SLIDING MODE BASED PREDICTIVE CONTROLLER OF A SPHEROIDAL UNDERWATER VEHICLE

(DOI No: 10.3940/rina.ijme.2017.a2.418)

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SUMMARY

This paper focuses on hydrodynamic modeling and control of spheroidal underwater vehicle. The vehicle considered in this paper is appendage free and unstable. Water jet propulsion system is used in this vehicle. The dynamics of the vehicle is highly unstable due to munk moment. The spheroidal shape underwater robot is used in nuclear reactor inspection, port security inspection, defence and ocean surveillance where external appendages are not required. A new and innovative control technique, Sliding mode based model predictive control is introduced in this paper. Sliding mode control technique is used to stabilize the vehicle and once the vehicle model is stabilized it is easy to apply Model Predictive Control (MPC). Model Predictive control technique is used to control the heading of spheroidal underwater vehicle. Simulation results show that the Sliding mode based predictive control performance is better than simple PD control and state feedback controller.

NOMENCLATURE

m	Mass of the vehicle (kg)
X_{udot}	Hydrodynamic added mass (kg)
Y_{vdot}	Fluid inertia in the lateral y direction due to time rate of change of sway velocity (kg)
I_{zz}	Moment of inertia along z-axis (kgm^2)
N_{rdot}	Fluid inertia moment about vertical body axis due to time rate of change of yaw (kgm^2)
U_c	Cruising speed (m/sec)
G_F	Linear force Gain (N/V)
G_M	Angular moment Gain (Nm/V)
γ_J	Jet angle (degrees)
Y	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)

1. INTRODUCTION

Spheroidal underwater robots (Mazumdar, Michael & Asada, 2015) are used for inspection of underwater infrastructure. These robots have multi degree of freedom manoeuvrability so that it can move sideways, up and down. These robots are used in nuclear reactors, defence and ocean surveillance applications. It can go in the depth of the ocean without harming the aquaculture (Mazumdar & Asada, 2014).

The spheroidal underwater robot is unstable but can make rapid sharp turns and move in different directions. Spheroidal robots provide wonderful features like it can be streamlined to minimize drag and possess diagonal inertia along with added mass and drag coefficients which help in reducing dynamic coupling. Moreover, as external appendages tend to create a risk of collisions and damage (Mazumdar & Asada, 2013). Eliminating external propellers and fins is an area of growing interest in underwater vehicles. So it is a boon for tasks that require close interaction with wildlife or missions where robustness to collisions is difficult (Fossen, 1994, Mazumdar, *et al*, 2012). Camera is fixed at nose of robot. It can orient using robot with pitch and yaw controls, it can also move vertically and in sideways (Menozzi, Hleinhos & Bandyopadhyay, 2008, Alvarez, Bertram & Gualdesi, 2009).

This paper considers modeling and control aspects. Conventional control techniques like PD control may not give satisfactory response in the presence of uncertainties and disturbances (Mazumdar, Michael & Asada, 2015, Budiyono, 2009). So combination of sliding mode and model predictive control technique has been implemented in this paper.

The main idea behind this hybrid technique is to stabilize and control the heading of spheroidal underwater vehicle. Model predictive Control (MPC) is an effective robust control technique. It has widely been used in various control applications such as process industries, robot manipulators, underwater vehicles, high performance electric motors, power electronics, automotive transmissions and engines (Seung, *et al*, 2009). Sliding mode control is used to stabilize the vehicle. Sliding mode control design consists of two steps. A feedback control law ‘u’ is developed and test the sliding condition. The control law is discontinuous across s(t) in order to account for the presence of modeling imperfection and disturbances (Yuh, 1990, Ahmad, Azadi & Alireza, 2014). The implementation of control switching is imperfect. This causes for chattering phenomenon. Chattering is not desirable phenomena. It requires high control activity. Further it may also generate high frequency dynamics ignored in the modeling stage. In the second step discontinuous control law ‘u’ is smoothed to obtain an optimal trade-off between tracking precision and control bandwidth (Boiko, *et al*, 2007). The first step concentrates on parametric uncertainty. Robustness to high frequency unmodeled dynamics is achieved in second step. Figure 1 represents the schematic diagram of a spheroidal underwater vehicle. [X Y Z] are the forces and [K M N] are torques. [u v w] are linear velocities and [p q r] are the angular velocities. [x y z] are linear positions of the vehicle and [φ θ Ψ] are angular positions of vehicle (Zool & Vina, 2015, Mcphail, 2009).

