SAI Intelligent Systems Conference 2016
September 21-22, 2016 | London, UK

Path Following of Underactuated Catamaran Surface Vessel (WAM-V) Using Fuzzy Waypoint Guidance Algorithm

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***Abstract*—In this paper, a waypoint tracking algorithm is developed for dealing with catamaran type of vessel called Wave Adaptive Modular Vessel (WAM-V) and this paper further proposes a PID differential thrust control of a manoeuvring WAM-V. This control design greatly simplifies the control design process and easily applied to underactuated twin hull and twin propeller vessels such as WAM-V. The WAM-V is controlled by differential thrust for surge and yaw motion control; is an underactuated vehicle. The fuzzy control rules are constructed based on the human operator's experience. The nomotos model derived from MMG mathematical model is developed to represent the WAM-V dynamics. The model and control algorithm are simulated using MATLAB and results are presented. The suggested fuzzy waypoint guidance control algorithm has shown good performance in terms of accuracy to track the waypoints.**

Keywords—Fuzzy Waypoint Algorithm; Underactuated Control; Differential Thrust Control' WAM-V; Intelligence Guidance and Marine Robotics

I. INTRODUCTION

Guidance and control of an unmanned robotic vessel are always a challenging problem because of unstructured, uncertain and potentially hostile environments. Nowadays, unmanned surface vessels (USV's) are much more equipped with the sensors like LIDAR, Cameras, Sonar, Hydrophone and pinger, communication equipments or other payloads. These are suitable for their routine mission such as environment monitoring, ocean observation, surveillance etc. In order to do these tasks the abilities such as navigation, collision avoidance, automatic berthing and autonomous guidance are very important. Wave Adaptive Modular Vessel (WAM-V) is an entirely new class of vessels and it contains a huge amount of potential in various applications [1].

Path tracking is a very challenging problem in terms of controller design, one should have a robust controller, which takes into account of external disturbances as well as generate accurate heading angle. Path tracking uses positional information, typically obtained from GPS, IMU and vehicle odometry, to control the vessel speed and steering to follow a specified path. For waypoint tracking the WAM-V is equipped with two sensors that is GPS and IMU. There are two propellers installed on port and starboardside of the two hulls. This means that only two controls are available, thus rendering the ship for the task of controlling 3 degrees of freedom (DOF). Waypoint guidance is very useful for terrestrial navigation, air navigation and ocean navigation. Although there are various control techniques are available in the literature but most of them are based on modern control theory. These methods, however, require precise mathematical models of the dynamic behaviour of the system. Fuzzy is an effective alternative approach for system which is difficult to model.

Automatic Navigation System called "SAFES" for harbor manoeuvring is developed for path planning, normal operations and collision avoidance [2]. Navigation path planning algorithm using fuzzy logic is developed for collision avoidance which can be used for waypoint tracking. The fuzzy reasoning fairly represents the behaviours and decision making almost like human operator [3], [4]. In literature, it is found that Dubins paths were used as optimal (shortest) path between two waypoints. These are constructed from two circular arcs and a line. In [5] an algorithm is introduced which selects the shortest Dubin path between two waypoints, but does not deal with waypoint reachability and with the direction of the next waypoints. Model predictive control (MPC) scheme using line of sight (LOS) algorithm for underactuated marine surface vessels is constructed and simulation results are presented [6]. Double loop fuzzy autopilot for waypoint tracking control is studied where the inner loop implements the ship course control and the outer loop implements the tracking control [7]. The fuzzy switched PID controller is designed for ship track keeping in which fuzzy PD controller is used to improve the response, reduce overshoot time and fuzzy PI controller is used to improve the stable accuracy [8]. Performance analysis of PID and fuzzy controller is studied for ship tracking and found that the fuzzy controller performance is better than PID in terms of tracking efficiency and computational time [9]. COLREGS- based collision avoidance algorithm is studied in the presence of moving obstacles [10].

The remainder of this paper is organized as follows: in the next section MMG mathematical model of WAM-V is described. The unique waypoint algorithm reasoned by fuzzy logic followed by PID controller is described in section 3 and section 4. Simulation results are presented and discussed in section 5, followed by a conclusion.

