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Autonomous Fuzzy Heading Control for a Multi-Wheeled Combat Vehicle

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ABSTRACT

This paper introduces the design and the implementation of a heading angle tracking controller using fuzzy logic for a scaled Autonomous Multi-Wheeled Combat Vehicle (AMWCV) to navigate in outdoor environments. The challenge of designing this control system is to control the steering of the front four wheels individually to obtain the correct heading angle of the vehicle. The main contribution of the paper can be summarized in the fact that it is designing four fuzzy controllers for navigation and tracking the desired heading angle while at the same time while controlling the steering of the front four wheels individually. The AMWCV is capable of forwarding and backward movement where all eight wheels are powered individually. The different heading angles are used and simulated using MATLAB software to evaluate the performances of the developed algorithms. In addition, the performance of the developed controllers is validated in the presence of noise and disturbance in order to evaluate the robustness of the controller's Simulation results show the performances and demonstrate that the developed controllers are effective in predicting the desired heading angle changes.

1. Introduction

The main goal of autonomous ground vehicles is to develop a physical system that can navigate autonomously without human intervention. Such vehicles have the capability to perform a critical task, especially for military applications. Furthermore, the appropriate design of the autonomous vehicles will increase the operational capabilities as well as the performance of such vehicles. Many research works have devoted their attention to developing and applying autonomy to multi-wheeled combat vehicles [1-3].

Nowadays, building autonomous multi-wheeled combat vehicles has drawn dramatic attention in both robotics and automotive engineering research [4-6]. The expected outcomes from applying autonomy to such vehicles are set to increase the combat capability, and soldiers stay safe in different battlefield scenarios.

Controller design and testing for autonomous ground vehicles have been widely studied by researchers around the world, especially for multi-wheeled combat vehicles. Applying autonomy to such vehicles is complicated due to their large dimensions, heavyweight, complex geometry, and dynamics. In the literature, there are many control algorithms applied to autonomous vehicles and mobile robots. There has been a long history in solving significant problems in this field, for example, autonomous path tracking [7-9], obstacle avoidance [10-12], control for mobile robots [13-15], and steering control [16-19].

Various control schemes and analyses have been proposed for controlling and improving autonomous vehicle performance, which includes Wildcat autonomous ground vehicle construction and implementation [20], autonomous ground vehicle path tracking [21-25], and navigation [26,27]. In addition, a heading angle tracking controller was developed and implemented by Sahoo [28] for unmanned ground vehicles with a linearized dynamic bicycle model. The authors applied a Point-to-Point navigation algorithm in order to control both the steering and heading angle while considering the limits on the rotation of the steering wheel and steering motor rate. Dadras [29] developed a Fractional Order Extremum Seeking Controller (FO-ESC) in order to control an autonomous ground vehicle to track a predefined reference path. The authors claim that the robustness and higher performance fractional-order operators lead ESC to perform better and more efficiently. Eski [30] developed a model based on an artificial neural network PID controller for trajectory control of an unmanned agricultural vehicle. The developed neural network model has the capability to learn the PID structure with a high level of performance.

Fuzzy logic (FL) is a powerful soft computing technique that controls complex systems based on human expert knowledge. Many research FL algorithms to control autonomous systems in the engineering field [31-33]. Furthermore, the main advantage of using FL is the easy implementation, efficient computation, and better performance [34]. On the other hand, a Proportional-Integral-Derivative (PID) controller is the prevalent control loop feedback mechanism widely used in industrial control systems. This classical controller attempts to eliminate the error between the actual and the desired output by calculating the appropriate control signal. This control signal adjusts the process accordingly based on smoothing the output movement and minimizing the rise time and peak error.

In this paper, a heading angle tracking algorithm based on fuzzy logic approach for a scaled autonomous multi-wheeled combat vehicle was developed. The introduced technique has the capability to track the desired heading angle by controlling the steering of the front four wheels of the vehicle individually. Several statistical analyses are applied to validate the performance and the robustness of the introduced controller in the presence of disturbances and noise. The simulation results demonstrated that the proposed algorithm controller successfully tracked the desired heading angle in a reliable and smooth way, while it is robust against the disturbance and noise

The paper is organized as follows. In section 2, the Autonomous Multi-Wheeled Combat Vehicle (AMWCV) model is presented. Section 3 describes the designed fuzzy logic controller. Section 4 demonstrates the simulation results and the validation based on statistical analysis. The conclusion is given in Section 5.