The schematic diagram of spheroidal underwater vehicle with coordinate axis is shown in Figure 1. All linear and angular positions and velocities are also mentioned in the Figure 1.

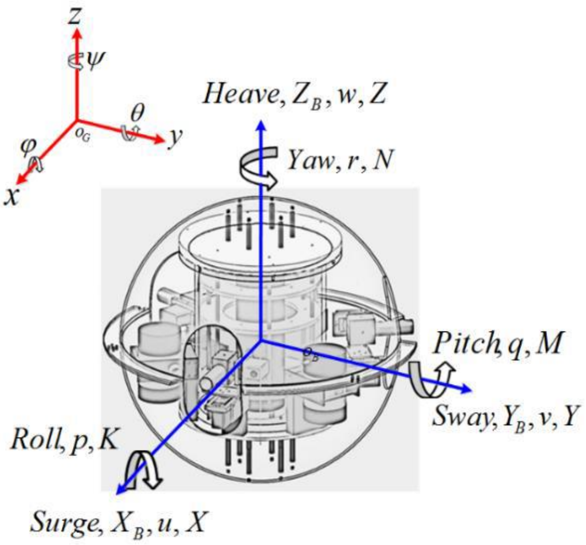

Figure 1 Schematic diagram of Spheroidal Underwater vehicle (Mazumdar & Asada, 2014)

All the symbols used in spheroidal underwater vehicle are mentioned in Table 1. Few control techniques have been applied on Underwater Vehicles to control and stabilize (see references 8-11). PD control technique has been applied for yaw control of Spheroidal Underwater Vehicle (Mazumdar & Asada, 2013, Rust & Asada, 2011).

Table 1: Symbols used in Spheroidal Underwater Vehicle (Zool & Vina, 2015)

DOF	Motion Descriptions	Forces/ Moments	Positions & Orientations	Linear & Angular velocities
1	Motion in the x direction(Surge, X_B)	X	x	u
2	Motion in the y-direction(Sway,Y_B)	Y	y	v
3	Motion in the z-direction(heave,Z_B)	Z	z	w
4	Rotation about x-axis(roll)	K	φ	p
5	Rotation about y-axis(Pitch)	M	θ	q
6	Rotation about z-axis(Yaw)	N	Ψ	r

Model Predictive Control is also the good option for multivariable systems like autonomous underwater vehicles and remotely operated underwater vehicles. The structure of the paper is as follows: Section 1 describes about Introduction. Spheroidal Underwater Vehicle Model and Sliding Mode Controller are developed in section 2. Model Predictive Control has developed in section 3. Simulation results and conclusions are highlighted in section 4 and 5.

2. MATHEMATICAL MODELLING OF SPHEROIDAL UNDERWATER VEHICLE

Considering the spheroidal underwater vehicle dynamics in the form of state equation (Mazumdar & Asada, 2014, Fossen, 2011).

