SET POINT TRACKING CONTROL OF A REMOTELY OPERATED VEHICLE USING MODEL PREDICTIVE CONTROL

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SUMMARY

This paper considers kinematics and dynamics of Remotely Operated Underwater Vehicle (ROV) to control position, orientation and velocity of the vehicle. Cascade control technique has been applied in this paper. The pole placement technique is used in inner loop of kinematics to stabilize the vehicle motions. Model Predictive control is proposed and applied in outer loop of vehicle dynamics to maintain position and velocity trajectories of ROV. Simulation results carried out on ROV shows the good performance and stability are achieved by using MPC algorithm, whereas sliding mode control loses its stability when ocean currents are high. Implementation of proposed MPC algorithm and stabilization of vehicle motions is the main contribution in this paper.

1. INTRODUCTION

Underwater vehicles helps human to understand ocean in a new ways. Important advances in underwater robots are improved efficiency, low cost and reduce the risks in marine operations (Ferreira *et al*, 2009). Underwater vehicles play an important role in scientific, industry and military operations. It often finds solutions that may not do through other conventional methods (Dyda, 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. Unmanned vehicles are further classified into Autonomous Underwater Vehicles (AUV's) and Remotely Underwater Vehicles (ROV's) (Ellery & Lynch, 2014; Arshad & Isa, 2013). This paper focuses on ROV control. ROVs are available in different sizes, shapes, weights and propulsion methods. Selection of size and shape of an ROV depends on application where it is used. It has been used in both research and industrial applications (Cao & Ren, 2010; Clement, 2012). Spheroidal and Egg shape underwater vehicles are mainly used in nuclear power plants for testing pipe leakages. Torpedos are used in scientific research (Fossen, 1994).

Modelling of an ROV 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 (Bibuli & Caccia *et al*, 2008; Corradini, Monteriu & Orlando, 2011). The design of an ROV for the motion control must consider motion stabilization and manoeuvring. So controller must be robust to withstand from model uncertainties, parameter variations. Model Predictive Control has been developed to control ROV and simulated in MATLAB environment for finding analysis, and stability.

Few control techniques have been applied on diving and steering control of a ROV. Sliding mode control has been applied on diving plane of ROV (Bessa *et al*, 2008; Corradini & Orlando, 1997). H infinity control was also applied on diving plane and steering plane (Kim, Kim & Mohan, 2014; Corradini & Orlando, 2014). Fuzzy Logic Controller and neural network control technique have been applied recently on decoupled control system (Falkenberg & Gregersen, 2014; Corradini *et al*, 2009).

This paper has five sections. Section 1 deals with the introduction. Section-2 discusses about modelling of a ROV. Section 3 is about proposed controller i.e., Model Predictive Control. Section 4 deals about results and Conclusions are highlighted in Section 5, References are presented in section 6.

2. MODELLING OF A REMOTELY OPERATED UNDERWATER VEHICLE

Two coordinates systems- Earth fixed frame and body fixed frame are essential to understand the motion of ROV. Earth fixed frame coordinates help to analyse the kinematics of ROV and Body fixed frame coordinates are used to analyse the dynamics of the ROV (Yuh, 1990; Corradini *et al* 2010). This paper considers both kinematics and dynamics of the ROV. State model has been formulated to analyse the set point trajectories of ROV. ROV considered in this paper has 4 degrees of freedom. The vector 'η' considers the position and orientation in earth fixed frame and vector 'υ' is the velocity and acceleration in body fixed frame. 'M' is 4×4 inertial matrix with added mass, $M_0+\Delta M$, $C(\upsilon)$ is the coriolis and centripetal force, $C_0(\upsilon)+\Delta C(\upsilon)$, $D(\upsilon)$ is the hydrodynamic damping terms, $D_0(\upsilon)+\Delta D(\upsilon)$. The vector $g(\upsilon)$ is a combined force or moment of the gravity and buoyancy, $g_0(\upsilon)+\Delta g(\upsilon)$. The vector $[X\ Y\ Z\ N]^T$ are the forces and torque with respect to body fixed frame. Five thrusters are used in this ROV [Gao, *et al*, 2015]. Figure.1 represents the Polaris ROV having earth and body fixed frame.

