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IMPLEMENTATION OF FUZZY STABILITY CONTROL IN A LOW-COST MICROCONTROLLER FOR HYBRID VEHICLES

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Abstract. *Nowadays with the development of technology and increased concern about the environment, new solutions are developed together with the control implementation. Therefore, this work aims to study the lateral stability of the hybrid vehicle and its electronic differential. However, applied in a low cost and simple hardware. This paper presents the results of the implementation of fuzzy stability control in Arduino which aims to control the yaw, speed and position of the vehicle. The fuzzy control was validated using the hardware-in-the-loop method. The Arduino can correct the trajectory of the vehicle with an actuation rate of approximately 0.1 s.*

Keywords: *fuzzy control, vehicle model, electric differential, microcontroller.*

1. INTRODUCTION

Nowadays, the automotive industry is facing challenges from more restricted environmental regulations and increasing market competition (Holjevac, Cheli, and Gobbi, 2019a). Hybrid electric vehicles (HEVs) appears as a feasible solution, for the new environmental vehicles market (Zhen et al., 2019).

These HEVs that use two or more power generation systems normally can be classified into two main groups: series hybrids and parallel hybrids. In a series hybrid, an internal combustion engine (ICE) works as a power generator to the electric motor (EM) and in a parallel hybrid, the ICE and the EM propel the vehicle (Corrêa et al., 2014).

The use of different propelling system, improves the vehicle fuel economy (Yazdani, Shamekhi, and Hosseini, 2015; Eckert et al., 2019), acceleration performance (Eckert et al., 2019, 2017) and driveability (Enang and Bannister, 2017; Ali and Söffker, 2018), besides the greenhouse gases emissions mitigation (Jardin et al., 2019). Among the HEV configurations, which combine ICE and electric traction system provide a good trade-off between the driving range and tailpipe emission reduction (Holjevac, Cheli, and Gobbi, 2019b).

The HEV powertrain configuration has a major role in the vehicle design, thus it determines the power flow path with modifies the fuel economy and dynamic performance of the vehicle (Hu, Jiang, and Zheng, 2018). Also, the studies of Rizzo et al. (2014) and Eckert et al. (2019) presented the transformation of a conventional frontal axle drive vehicle into a parallel hybrid electric vehicle, by the electrification of the rear wheels. Considering ordinary vehicles, a single drive system is responsible to move all the traction wheels, thus, it is necessary to use mechanical differential to distribute the torque. However, HEV architecture enables the use of the multi-drive system, vehicles with two or more drivers (Yamashita, 2018).

This independence is one of many active systems that can be used to improve handling, stability and comfort. The wheel torque control is used to produce yaw moment in vehicle improving stability and changing the vehicle trajectory (Yamashita, 2018). Direct yaw-moment control strategies (DYC) is used to control the lateral dynamics as an independent control input (Inoue et al., 2016). Moreover, Ding, Liu, and Zheng (2017) proposed (DYC) for in-wheel electric vehicles by using sliding mode and nonlinear disturbance observer techniques. Already Raksincharoensak, Daisuke, and Lidberg (2019) proposed a control law of the DYC system based on feedforward of front steering angular velocity and feedback of vehicle yaw rate.

Therefore, this study aims to implement directional control in a low-cost microcontroller Atmel ATmega328P 8 bits (Arduino) for lateral control. The control was developed for a hybrid vehicle with electric differential coupled on the rear axle beside in the hybridization kit present in Eckert et al. (2019a). The main objective of this work is to correct the trajectory of the vehicle by the differential torque on the rear motors controlled by the microcontroller. Furthermore, this

microcontroller is based on fuzzy logic, that is the state of art control technique regarding the management of complex vehicular systems (Krithika and Subramani, 2018). Moreover, the applied fuzzy control was also optimized by a genetic algorithm (GA) as presented by Eckert et al. (2018), aiming to find out the most adequate membership functions, rules and their respective weights.