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (1)$$

where state vectors are

$$x = [\upsilon \quad r \quad \psi]^T \;\&\, u = \Delta F_{J,23}$$

$F_{J,23}$ is the water jet force from Jet 2 and Jet 3. The state model is taken from (Mazumdar & Asada, 2014) where the matrices A and B are expressed in terms of physical parameters like masses, inertia, coefficients of moment, crusing speed, etc.

$$\begin{bmatrix} \dot{\upsilon} \\ \dot{r} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-mU_c}{m+m_{22}} & 0 \\ \frac{-U_c(m_{22}-m_{11})}{I_{zz}+m_{66}} & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \upsilon \\ r \\ \psi \end{bmatrix} + \begin{bmatrix} \frac{-n_y}{m+m_{22}} & \frac{n_y}{m+m_{22}} \\ \frac{c}{I_{zz}+m_{66}} & \frac{-c}{I_{zz}+m_{66}} \\ 0 & 0 \end{bmatrix} \Delta F_{J,23} \qquad (2)$$

For the typical values taken from (Mazumdar & Asada, 2014), the eigenvalues of A are {0 1.8173 -1.8173}. It is evident from the eigenvalues of A that the system is unstable. In order to stabilize the system, Sliding Mode Control has been considered in the paper.

2.1 SLIDING MODE CONTROL (SMC)

Sliding mode control (SMC) is a robust and effective technique to maintain system stability and desired performance in the presence of unmodeled dynamics. It consists of two phases namely sliding phase and reaching phase (Healey & Lienard, 1993). The trajectory moves towards origin of the equilibrium point in sliding phase. The vehicle trajectory starting from initial condition and moves toward the sliding manifold in reaching phase. It also maintains acceptable transient response characteristics in the presence of parameter variations and unmodeled dynamics (Ahmad, Azadi & Alireza, 2014).

Sliding mode control uses a switching control law to drive the vehicle's state trajectory onto the sliding surface in the state space. It is also used to maintain the vehicle's state trajectory on its surface for all subsequent times. This method guarantees that the output tracking error converges to zero in a finite time (Bessa, Dutra & Kreuzer, 2008, Seung, *et al*, 2009). In this paper, the control law is based upon the linear model. The functions of state variables are called as switching function.

$$S = \sigma_s x$$

Designing the switching function so that $\sigma_s = 0$ manifold (sliding mode) provides the desired dynamic performance. Computing a controller ensuring sliding mode of the system occurs in finite time. Chattering is one of the major limitation in Sliding mode control (Boiko, *et al*, 2007). In order to avoid chattering phenomena, a continuous function like hyperbolic tangent function or saturation function may be used. Hyperbolic tangent function is considered in this paper.

The closed loop poles are chosen in left hand side and also the dominant poles to give desired dynamic performance. Poles are chosen at [-0.1 -0.25-0.5j -0.26+0.5j].

The sliding surface is defined as

$$\sigma_s(t) = -27.69\vartheta - 14.21r - \psi \qquad (3)$$

The heading control law is computed [18] as

$$\delta_s(t) = 21.75\vartheta + 0.172r - 2.26\psi + 5\tanh(\sigma_s/5) \qquad (4)$$

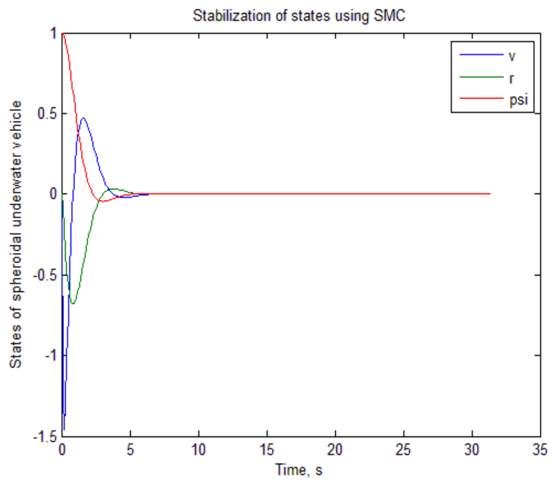

Figure 2 Stabilization of states using SMC

The control input (FJ2,3= δs) is of the form δs=δs-eq+δs-d δs-eq is calculated based on vehicle model. It is calculated using simple pole placement technique. It compensates for deviations from ideal performances due to parametric uncertainties. δs-d is calculated using continuous function, hyperbolic tangent function. It gives the desired robustness in the presence of disturbances and unmodeled dynamics without compromising vehicle stability.