2. Autonomous Multi-Wheeled Combat Vehicle (AMWCV)

A complete scaled unmanned multi-wheeled combat vehicle system was developed at the Vehicle Dynamics and Crash Research (VDCR) lab at the University of Ontario Institute of

Technology (UOIT) [35], as shown in Fig. 1. The developed AMWCV is a 1:6 scale model of an 8x8 electric combat vehicle that can perform multiple steering modes to meet situational needs. In addition, the eight wheels have to be powered individually. The vehicle is equipped with four axles, which can be operated in either 4WD or 2WD.

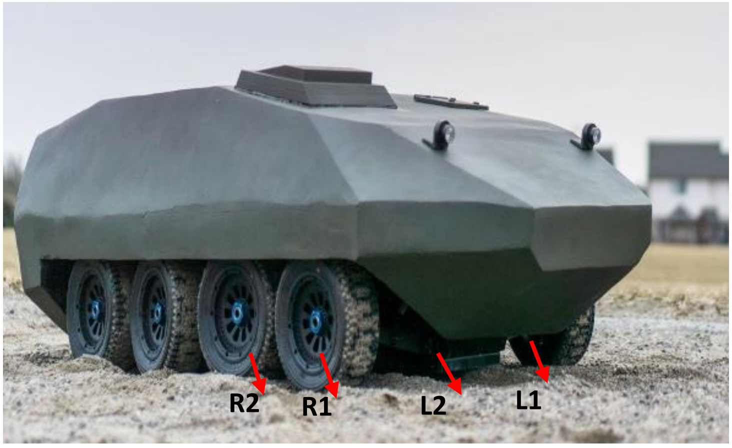


Fig. 1. Remotely operated multi-wheeled combat vehicle.

The vehicle can be navigating by generating four separate voltages responsible for controlling the direction of the front four wheels R1, R2, L1. L2 individually. The vehicle scheme is shown in Fig. 2.

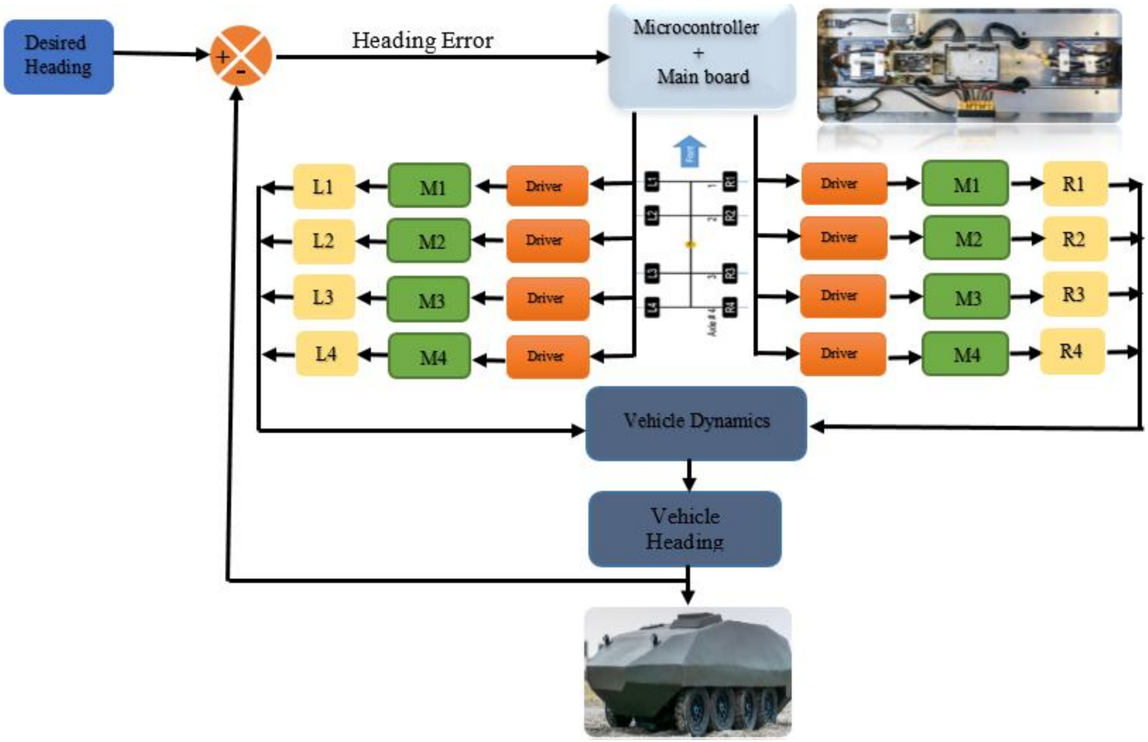


Fig. 2. Multi-wheeled combat vehicle scheme

2.1. Vehicle Features

The features of the remotely operated scaled multi-wheeled combat vehicle capabilities are as follow:

