Pure Pursuit Guidance and Model Predictive Control of an Autonomous Underwater Vehicle for Cable/Pipeline Tracking

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Abstract

This paper investigates a new approach for the guidance and control of an autonomous underwater vehicle (AUV). An integrated system is developed and simulated involving a proportional navigation guidance (PNG) law and model predictive control (MPC). The classical PNG law for missile systems has been tailored to guide the AUV by generating reference headings. MPC is used to track the reference trajectory (guidance commands), which is optimised using a genetic algorithm (GA). The performance of the closed loop system is evaluated in simulations with and without sea current disturbance and imposing actuator constraints. Simulation results for the case of a cable tracking mission and waypoint following clearly shows the superiority of the proposed algorithm.

1. INTRODUCTION

The technology and applications of unmanned underwater vehicles (UUVs) have been improving at a rapid pace. From missions such as cable/pipeline inspection to oil exploration and to mine clearing operations, they are routinely been deployed by the offshore and defence industry. This is mainly attributed to the fact that it does not require any human onboard thereby not jeopardizing any life. In addition, in cases such as deep-sea exploration, where human intervention is not possible, they are proved to be a viable tool. Although regular monitoring and inspection of cables/pipelines running in deep sea have emerged as an important issue, little attention has been paid to sub-sea cables or pipelines. This paper describes a novel approach to underwater vehicle cable tracking mission by employing an integrated guidance and control system using a PNG law for missile systems and MPC. The contemporary method to detect linear subsea objects is through active magnetic, passive magnetic or electromagnetic detectors mounted on a remotely operated vehicle (ROV) [1]. These sensors provide lateral and longitudinal displacement of the ROV from the target pipeline, but no target direction. Additional sensor is needed to measure the target orientation. This information is then used by the ROV pilot to steer the vehicle over the pipeline. Although ROVs have been employed for detection and tracking, their range of operation is constrained by the length of the tether. Furthermore, the need for a support vessel and an ROV operator adds to the cost of monitoring operation. One way to circumvent these problems is to render the vehicle autonomous, that is, they execute the task with minimal human intervention.

A variety of methodologies and concepts have been reported to perform object tracking by an underwater vehicle. An account of various AUV guidance schemes has recently been documented by Naeem *et al.* [2] while a comparison of classical and advance control strategies has been reported by Craven *et al.* [3]. In this paper, a modified PNG law is proposed for tracking underwater cables/pipelines employing a sonar system. MPC is used to track the reference commands generated by the PNG. The intent is to demonstrate the suitability of the integrated guidance and control scheme for detecting and tracking an undersea object, in this instance a pipeline, via simulation. The tracking of a pipeline by an AUV is first posed as an AUV-target interception problem. The classical PNG law is then employed to generate the guidance command signals to the AUV. Subsequently this is modified to achieve the desired target tracking trajectory objective.

1.1 Sonars

Recent advances in sonar technology provides a sophisticated means of finding fibre optic cable, plastic, metal and other materials suspended in mid-ocean or buried in a seabed [4]. This strategy entails use of an *active sonar* system for target (pipeline) detection. Active sonars employ echo ranging to detect an object whereas *passive* sonars pick-up acoustic radiation of ships, submarines etc, by an array of hydrophones. Some of the several other factors that influence this choice are:

1. *Active sonars* echo-range and therefore are capable of detecting even a submerged pipeline in the background of clutter i.e., reverberations, in which it appears. Vision based systems will have severe limitations in such a scenario which is very

likely to occur at sea bed due to underwater current and various other natural disturbances.

2. They can provide both range and orientation of the target, unlike magnetometers, which are non-directional and can easily mislead the AUV in presence of subsea ferrous deposits.
3. Presence of onboard *active sonar* can also be employed for retrieval of an AUV back to the mother ship once mission is accomplished. This has been investigated by Ahmad *et al*. [5] and is an area of ongoing research.
4. Sonic signals are the only practical and efficient way of long-range undersea communication, for instance between the mother ship and the AUV [6].

The broader aim of the authors is to render a underwater vehicle truly autonomous, incorporating features such as smart launch, mid-course guidance, target tracking, area search and finally, return and dock to the mother ship autonomously on completion of a given task.

2. PROBLEM DEFINITION

The following assumptions are made in order to formulate the guidance problem:

i) The AUV-target engagement is planar i.e. in the same plane.

ii) Although the pipeline is a continuous object, it is convenient to assume it as a point mass moving with a constant velocity. This condition can be ensured by considering only the latest value of echoed ping received by an onboard AUV sonar. The AUV is also considered as a constant velocity mass point.

iii) Complete navigational information of the target is available to the AUV.

Consider a two-dimensional engagement geometry in which the AUV and target are closing on each other at constant velocities V_p and V_e respectively as shown in Figure 1. An imaginary line joining the AUV and target is referred as the line of sight (LOS). The angle formed by the LOS with the fixed reference is λ and from the geometry is given as,

$$\lambda = \tan^{-1}\frac{h}{r} \tag{1}$$

where, h and r are the relative separation between the AUV and target perpendicular and parallel to the fixed reference respectively. The relative movement between the AUV and target causes the LOS to rotate through a small angle λ, indicating a displacement h between AUV and target perpendicular to the fixed reference. The length of LOS is a range R and represents the initial AUV-target distance. The problem is then to develop an integrated system which will make the initial range R between the AUV and target as small as possible at the end of expected intercept time. It will be shown later in simulation that it is a good starting point for achieving the desired tracking objective, without actually intercepting the target.

3. GUIDANCE AND CONTROL

Herein a PNG law is utilised to obtain the guidance commands. The guidance subsystem takes input from the sensors onboard the AUV. The sensors used could be global positioning system (GPS) for positioning on the surface, inertial navigation system (INS), compass etc. Information from the sensors is fused together and provided to the guidance system, which then generate commands to be followed by the AUV. A simple block diagram of the navigation, guidance and control system is depicted in Figure 2. MPC is used to track the reference commands from the guidance system. The selection of MPC for this paper is attributed to several factors, the most important being its ability to handle constraints in a natural and systematic way. The following subsections describe the PNG and MPC algorithms and their development.

3.1 Proportional navigation guidance law

The ultimate objective of the guidance law is to steer the AUV so that it will chase a target using a constant AUV velocity V_p and a controllable heading angle ψ_p. However, initially it will be regarded as an AUV-target interception problem and then subsequently modified to realise the desired “tail-chase” type AUV trajectory. The tail-chase type trajectory of interest is akin to that formed when a dog is chasing a cat. This type of trajectory will ensure that the AUV is always trailing behind the target and thus continuously monitor it at a close length. From the discussion of Section 2, it is intuitive that if the AUV is made to lie on the LOS and hold it there as well, a constant relative bearing between the AUV and target is ensured that is, the LOS of sight does not rotate, and interception will occur. This mechanisation can be realised using a PNG law.

Proportional navigation is a method of guidance, which generates command signals u_c , proportional to the LOS angle λ, so that the pursuing vehicle remains on the LOS. This can be mathematically stated as:

$$u_c \propto \lambda \tag{2}$$

$$u_c = k\lambda \tag{3}$$

Where, k is called the navigation constant and is an important design parameter. A judicious choice of k will ensure that the LOS does not rotate and hence no further input command is required. Thus, it influences both, the engagement trajectory as well as the command input. The proportional navigation guidance scheme is illustrated in Figure 3 and a good description on PNG can be found in [7].

