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Path Planning Combined with Fuzzy Control for Autonomous Ships

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***Abstract*—This paper is linked to a research proposing autonomous ships for risky humanitarian operations, like sea demining or poisonous spill recovery on the sea . This mission is based upon placing waypoints and the autonomous ships are under a Fuzzy control. Since ships have limited turning radii, a specific path planning strategy is developed, so the ship trajectory turns around waypoints at a suitable distance. The system is being tested with scaled ships.**

***Index Terms*—Autonomous ships, autonomous vehicle, sea demining, fuzzy control, path planning, waypoints.**

I. Introduction

The research target is to obtain an on-board control system for autonomous ships in charge of risky humanitarian operations, like demining areas or poisonous spills floating recovery [1].

The primary design focus is to develop a combined fuzzy control [2] with a special path planning based upon linking circumferences and tangent lines . These circumferences are presented surrounding waypoints, creating a path to follow [3]. The on-board control of the autonomous ships is based on a digital processing core, developing a complete hardware in this research, interfacing with propeller, rudder, self- localization sensors, compass, and water-speed meter.

The boat has two problems: one is velocity and heading control [4], against the influence of wind and streams; and the other problem is to have limited turning radii. The fuzzy controller makes possible to turn with a suitable velocity taking into account the radius of the circumference. And the input/output variables are chosen and normalized for being easy to tune the controller, even for following complex paths.

In order to have experimental confirmation, a scaled ship has been built and equipped with the on-board control system, which could be employed on real scale ships. A ship dynamics model has been established, using experimental data for validate it. Moreover, a simulation environment has been developed used for testing the new path planning and control system.

This paper will start defining the waypoint and its circumference associated, leading to show how the navigation algorithm works, including the development of the fuzzy controller used on board. Finally the paper shows successful results, validating the simulation environment with the real data acquired, aiming the researching focus to a real operational scenarios like sea demining.

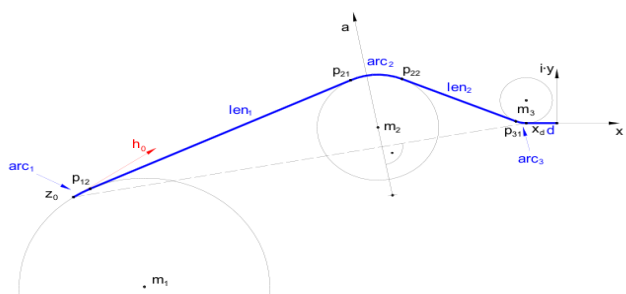

Fig. 1. Path determination.

II. Waypoint Navigation

A. Path definition

A confined region of sea to be explored can be characterized by a succession of lines and arcs delimiting its perimeter. This series of lines (len_n) and arcs (arc_n) are defined by circumferences and the tangents between them ($p_{n,2}$ to $p_{n+1,1}$), as it is shown in Figure 1. The idea is to define the circumference's centre as a waypoint. Creating with only storing a series of waypoints and their circumferences, a path to follow.

B. Navigation

We distinguish between two states with the variable HAC (Heading Alignment Circumference), depending on if we are tracking a line (HAC $= 0$) or and arc (HAC $= 1$). As it is shown at Figure 2, during the approaching len_1 (HAC $= 0$), the vehicle is reaching the tangent point to the actual circumference to acquire its arc_2. The control variable during this process is the relative heading reference $\chi_{r,ref}$.

The vehicle switches to HAC $= 1$ with the transition condition of

$$\frac{|\vec{x}_{tan}|}{R_n} < 1 \tag{1}$$

, and it still following the arc_2 while it is looking to the tangent point of the next circumference. Once the slope of the next tangent is not cutting the actual circumference, the vehicle switches to HAC $= 0$, and the algorithm starts again.