On application of above SMC to system (1), the state responses are obtained up to 30 sec for smooth manoeuvring and are shown in Figure 2. It is clear that all the states are stabilized. Now for achieving vehicle control further MPC is developed in section 3.

3. MODEL PREDICTIVE CONTROL (MPC)

MPC is an efficient and robust control technique for multivariable problems which are generally used in oil refineries and chemical plants since early 1980's (Budiyono, 2011). The main idea of using MPC is it can handle multiple degrees of freedom using a system model along with constraints. The optimal control input can be calculated using control algorithm so that the error gets minimized in a finite number of steps. For prediction of future output values, current and model measurements are taken into account. These results in calculation of changes in input variables based on predictions and actual measured values (Debasish & John, 2015). The output variable (ψ) also called as controlled variables (CV), while input variables (U) are called as manipulated variables (MV). Disturbance variables are called DV (random signal and noise) (Naeem, 2002).

The main advantages of MPC (Wang, 2010) techniques are:

- Constraints can be applied on both output as well as input variables. This technique has ability to operate closer to the constraints
- It can consider inherent non-linearity
- Time delays, inverse response, changing control objectives and sensor failure can be considered
- Warnings of potential problems as accurate model prediction are already known

It is seen from the MPC scheme block diagram given in Figure 3, that to predict the current values of controlled variables, spheroidal underwater vehicle model is used. The signal, which is the difference between the predicted and the actual output, acts as a control signal to a prediction block. This control signal is also known as residual. Since, MPC calculations are done at each and every sampling instant, these predictions are used for set point calculations and control calculations (Wang, 2010, Steenson, 2013). The constraints on input and output variables can be applied on both the types of MPC calculations. These model predictive control calculations determine the appropriate sequence of control moves so as to get the optimal results (Medagoda & Williams, 2012, Naeem, 2002).

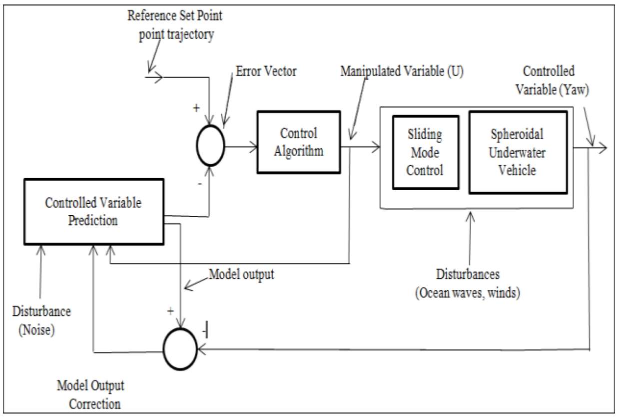

Figure 3 Model Predictive Control scheme of a Spheroidal Underwater Vehicle

The set point trajectory can be expressed in sequence of steps and the controlled variables as the cumulative effect of those steps. MPC controller calculates control law based on the cost function using the difference between set point trajectory and controlled variable. The disturbances considered while designing MPC are random signals and white noise. Disturbances like ocean waves, winds are considered on Vehicle trajectory. All these signals are considered in MATLAB programming. Using transformation matrix, equation (1) using equation (4) is converted in to augmented state model (Wang, 2010) for continuous MPC and complete derivation is available in (Truong, Wang & Gawthrop, 2006):

$$\begin{bmatrix} \dot{z}(t) \\ \dot{y}(t) \end{bmatrix} = \begin{bmatrix} A_m & 0_m^T \\ C_m & 0_{q\times q} \end{bmatrix} \begin{bmatrix} z(t) \\ y(t) \end{bmatrix} + \begin{bmatrix} B_m \\ 0_{q\times m} \end{bmatrix} \dot{u}(t) \qquad (5)$$

$$y(t) = \begin{bmatrix} 0_m & I_{q\times q} \end{bmatrix} \begin{bmatrix} z(t) \\ y(t) \end{bmatrix} \qquad (6)$$

where '0' is zero matrix, 'I' stands for identity matrix and z(t) is a transformation matrix. The continuous model is sampled to obtain discrete model for implementation and MPC analysis. So above augmented model is converted in equation (7) and (8).