3.1.1 Guidance law application

For implementing the guidance law of Equation 3, it is necessary to compute the LOS angle λ. This requires relative positions of the AUV and target in both the co-ordinates i.e.,

$$h = y_e - y_p \tag{4}$$

$$r = x_e - x_p \tag{5}$$

therefore,

$$\lambda = \tan^{-1}\left(\frac{y_e - y_p}{x_e - x_p}\right) \tag{6}$$

The components of the AUV velocity in the (x, y) plane can be stated as,

$$V_x = V_p \cos\psi_p \tag{7}$$

$$V_y = V_p \sin\psi_p \tag{8}$$

Hence, the differential equation for the components of the AUV position can be expressed as:

$$\dot{x}_p = V_x \tag{9}$$

$$\dot{y}_p = V_y \tag{10}$$

It is assumed that the AUV speed V_p and heading angle ψ_p are available to the guidance logic from an onboard speed log and gyro compass respectively. In certain cases both components of the AUV speed i.e., Equations 9 and 10 can be obtained directly from a Doppler log.

By integrating the above velocity component equations, the AUV position components (x_p, y_p) in the earth fixed co-ordinates can be found. Integrating Equations 9 and 10 from time t = 0 to t = t_f, and zero initial condition, that is, $x_p(0) = 0$ and $y_p(0) = 0$ will give:

$$x_p = \int_0^{t_f} V_p \, cos\psi_p \, dt \tag{11}$$

$$y_p = \int_0^{t_f} V_p \, sin\,\psi_p \, dt \tag{12}$$

where t_f is time until intercept.

Similarly, it is easy to get the target positions (x_e, y_e) in the earth coordinates. It is assumed that the target velocity V_e and orientation ψ_e is known as a function of time. These quantities can be either measured or estimated. Therefore, target positions are given by

$$x_e = x_{e0} + \int_0^{t_f} V_e \, cos\psi_e \, dt \tag{13}$$

$$y_e = y_{e0} + \int_0^{t_f} V_e \, sin\psi_e \, dt \tag{14}$$

Thus, by substituting Equations 11-14, in Equation 6, the LOS angle λ can be determined which on substitution in Equation 3 would generate appropriate guidance commands. This completes the guidance law mechanisation.

3.2 Model Predictive Control

Model Predictive Control (MPC) refers to a class of algorithms that compute a sequence of manipulated variable adjustments in order to optimise the future behaviour of a plant. Originally developed to meet the specialised control needs of power plants and petroleum refineries, MPC technology can now be found in a wide variety of application areas including chemicals, food processing, automotive, aerospace, metallurgy [8], to name but a few.

The development of MPC can be traced back to 1978 after the publication of the paper by Richalet *et* a*l*. [9] called the *model predictive heuristic control* (MPHC). Then Cutler and Ramaker from Shell Oil in 1979, 1980 developed their own independent MPC technology, *dynamic matrix control* (DMC), [10, 11]. Whilst the most popular form of predictive control called the *generalised predictive control* (GPC), has been devised by Clarke *et al.,* [12, 13] and is employed in this paper.

The process output is predicted by using a model of the process to be controlled. Any model that describes the relationship between the input and the output of the process can be 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 is used. Typically, the criterion is the difference between the predicted process output and the desired reference trajectory. A simple criterion function is

$$J = \sum_{i=1}^{H_p} [\hat{y}(k+i) - w(k+i)]^2 \qquad (15)$$

where $\hat{y}$ is the predicted process output, w is the reference trajectory, and H_p is the prediction horizon or output horizon. The structure of an MPC is shown in Figure 4. The controller output sequence u_{opt} over the prediction horizon is obtained by minimisation of J with respect to u. As a result the future tracking error is minimised. If there is no model mismatch i.e. the model is identical to the process and there are no disturbances and constraints, the process will track the reference trajectory exactly on the sampling instants. The following steps describe the MPC algorithm

i) Explicit use of a model to predict the process output along a future time horizon (Prediction Horizon).
ii) Calculation of a control sequence along a future time horizon (Control Horizon), to optimise a performance index.
iii) A receding horizon strategy so that at each instant the horizon is moved towards the future, which involves the application of the first control signal of the sequence calculated at each step. The strategy is illustrated in Figure 5.

The selection of MPC to control an AUV is attributed to several factors. Some of them are listed below.

- The concept is equally applicable to single-input, single-output (SISO) as well as multi-input, multi-output systems (MIMO).
- MPC can be applied to linear and nonlinear systems.
- It can handle constraints in a systematic way during the controller design.
- The controller is not fixed i.e., it is designed at every sampling instant so disturbances can easily be dealt with.

The optimisation of the performance index is done using a GA, which is motivated by the work of Duwaish and Naeem [14]. The following section describes the operation of a simple GA.

3.2.1 Genetic Algorithms

GAs, inspired by Darwinian theory, are powerful non-deterministic iterative search heuristics. GAs operate on a population consisting of encoded strings where each string represents a solution. Crossover operator is used on these strings to obtain the new solutions, which inherits the good and bad properties of their parent solutions. Each solution has a fitness value and solutions having higher fitness values are most likely to survive for the next generation. Mutation operator is applied to produce new characteristics, which are not present in the parent solutions. The whole procedure is repeated until no further improvement is observed or run time exceeds to some threshold [15]. The flowchart of a simple GA is presented in Figure 6 and the operation is explained as follows.

To start the optimisation, GA uses randomly produced initial solutions. This method is preferred when *a priori* knowledge about the problem is not available. After randomly generating the initial population of say N solutions, the GA uses the three genetic operators to yield N new solutions at each iteration. In the selection operation, each solution of the current population is evaluated by its fitness normally represented by the value of some objective function and individuals with higher fitness value are selected. Different selection methods such as roulette wheel selection (RWS) and stochastic universal sampling (SUS) can be used. The crossover operator works on pairs of selected solutions with certain crossover rate where the crossover rate is defined as the probability of applying crossover to a pair of selected solutions. There are many ways of defining this operator such as single point crossover, double point crossover, multi-point crossover etc. For example the single point crossover works on a binary string by determining a point randomly in the two strings and corresponding bits are swapped to generate two new solutions.

3.2.2 Control Law Development

The MPC is responsible to direct the AUV towards the reference trajectory generated by the guidance system. In order to generate the control moves a cost function is minimised. The cost function used here is given by

$$J = \sum_{i=1}^{H_p} e(k+i)^T Qe(k+i) + \sum_{j=1}^{H_c} \Delta u(k+j)^T R\Delta u(k+j) \qquad (16)$$

subject to

$$u^l \leq u(k+j) \leq u^u$$

where the superscripts l and u represents the lower and upper bounds on the input moves respectively. R is the weight on the rate of change of control moves and Q is the weight on the prediction error

$$e(k) = \hat{y}(k) - w(k)$$

where $\hat{y}(k)$ is the predicted process output and $w(k)$ is the reference trajectory generated by the PNG law. The second term in Equation 16 represents the penalty on the rate of change of control moves. This is augmented to prevent excessive movements of the rudder.

The following steps describe the operation of the MPC algorithm using GA. At any time step k

i) evaluate process outputs using the process model.

ii) use GA search to find the optimal control moves which optimise the cost function and satisfies process constraints. This can be accomplished as follows.

   (a) generate a set of random possible control moves.

   (b) find the corresponding process outputs for all possible control moves using the process model.

   (c) evaluate the fitness of each solution using the cost function and the process constraints.

   (d) apply the genetic operators (selection, crossover and mutation) to produce new generation of possible solutions.

   (e) repeat until predefined number of generations has reached and thus the optimal control moves are determined.

iii) apply the first optimal control move of the sequence generated in step (ii) to the process.

