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Depth Control of Autonomous Vehicle using MPC

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Abstract:

In this paper, an overview of Autonomous Underwater Vehicles (AUV) is presented whichdescribes the development and verification ofsix degree of freedom, non-linear simulation model. A nonlinear model of AUV is obtained throughkinematics and dynamics equations which are linearized about an operating point to get alinearized horizontal plane model.The system is modelled using INFANTE AUV hydrodynamic parameters that are controlled by path following control using MATLAB. The paper is concerned with depth control of AUV using Model Predictive Control without considering disturbanceswith the design of control laws that force a vehicle to reach and maintain a fixed position in vertical plane. The depth and pitch angle control of body fixed z-axis to a fixed point using MPC toolbox of MATLAB is shown in the paper. The paper summarizes the controller design steps, describes a technique for its practical implementation, and presents experimental results obtained with the INFANTE AUV using MATLAB.

1. INTRODUCTION

Autonomous Underwater Vehicle(AUV)refers to an autonomous robot equipped with suitable sensors and actuators which enable it to navigate in the subsea environment. It is an undersea system which has its own power and controlled by an onboard computer while doing a pre-defined task [2]. They are compact, self contained, low drag profile crafts powered by a single underwater DC power thruster. It uses on-board computers, power packs and vehicle payloads for automatic control, navigation and guidance. They have been operated in a semi autonomous mode under human supervision, which requires them to be tracked, monitored, or even halted during a mission so as to change the mission plan.

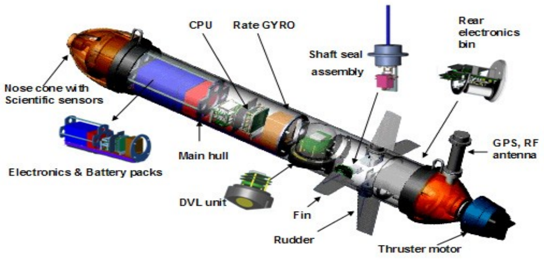

Fig.1: Structure of AUV

The AUVs have modular structure which consists a cylindrical main body blended with a nose cone at its front and a tapered tail section at its rear, giving it aefficient streamlined shape. Pressure Hull provides the majority of the buoyancy for the vehicle and space for components such as batteries and control electronics. Tail cone is designed to reduce the drag caused by the pressure drop at the end of the vehicle body. Nose section consists of scientific sensors like forward look sonar which helps in navigation. Main section encompasses of electronic circuitry, batteries, Rate GYRO. Rate GYRO is used to measure the yaw of the vehicle, main CPU, and Doppler Velocity Log (DVL) sensor that allows the vehicle to know the approximate distance it travelled in three orthogonal axes. Fins help in swimming. Rudder is the vertical and movable control, which is hinged to the fin and mainly controls the yawing movement of the vehicle. Thruster motor provides the necessary thrust to move in forward direction GPS antenna used to locate the exact position of AUV.

The challenges that an AUV faces are navigation, communication, autonomy, and endurance issues.
Automatic functioning is an important issue of AUVs which deals with circuit configurationand controller strategy. In this project work, the main concern is on the autonomy. During amission, an AUV may undergo different steering scenarios such as a complete turn at the end ofa trajectory, a severe roll during avoiding an obstacle or frequent depth changes while followinga tough seabed terrain.

The focus of this paper is to develop control algorithms for an AUV to accomplish path following of a desired path. Also, the non linear coefficients of AUV dynamics are linearized and the depth is controlled by putting constraints on pitch rate and yaw velocity using a linear controller such as a Model Predictive Controller technique.

2. AUV KINEMATICS AND DYNAMICS

Kinematics and dynamics of an AUV are described in Fig.2 where the motion of the body-fixed frame of reference is described relative to an inertial or earth-fixed frame.For implementing the path following control in x-y domain, only three Degree of Freedom (DoF) is considered i.e. surge equation of motion is along x-direction, sway equation of motion is along y-direction and yaw equation of motion is angular movement along z-direction. The corresponding kinematic equations are also considered.
To study the motion of marine vehicle 6 degrees of freedom are required since to describeindependently the complete position and orientation of the vehicle we require 6 independentcoordinates.

