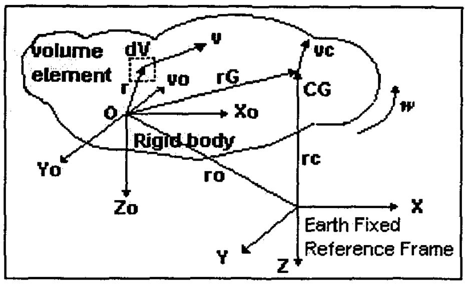

Fig 2.2 : Body fixed and earth fixed reference frame.

Applying this notation to (2.2) and (2.3) yields:

Surge motion equation

$$X = m\begin{bmatrix} \dot{u} - vr + wq - x_G(q^2 + r^2) + y_G\,(pq - \dot{r}) \\ + z_G\,(pr + \dot{q}) \end{bmatrix}$$

Sway motion equation

$$Y = m\begin{bmatrix} \dot{v} - ur + wp + x_G(pq + \dot{r}) - y_G\,(p^2 + r^2) \\ + z_G\,(qr - \dot{p}) \end{bmatrix}$$

Heave motion equation

$$Z = m\begin{bmatrix} \dot{w} - uq + vp + x_G(pr - q) + y_G\,(qr + \dot{p}) \\ - z_G\,(p^2 + q^2) \end{bmatrix}$$

Table 1: Notation used for marine vehicle.

DOF		force and moments	linear and angular vel.	position and Euler angles
1	motion in the x – direction (surge)	X	u	x
2	motion in the y – direction (sway)	Y	v	y
3	motion in the z – direction (heave)	Z	w	z
4	rotation about the x – direction (roll)	K	p	ϕ
5	rotation about the y – direction (pitch)	M	q	θ
6	rotation about the z – direction (yaw)	N	r	ψ

Pitch rotation equation

$$K = m\left[\, y_G(\dot{w} - uq + vp) - z_G(\dot{v} - wp + ur)\right] + I_x \dot{p}$$
$$+ (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy}$$

Roll motion equation

$$M = m\left[\, z_G(\dot{u} - vr + wq) - x_G(\dot{w} - up + vp)\right] + I_y \dot{q}$$
$$+ (I_x - I_z)rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{zx} + (qp - \dot{r})I_{yz}$$

Yaw motion equation.

$$N = m\left[\, x_G(\dot{v} - wp + ur) - y_G(\dot{u} - vr + wq)\right] + I_z \dot{r}$$
$$+ (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rp - \dot{p})I_{zx}$$

III. CONTROL SYSTEM DESIGN

The methodology adopted for the design control system is Decoupled control system. The dynamic equations of motion can be divided into 3 non-interacting (or lightly interacting) subsystem.

1) Speed system u(t)
2) Steering system v(t), r(t) and yaw(t)
3) Diving system w(t), q(t), theta(t) and z(t)

These 3 subsystem can be controlled by means of propeller with *n*(t) revolution, a rudder with deflection δr (t) and a stern plane with deflection δs (t).

A. Speed Control System

The desired forward speed *ud* can be achieve by controlling the propeller revolution *n* while neglecting the interaction from sway, heave, roll, pitch and yaw. All the parameters except for the surge *u* and propeller revolution *n* are assumed to be constant. Proper tuning of the PI controller will ensure that *n* tracks the desired propeller revolution *nd*. The propeller revolution can be measured with a pulse counter while the forward speed can be measured with Acoustic Doppler velocimeter. The designed forward speed control system is shown in fig. 3.1.

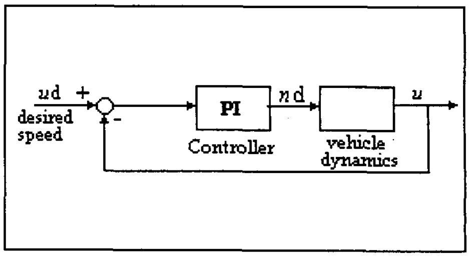

Fig 3.1 : Speed control system using PI controller

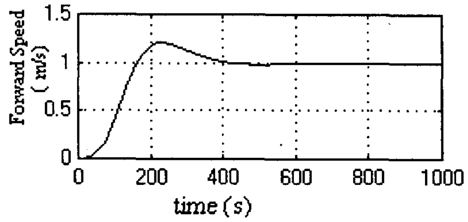

Fig 3.2 : Actual forward speed with unity step input

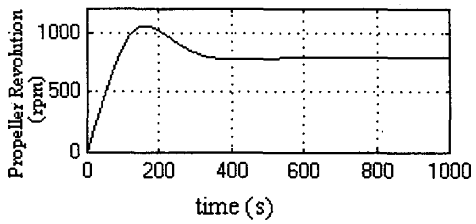

Fig 3.3 : Propeller revolution versus time for forward speed control system.