- This vehicle is capable of forwarding and backward movement where all eight wheels are powered individually
- Alternate between three unique steering configurations
- Have the capability to operate under extreme conditions such as summer heatwaves, winter freezes.
- Provide sufficient ground clearance to overcome obstacles like large objects.
- Capability to steer on multiple surfaces such as sand, dirt, snow, mud, and pavement
- High maneuverability to operate in confined areas
- Able to climb over steep terrain and reach moderate speeds similar to that of the full model

In order to obtain the vehicle model, numerous system identification methods were considered to solve the vehicle identification problem [36], where ARMAX, ARX, OE, BJ, SS, and TF models were considered. Finally, the identified vehicle model is defined as follows:

$$G(s)_{Total} = G_{R1}(s)\, u_{R1} + G_{R2}(s)\, u_{R2} + G_{L1}(s)\, u_{L1} + G_{L2}(s)\, u_{L2}$$

Where

$$G_{R1}(s) = \frac{-3.453\, s - 0.6946}{s^2 + 0.1762\, s + 0.1323} \qquad G_{R2}(s) = \frac{-7.118\, s + 1.158}{s^2 + 0.388\, s + 0.3099}$$

$$G_{L1}(s) = \frac{5.76\, s + 0.1182}{s^2 + 0.2714\, s + 0.1083} \qquad G_{L2}(s) = \frac{7.382\, s + 0.8258}{s^2 + 0.5481\, s + 0.2887}$$

3. Design of the Fuzzy Logic Controller (FLC)

The developed fuzzy logic controller is to enables the vehicle to track a pre-defined heading angle. The main structure of the fuzzy logic controller consists of three processes as follows: fuzzification process, inference process, and defuzzification process, as shown in Fig. 3. The first process in designing FLC is fuzzification. In this step, the inputs and outputs transform from real values into grades of membership. The second step is the fuzzy inference process. In this step, the input data using fuzzification will be mapped and conduct the fuzzy reasoning process. The third step is the defuzzification process which transforms the membership degree of fuzzy sets into a crisp set that can be applied to the real system.

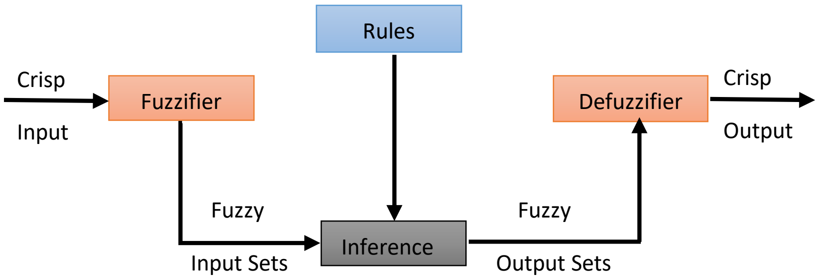


Fig. 3. Block diagram of fuzzy logic controller

The challenge in designing a fuzzy logic controller is to obtain the appropriate fuzzy rules and membership functions due to the AMWCV behavior to fulfill the objective of the heading angle control. For this purpose, four fuzzy controllers are designed for R1, R2, L1, L2. The developed four fuzzy logic controllers take one input: the heading angle error, which is the difference between the desired and the actual vehicle heading angle. The output of the controller is the PWM for each wheel to control the vehicle's heading angle. Fig. 4 illustrates an experiment test for the AMWCV system measuring the inputs/outputs data. It also shows the relation between the PWM inputs for each motor and the output vehicle heading angle, which are very helpful for defining the appropriate rules in the designing process for the fuzzy controller.