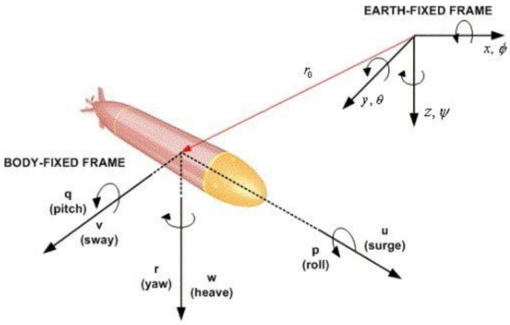

Fig.2: AUV Co-ordinate system
To describe position and translation motion first three sets of coordinates and their time derivatives are required. While for orientation and rotational motion last three sets of coordinates and their time derivatives are required.

DOF	MOTION	Forces	Linear and angular velocity	Position
1	Motion in x-direction(surge)	X	u	x
2	Motion in y-direction(sway)	Y	v	y
3	Motion in z-direction(heave)	Z	w	z
4	Rotation in x-direction(roll)	K	p	ϕ
5	Rotation in y-direction(pitch)	M	q	θ
6	Rotation in z-direction(yaw)	N	r	ψ

Table 1: Notation used for AUV modelling
The kinematics equations of AUV are generally represented using two coordinate frames i.e. earth fixed frame and body-fixed frame [24]. The velocity parameters of the AUV are determined from the body-fixed frame and using a transformation matrix, the velocity in the earth fixed frame is determined.

The transformation matrix $J_1(\eta)$ and $J_2(\eta)$ are defined as follows,

$$J_1(\eta_2) = \begin{bmatrix} cos(\Psi) & -sin(\Psi) & 0 \\ sin(\Psi) & cos(\Psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} cos(\theta) & 0 & sin(\theta) \\ 0 & 1 & 0 \\ -sin(\theta) & 0 & cos(\theta) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos(\varphi) & -sin(\varphi) \\ 0 & sin(\varphi) & cos(\varphi) \end{bmatrix} \quad (1)$$

$$J_2(\eta_2) = \begin{bmatrix} 1 & sin(\varphi)tan(\theta) & cos(\varphi)tan(\theta) \\ 0 & cos(\varphi) & -sin(\varphi) \\ 0 & sin(\varphi)/cos(\theta) & cos(\varphi)/cos(\theta) \end{bmatrix} \quad (2)$$

where, $J_1(\eta_2)$ is utilized for the conversion of body fixed linear velocities(u , v, w) to earth fixed linear velocities $(\dot{x}, \dot{y}, \dot{z})$ and $J_2(\eta_2)$ is used for converting the body- fixed angular velocities (p, q, r) to earth fixed angular velocities $(\dot{\theta}, \dot{\varphi}, \dot{\Psi})$.

The complete transformation between body-fixed and earth-fixed frames represent the kinematics equation of the AUV which is given as follows,

$$\begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta 2} \end{bmatrix} = \begin{bmatrix} \mathrm{J1}(\eta 2) & 0_{3\times 3} \\ 0_{3\times 3} & \mathrm{J2}(\eta 2) \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix}$$

where, $\dot{\eta}_1 = [\dot{x}, \dot{y}, \dot{z}]^{\mathrm{T}}$ and $\dot{\eta 2} = \left[\dot{\theta}, \dot{\varphi}, \dot{\Psi}\right]^T$ represents the AUV velocities in the earth fixed frame. The corresponding body-fixed velocities of the AUV are $\nu_1 = [\mathrm{u}, \mathrm{v}, \mathrm{w}]$and $\nu_2 = [\mathrm{p}, \mathrm{q}, \mathrm{r}]$.