B. Steering control system

The steering or heading control system for the AUV can be designed by controlling the amount of rudder angle deflection δr. For the UTM-AUV prototype, it can be assume that the maximum rudder angle is +-20 degree. All the dynamic parameters except for the sway velocity *v*, angular velocity in Yaw *r* and heading angle Ψ are assume to be constant. The feedback signal to the control system is yaw angle in degree and it can be measure by using compass and the rate measurements usually are obtained by a rate gyro or rate sensor.

The control law is simply taken to be:

$$\delta r = Kp(\Psi d - \Psi)$$

Where

$(\Psi d - \Psi)$ is the yaw error.

The performance of the control system is shown in fig. 3.5, 3.6 and 3.7 where the yaw angle is changed 10 degree starting at times 50 second. The heading control system is shown in fig. 3.4.

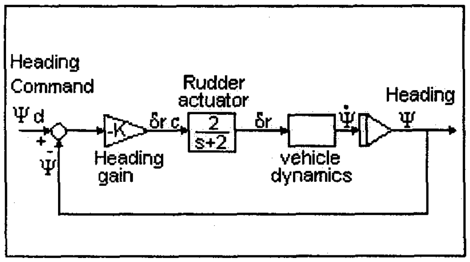

Fig 3.4 : Heading control system

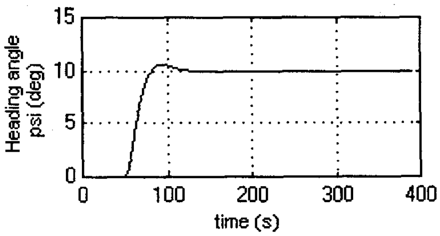

Fig 3.5 : The heading angle is changed 10 degree at time 50 second.

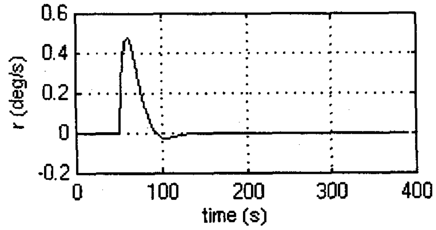

Fig 3.6 : Angular velocity about Z-axis (Yaw)

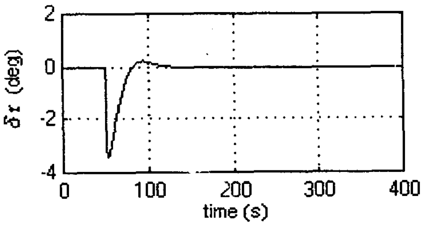

Fig 3.7 : Rudder deflection in degree.

C. Diving Control System

The diving equations of motion should include the heave velocity w, the angular velocity in pitch q, the pitch angle θ, the depth z and the stern plane deflection δ s. The forward speed u is assumed to be constant and the sway and yaw mode can be neglected. The depth of the vehicle is controlled by the amount of deflection of the stern plane.

During forward motion, an elevator surface on the vehicle is deflected by a selected amount of degree (δ s). This deflection causes the vehicle to rotate about the pitch axis (θ). The pitch of the vehicle creates a vertical force that causes the vehicle to submerge or rise.