II. Mathematical Model

The MMG- type modular maneuvering model [11], [12] has been found to be suitable for investigation, such a vessel's maneuvering characteristics of two propeller vessel. The MMG (Mathematical Models of Maneuvering Motion Group) was proposed in March 1976 in the second edition of the Japan Towing Tank Committee. The model consists of hull, propeller and rudder characteristics with their interaction effect. For aquatic applications WAM-V movement can be described by 3-degrees of freedom which lies in the plane parallel to the surface of the water, namely surge, sway and yaw. WAM-V is equipped with springs, shock absorbers, and ball joints, giving enough agility to the vessel and damping stresses to the structure and payload as shown in Fig.1. The system dynamics of WAM-V can be described using equation (1), (2) and (3). Equation (4) and (5) describe the force and moment caused by the propeller. The subscript (P) and (S) are defined as the port and starboard propeller.

$$m(\dot{u} - vr) = X_{\dot{u}}\dot{u} + X_{vv}v^2 + X_u(U) + Xp \tag{1}$$

$$m(\dot{v} + ur) = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + (Y_r + X_{\dot{u}}u)r + Y_{vvv}v^3 \tag{2}$$

$$I_{zz} \cdot \dot{r} = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_v v + N_r r + N_{vvv}v^3 + Np \tag{3}$$

$$X_P = \left(1 - t_P\right)\left(T_{(S)} + T_{(P)}\right) \tag{4}$$

$$N_P = \left(1 + d_{NP}\right)\left(T_{(S)} - T_{(P)}\right)y_P \tag{5}$$

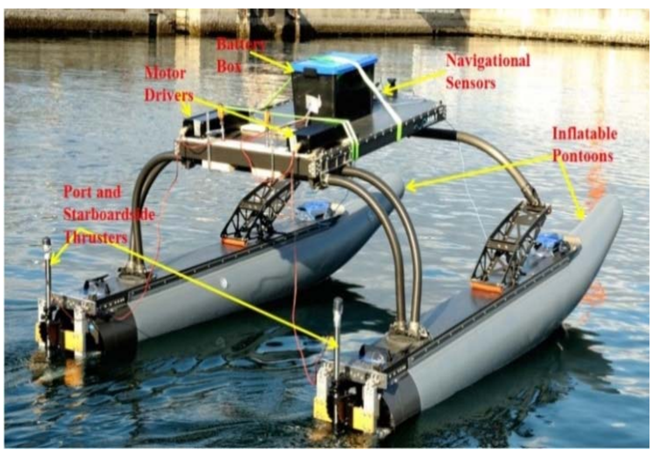

Fig. 1. WAM-V Catamaran robot

Where u is heading, speed, v is side slipping speed and r is the yawing angular velocity. t_P is the thrust deduction factor generated by the propeller in x-direction. The value taken here is 25%. d_{NP} is the propeller influence factor to the Y and N directions. I_{zz} is the rotational inertia. y_P is the center distance between the two hulls. The main physical dimension of WAM-V used in this study is shown in Table.I.

When the WAM-V motion parameters u, v and r is very small, the higher order can be omitted and the derivative of the forces and moments respect to a given variable indicates the change in the fluid forces and moments when the given variables are changed slightly from the equilibrium value, with all other variables remaining at their equilibrium value. The ship resistance force $(X_u(U))$ and hydrodynamic derivatives are calculated with the help of captive model test of WAM-V [13]. WAM-V's movement response equation controlled by the traditional rudder and can be regarded as the extension of the famous 2nd order K-T equation proposed by Nomoto [14] on the ship which integrates the propeller and the rudder as a whole is derived [13] from MMG model.

TABLE I. Features of WAM-V

Parameters	***Measurements***
Hull Length	3.91 m.
Hull Diameter	4.26 m.
Overall Vehicle Height	1.27 m.
Overall Vehicle Width	2.44 m.
Payload	136 Kg. (Maximum)
Full Load Displacement	255 Kg.
Draft	0.165 m.
Primary Sensors	GPS, Camera, LRF, INS, Hydrophone- Pinger

III. Waypoint Guidance Algorithm

A fuzzy guided waypoint algorithm and fuzzy reasoning which includes fuzzy rules are defined as follows.