Dynamics of the AUV consists of nonlinearity and coupling between various terms, accordingly following are the dynamic equation along the respective axis.

- Surge Motion:

$$m[\dot{u} - vr + \omega q - x_g(q^2 + r^2) + y_g(pq - \dot{r}) + z_g(pr + \dot{q})] = X \quad (4)$$

- Sway motion:

$$m[\dot{v} - wp + ur - y_g(p^2 + r^2) + z_g(qr - \dot{p}) + x_g(pq + \dot{r})] = Y \quad (5)$$

- Heave motion:

$$m[\dot{w} - uq + vp - z_g(q^2 + p^2) + x_g\,(pr - \dot{q}) + y_g(rq + p] = Z \quad (6)$$

- Roll motion:

$$I_x\dot{p} + (I_z - I_y)qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} + m\left[y_g\left(\dot{w} - u\dot{q} + vp\right) - z_g(\dot{v} - wp + ur = K \quad (7)$$

- Pitch motion:

$$I_y\dot{q} + (I_x - I_z)pr - (\dot{p} + qr)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} + m\left[z_g\left(\dot{u} - v\dot{r} + wq\right) - z_g(\dot{w} - uq + vp = M \quad (8)$$

- Yaw Motion:

$$I_z\dot{r} + (I_y - I_x)pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{zx} + m\left[x_g\left(\dot{v} - w\dot{p} + ur\right) - y_g(\dot{u} - vr + wq)\right] = N \quad (9)$$

The first three equations correspond to translational motion of the vehicle while the last threeequations deal with the rotational motion of the vehicle.

These equations can be simplified by considering only body relative surge, sway, yaw rate & earth relative position, heading & yaw angle. and again neglecting all out of plane terms results in:

$$m\left[\dot{u} - vr - x_g r^2 + y_g\dot{r}\right] = X \quad (16)$$

$$m\left[\dot{v} + ur - y_g r^2 + x_g(\dot{r})\right] = Y(17)$$

$$I_z\dot{r} + m\left[x_g\left(\dot{v} \dot{+} ur\right) - y_g(\dot{u} - vr)\right] = N$$

Here, X,Y& N are vehicle parameters and are combination of various external forces such as added mass, hydrodynamic damping, hydrostatics etc.

3. PATH FOLLOWING CONTROL STRATEGY FOR AN INDIVIDUAL AUV

Let the desired path, P which the AUV is to follow Fig.3. It is intended to design a control law such that the AUV will follow the desired path P. A path following controller for an under actuated AUV is to be designed such that it steers the AUV towards the desired path P while maintaining a constant velocity in the forward motion.

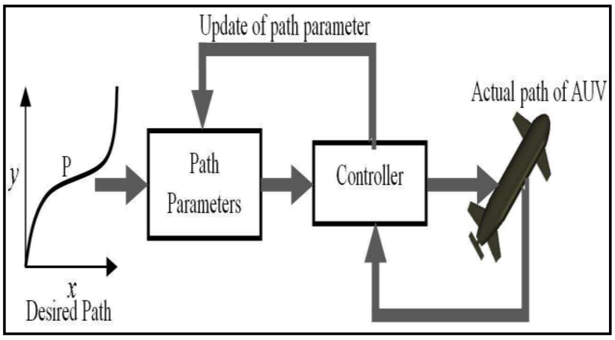

Fig. 3: Path following controller implementation

Using the linearized hydrodynamics coefficients as described in equations 1-18, the dynamics simulation of the AUV is obtained assuming a fixed value of propeller thrust & rudder angle. The vehicle has to follow a circular path which is given as an input to the vehicle. The results after simulation as obtained is shown in the result section as described below in the paper.

4. MODEL PREDICTIVE CONTROLLER

It is a type of control in which the current control signal is determined such that a desirable output behaviour results in the future. This future behaviour is a function of past inputs to the process as well as the inputs that we are considering to take in the future. In MPC structure, theprocess measurements can be computed by a feedback or feed forward path.