$$x(k+1)=Ax(k)+Bu(k) \qquad (7)$$

$$y(k)=Cx(k)+Du(k) \qquad (8)$$

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

$$x(k+n) = A^n x(k) + A^{n-1}Bu(k) + A^{n-2}Bu(k+1) + \ldots + ABu(k+n-2) + Bu(k+n-1) \qquad (9)$$

The system output can be determined simply using

$$y(k+n)=Cx(k+n)+d(k+n);\ \ d(k+n)=d(k); \qquad (10)$$

substituting eq.(9) in eq.(10), output equation can be written as

$$y(k+n) = CA^n x(k) + CA^{n-1}Bu(k) + CA^{n-2}Bu(k+1) + \ldots + CABu(k+n-2) + CBu(k+n-1) + Du(k) \qquad (11)$$

This prediction consists of past and future data, so it is important to be careful with notation and also in the formation of predictions (Martin & Dierk, 2002).

A general notation used in the paper is double subscript (Wang, 2010). Sample of the prediction (how many steps ahead) is represented in first step and the sample at which prediction was made (only used for prediction and not past) in the second step

For example the meaning of

$$x(k+3\,|\,k)\ \&\ y(k+5|k+2)$$

as prediction of x at sample (k+3) where prediction was made at sample k and prediction of y at sample (k+5) where prediction was made at sample (k+2)

The n step ahead prediction in generalized form is represented as

$$x(k+n\,|\,n) = A^n x(k) + A^{n-1}Bu(k\,|\,k) + A^{n-2}Bu(k+1\,|\,k) + \ldots ABu(k+n-2\,|\,k) + Bu(k+n-1\,|\,k) \qquad (12)$$

$$y(k+n\,|\,n) = CA^n x(k) + CA^{n-1}Bu(k\,|\,k) + CA^{n-2}Bu(k+1\,|\,k) + \ldots CABu(k+n-2\,|\,k) + CBu(k+n-1\,|\,k) + d(k) \qquad (13)$$

N_p and N_c are prediction and control horizon respectively. The control law 'U' (manipulated variable) is

$$U = [\Delta u^T(k)\ \Delta u^T(k+1)\ \ldots\ldots\Delta u^T(k+N_c-1)]^T \qquad (14)$$

$$x(k) = [x^T(k+1\,|\,k)\ x^T(k+2\,|\,k)\ldots\ldots x^T(k+N_p\,|\,k)]^T \qquad (15)$$

Computing the future state vectors and output vectors (Wang, 2010) as

$$Y=Fx(k) + \Phi u \qquad (16)$$

$$where\quad F = \begin{bmatrix} CA \\ CA^2 \\ CA^3 \\ . \\ . \\ CA^n \end{bmatrix} \quad \&$$

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

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

$$R_s^T = [I \ I \ I \ldots I] r(k)$$

where r(k) is the reference vector at sample instant k. 'I' is the identity matrix. Then the cost function for MPC design (Truong, Wang & Gawthrop, 2006) is

$$J=(R_s-Y)^T Q(R_s-Y) + \Delta U^T R \Delta U \quad (17)$$

where R is a symmetric positive definite and input weighing matrix to be selected. Q is the output weighting matrix. Analysis gives the minimizing control in the absence of constraints as

$$\Delta U = (\Phi^T \Phi + R)^{-1} \Phi^T F z(k_i) \quad (18)$$

where the required matrix inverse is assumed to exist.

3.1 TUNING OF MPC

In order to implement the MPC as explained above to spheroidal vehicle control, following parameters are required to be defined and assigned values.

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

3.2 IMPLEMENTATION ALGORITHM

Step1: Considering spheroidal vehicle model from equation (1) and select the desired closed loop poles to compute the sliding mode control law using equation (4) to stabilize the vehicle.