The navigation flow chart is shown at Figure 3

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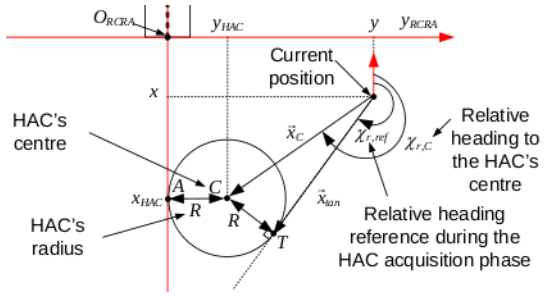

Fig. 2. HAC acquisition

III. Fuzzy Controller design

A. Requirements

The main requirement is to control the vehicle's speed under $2.57m/s$, avoiding the sliding of the vehicle, that means that the vehicle's *true heading* and the vehicle's *heading* shall be almost the same. The secondary requirements are to follow the path plan as close as possible, and to cover the total path as fast as possible. That means that we have to control the velocity as high as possible, without going too fast during the arcs.

B. Control Variables

The natural way, according to the requirements, is selecting the input control variables as the vehicle's velocity respecting the water and the heading reference angle $\chi_{r,ref}$. For controlling the amount of velocity, to choose the distance to the tangent point $|\vec{x}_{tan}|$ and the waypoint's radius R as well.

The output variables of the vehicle are the thrust Force F and the deflection of the surface control or rudder α. Both are within a physical constraint range, thrust is limited to the motor's maximum force of 9 Newtons, and α to the maximum deflection range within $[-\frac{\pi}{4}, \frac{\pi}{4}]$.

C. Membership functions

The four input and the two output variables are classified according to Figures 4 and 5. Where the ranges of the variables have been normalized according the next criteria:

- Velocity: To meet the main requirement, this variable is normalized by $2m/s$, consider to this amount as *fast*.
- Heading reference $\chi_{r,ref}$: This variable is obviously normalized by pi.
- Waypoint radius R: This variable is normalized by $10m$, considering this amount as *high* radius.
- Distance to the target point $|\vec{x}_{tan}|$ D: This variable is normalized by $5m$, considering this amount as *far* distance.
- Thrust force F: This variable is normalized by $9N$ as it is the maximum force given by the motor.
- Rudder deflection angle α: This variable is normalized by $\pi/4$ as is the maximum physical deflection allowed.

D. Fuzzy Controller rules

The rules have to allow the covering of the perimeter in minimum time. Thus the vehicle has to navigate at the maximum velocity allowed, controlled by the thrust force of the vehicle's motor. The next requirements have to be achieved:

1) Maximum velocity allowed: $2.57m/s$.
2) While HAC $= 1$ the velocity has to be adapted to the curve's radius.
3) Minimum velocity of $0.6m/s$ is needed to allow vehicle turns.

The next rules achieve these requirements as follows:

1) IF D is *low* AND R is *low* AND *velocity* is NOT *slow* THEN F is *midlow*.
2) IF D is *low* AND R is *high*
   - AND *velocity* is *slow* THEN F is *midfull*.
   - AND *velocity* is *mid* THEN F is *midlow*.

