MODEL PREDICTIVE CONTROL OF AN AUV USING DE-COUPLED APPROACH

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SUMMARY

This paper considers the decoupled dynamics and control of an Autonomous Underwater Vehicle (AUV). The decoupled model consists of speed, steering and depth subsystems. Generally AUV model is unstable and nonlinear. The central theme of this paper is the development of model predictive control (MPC) for underwater robotic vehicle for ocean survey applications. The proposed MPC for decoupled structure can have simple implementation. Simulation results have been presented which confirm satisfactory performance. Decoupled approach is well suitable for applying control.

NOMENCLATURE

m	Mass of the vehicle (kg)
$X_{\dot{u}}$	Hydrodynamic added mass (kg)
$Y_{\dot{u}}$	Fluid inertia in the lateral y direction due to time rate of change of sway velocity (kg)
I_z	Moment of inertia along z-axis (kgm^2)
$N_{\dot{r}}$	Fluid inertia moment about vertical body axis due to time rate of change of yaw (kgm^2)
υ	Linear motion in y direction (m/sec)
ψ	Yaw angle of spheroidal underwater vehicle (deg)
r	Yaw angular velocity of spheroidal underwater vehicle (deg/sec)
q	Angular velocity about y-axis, rad/sec
θ	Angular position about y-axis, rad
z	Linear position along z-axis, m

1. INTRODUCTION

Underwater vehicles help human to understand ocean in a new ways. Important advances in underwater robots are improved efficiency, low cost and reduced risk in marine operations. Underwater vehicles play an important role in scientific, industry and military operations (Eski & Yildirim, 2014); (Bong, 2015). Underwater Vehicles are categorized into several groups based on their performance characteristics. According to the method of control, underwater vehicles are classified into two categories namely manned and unmanned (Chen-W, Jen-Shiang & Jing-Fa, 2013) (Kim & Yuh, 2011). Unmanned vehicles are further classified into Autonomous Underwater Vehicles (AUV's) and Remotely Underwater Vehicles (ROV's).

Modeling of an AUV is a difficult process. It consists of hydrodynamic, hydrostatic, electrical and mechanical parameters. In addition with these difficulties, there are some uncertainties, parameter variations due to ocean currents, waves and environment (Sorenson, 2005), (Fossen, 1994). So it is very difficult to analyse the overall model of an AUV. AUV is decoupled into three subsystems namely speed, steering and diving control (Antonelli *et al*, 2003) (Herman, 2009). The design of an AUV for the motion control must consider motion stabilization and maneuvering. So controller must be robust to withstand model uncertainties and parameter variations (Filaretoy & Yukhimets, 2012), (Kim & Yuh, 2011). Model Predictive Control (MPC) has been applied for coupled model of an AUV (Budiyono, 2011). The application of MPC on decoupled model of AUV has not been attempted earlier.

Few control techniques have been applied on diving and steering control of an AUV. Sliding mode control has been applied on diving plane of AUV (Huizhen & Fumin, 2012), (Healey & Lienard, 1993). H infinity control was also applied on diving plane and steering plane (Santhakumar & Asokan, 2012). Fuzzy Logic Control and neural network control techniques have been applied recently on decoupled AUV system (Eski & Yildirim, 2014), (Lynch & Ellery, 2014).

This paper has five sections. Section 1 deals with the introduction about decoupled system and modeling. Section 2 discusses about Decoupled model of an AUV. Section 3 is about proposed controller i.e., Model Predictive Control. Section 4 deals about results and Conclusions are highlighted in Section 5.

2. DECOUPLED MODEL OF AN AUV

The AUV model is decoupled into three sub systems: Speed, Steering and Depth, as shown in figure 1. Model Predictive Control has been applied on each subsystem of AUV. Reference (Ref.) inputs and outputs (o/p) of an AUV are speed, steering and depth. Table-I presents the states and inputs of AUV subsystem.