Both kinematics and dynamics are considered in this paper. The kinematic model of ROV is described by the following equation (Humphris, 2010; Skjetne *et al*, 2014)

$$\dot{\eta} = J(\eta).\upsilon \tag{1}$$

where $\eta = [x, y, z, \psi]^T$ represents the position and orientation of ROV in earth fixed frame

$\upsilon = [u, v, w, r]^T$ represents the linear and angular velocity of ROV in body fixed frame

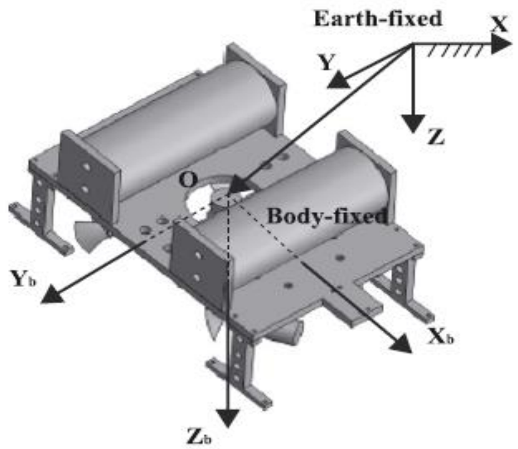

Figure.1 Earth fixed coordinates and body fixed coordinates of ROV (Gao *et al*, 2015)

where, J(η) is the kinematic transformation matrix used to express the transformation from body fixed frame to earth fixed frame. It can be represented as

$$J(\eta)=\begin{bmatrix} cos(\psi) & -\sin(\psi) & 0 & 0 \\ sin\psi & cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The dynamic equation of an ROV is represented by

$$M\dot{\upsilon}+C(\upsilon).\upsilon+D(\upsilon)+g(\eta)=\tau+J^T(\eta)d \quad (2)$$

$$\tau = Hu \quad (3)$$

Uncertainties are also added up to 15 % on added mass 'm' to check for robustness.

$$M_0=\begin{bmatrix} m-X_{\dot{u}} & 0 & 0 & 0 \\ 0 & m-Y_{\dot{v}} & 0 & 0 \\ 0 & 0 & m-Z_{\dot{w}} & 0 \\ 0 & 0 & 0 & m-N_{\dot{r}} \end{bmatrix}$$

$$C_0(\vartheta)=\begin{bmatrix} 0 & 0 & 0 & -(m-Y_{\dot{v}})\vartheta \\ 0 & 0 & 0 & -(m-X_{\dot{u}})u \\ 0 & 0 & 0 & 0 \\ (m-Y_{\dot{v}})\vartheta & (m-X_{\dot{u}})u & 0 & 0 \end{bmatrix}$$

$$D_0(\vartheta)=\begin{bmatrix} X_u+X_{u|u|}u & 0 & 0 & 0 \\ 0 & Y_\vartheta+Y_{\vartheta|\vartheta|}\vartheta & 0 & 0 \\ 0 & 0 & Z_w+Z_{w|w|}w & 0 \\ 0 & 0 & 0 & N_r+N_{r|r|}r \end{bmatrix}$$

$g_0(\eta) = [0\ 0\ W_B\text{-}W\ 0]^T$

$$H=\begin{bmatrix} \cos a & \cos a & -\cos a & -\cos a & 0 \\ -\sin a & \sin a & \sin a & -\sin a & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -L & L & L & -L & 0 \end{bmatrix}$$

where J $\in\mathbb{R}^{4\times4}$ is the rotation matrix, M $\in\mathbb{R}^{4\times4}$ is the mass matrix, C $\in\mathbb{R}^{4\times4}$ is the Coriolis and centripetal force matrix and D $\in\mathbb{R}^{4\times4}$ is the damping matrix, g $\in\mathbb{R}^{4\times1}$ is a vector with restoring forces, d is the external disturbance vector, $\mathbb{R}^{4\times1}$, τ is the system control vector $R^{4\times1}$, H is the dynamic distribution matrix, $\mathbb{R}^{4\times5}$ and 'u' is the force vector $\mathbb{R}^{5\times1}$.