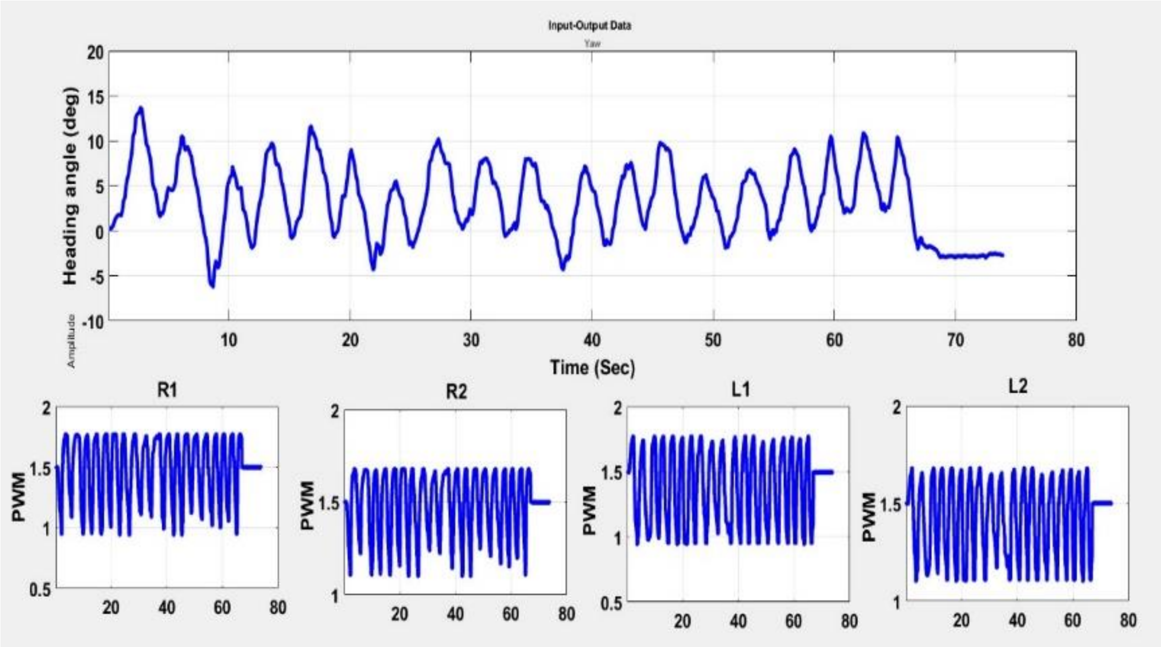


Fig. 4. Experiment Results for the recorded input and output signals

Triangular and trapezoidal membership functions are defined for the input and output variables. The input is the vehicle heading angle, and the output is the PWM for each wheel. The input/output variables for the first controller are defined by five membership functions NB, N, Z, P, and PB, as shown in Fig. 5. Consequently, the input and output variables for the second, third and fourth fuzzy controllers are defined by three membership functions N, Z, and P as shown in Fig. 6-8.

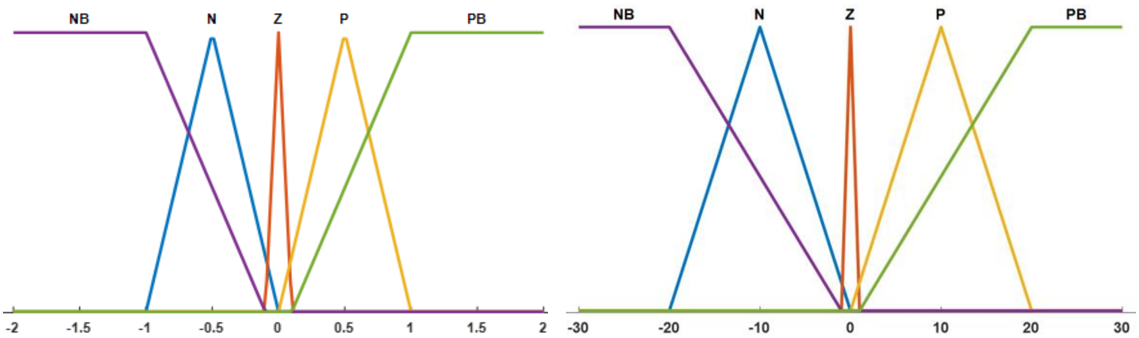
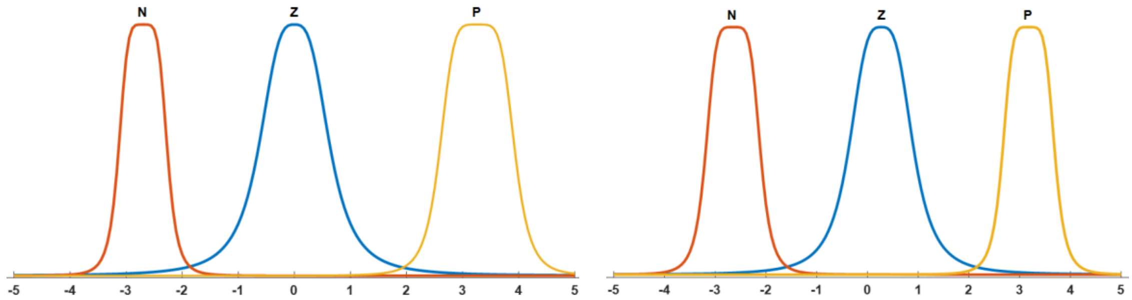
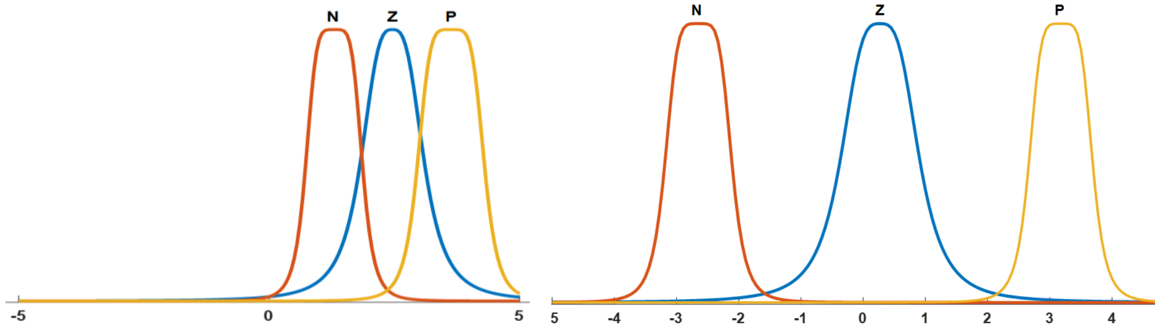