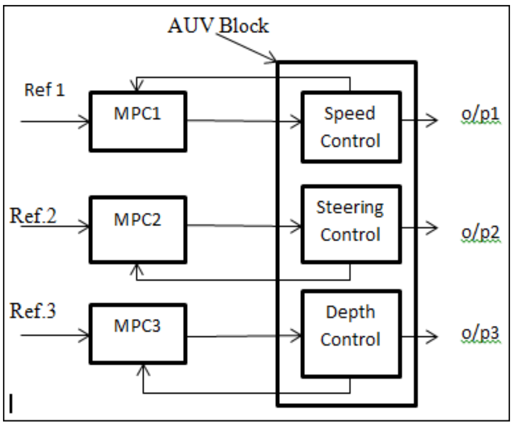

Figure.1 Implementation of MPC on De-coupled system of AUV

Table I AUV subsystem states and inputs

Sub systems	states	Inputs
Speed	$x(t) = u(t)$	$n(t)$
Steering system	$x_1(t)=\upsilon(t)$; $x_2(t)=r(t)$; $x_3(t)=\psi(t)$	$\delta_r(t)$
Diving system	$x_1(t)=w(t)$; $x_2(t)=q(t)$;$x_3(t)=\theta(t)$;$x_4(t)=z(t)$	$\delta_s(t)$

Vehicle model (Eski & Yildirim, 2014) is taken as a case study for the analysis of decoupled control system in this work.

2.1 SPEED CONTROL SYSTEM

This subsystem considers only surge equation of motion of AUV. Assuming that the interactions with sway, heave, roll, pitch, yaw motions are neglected. The AUV has homogeneous mass distribution and xz-plane symmetry so that $I_{xy}=I_{yz}=0$. The surge equation of motion can be written as (Eski & Yildirim, 2014), (Fossen, 1994).

$$(m-X_{\dot{u}})\dot{u}(t) = X_u u(t)-X_{ul}u(t) + (1-tp)\ T$$

or

$$M\dot{u}(t) + R\ u(t) = F \tag{1}$$

where $u(t) = \frac{dy(t)}{dt}$ is speed and $\dot{u}(t)$ is acceleration,

$$F = (1-t_p)\ T$$

The above equation can be written as

$$M\frac{d^2y(t)}{dt^2} + R\frac{dy(t)}{dt} = F \tag{2}$$

Equation (2) can be written in state model as

$$\begin{bmatrix}\dot{x}_1(t)\\ \dot{x}_2(t)\end{bmatrix} = \begin{bmatrix}0 & 1\\ 0 & a_1\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix} + \begin{bmatrix}0\\ b_1\end{bmatrix}F \tag{3}$$

$$y(t)= [0\ \ 1]\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}$$

Equation (3) is in the form of $\dot{x}$ =Ax+Bu

$$a_1= -\frac{R}{M};\ b_1=\frac{1}{M};\ x_1(t) = y(t);\ x_2(t) = \frac{dy(t)}{dt}$$

$$M= (m-X_{\dot{u}}),\quad R= X_{ul}- Xu$$

where 'm' is the vehicle mass. $X_{\dot{u}}$ is the added mass. The coefficient X_u and X_{ul} are the linear and quadratic damping term in surge. t_p is the thrust deduction coefficient and T is the thrust (Bong, 2015), (Bessa, Dutra & Kreuzer, 2010).

2.2 STEERING CONTROL

Considering AUV moves in the horizontal plane, yaw moment on the vehicle is caused due to the change in rudder angle and results in changing the heading direction of the vehicle. The three states related to steering control are sway $\upsilon(t)$, yaw r(t) and yaw angle $\psi(t)$. The control input is the deflection of the rudder angle $\delta_r(t)$. The fluidic forces are linearized and the equations of the steering subsystem are

$$\begin{bmatrix}m - Y_{\dot{\upsilon}} & mx_G - Y_{\dot{r}} & 1\\ mx_G - N_{\dot{\upsilon}} & I_z - N_{\dot{r}} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\dot{\upsilon}\\ \dot{r}\\ \dot{\psi}\end{bmatrix} - \begin{bmatrix}Y_\upsilon u_0 & Y_r u_0 & 0\\ N_\upsilon u_0 & N_r u_0 & 0\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\upsilon\\ r\\ \psi\end{bmatrix} = \begin{bmatrix}Y_{dr}u_0^2\\ N_{dr}u_0^2\\ 0\end{bmatrix}\delta_r(t) \tag{4}$$

In vehicle dynamics, assuming cross coupling terms in the mass matrix, x_G and y_G are zero. This assumption has been considered based on vehicle symmetry and rudders are very close to equidistance from body centre. So the above vehicle dynamics can be written as

$$\begin{bmatrix}m - Y_{\dot{\upsilon}} & 0 & 0\\ 0 & I_z - N_{\dot{r}} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\dot{\upsilon}\\ \dot{r}\\ \dot{\psi}\end{bmatrix} - \begin{bmatrix}Y_\upsilon u_0 & Y_r u_0 & 0\\ N_\upsilon u_0 & N_r u_0 & 0\\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\upsilon\\ r\\ \psi\end{bmatrix} = \begin{bmatrix}Y_{dr}u_0^2\\ N_{dr}u_0^2\\ 0\end{bmatrix}\delta_r(t) \tag{5}$$