2. VEHICLE MODEL

The direct yaw control must be capable of supply different speeds for each wheel depending on the vehicle condition. The low-speed turning behavior of a vehicle is described by Ackermann geometry (Gillespie, 1992), as shown in Fig. 1. In this case, all wheels revolve around the same point, therefore, the outer wheels must present a greater tangential velocity than the internal wheels at the curve. As the vehicle is in low speed, the lateral forces and the slip angle of the tires can be disregard.

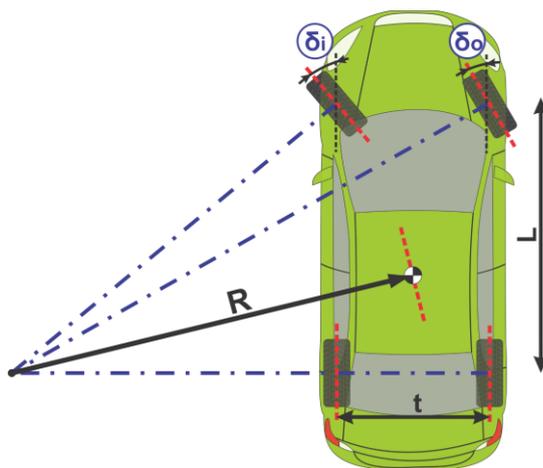


Figure 1. Geometry of a turning vehicle.

As the ideal steering angles for the front wheels are established by the Ackermann's geometry as shown in Fig. 1. The steer angles can be defined as Equations (1) and (2) (Milliken and Milliken, 1995).

$$\delta_i = tg^{-1}\left(\frac{L}{R-t/2}\right) \tag{1}$$

$$\delta_o = tg^{-1}\left(\frac{L}{R+t/2}\right) \tag{2}$$

Where δ_i and δ_o are the steering angle of the inner and outer front wheels, R is curvature radius, t is the track of vehicle and L is the wheelbase.

However, at high speed, lateral forces and slip angle cannot be disregard. Fig. 2 shows the dynamic behavior of the vehicle, where the lateral force and the slip angle influence vehicle behavior and should be associated with the tire model. Because of that, the Pacejka 87 model (Genta, 1997) is presented in Equation (3).

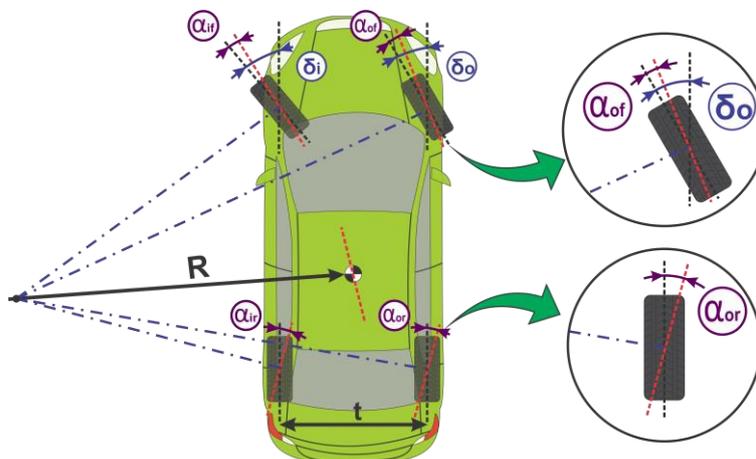


Figure 2. Dynamic four-wheel model.

$$F_y(\alpha) = D \cdot \sin(C \cdot \arctan(B \cdot (1 - E) \cdot (\alpha + S_h) + E \cdot \arctan(B \cdot (\alpha + S_h)))) + S_v \quad (3)$$

Where B , C , D , E , S_h and S_v are the tire parameters depending on normal forces, α is the slip angle and F_y is the lateral force. This lateral force is a function of the slip angle for different normal forces as shown in Fig. 3. It is important to notice that higher is the normal force the greater the lateral force. After a 5°, the lateral force tends to be constant.