Step2: Develop the augmented model which is useful for implementation of model predictive control using equation (5).

Step3: Discretize the dynamic model of a spheroidal underwater vehicle which is convenient for MPC calculations in equations (7) and (8).

Step4: Compute the MPC control law (manipulated variable) 'U' using cost function from equation (18).

Step5: Apply U to stabilized vehicle model for yaw control performance of a spheroidal underwater vehicle as per the scheme of Figure 3.

Step6: Time domain performance parameters are calculated and shown in table 3.

The above algorithm is also described in the following flow chart (Figure 4) to compute the control law.

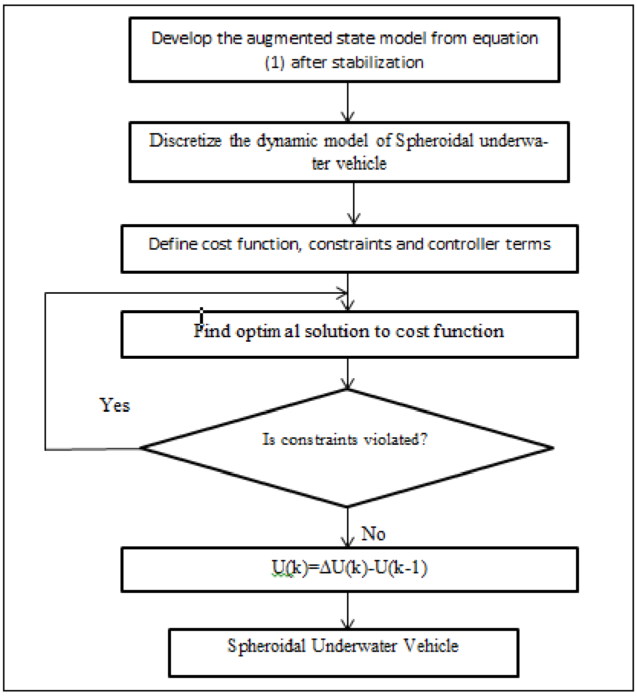

Figure 4 Implementation of MPC on Spheroidal Underwater Vehicle

4. SIMULATION EXERCISE

The spheroidal vehicle model and parameter values are taken from (Mazumdar & Asada, 2014) for implementing the proposed control scheme. The vehicle is stabilized by choosing desired poles using SMC as explained in section 2.1. The tuning parameters have been selected for implementation of MPC and are listed in Table 2.

Table 2: Parameters used in MPC Controller

Parameter	**Value**
Model Horizon	30
Control interval	0.2
Prediction horizon	10
Control horizon	2
Input Weight, R	1
Output Weight, Q	12

Since the vehicle model is in spheroidal shape and moves in multiple directions, the reference set point trajectory is considered as sinusoidal.

On application of the proposed control scheme with above values of parameters, the controlled response along with the reference is obtained and shown in Figure 5 for Yaw angle control. The response obtained follows very closely the reference and demonstrate the effectiveness of proposed control.

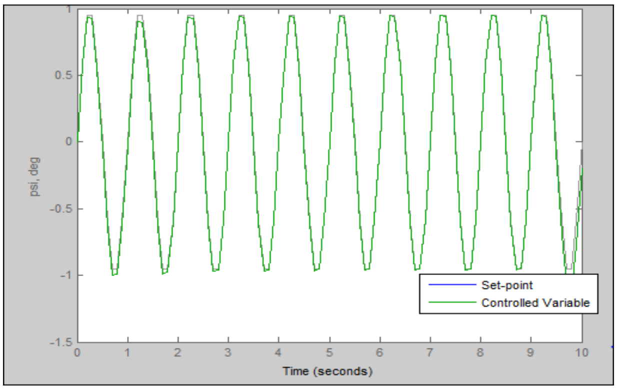

Figure 5 Yaw angle control of a vehicle subjected to sinusoidal input.