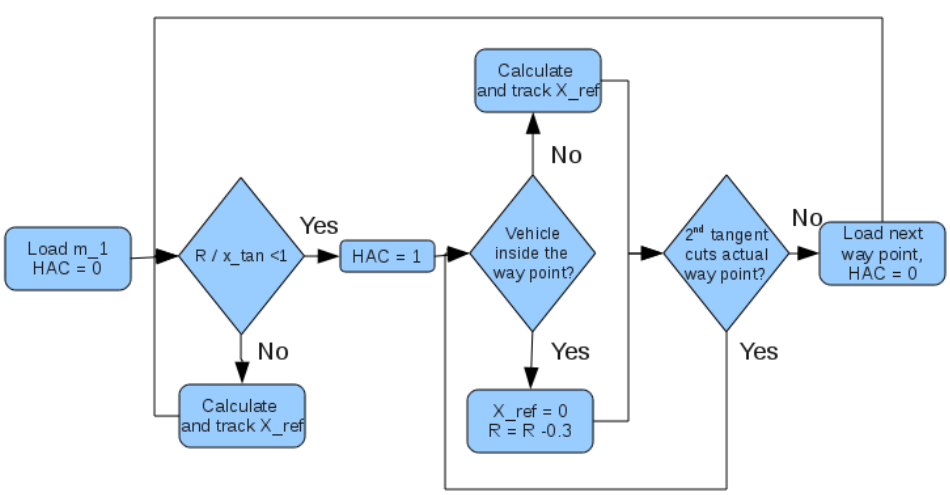

Fig. 3. Path following algorithm.

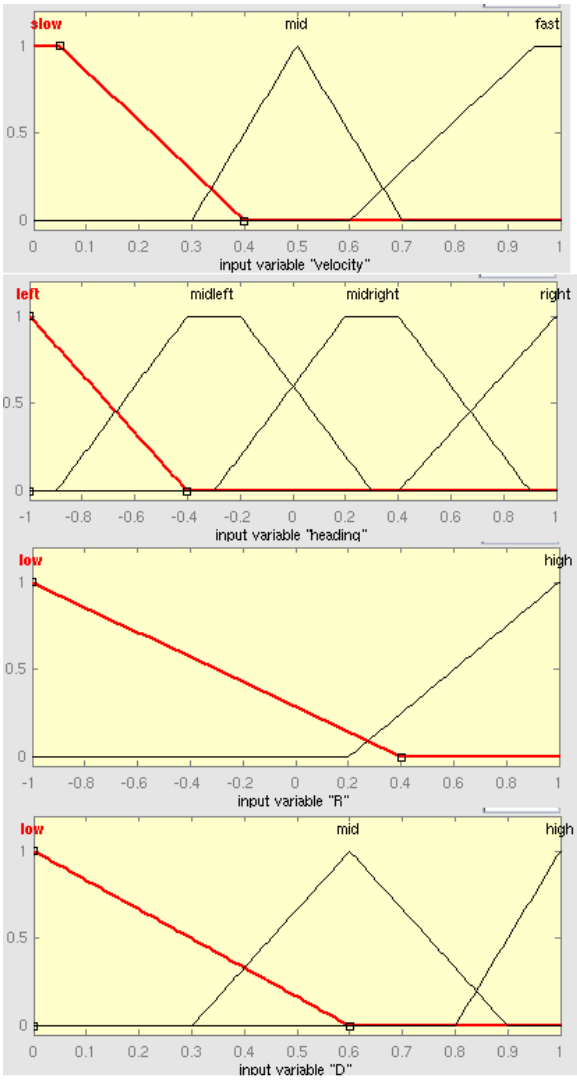

Fig. 4. Membership functions of input variables.

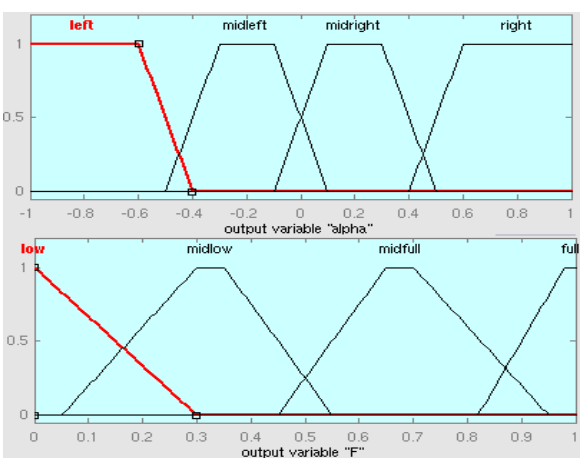

Fig. 5. Membership functions of output variables.