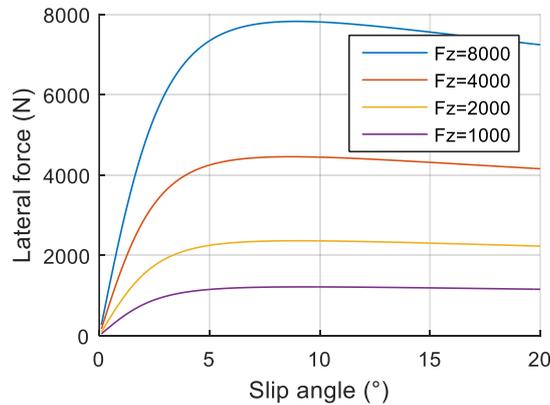


Figure 3. Lateral force as a function of slip angle (Yamashita et al., 2017).

3. FUZZY CONTROL

As mention before, this work is based on a configuration of a hybrid vehicle where present an electric motor connected to each rear wheel is present in Fig. 4. Therefore, to deal with the complicated nonlinear mathematic of the tire, a fuzzy logic control was designed.

The fuzzy control aims to control the yaw, speed and position of the hybrid vehicle. For this, it uses as input the speed, yaw angle and steer angle of the vehicle, and as output the torque that should be applied in each rear wheel. Figure 4 presents a scheme of the control developed in Simulink/Matlab™, the steering angle obtained by the maneuver that the driver requires, the yaw angle obtained by the accelerometer in the center of gravity and the speed obtained by wheel rotation.

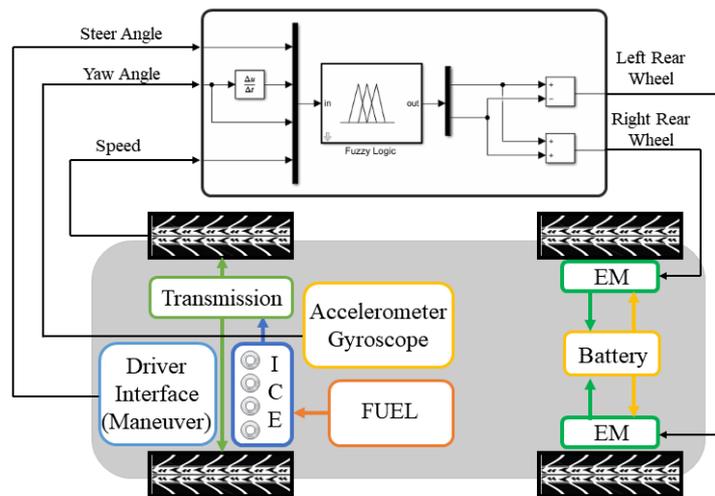


Figure 4. Fuzzy Logic Controller Diagram.

To design the fuzzy control three degrees of membership functions were defined for each input and output variable as shown in Fig. 5. All degrees are described by Gaussian membership functions, due to the smoothness of this type of function and the reduced number of parameters for its characterization compared to triangular and trapezoidal functions. The Gaussian function is defined by the mean (μ) and deviation standard (σ) as presented in Eq. (4).

$$mf(x) = e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4}$$

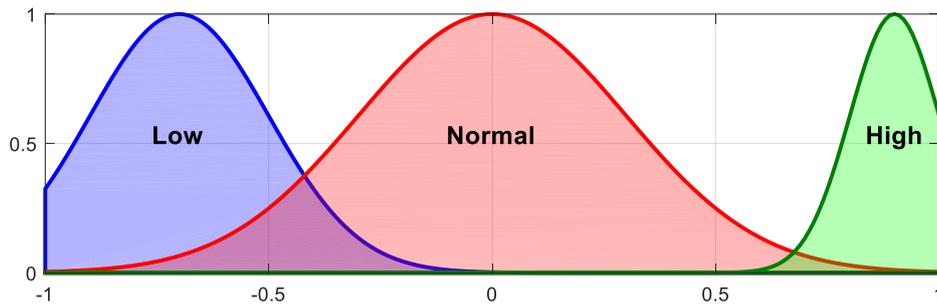


Figure 5. Gaussian membership functions example.