Defining states $x_1 = \Delta\upsilon$ and $x_2 = \Delta\eta$, gives the following linear time varying model

$$M\dot{x}_1+Cx_1+Dx_1+gx_2=\tau+J^T(\eta)d \quad (4)$$

$$\dot{x}_2=Jx \quad (5)$$

From the above equation state model can be written as

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix} -M^{-1}[C+D] & -M^{-1}g \\ J & 0_{4\times4}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}-M^{-1}\tau\\ 0_{4\times4}\end{bmatrix}u+[-M^{-1}J^T(\eta)]d \quad (6)$$

which can be written in state equation form as

$$\dot{x} = Ax + Bu + Gd \quad (7)$$

where 'd' is disturbance variable.

In this paper dynamic model is considered to track the vehicle easily and proposed control technique can also easily applied. Kinematic model is not preferred to reduce control effort

III Stabilization of vehicle states using Pole Placement Technique

Pole placement technique is a control strategy which has been widely used in various applications. Pole placement technique using state feedback gains K such that the cost function J is minimized (Lee *et al*, 2010; Bars & Jaulin, 2012). This ensures that the gain selection is optimal for the cost function specified.

The feedback control is a linear function of state as

u=-Kx

'K' is computed using Ackermann's formula

$$K=[0\ 0\ ....1][B\ AB\ A^2B\ ...\ A^{n-1}B]^{-1}\Delta(A) \quad (8)$$

where $\Delta(A) = A^n+A^{n-1}B+A^{n-2}B+A^{n-3}B+..$

An advantage of using this control scheme is that the system designed will be stable and robust.

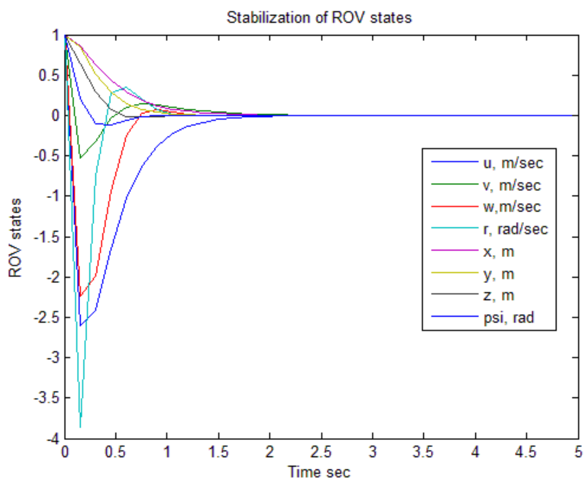

Figure 2 Vehicle states of an ROV

Simulations have been carried out in MATLAB for stabilization of all the states of ROV where model is taken from (Gao *et al*, 2015). The pole placement technique has been applied for this system. Figure 2 presents the position and velocity states of an ROV. It is evident from the responses that all the responses of the states are stabilized and reach steady state quickly.

3. MODEL PREDICTIVE CONTROL

MPC is an advanced control technique for multivariable problems which are generally used in oil refineries and chemical plants for years. The basic principle of MPC is as follows. Let us consider a Multiple-input Multiple-output (MIMO) model with appropriate constraints on input-output variables. For prediction of future output values, current and model measurements are taken into account. This result in calculation of changes in input variables based on predictions and actual measured values. The output variables also called as controlled variables or CVs, while input variables are called as manipulated variables or MVs. Measured disturbance variables are called DVs or feed forward variables (Rau & Schroder, 2002; Debasish & Lygeros, 2015). It is easy to handle constraints when a vehicle is running with different speeds (Rau & Schroder, 2002).

Formulating discrete state space model from equation (6) & (7)

$$x(k+1) = Ax(k)+Bu(k) + Hd(k) \tag{9}$$

$$y(k) = Cx(k) \tag{10}$$

A general n-th order expression of the n step ahead prediction assuming negligible disturbance is given as follows

$$x(k+n)= A^{n}x(k)+A^{n-1}Bu(k)+A^{n-2}Bu(k+1)+\ldots.+ABu(k+n-2)+Bu(k+n-1) \tag{11}$$

The system output can be determined simply using

$$y(k+n)=Cx(k+n) \tag{12}$$

substituting equation (11) in eq no (12), we get

$$y(k+n)= CA^{n}\, x(k) +C(A^{n-1}Bu(k)+A^{n-2}Bu(k+1)+\ldots+ABu(k+n-2)+Bu(k+n-1)) \tag{13}$$

This prediction mixes up past and future data, so it is advisable to be more careful with notation and construction of the predictions. Augmented state model can develop from equations (11) and (13). The sampling time considered to develop discrete model is 0.02 sec.