4. SIMULATION RESULTS

The proposed guidance and control algorithm has been applied to an AUV simulation model supplied by QinetiQ, based on the AUTOSUB vehicle [16], having a torpedo-shaped hull. Dimensionally, the model represents an AUV that is 7m long, approximately 1m in diameter and has a nominal displacement of 3600 kgs.

The equations of motion describing the dynamic behaviour of the vehicle in the yaw, sway and roll modes can be written in the state-space representation as given by Marshfield [17]:

$$\mathbf{E}\dot{\mathbf{x}} = \mathbf{F}\mathbf{x} + \mathbf{G}\mathbf{u} \tag{17}$$

where

$$\mathbf{E}=\begin{bmatrix} (m-Y_{\dot{v}}) & -Y_{\dot{R}} & 0 & -(Y_{\dot{P}}+mZ_G) & 0 \\ -N_{\dot{v}} & (I_Z-N_{\dot{R}}) & 0 & -N_{\dot{P}} & 0 \\ 0 & 0 & 1 & 0 & 0 \\ -(K_{\dot{v}}+mZ_G) & -K_{\dot{R}} & 0 & (I_X-K_{\dot{P}}) & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{F}=\begin{bmatrix} Y_{UV}U & (Y_{UR}-m)U & 0 & Y_{UP}U & 0 \\ N_{UV}U & N_{UR}U & 0 & N_{UP}U & 0 \\ 0 & 1 & 0 & 0 & 0 \\ K_{UV}U & (K_{UR}+mZ_G)U & 0 & K_{UP}U & -mgBG \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\mathbf{G}=\begin{bmatrix} Y_{UU\delta ru}U^2 & Y_{UU\delta rl}U^2 & 0 & 0 & 1 & 1 \\ N_{UU\delta ru}U^2 & N_{UU\delta rl}U^2 & l_\phi & -l_\phi & l_\psi & -l_\psi \\ 0 & 0 & 0 & 0 & 0 & 0 \\ K_{UU\delta ru}U^2 & K_{UU\delta rl}U^2 & \gamma_\phi & -\gamma_\phi & \gamma_\psi & -\gamma_\psi \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{u}=\begin{bmatrix}\delta_{Stern-upper} & \delta_{Stern-lower} & \delta_{Stern-port} & \delta_{Stern-starboard} & \delta_{Bow-upper} & \delta_{Bow-lower}\end{bmatrix}^T$$

and the state variables are v, r, ψ, p, ϕ (see Appendix A for a nomenclature). However, it should be noted that for this study, the upper and lower canards are the only surfaces used to control the yaw dynamics. A simplified linear model of the yaw dynamics of the vehicle is extracted from the above set of equations using system identification techniques. The identified model is of the form:

$$\dot{\mathbf{x}}=\mathbf{A}\mathbf{x}+\mathbf{B}\mathbf{u} \tag{18}$$

where, **A** and **B** are the state and input coupling matrices respectively. More precisely, the two dimensional core state-space model is given by,

$$\begin{bmatrix}\dot{\psi} \\ \dot{r}\end{bmatrix}=\begin{bmatrix} a & b \\ c & d \end{bmatrix}\begin{bmatrix}\psi \\ r\end{bmatrix}+\begin{bmatrix} e \\ f \end{bmatrix}u \tag{19}$$

where a, b, c, d, e, and f are constant parameters. Moreover, the continuous time yaw model of the AUV is discretised at a sampling frequency of 2 Hz owing to the requirements of the digital MPC controller.

The ultimate objective of this paper is the development and simulation of an integrated guidance and control system for an AUV to follow a subsea cable/pipeline for inspection purpose. The program has been written in MATLAB/SIMULINK environment. The guidance law is developed in SIMULINK while the control system has been designed in MATLAB which are then combined to form an integrated guidance and control system as shown in Figure 7. It was mentioned in Section 2 that the AUV and pipeline are considered as point masses moving at a constant velocity. It is also assumed that the AUV and target are moving at the same speed i.e.,

$$\frac{V_P}{V_e} = 1 \tag{20}$$

The target frame of co-ordinate (FOC) with respect to the AUV is (0,10) representing the seabed. Whereas, the initial AUV co-ordinates in the inertial 2-dimensional frame of reference (x,y) plane are (0, 200) with respect to the target FOC. Further, it is assumed that the target obeys Equation 21, and is heading eastwards from the initial FOC.

$$\begin{aligned} x(t) &= x_0 + V_e t \\ y(t) &= h \end{aligned} \tag{21}$$

V_e and h begin fixed. The target, a "fleeing" pipeline is travelling at a constant distance h from the AUV's inertial FOC. The AUV is to be launched from a mother ship in the vicinity (0, 200) of the target to intercept it. This completes the tail-chase problem definition. A navigation constant of k = 1 has been chosen since for this value, the AUV trajectory changes at the same rate as the imaginary LOS joining the target and the AUV. This type of flight profile is often referred as "pursuit course" and the corresponding guidance law as pure pursuit. The trajectory is similar to that formed by a predator when pursuing a prey, for instance, a dog-cat or hound-hare pursuit. The predator always prefers to tail chase a target rather than intercept it by establishing a lead angle. This characteristic is exploited by the authors to achieve the pipeline-tracking objective and is discussed next.

Since it is desired to *follow* rather than *intercept* the target, a bias is introduced to Equation 4, which in effect alters the guidance signal issued by the PNG law of Equation 3. This essentially prevents the value of h in Equation 4 from reducing to zero thus precludes the AUV from intercepting the target. The value and the time of introduction of the bias would be user defined, depending on at what depth above the target (pipeline) the AUV is expected to operate.

Parameters used in all the simulations are provided in Table 1. The actuator movement is constrained between $\pm 25^o$. A bias of 10 m is introduced after 40 sample times of the simulation run. In a real system, this value could be kick off by a pressure-depth sensor on an AUV, after descending to a depth of 10 meters above the seabed. The simulation is run for 300 samples and the result is depicted in Figure 8. The rudder deflections and AUV heading are also shown in Figure 9 and 10 respectively. The AUV charts out a *pursuit course* for the first 150 m of distance travelled. With the introduction of a 10 m bias signal at the end of 150 m, the vehicle maintains a desired longitudinal position h, while tracking the cable laterally without intercepting it.

Next, waypoint following by Healey and Lineard [18] is considered and the effect of sea current disturbance is investigated. The circle of acceptance is taken as twice the length of the vehicle. First, simulation is run without any sea current disturbance with actuator movement restricted to 25^o in either left or right direction. The result is depicted in Figure 11 clearly showing that the AUV is closely following the waypoints without much control effort and within the constrained limit as shown in Figure 12. The mean square error (MSE) between the actual and ideal AUV distance from the waypoints without any disturbance is approximately $45m^2$. Finally, the simulation is run for a sea current disturbance of $1ms^{-1}$ in the positive-y direction and with actuator constraints. As shown in Figure 13, the disturbance is trying to knock the vehicle off the track, but the controller is still able to cope with it and reaches the target waypoints. The MSE is about 800m^2, much larger than the no disturbance case, although the vehicle follows all the waypoints even in the worst case scenario of the sea current mentioned above. The rudder movement is also confined within the specified limits as depicted in Figure 14, although it is lot more aggressive as compared to the no disturbance case. A statistical analysis reveals that the standard deviation of rudder deflections in the presence of wave disturbance is about 10^o while it is approximately half that value without any disturbance.