In defuzzification is used the center of area method, this method calculates the centroid of the area obtained in inference. Equation (5) the calculation of the centroid.

$$\bar{x} = \frac{\sum x \cdot mf(x)}{\sum mf(x)} \tag{5}$$

In the fuzzy controller, the parameters that determine the membership functions, the rules and their respective weights were obtained by optimizations, based on the method of the genetic algorithm. The optimization algorithm tests values for the parameters of the controller and simulates its performance by comparing the trajectory of the controlled vehicle with the trajectory of the desired vehicle. This fuzzy controller configuration method is presented in Eckert et al. (2019b). The simulation uses an actuation rate of 0.01 seconds.

Each variable is classified into three levels by the membership functions, which are determined by two parameters. The mean value (μ) of the membership functions that define the second degree of membership of the variables was defined as zero. Therefore, each variable presents five parameters, totaling thirty parameters to be optimized.

In the inference to define the rules, initially, all possible combinations of inputs levels have been arranged and the output variables were disassociated, so each combination of levels of input variables may imply different levels with different degrees of support for each output variable. In this way, there are four hundred and eighty-six possible rules.

In Figure 6, a diagram illustrating the process of obtaining the controller parameters is presented. In the process there are two optimizations, in the first, the optimization algorithm tests values for the five hundred and sixteen parameters in the vehicle model, the trajectory generated by the model is compared with the desired trajectory, and the variation between the trajectories is computed.

At the end of the first optimization, the rules pass through a selection, in which the degrees of support obtained in the optimization are compared. For each combination of input variables, only two rules are selected, each associated with one of the outputs. The rules chosen are those with the highest degrees of pertinence. After the selection, of the four hundred and eighty-six rules there are only one hundred and sixty-two rules.

To finalize the process a second optimization is performed, this time with one hundred and ninety-two parameters. The parameters obtained in the second optimization are the final parameters that will be implemented in the controller.

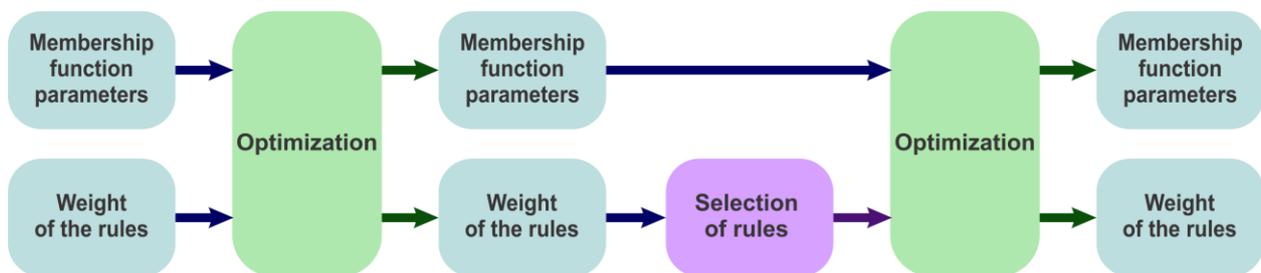


Figure 6. Diagram of the method of configuring the fuzzy controller.

Figure 7 shows the membership functions for each variable obtained in the optimization, it is possible to note the distribution of the mean and standard deviations obtained for each level of the variables. The differential torque functions have similar standard deviations, however, for the velocity they are different.