Compactly,

$$M\dot{x}-C_d x=Du \quad\text{or}\quad \dot{x} = (M^{-1}C_d)\ x+(M^{-1}D)u \tag{6}$$

which is in the form of $\dot{x}$ =Ax+Bu, and taking the parameter values from (Eski & Yildirim, 2014) the matrices become

$$A=\begin{bmatrix}-1.0094 & -0.6794 & 0\\ -0.5366 & -0.8274 & 0\\ 0 & 1 & 0\end{bmatrix};$$

$$B=\begin{bmatrix}0.2191\\ -1.1868\\ 0\end{bmatrix};$$

2.3 DEPTH CONTROL

Assuming AUV moves in the longitudinal plane, the pitch and depth can be controlled by changing the stern planes (two horizontal fins) deflection. The depth control will depends on pitch control. When the AUV moves at constant speed, the pitch angle change will results rising or diving of the vehicle and finally changes the depth of the AUV (Watson & Green, 2014).

Four states related to depth control of an AUV are heave velocity w(t), pitch rate q(t), pitch angle $\theta(t)$ and depth z(t).

The equations associated with dive plane are (Eski & Yildirim, 2014)

$$\begin{bmatrix} m - X_{\dot{u}} & -(mx_g + Z_{\dot{q}}) & 0 & 0 \\ -(mx_G + M_{\dot{w}}) & I_{yy} - M_{\dot{q}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} - \begin{bmatrix} Z_w & mU + Z_q & 0 & 0 \\ M_w & -mx_G U + M_q & 0 & M_\theta \\ 1 & 0 & 0 & -U \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ z \\ \theta \end{bmatrix} = \begin{bmatrix} Z_{\delta_s} \\ M_{\delta_s} \\ 0 \\ 0 \end{bmatrix} \quad (7)$$

State vectors are defined as $x = [w\ q\ z\ \theta]^T$ and the input vector is $u = [\delta_s]^T$. Matrix equation takes the form

$$M\dot{x} - C_d x = Du$$

or

$$\dot{x} = (M^{-1}C_d)x + (M^{-1}D)u \quad (8)$$

which is in the form of $\dot{x} = Ax + Bu$, considering the numerical values from (Eski & Yildirim, 2014)

$$A = \begin{bmatrix} -2.38 & 1.57 & 0 & 0 \\ 4.23 & -1.19 & 0 & -0.70 \\ 1 & 0 & 0 & -1.54 \\ 0 & 1 & 0 & 0 \end{bmatrix}; \quad B = \begin{bmatrix} -1.37 \\ -3.83 \\ 0 \\ 0 \end{bmatrix}$$

3. MODEL PREDICTIVE CONTROLLER

MPC technique has been applied on decoupled model of AUV for controlling speed, steering and depth assuming ocean currents and other disturbances. An algorithm has been developed for maintaining the vehicle with desired set points. The key elements of MPC are cost function and constraints. The cost function is minimized using an algorithm and applied on controller for desired response (Mayne, Seron & Rakovic, 2006). Constraints can be chosen on inputs, states and outputs. Model is important in MPC.

MPC calculations are developed at each sampling instant, these predictions are used for set point calculations and control calculations. The constraints on input and output variables can be applied on MPC calculations. The model predictive control calculations determine the appropriate sequence of control moves so as to get the optimal results (Budiyono, 2011), (Liuping, 2009).

Considering the AUV model to be controlled as

$$\begin{aligned} \dot{x}_m(t) &= A_m x_m(t) + B_m u_m(t) \\ y_m(t) &= C_m x_m(t) \end{aligned} \quad (9)$$

where $x_m(t)$ is the state vector of dimension n_1. A_m, B_m and C_m have dimension $n_1 \times n_1$, $n_1 \times m$ and $q \times n_1$, respectively.