Root Locus diagram of controlled spheroidal underwater vehicle is shown in Figure 6 and it is having better stable region when compared with conventional PD control in (Mazumdar & Asada, 2014).

Heading control of a spheroidal underwater vehicle subjected to step input is also obtained and shown in Figure 7. It has good transient and steady state response. The time domain specifications such as rise time (t_r), Maximum peak overshoot (M_p), settling time (t_s) are calculated for the proposed scheme and also for the responses from other control schemes from the literature. The performance of proposed scheme results best than other control schemes.

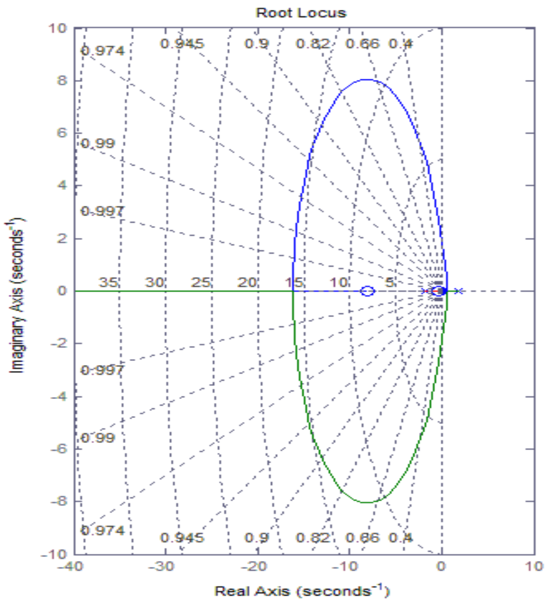

Figure 6 Root Locus Diagram of Spheroidal Underwater Vehicle

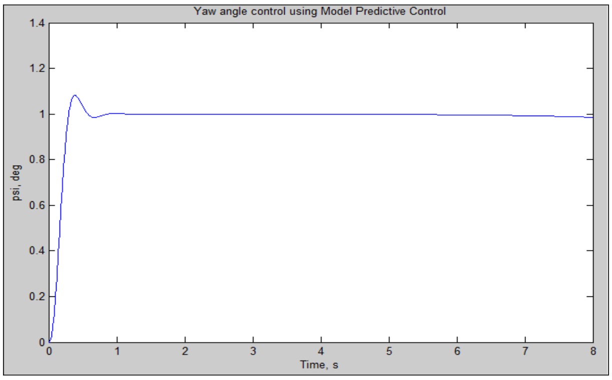

Figure 7 Heading Control of spheroidal underwater vehicle

Comparative analysis of spheroidal underwater vehicle have made from present paper, with (Mazumdar & Asada, 2014) and (Prasad & Swarup, 2015) and listed in Table 3.

Table 3 Time domain characteristics of the vehicle

Control Methods	Rise time, t_r(s)	Maximum Peak Overshoot, Mp (%)	Settling time, t_s(s)
1.a)Combined state feedback & Estimator	1.38	4.85	3.95
b)Pole selection based on ITAE	2.23	2.41	7.31
c)Pole selection based on Bessel Function	2.98	0.815	4.72
2. LQR	5.61	0.999	10.2
3.PD Control[2]	3.05	4.9	7.88
4.MPC (Proposed)	0.36	0.4	1.24

5. CONCLUSIONS

Spheroidal underwater vehicle model considered in this paper is unstable and complex system. The main contributions of the paper are stabilization of the Spheroidal underwater vehicle model using sliding mode technique and set point tracking of spheroidal underwater vehicle using model predictive control. So combination of SMC and MPC formulation has been developed to stabilize and track the vehicle in desired set point (yaw angle). MATLAB simulation results show the effectiveness of the vehicle tacking in desired path. From the results it is clear that vehicle is stabilized and also following set point trajectories. It has good transient and dynamic behaviour when compared with PD and other control techniques. The dynamic position can also be controlled using proposed control scheme.

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