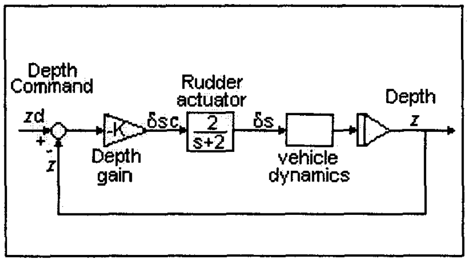

Fig 3.8 : Depth control system

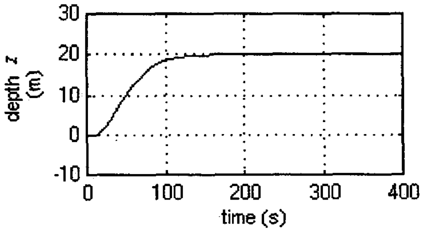

Fig 3.9 : The depth is changed about 20 m

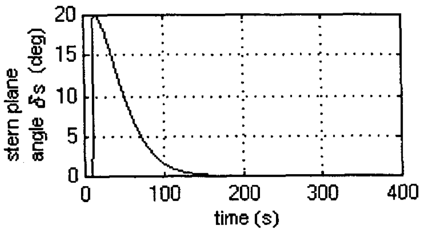

Fig 3.10 : The stern plane deflection (δs) in degree.

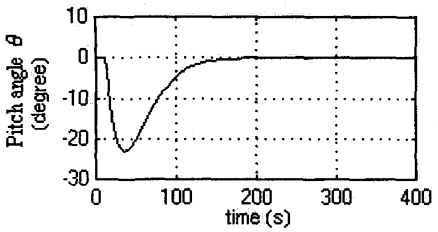

Fig 3.11 : Rotation over pitch angle in degree.

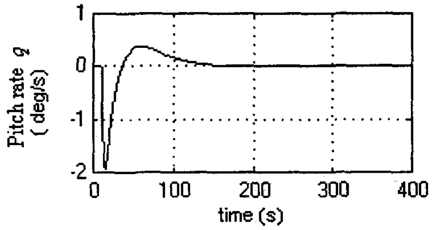

Fig 3.12 : Pitch rate in (deg/s).

The designed diving control system is shown in fig. 3.8. The pitch angle θ can be measured by inclinometer while the pitch rate q can be measured by a rate gyro or rate sensor. The depth z can be measured by pressure meter. This approach assumed the heave velocity w is small and can be neglected since small AUV move slowly in vertical direction.

IV. REAL TIME SIMULATION

This section describes the implemention of real time simulation for the designed control system by using Matlab, Simulink and Real-Time Workshop. Matlab is a high–performance language for technical computing. The Matlab can solve many technical-computing problems, especially those with matrix and vector formulation. Typical uses of matlab include math and computation, Algorithm development, modeling, simulation and prototyping, data analysis, visualization, scientific and engineering graphics.

Simulink is a companion program to matlab with interactive system for modeling, simulating and analyzing dynamical systems. It uses graphical modeling environment to represent the system and make the simulation process easy and interactive.

Real-Time Workshop (RTW) is one of the simulink toolboxes. The RTW generate customizable C code from simulink model and run it on a variety of real time system. In this paper, the selected real time system is generic real time target.

The Simulink create a model file (model.mdl) from the block diagram of the system. This file contains all the information of the simulation environment including sampling time, signal type and block parameter. By using the information in this file, the RTW create a customizable C code (model.c), header files (model.h and Model_export.h), register file (model.reg) and parameter file (model.prm). The C compiler linked all these files together with generic real-time makefile to create an executable file (model.exe). This executable file can run independently under dos mode or windows platforms. The performances of the control system which represented and run by the executable file can be analyzed in Simulink environment at the host PC.

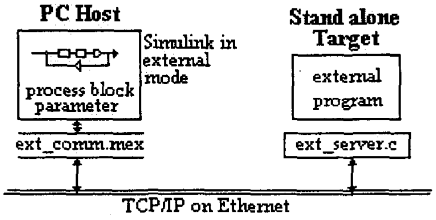

Fig 4.1 : TCP-based client/server implementation in external mode using Real-time Workshop.

V. CONCLUSION

This paper describes the design of electronic control system for the UTM-AUV. The AUV prototype that was used in this paper for modeling purpose is NPS-AUV. The non-dimensional hydrodynamic derivatives that were used will be replace in future according to the UTM-AUV prototype when the construction of the prototype is complete. A few thing have been in consideration for future works such as adding sensors and measurement devices to the PC to provide feedback signal from real world. The sensors and the measurement devices can be connected to the PC via parallel port. We are also considering to use Sliding mode control system since it was reported successfully applied to most AUV in the world.

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