Now this model is converted to axillary model with axillary variables for MPC formulation

$$\begin{aligned} z(t) &= \dot{x}_m(t) \\ y(t) &= C_m x_m(t) \end{aligned} \quad (10)$$

The augmented state space model using the derivative of control system is

$$\begin{bmatrix} \dot{z}(t) \\ \dot{y}(t) \end{bmatrix} = \begin{bmatrix} A_m & 0_m{}^T \\ C_m & 0_{q\times q} \end{bmatrix} \begin{bmatrix} z(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} B_m \\ 0_{q\times m} \end{bmatrix} \dot{u}(t) \quad (11)$$

$$y(t) = \begin{bmatrix} 0_m & I_{q\times q} \end{bmatrix} \begin{bmatrix} z(t) \\ y(t) \end{bmatrix} \quad (12)$$

which is in the form of

$$\dot{x}(t) = Ax(t) + B\dot{u}(t)$$

$$y(t) = Cx(t) \quad (13)$$

where

$$A = \begin{bmatrix} A_m & 0_m{}^T \\ C_m & 0_{q\times q} \end{bmatrix}(t), \quad B = \begin{bmatrix} B_m \\ 0_{q\times m} \end{bmatrix}(t),$$

$$C = \begin{bmatrix} 0_m & I_{q\times q} \end{bmatrix}$$

The cost function considered for optimization is

$$J = \eta^T \Omega \eta + 2\eta^T \psi x(t_i) + \text{constant} \quad (14)$$

where η is Laugree coefficient vector, ψ, ω are matrices which can be computed from A, B, C and weighing matrices (Zhen & Jing, 2010)

With the help of receding horizon control principle (i.e., the control action uses only the derivative of the future control signal at τ=0,) the derivative of the optimal control for the unconstrained problem with finite horizon prediction is

$$\dot{u}(t) = \begin{bmatrix} L1(0)^T & 0_2 & \cdot & \cdot & \cdot & o_m \\ o_1 & L2(0)^T & \cdot & \cdot & \cdot & o_m \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ o_1 & o_2 & \cdot & \cdot & \cdot & Lm(0)^T \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \cdot \\ \cdot \\ \cdot \\ \eta_m \end{bmatrix}$$

where L is the Laguerre function For an arbitrary time t, $\eta = -\Omega^{-1}\psi\, x(t)$, the continuous time derivative of the control is

$$\dot{u}(t) = -\begin{bmatrix} L1(0)^T & 0_2 & \cdots & o_m \\ o_1 & L2(0)^T & \cdots & o_m \\ \vdots & \vdots & \ddots & \vdots \\ o_1 & o_2 & \cdots & Lm(0)^T \end{bmatrix} \Omega^{-1}\psi x(t)$$

$$= -K_{mpc}x(t)$$

where the feedback gain matrix is

$$K_{mpc} = \begin{bmatrix} L1(0)^T & 0_2 & \cdots & o_m \\ o_1 & L2(0)^T & \cdots & o_m \\ \vdots & \vdots & \ddots & \vdots \\ o_1 & o_2 & \cdots & Lm(0)^T \end{bmatrix} \Omega^{-1}\psi$$

From the above equation, the receding control law is of state feedback control because of the dependence on the current state variable x(t). The augmented state space model (Mayne, Seron & Rakovic, 2006) is

$$\dot{x}(t) = A\,x(t) + B\,\dot{u}(t)$$

From augmented state space model where the input is $\dot{u}(t)$. The closed loop control system is

$$\dot{x}(t) = (A - BK_{mpc})x(t) \quad (15)$$

The closed loop eigenvalues of the predicted control system can be evaluated from the equation (15).

The control law is calculated for each sub system of AUV from equations (3), (6), (8) and simulated in MATLAB environment. Table II gives the simulation parameters used in Model Predictive Controller Design.

The following steps involved in proposed MPC tuning

1. Model Horizon: The model horizon N should be chosen such that $N\Delta t \geq$ open-loop settling time. Values of N can be chosen between 20 and 70
2. Prediction Horizon: It calculates how far into the future the control objective reaches. Increasing Np results in a more conservative control action but it increases the computational effort. Np=N+Nu. Np is prediction horizon and Nu is the control horizon
3. Control Horizon: It determines the number of control actions calculated into the future. Too large value of NU results in excessive control action. Smaller value of Nu yields a controller relatively insensitive to model errors.
4. In optimization usually weighting factors should be in proper limits. Larger values of weights penalize the magnitude of Δu more and results less vigorous control actions.

Table II Simulation Parameters of MPC used in Decoupled AUV

Simulation Parameters	Value
Desired Depth, m	100
Desired Position, m	1
Desired Speed m/sec	1
Sampling time s	0.2
Time in sec	(0-10) & (0-40)
Control horizon	5
Prediction Horizon	50

4. RESULTS

All the simulations are carried out in MATLAB environment.

a) In Figure 2 set point for depth control is taken as 100 m below the sea level. The vehicle is also following the same set point
b) In Figure 3 and 4 step and sinusoidal inputs are taken as set points. Steering system of Vehicle is tracking in the same set point.
c) In Figure 5 vehicle is following forward surge speed motion. It has good transient and steady state response.