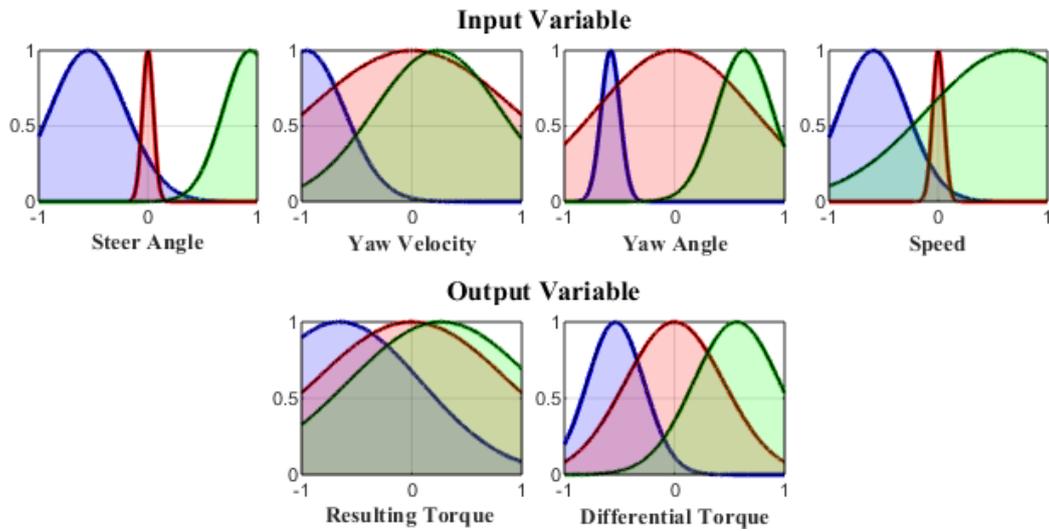


Figure 7. Membership function of control variables.

Table 1 shows the rules and their respective weight, obtained by the optimization for the resulting torque in the rear axle of the vehicle. Assuming that the signal control receives as input a low level of steering (δ_L), a low level of speed (V_L), a low level of yaw (γ_L) and a low level for the yaw velocity ($d\gamma_L$), the resulting torque level on the rear axle will be high (H), associated with a weight of 0.78. Table 2 shows the rules and their respective weight, obtained by the optimization for the differential torque in the rear axle of the vehicle.

Table 1. Rules and their respective weight obtained by the optimization for the resulting torque in the rear.

		δ_L			δ_N			δ_H		
		V_L	V_N	V_H	V_L	V_N	V_H	V_L	V_N	V_H
γ_L	$d\gamma_L$	H (0,78)	H (0,84)	H (0,88)	H (0,57)	N (0,53)	L (0,70)	N (0,49)	H (0,38)	H (0,78)
	$d\gamma_N$	H (0,19)	B (0,84)	N (0,25)	L (0,59)	N (0,26)	N (0,94)	L (0,63)	L (0,78)	H (0,70)
	$d\gamma_H$	H (0,46)	N (0,38)	H (0,56)	N (0,84)	N (0,94)	L (0,27)	L (0,50)	N (0,63)	H (0,79)
γ_N	$d\gamma_L$	N (0,25)	H (0,67)	H (0,33)	H (0,35)	H (0,98)	H (0,13)	H (0,75)	H (0,17)	H (0,52)
	$d\gamma_N$	L (0,37)	L (0,20)	L (0,94)	H (0,34)	H (0,60)	N (0,93)	H (0,65)	L (0,10)	L (0,39)
	$d\gamma_H$	L (0,11)	N (0,08)	H (0,75)	L (0,73)	N (0,87)	H (0,75)	N (0,79)	N (0,33)	N (0,71)
γ_H	$d\gamma_L$	N (0,45)	L (0,86)	H (0,50)	H (0,20)	H (0,30)	H (0,50)	H (0,63)	H (0,22)	L (0,55)
	$d\gamma_N$	N (0,76)	H (0,72)	H (0,22)	N (0,51)	H (0,26)	H (0,43)	H (0,63)	N (0,79)	L (0,05)
	$d\gamma_H$	H (0,52)	N (0,57)	L (0,58)	H (0,37)	L (0,24)	H (0,78)	L (0,75)	N (0,35)	L (0,93)

Table 2. Rules and their respective weight obtained by the optimization for the differential torque in the rear axle.