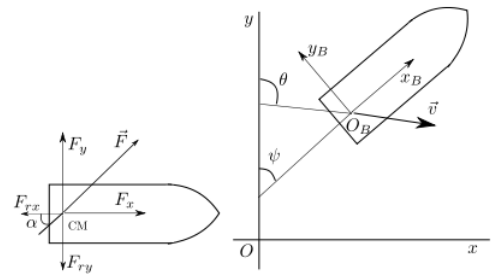

Fig. 6. System's variables.

- AND *velocity* is *fast* THEN F is *low*.

3) IF D is *mid*
   - AND R IS *low* AND *velocity* is NOT *fast* THEN F is *midlow*.
   - AND R IS *high* AND *velocity* is NOT *slow* THEN F is *midfull*.
4) IF D is *high*
   - AND *velocity* is NOT *fast* THEN F is *full*.
   - AND *velocity* is *fast* THEN F is *midfull*.

Concerning the turns, the rules are more straightforward, keeping in mind that when the vehicle has slow velocity, it needs more rudder deflection to achieve a successful quick turn. The next rules achieve this requirements as follows:

1) IF *heading* is *left* THEN α is *left*.
2) IF *heading* is *right* THEN α is *right*.
3) IF *heading* is *midleft*
   - AND *velocity* is NOT *fast* THEN α is *left* ELSE is *midleft*.
   - AND *velocity* is NOT *fast* THEN α is *right* ELSE is *midright*.

Finally, a centroidal defuzzification is used to find the crisp output.

IV. Simulation Environment

A Matlab/Simulink simulation environment has been created implementing the vehicle's physical model, the path planning algorithm and the vehicle's fuzzy controller, as it is shown in Figure 7.

The nonlinear model consists of 3 Degrees of Freedom (DoF) equations of motion. These are

$$\dot{u} = \left(F\cos\alpha\sin\theta - \mu_t u - \mu_d u^3\right)\frac{1}{m} \tag{2}$$

$$\dot{v} = \left(F\cos\alpha\cos\theta - \mu_t v - \mu_d u^3\right)\frac{1}{m} \tag{3}$$

$$\dot{\omega} = \left(F d_{cm}\sin\alpha - \mu_r\omega\right)\frac{1}{I} \tag{4}$$

Where u and v are the water-speed in an inertial frame, α is the rudder deflection, θ the true heading, μ_t and μ_d are dynamic friction coefficients, m and I and the mass and the

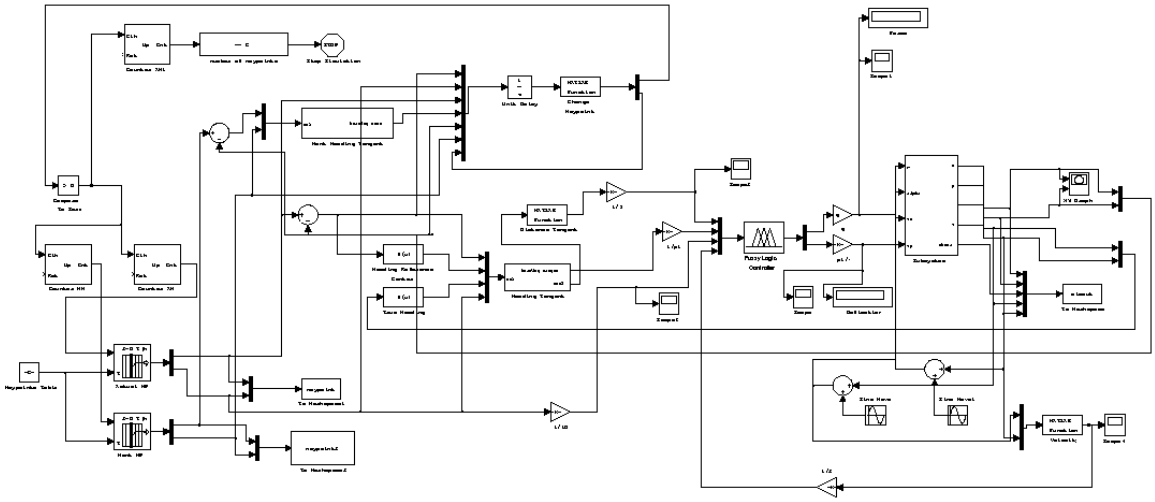

Fig. 7. Simulation environment made in Simulink.