Fig. 5. (a) Fuzzy-1 Input membership function for the heading angle (b) Output membership function for PWM



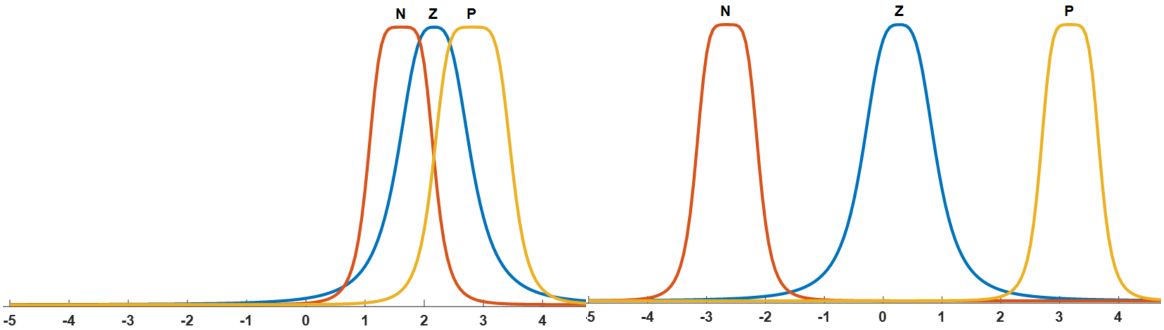
(a) (b)

Fig. 6. (a) Fuzzy-2 Input membership function for the heading angle (b) Output membership function for PWM



(a) (b)

Fig. 7. (a) Fuzzy-3 Input membership function for the heading angle (b) Output membership function for PWM



(a) (b)

Fig. 8. (a) Fuzzy-4 Input membership function for the heading angle (b) Output membership function for PWM

The membership function parameters have been tuned by successive iterations based on the obtained heading angle values. Fig. 9 shows the final intelligent control loop for AMWCV using four fuzzy controllers to reach the desired heading angle.