5. CONCLUSIONS

Periodic inspection and monitoring of sub-sea cables/pipelines have emerged as important issues. Although currently being done using ROVs, their endurance and capabilities are limited. This paper proposes sonar-based detection and tracking of ocean floor pipelines and cables and is posed as a two-stage problem. In the first stage, utility of classical PNG law is demonstrated in intercepting a *fleeing* target, while in the second stage, the guidance law is modified to achieve the target tracking objective albeit without ever intercepting it. MPC is used to generate control commands for the actuators to keep the vehicle as close as possible to the reference trajectory. Actuator constraints are also handled in an efficient way during the controller design. The proposed integrated guidance and control system accomplishes target detection as well as tracking objective without losing sight of the target. Incorporation of this guidance and control scheme is expected to increase the range of AUV, as no human intervention is essential for guiding the vehicle. The range would only be limited by the availability of onboard power supply.

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APPENDIX A: Nomenclature of the AUV Equation Parameters

E, F, G	State equation matrices
m	Mass
p, r	Roll and yaw angular velocity components
u, v	Surge and sway linear velocity components
ψ, ϕ	Yaw and roll angles
I_X, I_Z	Inertia components
K, N	Roll and yaw moments
Y	Y direction force component
B	Buoyancy force
G	Centre of mass
K_{UP}	Dimensional hydrodynamic coefficients of roll
$\mathbf{N}_{UU\delta ru}$	Dimensional hydrodynamic coefficient of yaw w.r.t canard upper
λ_{ϕ}, λ_{ψ}, γ_{ϕ}, γ_{ψ}	Roll and yaw moment arm lengths
$\delta_{Bow-upper}$	Input from upper canard rudder
$\delta_{Stern-port}$	Input from port stern hydroplane
$\delta_{Stern-upper}$	Input from upper stern rudder