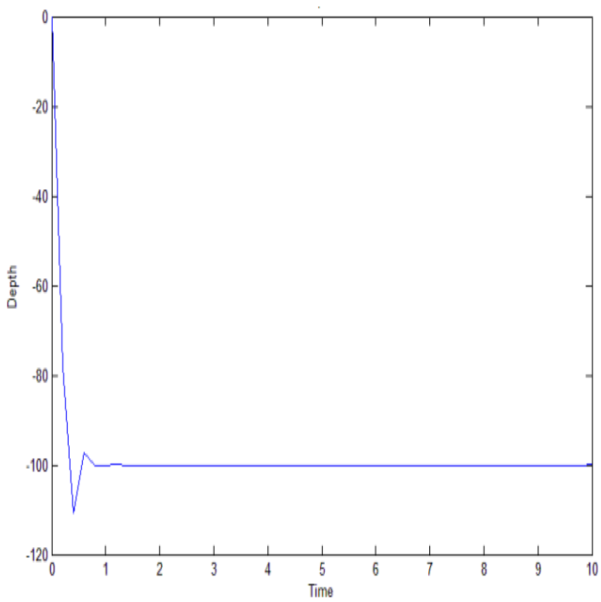

Figure.2 Depth Control of an AUV

Figures 3 and 4 are steering control with respect to step and sinusoidal input.

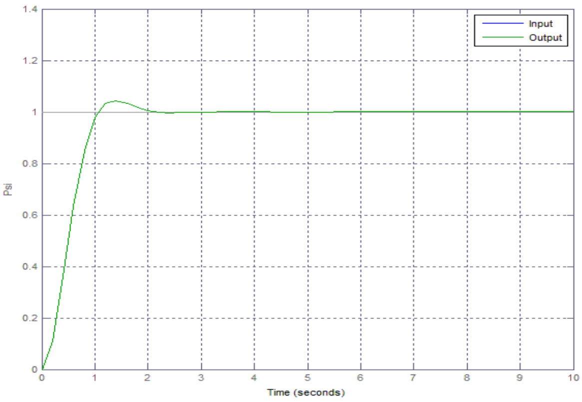

Figure.3 Heading Control of an AUV

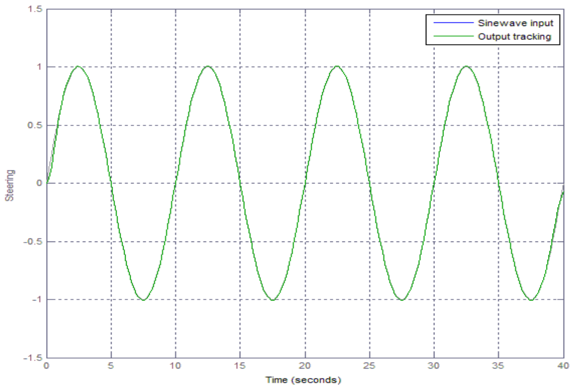

Figure.4 Steering Control of AUV

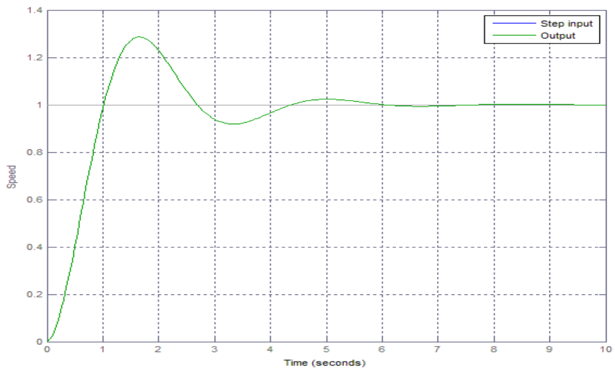

Figure.5 Speed Control of AUV

5. CONCLUSION

Dynamics of Decoupled system of an AUV is considered in this paper. Control can easily applied on decoupled model compared to overall model. The presented MPC algorithm is based on a state space model of an AUV and is therefore flexible to be used for decoupled systems. Concept of moving horizon is used to find the control law. Simulation has been carried out in MATLAB environment. The simulation results demonstrate the effectiveness of the proposed control method. Further the performance can be improved by considering the higher level of MPC.

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