The block diagram of Model Predictive Control is shown in figure 3

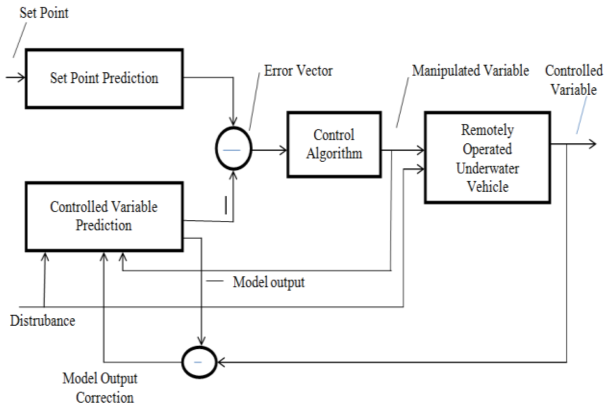

Figure 3 Block diagram of a MPC

Figure.3 is the implementation of MPC on ROV model. A flowchart has been developed for maintaining the vehicle in 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. Constraints can be chosen on inputs and outputs (Monteriu, Corradini & Orlando, 2009). Model is very important in MPC. Inaccurate model may lead poor prediction instead of better. MPC can easily apply on discretised model. Bilinear transformation is used for this purpose.

$$U= [\Delta u^{T}(k) \quad \Delta u^{T}(k+1) \ldots \quad \Delta u^{T}(k+N_c-1)]^{T}$$
$$x(k)= [x^{T}(k+1|k) \quad x^{T}(k+2|k) \quad \ldots.x^{T}(k+N_p|k)]^{T}$$

The state space model is used to compute the future state vectors and output vectors

$$Y=Fx+\emptyset u \tag{14}$$

Where $F=\begin{bmatrix} CA \\ CA^{2} \\ CA^{3} \\ . \\ . \\ CA^{n} \end{bmatrix}$ and

$$\emptyset = \begin{bmatrix} CB & 0 & 0 & 0 & \ldots. & 0 \\ CAB & CB & 0 & 0 & \ldots. & 0 \\ CA^2B & CAB & CB & 0 & \ldots. & 0 \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ CA^{n-1}B & CA^{n-2}B & CA^{n-3}B & . & . & CA^{n-N_c}B \end{bmatrix}$$

Introducing the set-point or reference vector of length N_p as

$$R_s^T = [I \;\; I \ldots\ldots \quad I]^T$$

where r(k) is the reference vector at sample instant k. I is the identity matrix. Then the cost function for MPC design is

$$J = (R_s-Y)TQ(R_s-Y)+\Delta U^T R \Delta U \qquad (15)$$

where R is a symmetric positive definite matrix to be selected. Q is output weighing matrix. Above control law is not only used to track vehicle but also used to reduce disturbance using filter. Routine analysis now gives the minimizing control in the absence of constraints as

$$\Delta U=(\emptyset^T\emptyset + R)^{-1}\emptyset^T(Rr(k_i)- Fx(k_i)) \qquad (16)$$

where the required matrix inverse is assumed to exist. Q and R are chosen based on corresponding interested states

The flow chart of MPC is given in figure.4

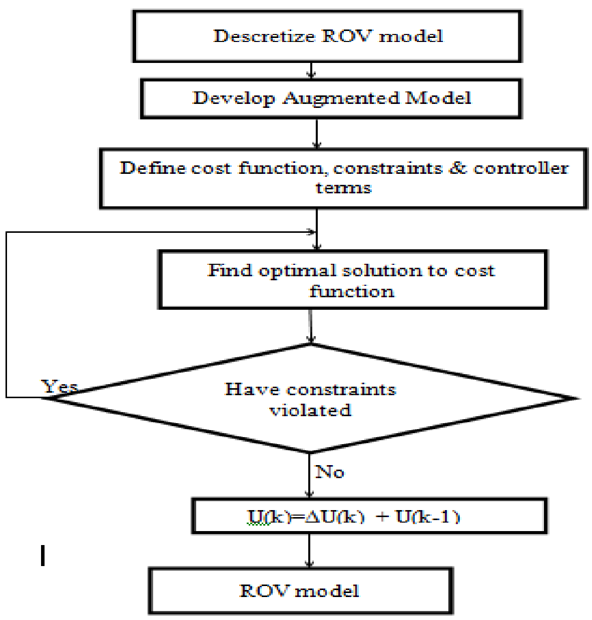

Figure.4 MPC flowchart

Table-I: Polaris ROV physical parameters (Gao *et al*, 2015)