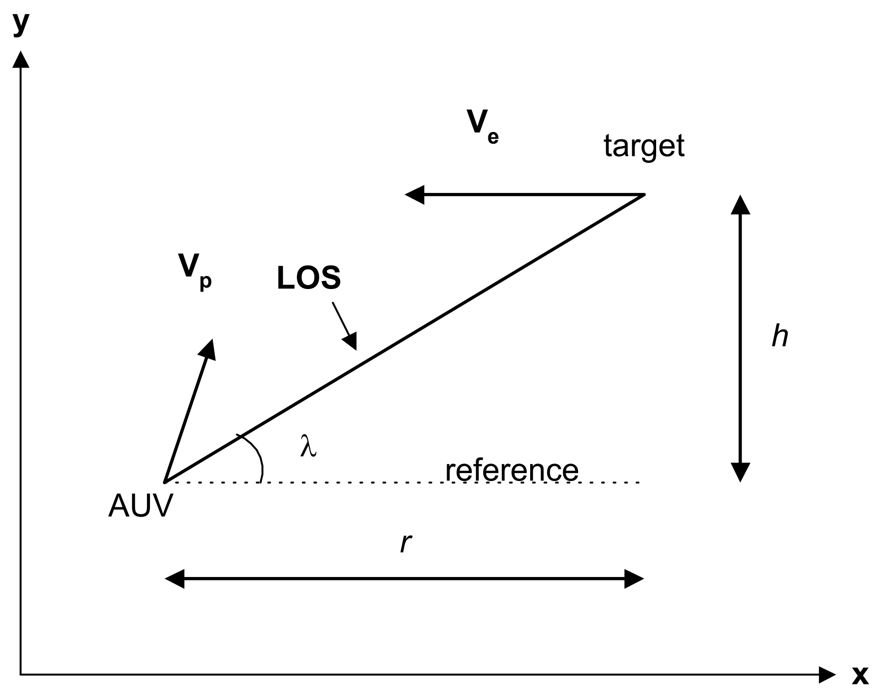

Figure 1. AUV-target engagement geometry

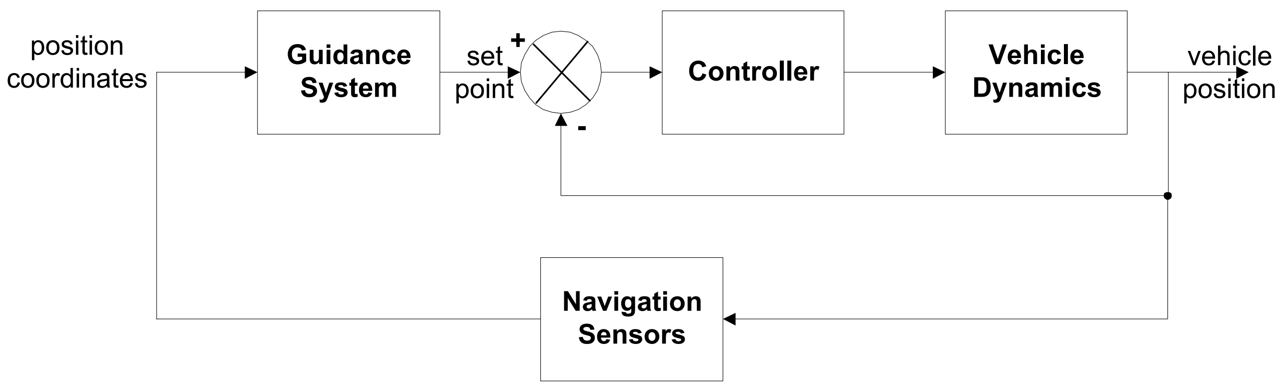

Figure 2. Navigation, Guidance and Control of a Vehicle

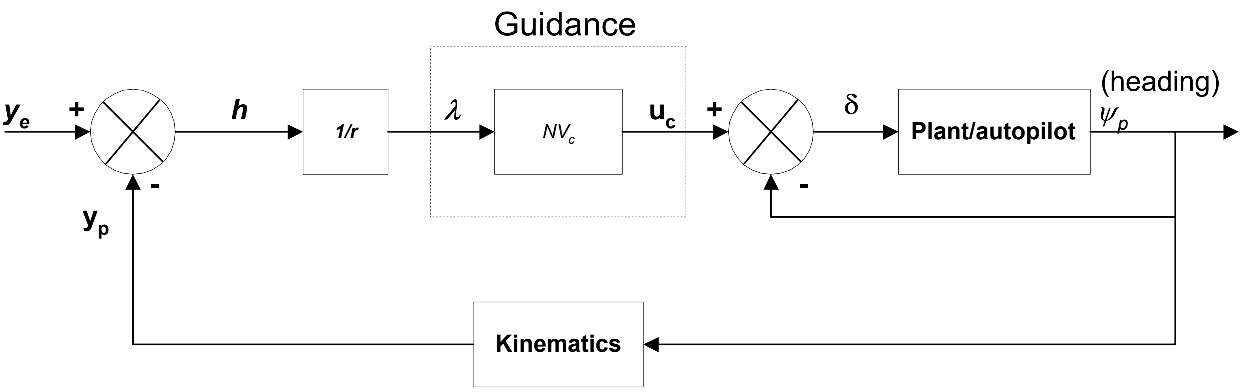

Figure 3. Proportional Navigation Guidance (PNG) Loop

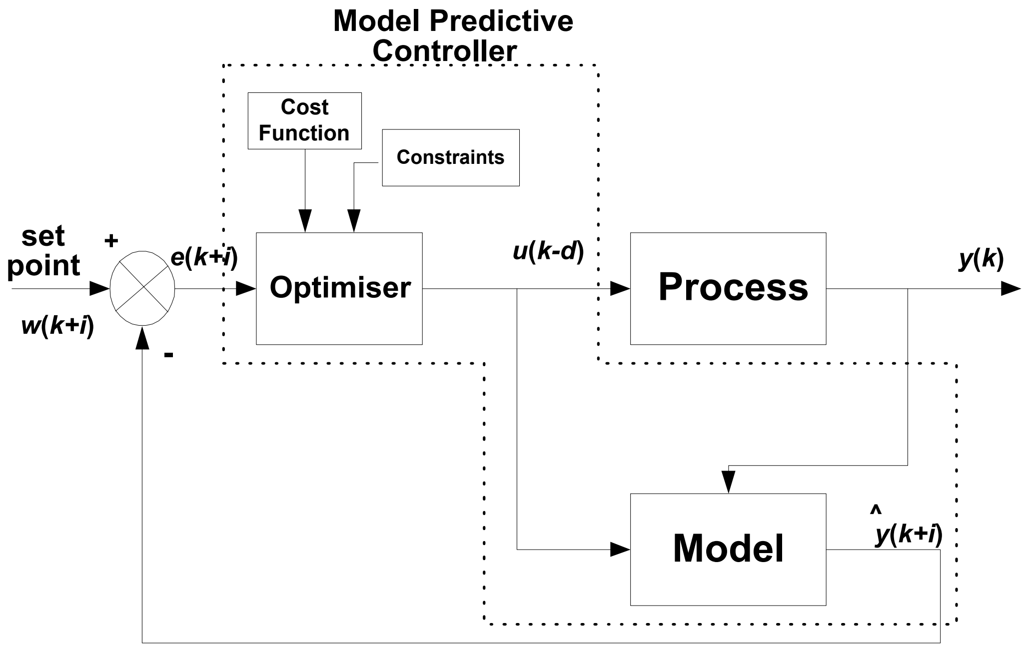

Figure 4. Structure of Model Predictive Control

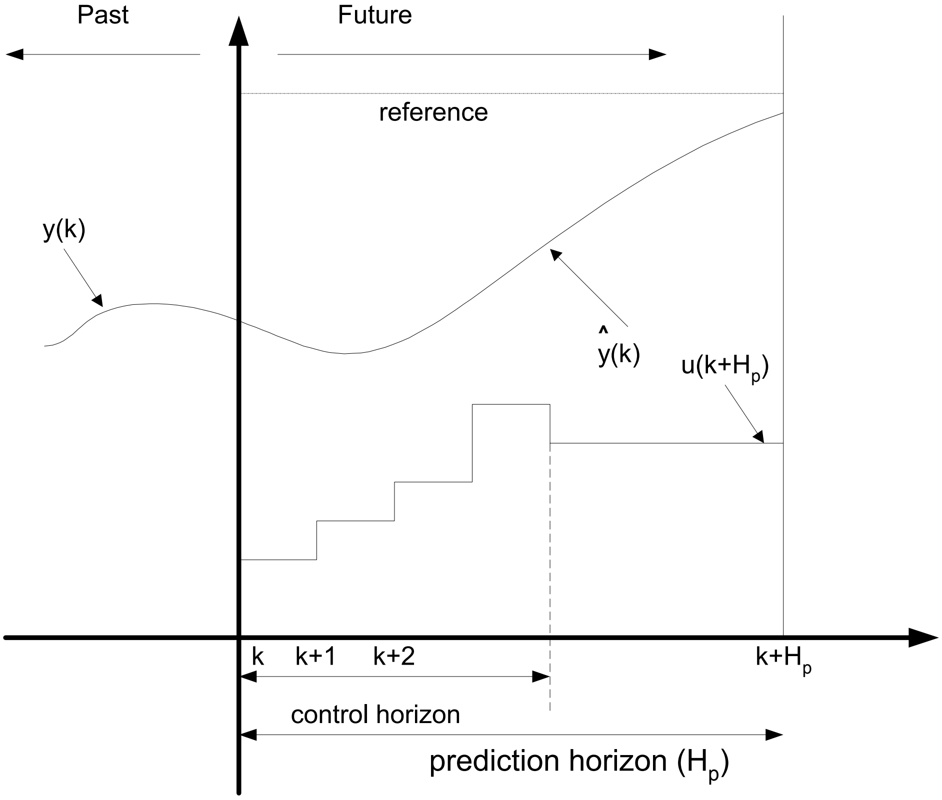

Figure 5. Predicted output and the corresponding optimum input over a horizon H_p, where $u(k)$, optimum input, $\hat{y}(k)$, predicted output, and $y(k)$, process output

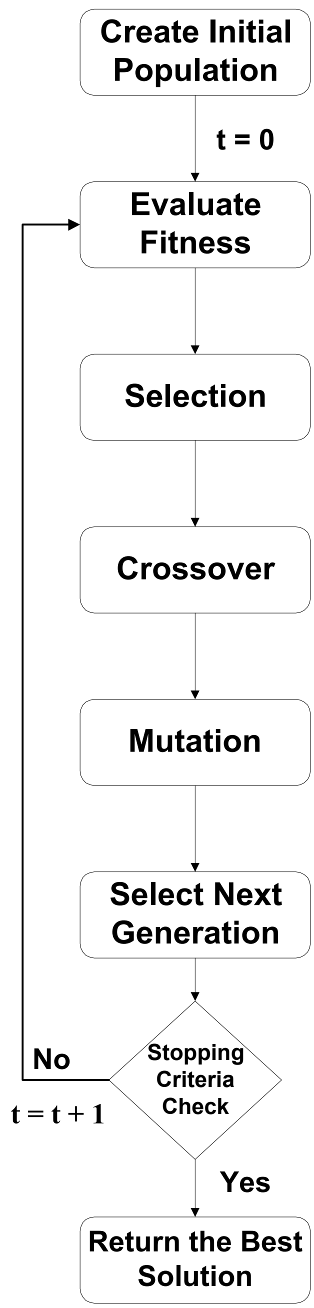

Figure 6. Flowchart of a Simple Genetic Algorithm

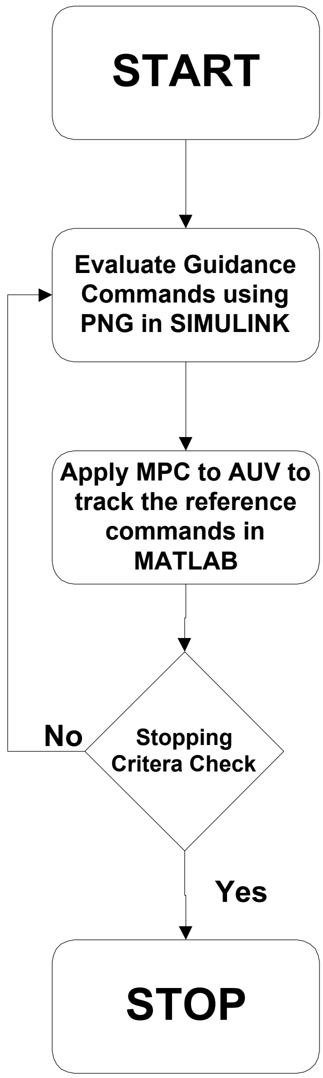

Figure 7. Integration of Guidance and Control Systems in MATLAB/SIMULINK environment