		δ_L			δ_N			δ_H		
		V_L	V_N	V_H	V_L	V_N	V_H	V_L	V_N	V_H
γ_L	$d\gamma_L$	N (0,90)	H (0,64)	L (0,26)	N (0,90)	N (0,87)	N (0,01)	N (0,56)	H (0,68)	L (0,07)
	$d\gamma_N$	N (0,68)	N (0,22)	L (0,38)	N (0,44)	N (0,78)	N (0,54)	H (0,18)	N (0,81)	N (0,65)
	$d\gamma_H$	L (0,15)	H (0,80)	L (0,58)	N (0,16)	L (0,72)	H (0,18)	L (0,64)	N (0,11)	H (0,21)
γ_N	$d\gamma_L$	L (0,32)	L (0,77)	M (0,34)	H (0,81)	H (0,40)	H (0,03)	H (0,94)	H (0,83)	N (0,86)
	$d\gamma_N$	H (0,70)	H (0,01)	M (0,54)	N (0,66)	N (0,97)	H (0,87)	L (0,52)	N (0,50)	L (1,00)
	$d\gamma_H$	N (0,29)	N (0,43)	H (0,34)	N (0,07)	H (0,29)	N (0,68)	L (0,63)	H (0,95)	N (0,84)
γ_H	$d\gamma_L$	N (0,95)	N (0,07)	L (0,16)	H (0,86)	N (0,02)	N (0,60)	H (0,58)	L (0,52)	N (0,93)
	$d\gamma_N$	N (0,65)	L (0,60)	M (0,33)	L (0,82)	L (0,45)	H (0,47)	N (0,63)	L (0,95)	L (0,19)
	$d\gamma_H$	L (0,13)	N (0,62)	H (0,08)	H (0,58)	H (0,82)	H (0,59)	H (0,90)	N (0,80)	L (0,78)

Observing the weights of the rules presented in Tab. 1 and Tab. 2 it is possible to note that some of the rules have close values of zeros. These rules should not influence the directional control of the vehicle.

4. HARDWARE-IN-LOOP

After developing the fuzzy control in Matlab, the best result obtained in the optimization was implemented in a low-cost microcontroller. The microcontroller chosen to implement the control was an Arduino board. In recent years, Arduino boards have become popular as a solution for rapid prototyping tools for electronic circuits (Yamashita et al., 2018). They have analog inputs that could receive the signals from speed, yaw and steer sensors.

Arduino Boards has been presenting efficacy as acquisition, actuation and control systems in various areas of science. It is possible to cite as an example the works done in the measurement of the velocity of soil infiltration (Fatehnia et al., 2016), in the development of controlled stimulus isolators allowing highly accurate (Sheinin, Lavi, and Michaelevski, 2015) and data acquisition (Yamashita et al., 2018).

Due to the low memory of the Arduino, the processing done uses integer variables. An integer variable is stored in 8 bits, this way it is possible to make calculations with four precision houses. The error in the calculation of the torque due to the precision of the Arduino is of the order of 0.1 N.

Table 3 shows the average time the Arduino spends processing each step of the Fuzzy controller. It is possible to note that the step that most demands microcontroller processing is the defuzzification, in this step a numerical integration occurs to determine the location of the centroid.

Table 3. Average processing time of each step of the controller.