A. Algorithm Description

A waypoint guidance algorithm based on fuzzy logic analyzes analog input values in terms of logical variables that takes on continuous values between 0 and 1, in contrast to classical or discrete logic. The waypoint heading guidance algorithm is realized by fuzzy control methods used for SAFES (system for safety navigation) [2] and [3]. The fuzzy logic waypoint-heading commands targeting two waypoints at one time is generated. However, near the turning point, the fuzzy reasoning system will decide the appropriate course define by the next two WP's as follows equation (6)

$$\Psi_1 = \Psi_1 + (\Psi_2 - \Psi_1)^* CDH \tag{6}$$

Where
Ψ_1 : order of course
Ψ_1 : course of the shortest path to the next WP
Ψ_2: course of the shortest path to the second next WP

In this algorithm, to judge the nearness of the waypoint, TCPA (time to closest point of approach) and DCPA (distance of the closest point of approach) are used for fuzzy reasoning. Fig 2 (a) shows the course changing command near a course changing point (WP) and Fig 2 (b) shows the bearing relationship between the ship and waypoint.

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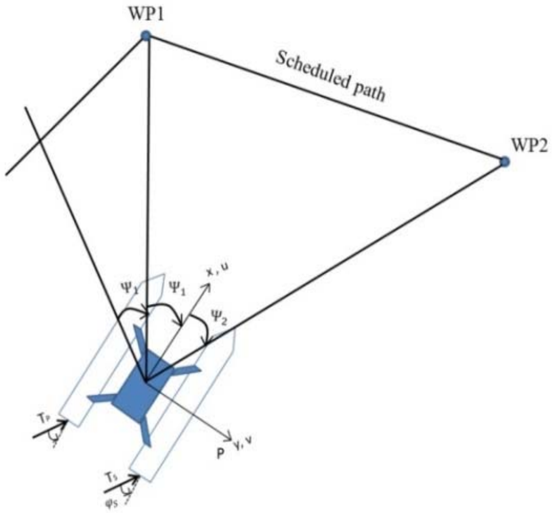
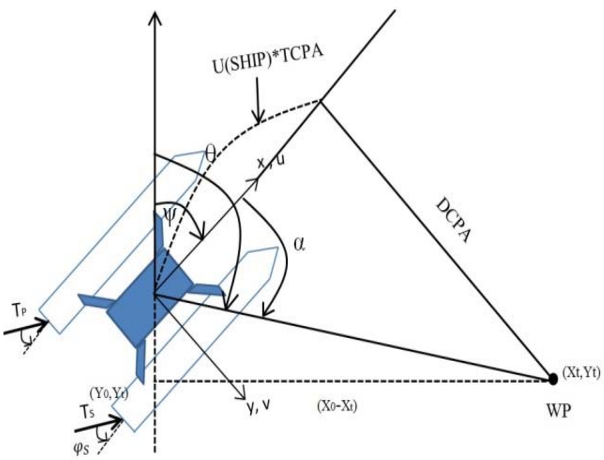


(a)



(b)

Fig. 2. (a) Course command near a course changing point (b) Bearing relationship between ship and waypoint

If DCPA is very short and TCPA is also very short, then CDH is very big. It means if the ship is far from second waypoint then the command course will consider only for the next waypoint. However, with the increase of nearness the command course will modify by considering both next and second next waypoint. The algorithm is listed step by step below.

1) Initialize: Waypoints (WP) Wi= (Xi, Yi), Wi+1=(Xi+1, Yi+1) & Current Vehicle Position P= (Xt, Yt), Ψ

2) Distance between the ship and nearest way point (D): $D = \sqrt{(X0 - Xt)^2 + (Y0 -}$ (b)

3) Calculate the Bearir (a) f WayPoint from the ship $(\theta) = \theta = atan2\frac{(Yt-Y0)}{(Xt-X0)}$

4) Calculate: $\alpha = \theta - \Psi$

5) Calculate TCPA (Time to closest point of approach) and DCPA (Distance of the closest point of approach)

$$DCPA = D|\sin\alpha|$$

$$TCPA = \frac{D\cos\alpha}{U_{ship}}$$

6) Scale effect: The TCPA and DCPA are used in non-dimensionalised form

$$DCPA' = \frac{DCPA}{L}$$

$$TCPA' = \frac{TCPA}{L}$$

7) Switching of Waypoint: When TCPA<0 then switch the next waypoint

8) Course: $\Psi_1 = \Psi_1 + (\Psi_2 - \Psi_1)^* CDH$

CDH: Reference degree to the second WP (0≤CDH≤1), calculated by fuzzy. The nearness of the waypoint is judged using Fuzzy logic by calculation TCPA, DCPA and CDH. The waypoints are stored in a database and are used to generate the desired trajectory to follow.