There are mainly three components available in MPC structure(i). The process model (ii).The cost function (iii). The optimizer

The information about the controlled process and prediction of the response of the process values according to the manipulated control variables are done by the process model. Then the error is reduced by the minimization of the cost function. The general structure of Model Predictive Controller is shown in Fig.4.

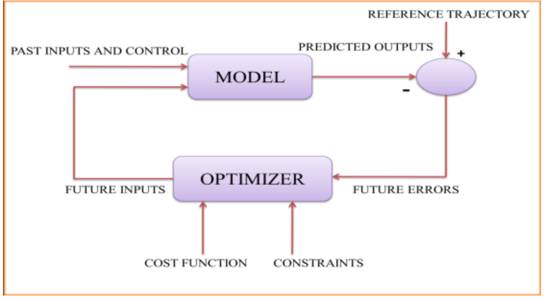

Fig.4. General Structure of Model Predictive Controller

It provides functions, an application, and Simulink blocks for systematically analyzing, designing, and tuning model predictive controllers. The diagnose issues leading to runtime failures can be processed by using this toolbox and provides advice on changing weights and constraints to improve performance and robustness.

The process output is predicted by using a model of the process to be controlled that describes the relationship between the input and the output of the process used. Further if the process is subject to disturbances, a disturbance or noise model can be added to the process model. In order to define how well the predicted process output tracks the reference trajectory, a criterion function which is the difference between the predicted process output and the desired reference trajectory is used.

The MPC control strategy was simulated using MPC toolbox which is a MATLAB-based toolbox. The Cost function is given as

$$J=\sum_{i=1}^{N}\left(\sum_{j=1}^{n_y}\left(w_j^y e_{yij}\right)^2+\sum_{j=1}^{n_u}\left[\left(w_j^u e_{uij}\right)^2+wj\Delta u\Delta uij2\right.\right.$$

Where
N = number of controller sampling intervals in the scenario

n_y= number of controlled outputs

n_u = number of manipulated variables

e_{yij} = set point (or reference) tracking error i.e. the difference between output j and its set point at time step *i*

e_{uij} = deviation of manipulated variable *j* from its target value at time step *i*

Δu_{ij} = change in manipulated variable *j* at time step*i*

w_j^y = performance weight for output *j*

w_j^u = performance weight for manipulated variable

The MPC can be selected to control an AUV process because the concept is equally applicable to single-input, single-output (SISO) as well as multi-input, multi-output systems (MIMO). It can also be applied to linear and nonlinear systems and can handle constraints in a systematic way during the controller design.

5. CONTROL SYNTHESIS

To develop a depth controller, the vehicle's forward nominal speed $u = u_0$ is assumed to be constant and the vertical plane model is formally written as

$$\frac{dx_v}{dt}=F_v(x_v,u_v),$$

where x_v=[w, q, θ]' € $\underline{R}^3$ is the state vector, u_v=[δ_b, δ_s]' € $\underline{R}^2$ is the input vector, and F_v : $\underline{R}^3 \times \underline{R}^2 \rightarrow \underline{R}^3$ is a nonlinear function that is easily obtained from the surge, and pitch equations of motion, together with kinematics depth and pitch relationships described in detail in the section above stated. The model for the vertical plane was linearized about the equilibrium point determined by [w0; q0; z0; y0]' = [0, 0 , 0, 0]' and u0 =[δ_b, δ_s]' =[0,0]'. The resulting linearized model Eigen values are presented in Fig.5.