Fuzzy step	Average processing time
Fuzzification	0.019 s
Inference	0.030 s
Defuzzification	0.047 s
Total	0.096 s

In order to validate this control, the hardware-in-the-loop method was developed and implemented. The Arduino board and MatLab (computer) send and receive data by serial communication; they convert the value of the variables into four bits and send to another. The software Matlab predicts the behavior of the vehicle. The Arduino receives the speed, yaw, steering inputs of the vehicle, processes, and returns the torque that should be employed on each rear wheel as mention before in the fuzzy control. The computer inserts into the model the torques informed by the Arduino and predicts the behavior of the vehicle in the next instant. This process is repeated until the end of the simulation. Figure 8 presents a diagram of the hardware-in-loop operation.

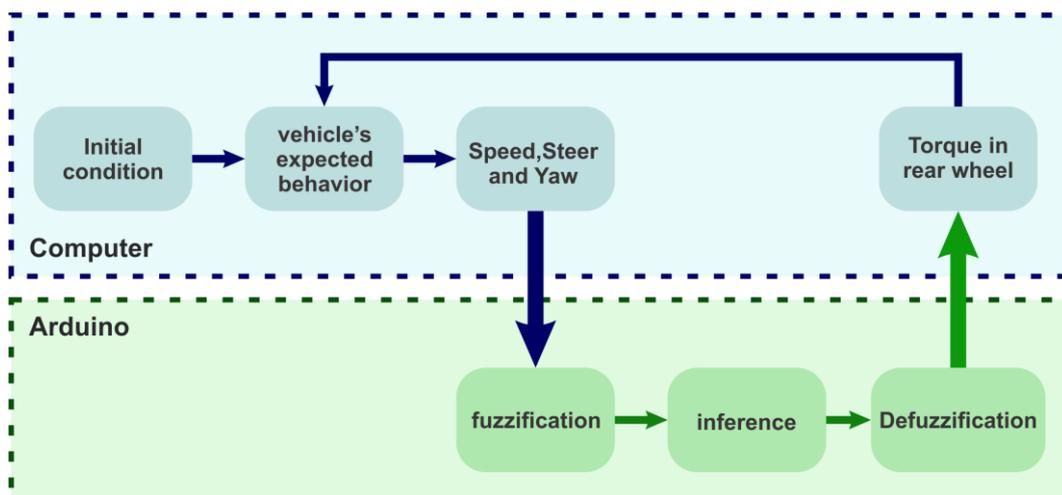


Figure 8. Hardware in loop simulation diagram.

The Arduino can execute the control with an actuation rate of approximately 0.1 s. Figure 9 presents the control response, the blue curve shows the desired trajectory, the red curve shows the uncontrolled vehicle trajectory and the black curve shows the controlled vehicle trajectory. It is possible to observe that the controlled vehicle trajectory overlaps with the desired trajectory, proving that the control implemented in the Arduino board can correct the trajectory of the

vehicle. Finally, the actuation rate achieved by Arduino proved to be sufficient to generate satisfactory results hardware-in-the-loop simulation.

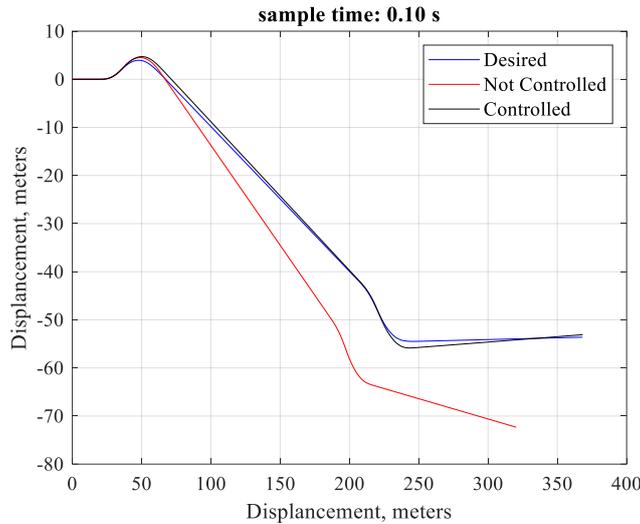


Figure 9. Control response for an actuation rate of 0.10 s.