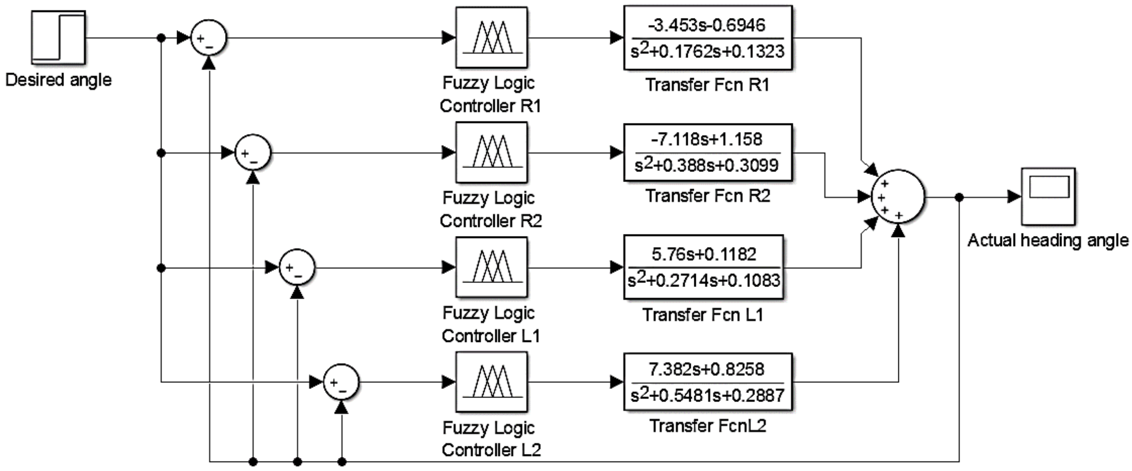


Fig. 9. Fuzzy heading angle controller Simulink diagram for the R1, R2, L1, L2

4. Simulation and results

In this section, the simulation results of the developed controller for the heading angle control will be discussed.

4.1 Fuzzy Logic Controller

The system closed-loop step response performance using the developed fuzzy logic controller compared with the uncontrolled system shown in Fig. 10. It can be noticed that the steady-state error for the closed-loop performance of the uncontrolled system is high, while after applying fuzzy controller, the steady-state error reaches zero and settling time is 0.03sec.

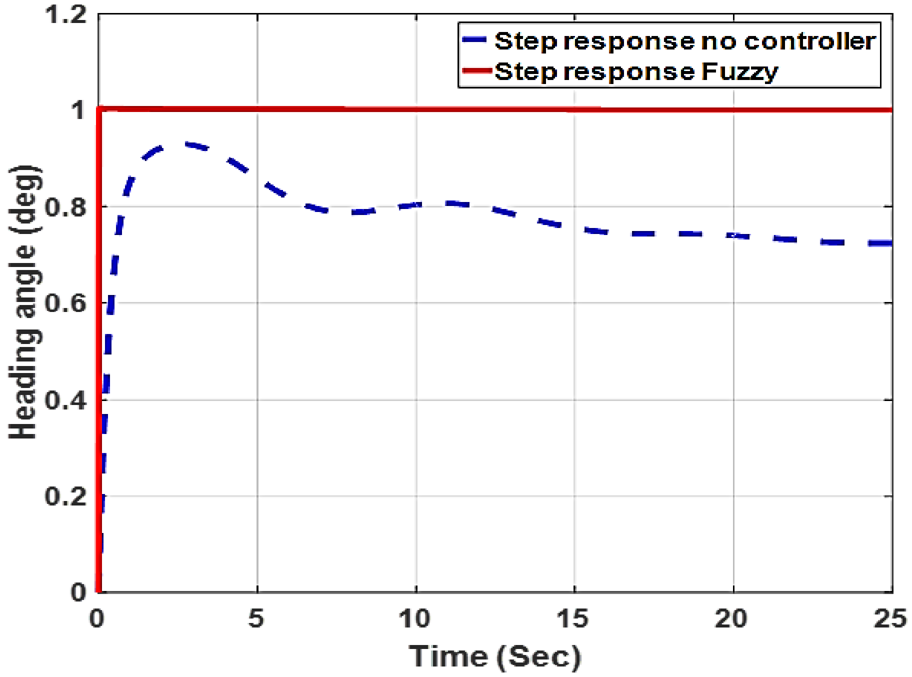


Fig. 10. Comparison of the transient response of the heading angle for the fuzzy controller and uncontrolled system

The evaluation of the proposed controller for tracking a predefined heading angle to reach 25 degrees is shown in Fig. 11. The obtained result clarifies that the FLC is able to track and follow the desired heading angle. In addition, the error between the desired and the actual is smaller, especially when the heading angle changes (during the turning).