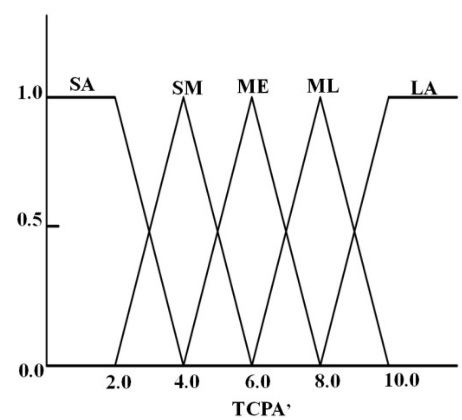
B. Fuzzy Reasoning

Fuzzy control provides a systematic methodology for representing, manipulating and implementing a human heuristic knowledge about how to control the system. Define TCPA' and DCPA' as the inputs to the fuzzy controller and CDH is the output. The linguistic variables are defined as:

TCPA' = {SA, SM, ME, ML, LA}
DCPA'= {SA, SM, ME, ML, LA}
CDH= {SA, SM, ME, ML, LA}
Where SA= SMALL, SM= SMALL MEDIUM,
ME=MEDIUM, ML=MEDIUM LARGE, LA=LARGE

The Minimum-maximum method is utilized to represent the premise and implication, and COG for for defuzzification. The complete fuzzy system involves some 25 fuzzy rules with 5 linguistic variables. Experience of human operators is explicitly integrated into the control rules of the fuzzy logic.

The membership function of TCPA', DCPA' and CDH are given in fig. (3) and the control rules to reason CDH is shown in table (II). The fuzzy control surface is shown in fig. (4).



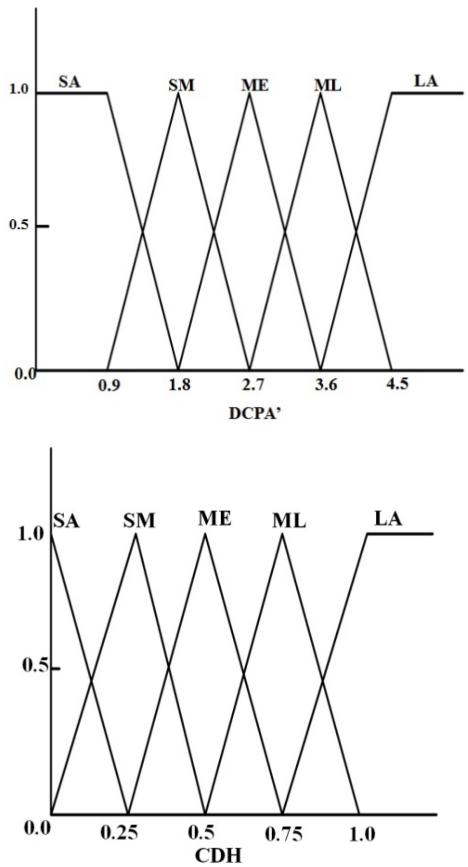


Fig. 3. Membership function for course changing algorithm

TABLE II. CONTROL RULES

		TCPA'				
		SA	SM	ME	ML	LA
DCPA'	SA	LA	ML	ME	SM	SA
	SM	ML	ME	SM	SA	SA
	ME	ME	SM	SA	SA	SA
	ML	SM	SA	SA	SA	SA
	LA	SA	SA	SA	SA	SA

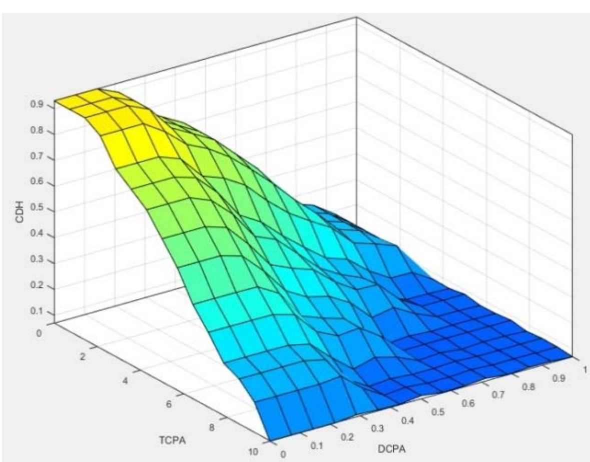


Fig. 4. Fuzzy Control Surfaces

IV. CONTROL DESIGN

In this research a PID feedback controller is used to correct the course generated by the fuzzy reasoned waypoint guidance algorithm. When WAM-V is sailing at given speed and a given heading, turning of the propellers an cause the effect of a rudder. The difference between a traditional movement response equation is that the manoeuvre control variable is generated by the force caused by the thrust force difference between port and starboard not the rudder. Guidance and control system layout is shown in Fig. (5).