Parameters	Value	Parameters	Value
m/kg	5.1	X_u/(kg/s)	-11.2
W/N	50	Y_ϑ/(kg/s)	-13.5
B/N	50.4	Z_W/(kg/s)	-16.5
Z_B/m	-0.05	N_r(kg.m²/(s.rad)	-9.6
I_x/(kg.m²)	0.2	$X_{u\|u\|}$/(kg/m)	-3.2
I_y/(kg.m²)	0.6	$Y_\vartheta + Y_{\vartheta\|\vartheta\|}$/(kg/m)	-2.7
I_z/(kg.m²)	0.9	$Z_w + Z_{w\|w\|}$/(kg/m)	-3.5
$\boldsymbol{X_{\dot u}}$/kg	-3.3	$\boldsymbol{N_{r\|r\|}}$/(kg.m²/rad²)	-1.3
$\boldsymbol{Y_{\dot v}}$/kg	-4.3	τ_{fmax}/N	1.6
$\boldsymbol{Z_{\dot w}}$/kg	-6.4	τ_{bmax}/N	-3.2
$\boldsymbol{N_{\dot r}}$/(kg.m²)	-1.8		

4. RESULTS

Simulation Results:

The proposed MPC scheme has been implemented in MATLAB on a ROV with parameters taken from (Gao *et al*, 2015) and written in Table I. The Step response of ROV states has been obtained using MPC flow chart. All vehicle states are taken on y-axis and time is taken on x-axis. From figure.5 it is clear that all the states have good transient and steady state responses.

5. CONCLUSIONS

In this paper, the motion control problem for remotely operated underwater vehicle "Polaris" (Gao *et al*, 2015) has been considered. The main contributions of this paper are 1) stabilization of vehicle states is obtained with the help of simple pole placement technique 2) Model Predictive Control is then applied on ROV model to track the vehicle states in desired set point trajectories. Constraints have been considered on states and inputs of the ROV. Finally, simulation result demonstrates the effectiveness of the proposed control method. Further the performance can be improved by considering the higher level of MPC. Unit step input signal is considered as reference signal for stable response compared with sinusoidal signals. Sinusoidal signals are unstable which are not desired for Marine Vehicle applications.

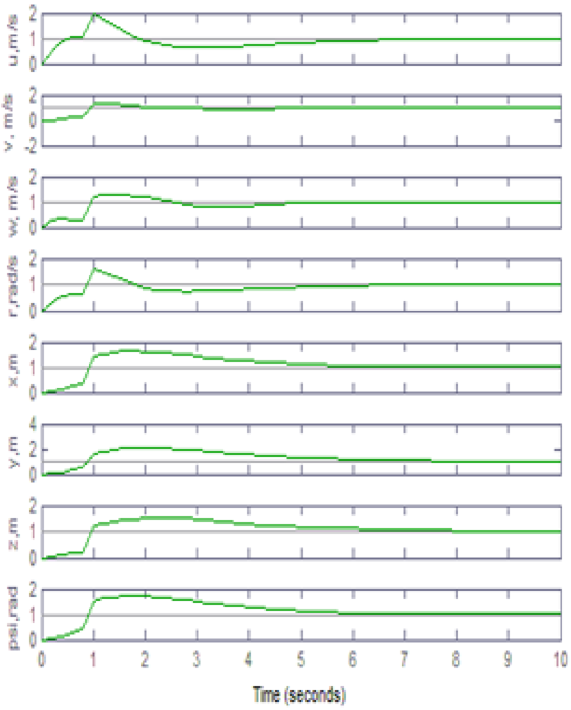

Figure.5 shows the vehicle states subjected to unit step reference trajectories

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