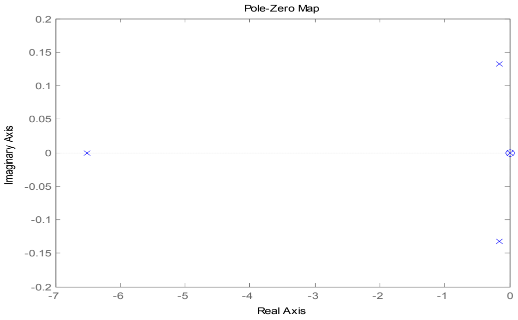

Fig.5.Linearized model Eigen values

The model exhibits an Eigen value at zero and three stable Eigen values that link together the variables w, q and y. The state space linearized dynamics and input matrices for the forward velocity of 2.0 m/s are represented below:

$$A=\begin{bmatrix} -1.4 & 2.763 & 0 & 0.078 \\ 2.108 & -5.419 & 0 & -0.312 \\ 1 & 0 & 0 & -2 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$B=\begin{bmatrix} -0.797 & -0.201 \\ 1.588 & -0.809 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The state space matrix A has one second-order mode with a natural frequency of0.132 rad/s, a real Eigen value at -6.5 rad/s, and a zero Eigenvalue.

The synthesis of MPC was carried out in the following steps. First, the parameter of MPC is chosen considering the given linearized model. The prediction horizon and control horizon are chosen to be $H_p = 10$ & $H_u= 2$, respectively. The time elapsed between control moves is 0.01 sec. The constraints for the input and state variables are given as:

For the input variable, the pitch is constrained for vertical control is limited by

$-0.2 \leq \theta \leq 0.2$

For the state variables, the pitch rate(rad/sec) is constrained to

$-20 \leq q \leq 20$

The forward velocity u(m/s) is limited by

$-25 \leq u \leq 25$

while, the heave velocity w and the surge velocity v are not constrained.

The second step is determining the input and output weight parameters. For the input variable, θ no weight is assigned meaning that θ is allowed to vary freely between its minimum value and maximum value. However, the rate weight of θ must be assigned non-zero value since in reality the rate of change of pitch angle is limited. The rate weight of θ is chosen to be 0.3993. The output weight of 0.246 is assigned to depth and pitch rate. No weight is assigned to the other state variables. Overall, the choice of weight is guided by the trade-off between the robustness and the combined disturbance rejection and set-point tracking. The control synthesis is performed using MPC design tool in MATLAB.The Simulink diagram using the above stated constraints is as follows:

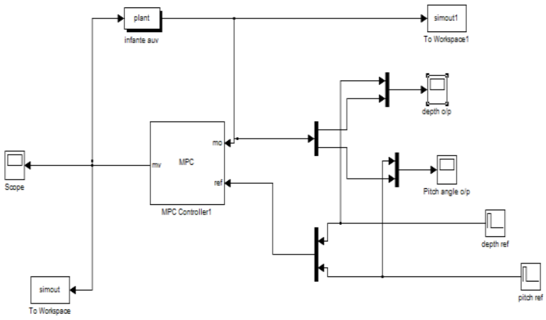

Fig.6. : Simulink diagram for depth and pitch control

The step response is chosen as a reference setpoint for the depth and the pitch angle and the results obtained after the simulation are described in the result section in the paper as detailed below.

6. RESULTS

The parameters of AUV are tracked and calculated in such a way that a prototype has to strictly follow a circular path.Using the linearized hydrodynamics coefficients as described in equations 1-18, the dynamics simulation of the AUV is obtained assuming a fixed value of propeller thrust & rudder angle.The simulation of the MATLAB program shows that the vehicle is tracking a perfect circle as the input is provided to the vehicle.

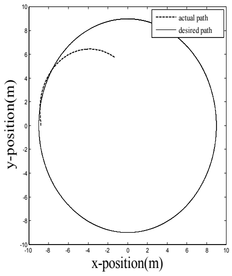

Fig.8. Dynamics Simulation of AUV

The simulation of AUV is done in next using MPC tool, considering depth and pitch angle parameters as described in the section 5, where the control synthesis of AUV is done and the transformation matrices are generated using various parameters of INFANTE AUV. It should be noted down that the depth and pitch angle of AUV is controlled without considering the effect of external disturbances.