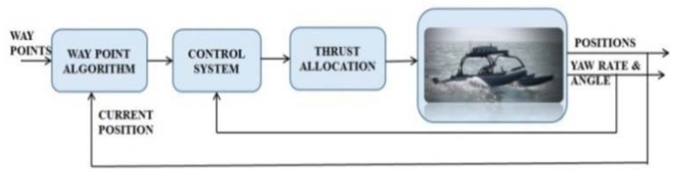


Fig. 5. Guidance and Control System Layout

When the revolution speed of the two propellers on the port and starboard are different than three conditions can be generated

$$\left(T_p \sim T_s\right) = 0 \text{ Straight Line}$$

$$\left(T_p \sim T_s\right) > 0 \text{ Clockwise Turning}$$

$$\left(T_p \sim T_s\right) < 0 \text{ Anticlockwise Turning}$$

We performed free running open loop trials to measure the turning rate at different thrust. These tests involved applying commands to the thrusters in order to achieve desired heading. The thrust allocation to port and starboard side propeller (τcom) is generated using a lookup table. The simulation is performed at constant vessel speed. The equation (7) represents the differential command that needs to be generated for thrust allocation to the port and starboard side.

$$\tau_{order} = K_p\left(\psi_d - \psi\right) - K_d\left(r_d - r\right) + K_i\int_0^t \left(\psi_d - \psi\right) d\tilde{\psi} \tag{7}$$

Where a proportional gain (K_p), Integral gain (K_i) and derivative gain (K_d) are the regulator design parameters. These parameters are tuned in order to avoid the overshoot and steady state errors.

The control system provides the necessary feedback signal to track the desired yaw angle. This system processes information to infer the state of the WAM-V plant and to generate an appropriate command for the actuators so as to reduce the reference heading and actual heading. This differential command added with the thrust allocation command generated using looking table is combined and allocated to both the thrusters as given by eqn. (8) and eqn. (9) [15].

$$T_{port} = \tau_{com} + \tau_{order} \tag{8}$$
$$T_{starboard} = \tau_{com} - \tau_{order} \tag{9}$$

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V. SIMULATION RESULTS AND DISUSSION

To verify the effectiveness of the fuzzy waypoint guidance algorithm, the feedback PID control system is simulated with the help of Matlab/Simulink. The waypoint coordinates are input as Earth-fixed coordinate system.

Matlab simulation results of both given waypoints and obtained from PID trajectory are plotted in Fig (6). Red color indicates the reference trajectory and blue colour trajectory indicates the obtained PID trajectory. The waypoints are given in latitude and longitude of earth fixed coordinate system as WP1= (10, 5), WP2= (35, 20) and WP3= (50, 16).

Here, fuzzy reasons the desired heading and PID controller decide the differential thrust force. The resultant trajectory seems quiet satisfactory. The Heading graph is plotted in fig. (7) In which pink colour shows the reference heading and blue colour shows the heading obtained from PID, matching quite satisfactory and showing that the fuzzy guided waypoint algorithm with PID autopilot has good property of course keeping and changing.

The TCPA' and DCPA' graph is shown in fig (8) and fig (9). The TCPA' graph shows that when the WAM-V is reaching to the waypoints it goes to zero. The DCPA' graph shows as the vessel is near the waypoint it goes to zero.