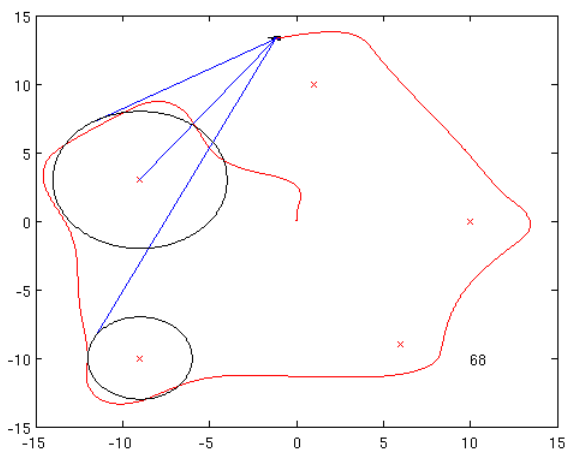

Fig. 8. Path following simulation under heavy streams.

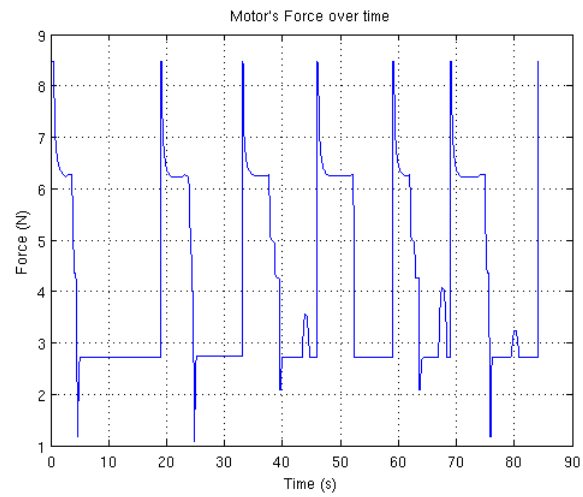

Fig. 9. Force over time under heavy streams.

inertia moment of the ship, ω the ship's angular velocity, F the motor force, and d_{cm} the distance between the motor and the Ship's Centre of gravity (CoG).

All the variables are represented in Figure 6.

A scenario with disturbances (heavy streams of water over the XY axis) is simulated with several waypoints and circumferences with different radii, covering a random confined region. This setup is shown in Figure 8 stating the total navigation time in seconds. The path followed is not so smooth because the disturbances, even introducing the vehicle inside the circumferences. But the navigation algorithm shows to be robust with changing to the next waypoint correctly in every moment. Also the fuzzy controller recovers the vehicle to the right trajectory within an acceptable error, showing the robustness of the controller under the presence of heavy disturbances.

Figure 9 shows the force done by the vehicle's motor. Large spikes are because the *high* distance to the target point and the *no-fast* velocity, and the smaller spikes are because the needed of turn if the velocity is *low*.

Figure 10 shows the rudder deflection with a little overdamping. Spikes are due to the waypoint change, and fast descents of deflection means that the vehicle is with HAC = 1. A bigger deflection is needed for a turn as the vehicle's velocity is *midslow / slow*. While in the classic control theory this is an issue, it is easy to implement it in a fuzzy controller with the last two rules proposed. The rudder never rises to its physical maximum as well, staying within a relatively small range of 50% over the maximum range.