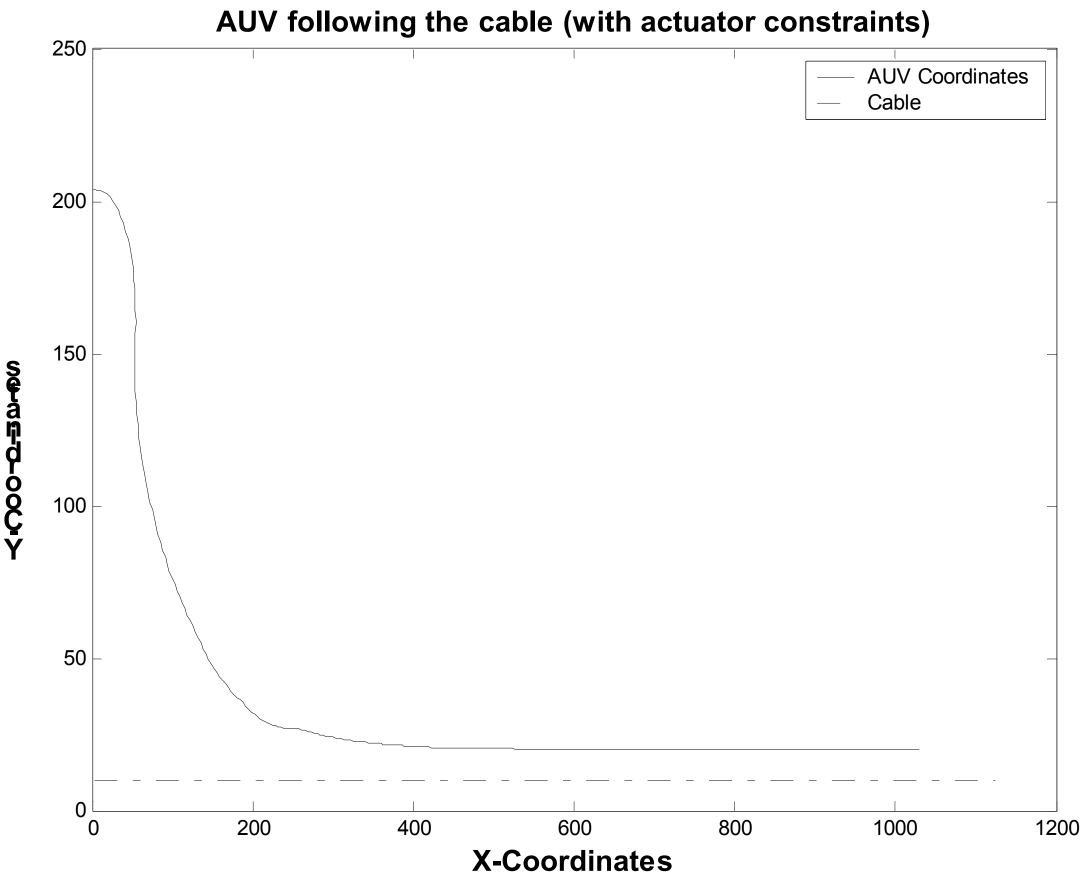

Figure 8. AUV and target position co-ordinates for the constrained case. AUV is tracking the cable at a specified height.

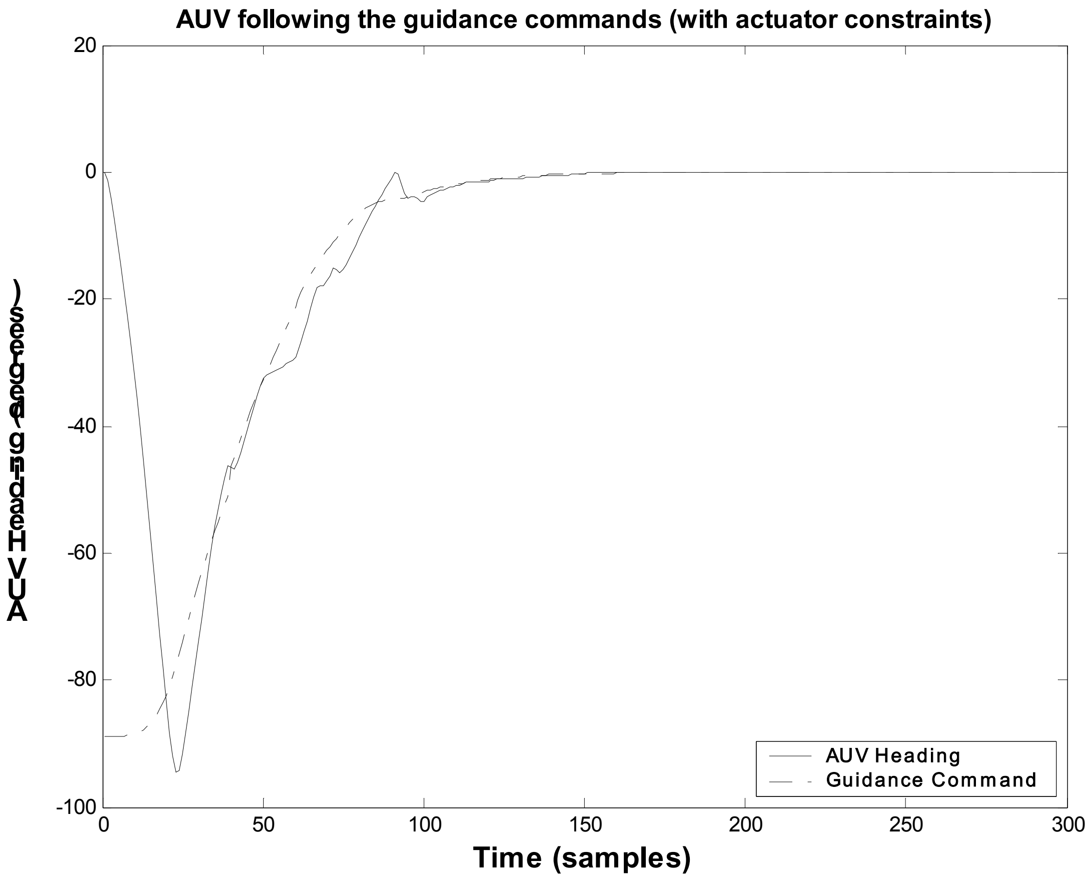

Figure 9. AUV heading controlled by the MPC following closely the guidance commands generated by the PNG