As a case study the AUV is to follow the pitch angle and depth setpoint defined as a pulse at t= 10 s with the amplitude of 8 m and period of 100 sec. The weight is tuned in order to increase input rate penalities relative to setpoint penalties.

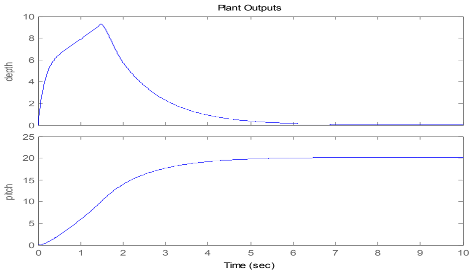

Fig.9. Response of the predicted outputs controlled by MPC.

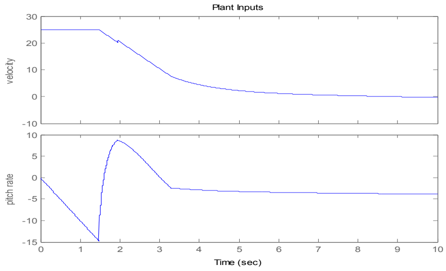

Fig.10: Response of the predicted manipulated input variables.

It can be shown by the simulation results using MPC controller that the depth and pitch angle is tracked properly with a deviation at 1.5 sec and afterwards the stability is achieved between setpoint tracking and disturbance rejection.

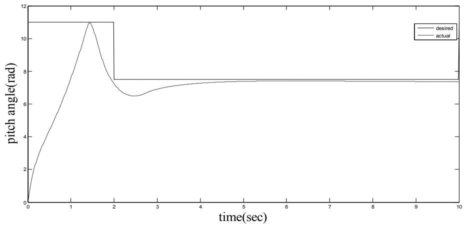

Fig.11: O/p response of pitch angle after simulation

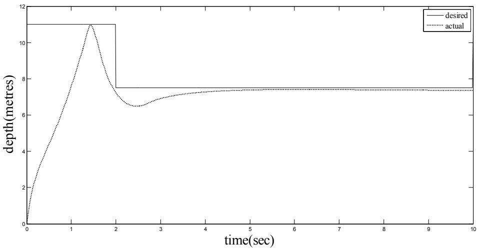

Fig.12 : O/p response of depth after simulation

The optimization of the control input is done considering the weighted tracking error between the predicted output and reference trajectory. The proposed MPC controller is shown to be robust against disturbance while maintaining an acceptable setpoint tracking performance.

7. CONCLUSIONS

This paper addressed the path following control problem of an Autonomous Underwater Vehicle. As discussed in the sections above, the controllers for path following problem is developed.

The development of path following controller for an AUV has been successfully implemented using MATLAB & SIMULINK considering the nonlinearities and coupling terms in the dynamic equation. The path following controller for an AUV is developed using Lyapunov theory where the coupling of rudder angle between sway motion and yaw motion has been considered. Also the control of forward motion i.e. surge motion is included for forward motion control. The gains of the controller are also adapted according to the error derived while following the path.

A new approach to control the yaw angle of an AUV using MPC has been demonstrated. The results produced are for stationary targets and are quite encouraging as the actuator constraints are handled in an efficient way. Dealing non-stationary targets using the proposed algorithm is an area of active research. The controllers implementedhave proven extremely reliable over a long series of missions with the INFANTE AUV. Further problems that can be researched further include AUV control close to the surface in the presence of strong wave action and AUV terrain following.

In the work described here, 6DoF is considered in the dynamic equations and these are used for implementation of different controllers. The effects of ocean current has not been considered in the development of control law of the AUV, so, for real-world situation there is need to consider the above effect in the control development certainly. Further, to address the uncertainties in the AUV parameters such as hydrodynamic effect and oceanic current, there is a need to develop robust controller.

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