V. Experiment Platform

The Autonomous Marine Surface Vehicle (AMSV) is a zodiac made of fiberglass-epoxy, having a length of 1m, a beam of 0.3 m, and displacing 3.0Kg (Fig. 11). The boat's

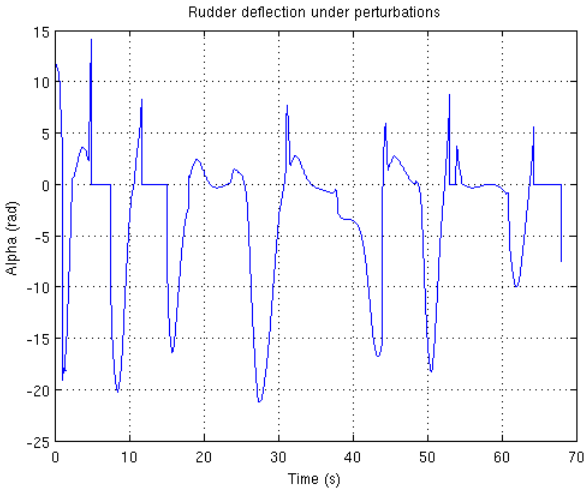

Fig. 10. Rudder deflection over time under pertubations.

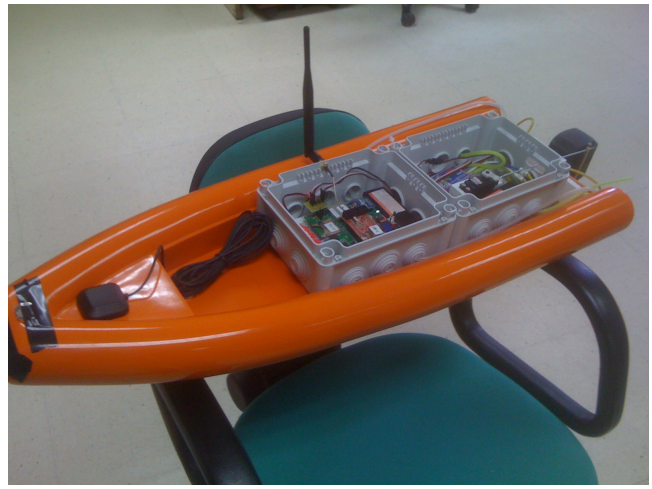

Fig. 11. AMSV geared.

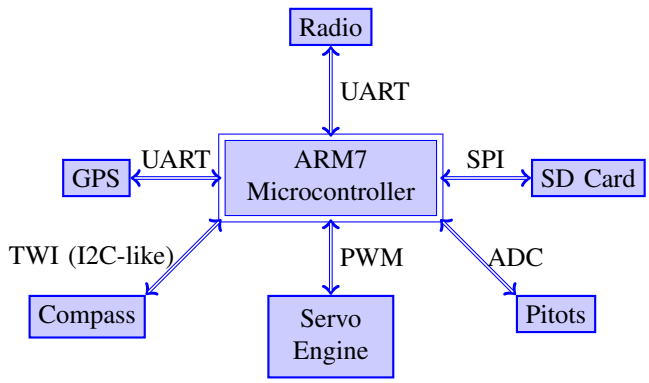

Fig. 12. Hardware description.

cruising speed is approximately 2.3m/s with an endurance of nearly 6 hours, affording multiple long missions until battery recharge.

The AMSV is geared with actuators for heading and speed control. The most conventional solution is by using a propeller and a rudder, having a Pulse Width Modulation (PWM) signal for heading and another one for speed control.

In order to control and monitor the ship, the following sensors and components are used:

- ARM7 Microcontroller.
- Compass to measure heading @ 10Hz.
- Pressure sensor for water-speed measurements @ 10Hz.
- GPS receiver for global positioning @ 1Hz.
- Radio link for external control and monitor data.
- All data read from the sensors is saved in an SD card using the FAT32 file system.
- A DC motor and a standard servo. These are controlled using PWM signals.