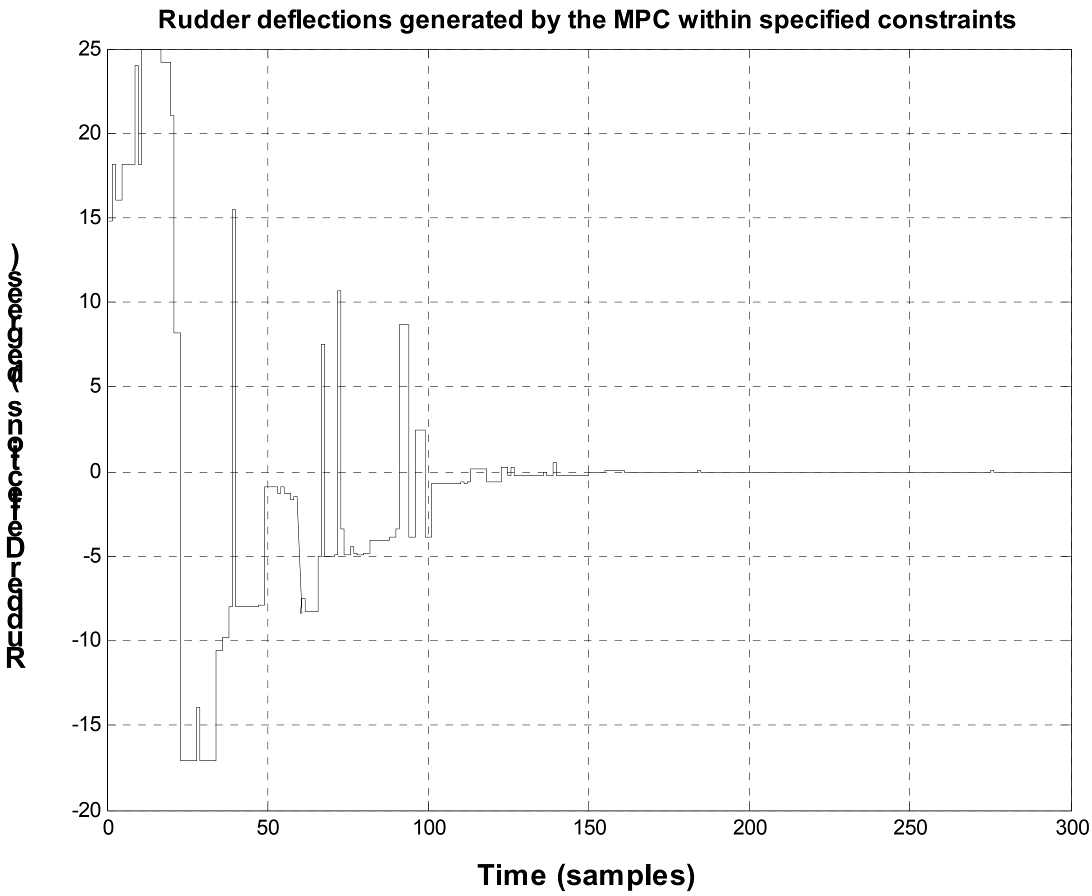

Figure 10. Rudder deflections generated by the controller within specified constraints needed to track the reference trajectory (guidance commands).

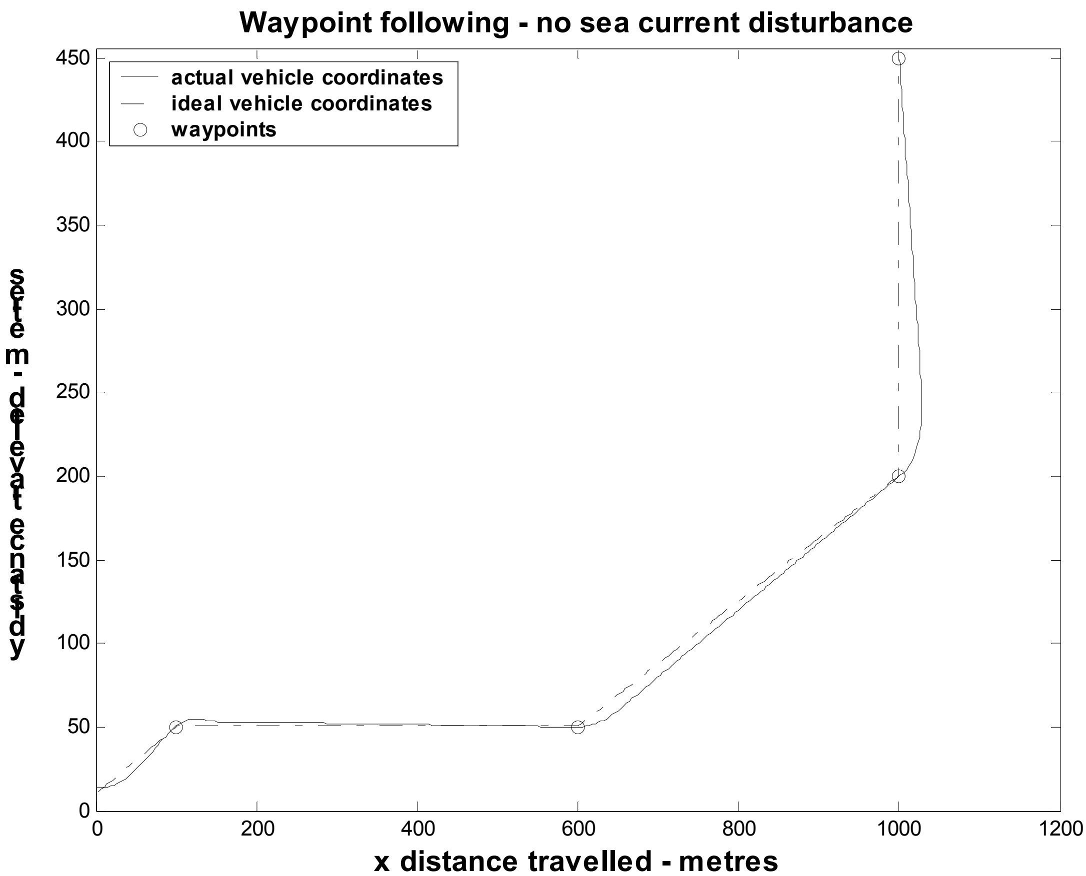

Figure 11. AUV and target position co-ordinates for the constrained case without sea current disturbance. The AUV is closely following the target waypoints

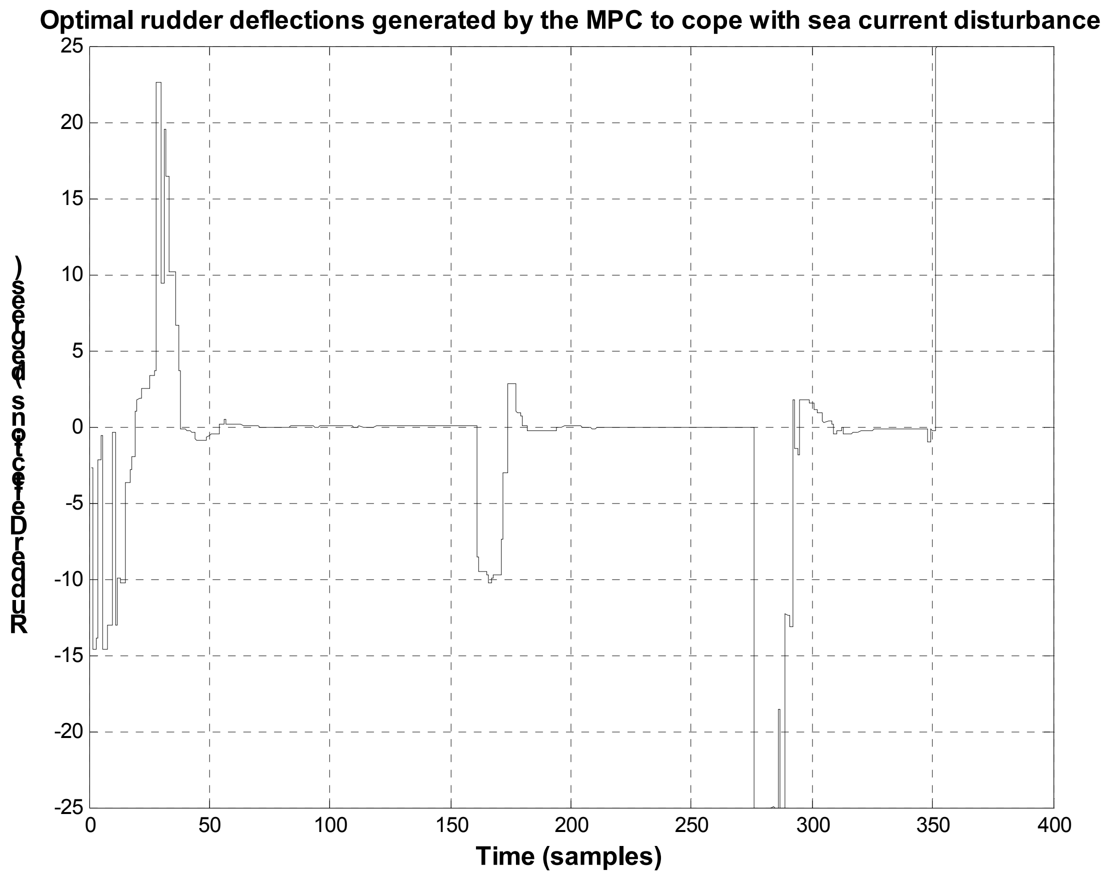

Figure 12. Rudder deflections generated by the controller needed to track the waypoints for the constrained case and without sea current disturbance.