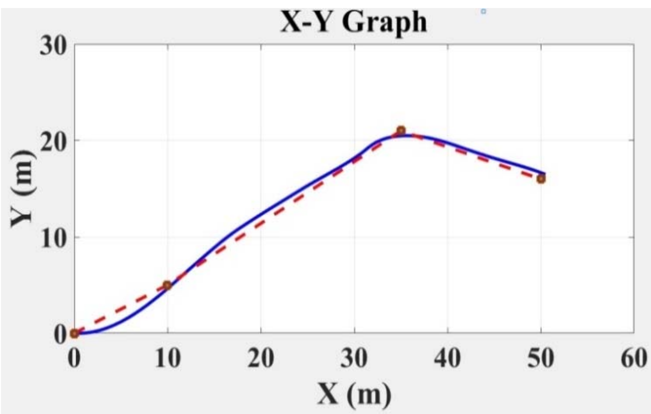

Fig. 6. X-Y plot of Waypoint

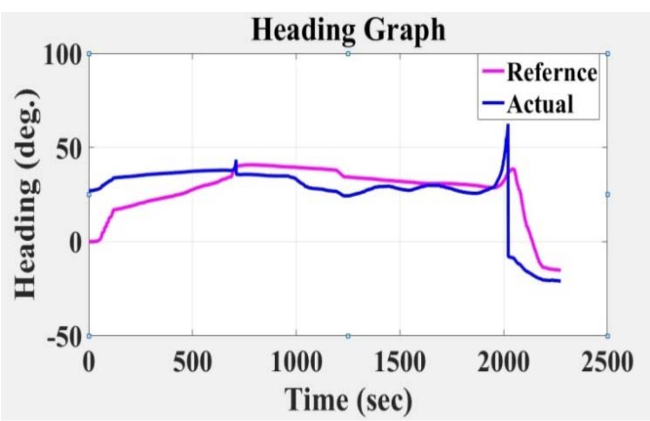

Fig. 7. References and Actual Heading Graph

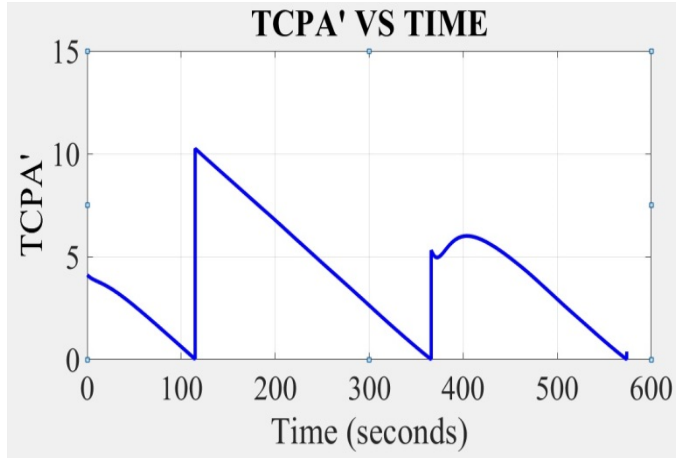

Fig. 8. TCPA' graph Vs Time

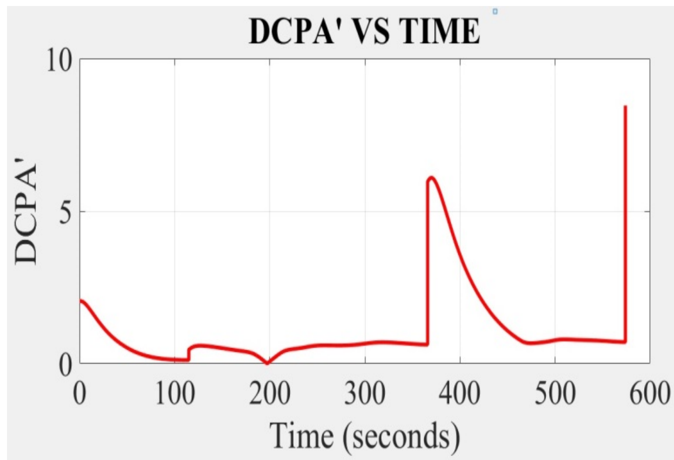

Fig. 9. DCPA' graph Vs Time

VI. CONCLUSION AND FUTURE WORK

This paper describes a robust waypoint algorithm which is reasoned by fuzzy and the algorithm is implemented in Wam-V surface vessel followed by PID controller. The waypoint algorithm is comparatively simple, robust and can be implemented in any kind of system. The mathematical model (MMG) for ship manoeuvrability is derived for catamaran vessel WAM-V. The simulation results of waypoint tracking show that the fuzzy reasoned waypoint algorithm followed by a PID feedback controller gives satisfactory performance. There are many applications possible using this algorithm of tracking. Control design for high speed autonomous vehicles such as WAM-V is challenging due to uncertainty in dynamic models, significant sea disturbances, underactuated dynamics and overestimated or underestimated of hydrodynamic parameters. Future work includes more robust control techniques will be applied to improve the autonomous behaviour of the system. We believe that tremendous opportunity exists for modular and customized WAM- V.

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