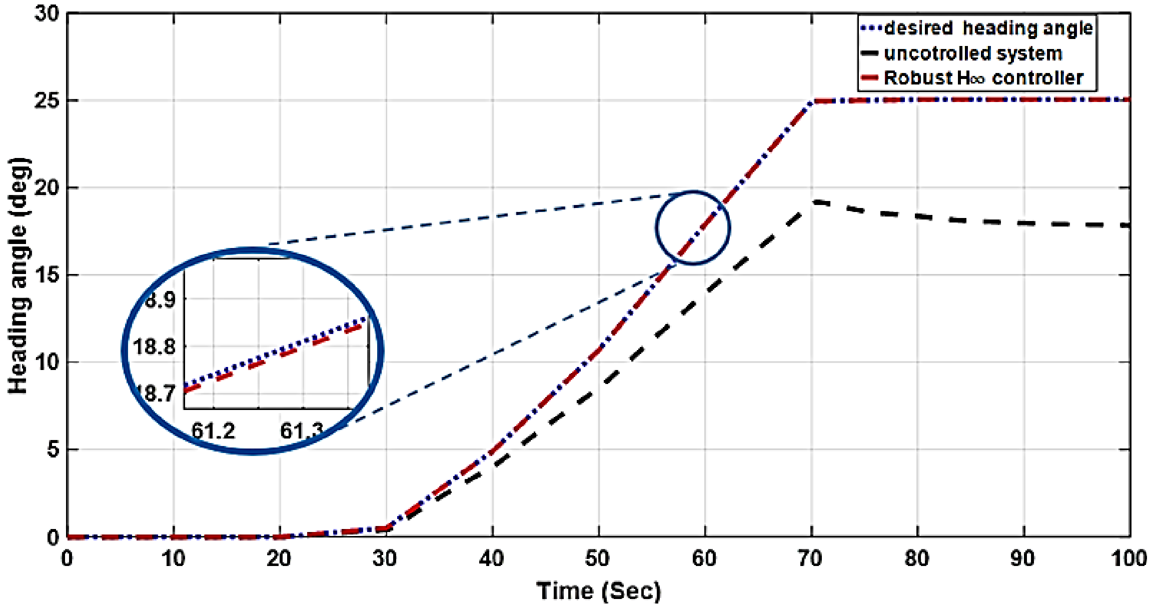


Fig. 11. Comparison of tracking heading angle using fuzzy and PID controllers to reach the desired 25-degree heading angle.

This scenario, it is comparing the proposed FLC with the desired heading angle, as shown in Fig. 12. It can be noticed that the FLC is able to track and follow the desired heading angle, with more accurate tracking for the desired heading angle.

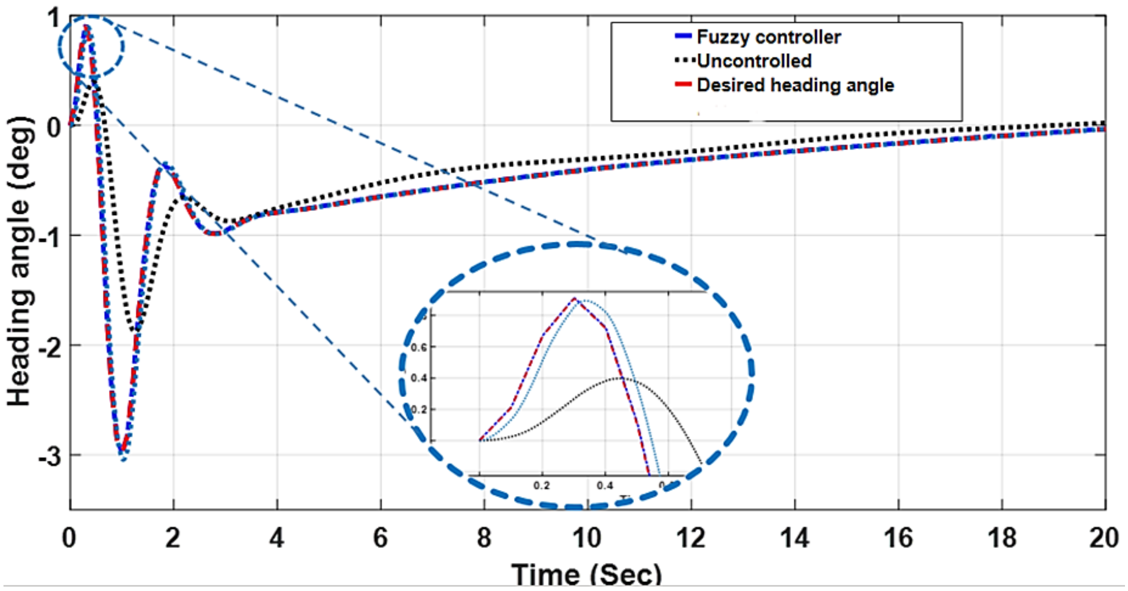


Fig. 12. Comparison of tracking heading angle using fuzzy and PID controllers to reach the desired heading angle

4.2 Validation in the presence of Disturbance and Noise

a) Disturbance Rejection

In this section, the performance evaluation of the proposed algorithm for disturbance rejection during certain maneuvers was introduced. An impulse disturbance was applied to the system output. The obtained result in the presence of disturbance is shown in Fig. 13. It can be noticed that the settling time of the fuzzy controller is very low. Consequently, in the presence of disturbance, the convergence using the fuzzy controller is better, which rejects 50% of the disturbance within 0.06 sec and rejects 95% of the disturbance within 0.09 sec. In addition, it has the lowest control efforts after applying the disturbance.