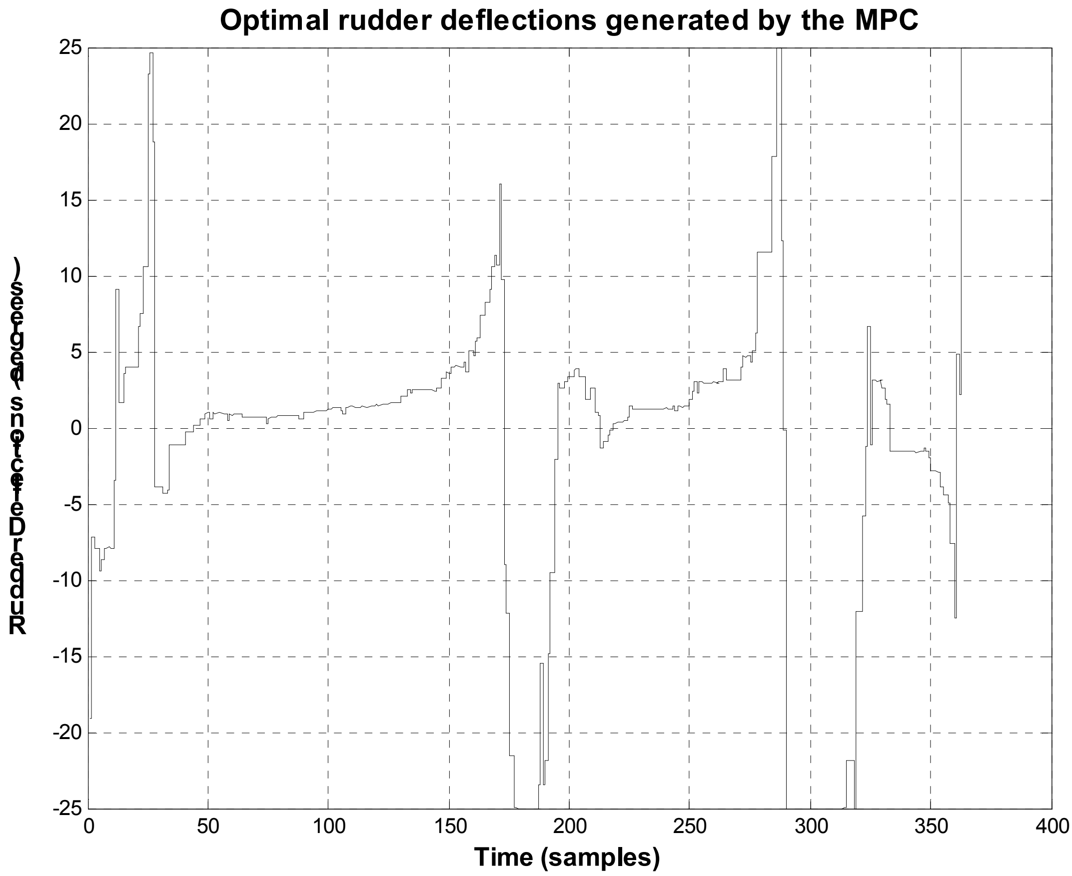

Figure 13. Rudder deflections generated by the controller needed to track the way-points for the constrained case and with sea current disturbance in the +ve y-direction

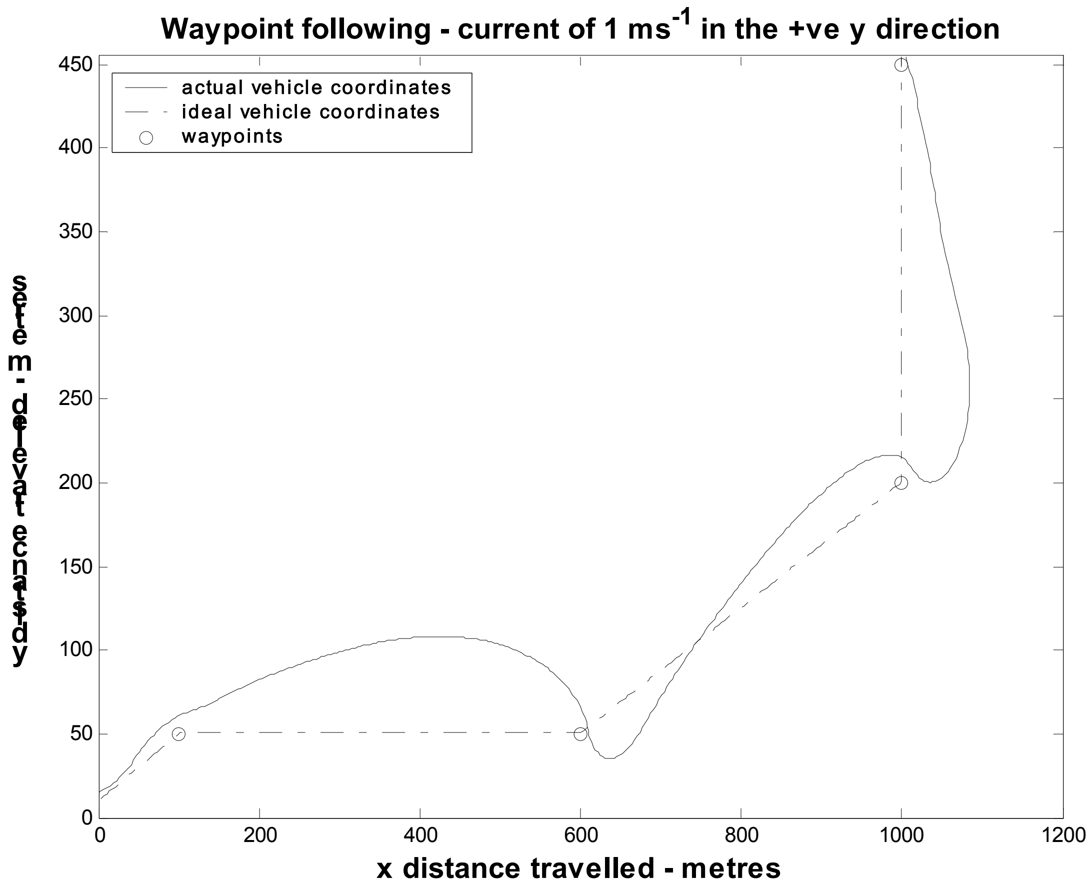

Figure 14. AUV and target position co-ordinates for the constrained case with sea current disturbance in the +ve y-direction. The AUV is closely following the target waypoints

Parameter	***Value***
Prediction Horizon	5
Control Horizon	3
Population Size	100
Number of Generations	10
Mutation Probability	0.05
Crossover Probability	0.1
Q	1
R	0.5

Table 1. Simulation parameters for the GA and MPC