All the on board software has been developed in C. This is summarized in Figure 12 and shown in Figure 11.

VI. Experiments

The next real experiment was done to validate the behaviour simulation. The experiment, in Figure 13 has taken place at $40.385231°N$, $3.683786°W$ coordinates, where 6 waypoints with different radii describes a *pseudo eight* path shown in Figure 14. The AMSV's behaviour was same as in simulations, following the tangent to the actual circumference and watching the next circumference to determine when to change it. The experiment day was almost quiet, with the presence of soft wind, and a low current due to a central fountain. Under this series of soft disturbances, the algorithm navigation and the controller have shown to follow the path in a smooth way.

The Figure 15 shows the motor variations while the AMSV is navigating among several waypoints, showing a very similar behaviour as it was predicted in simulations. The bigger spikes correspond to the situations where the AMSV is far from the actual waypoint's tangent, and the mid spkikes are related to increase velocity to aid turning.

The Figure 16 shows the rudder deflection among waypoints. The spikes are related to changing the waypoints, and the stabilization closer to zero are the values related to following the waypoint's circumference. The behaviour is very similar to the simulations.

Fig. 13. Zodiac following a real path.

Fig. 14. Real path followed.

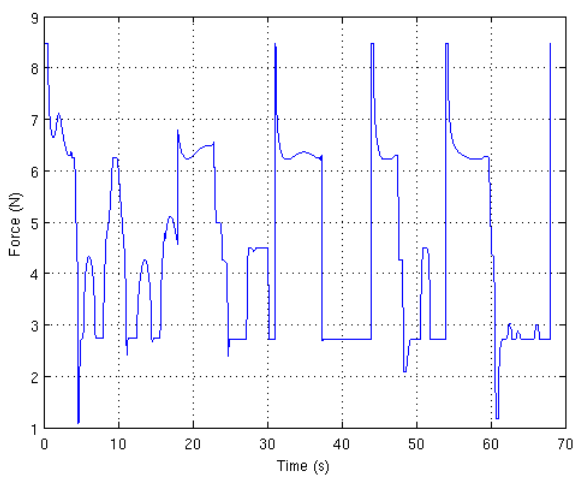

Fig. 15. Real motor's force over time.

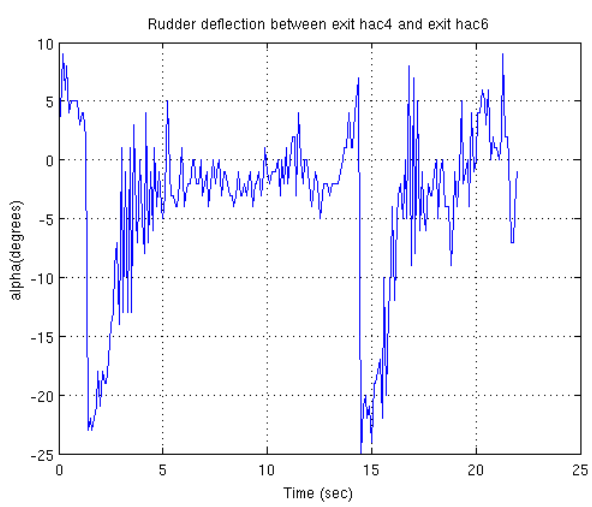

Fig. 16. Real deflection rudder over time.

VII. Conclusions

This paper has shown how this path planning algorithm is robust and straightforward to be implemented in an autonomous vehicle, following lines and arcs with only storing a list of waypoints and radii. The description of a complex path is simple, being easy to store in the controller on board. Also, this path planning developed is suitable to be used with a fuzzy controller without any complex mathematical model, making it easy to handle the nonlinear model equations presented in this paper, moreover, the controller shows to be robust against disturbances. The most important conclusion is that the simulation environment has been validated with the real acquired data, allowing us to step into real scenarios where the AMSVs could be involved. Leading us to arise cooperation scenarios with these vehicles.

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