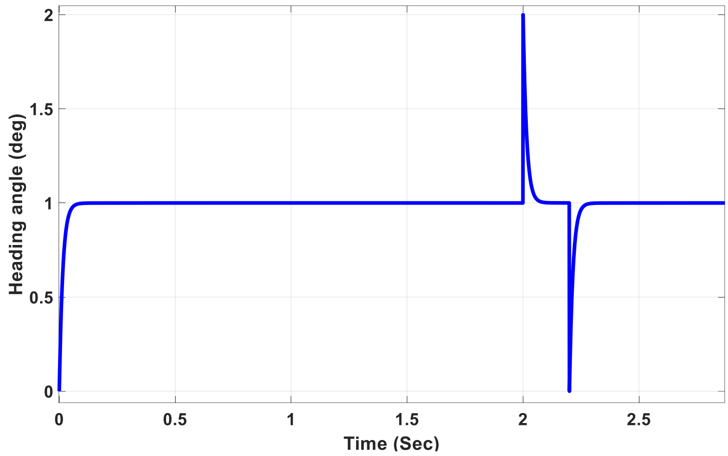


Fig. 13. disturbance rejection using the fuzzy logic controller

b) Noise Sensitivity

In this section, the performance of the proposed algorithms will be evaluated in the presence of noise. For this purpose, white Gaussian noise was applied at the output of the system. The obtained step response in the presence of noise is shown in Fig. 14. This shows that the controller still able to follow the desired input in the presence of noise. Consequently, based on the obtained result, it can be found that the fuzzy logic controller is less sensitive to additive noise.

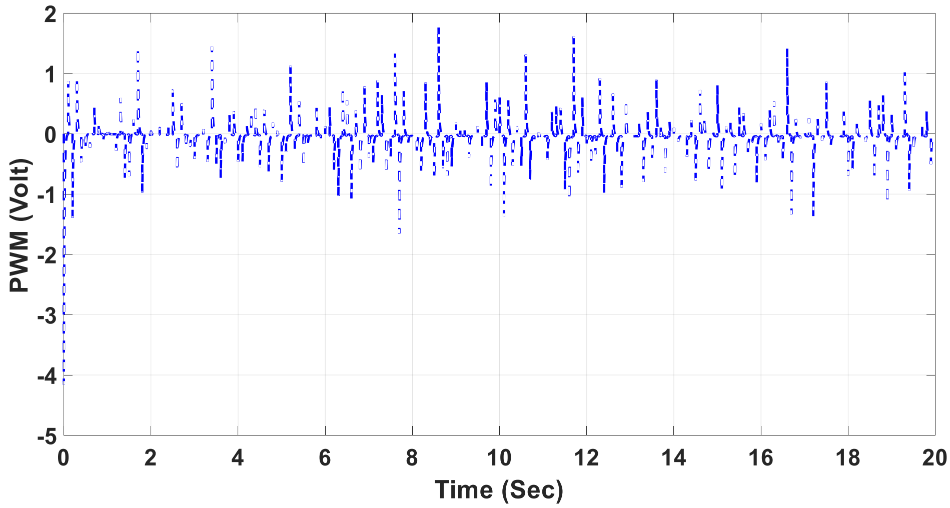


Fig. 14. Control effort in the presence of noise using fuzzy logic controller

5. Conclusion

This paper presented a controller design, tuning for an autonomous scaled multi-wheeled combat vehicle. A fuzzy logic controller has been proposed for heading angle control. The developed control algorithm is tested with the vehicle model for heading control in simulation. The obtained results have been presented to validate the developed algorithm. The study of all obtained results using the developed FLC algorithm led us to believe that there is a trade-off in any control strategy we choose. Based on the performance of the systems, the fuzzy logic controller showed the best results, which can follow the desired heading angle with very low steady-state error and settling time. In addition, it can reject the disturbance within a very short time. In addition, the fuzzy logic controller is less sensitive to applied noise.

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