Simulation tests were executed with actuation rates of 0.15 and 0.20 seconds to verify the robustness of the developed control. Figure 10 presents the results obtained in the simulations, it is possible to observe that the control does not present an efficient performance in correcting the trajectory of the vehicle in both cases. The difficulty of control in correcting the vehicle trajectory increases with the controller actuation rate.

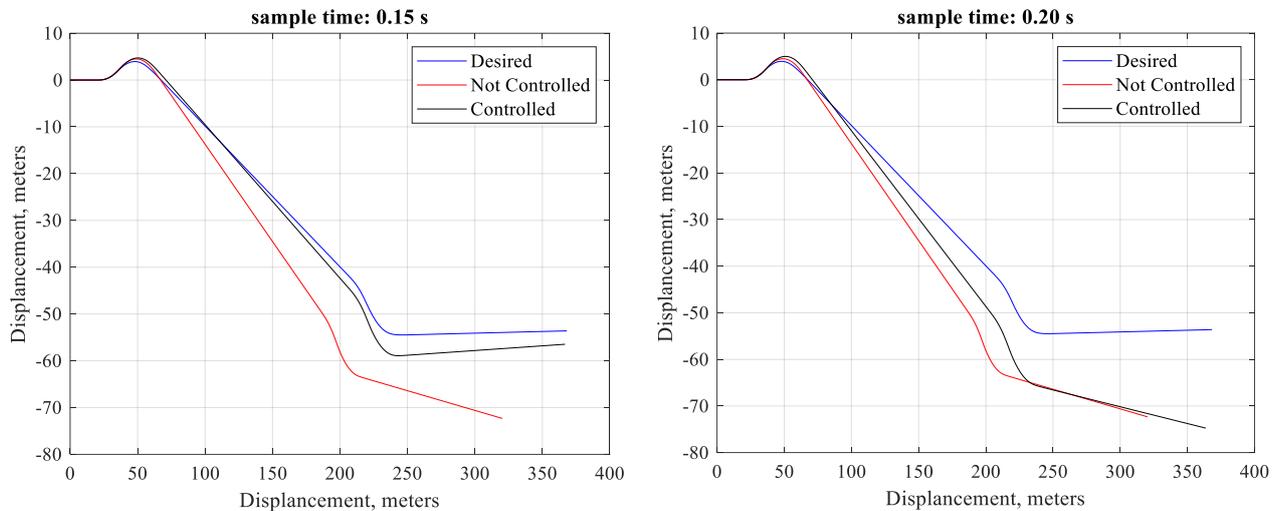


Figure 10. Control response for an actuation rate of 0.15 s and 0.20 s.

For a correct vehicle trajectory, the controller must act at a maximum rate of 0.10 seconds; therefore, this is the limit to generate an adequate correction. In this case, the microcontroller may not correct the vehicle's path if it misses some actuation point due to an error in data processing or communication. Other microcontrollers such as National Instruments (NI) RoboRIO and Texas Instruments (TI) Delfino can be an alternative to implementing fuzzy control on a real vehicle. In some studies of power management strategy, the NI RoboRio and TI Delfino controllers are used, respectively, for hybrid (Roda et al., 2018) and electric (Wieczorek et al., 2018) vehicles control.

5. CONCLUSION

In this paper, a handling improvement system based on direct yaw moment control was developed. This control system was applied to an HEV with distributed drive, equipped with in-wheel motors at the rear axis. The designed controller was based on fuzzy logic and it was optimized by a genetic algorithm, that defined the best combination of membership functions, rules and weights that enhance the vehicle handling control.

To validate the developed fuzzy control, the hardware-in-the-loop simulation was implemented in Arduino microcontroller and Matlab, showing that it is able to correct the trajectory of the vehicle under normal driving conditions.

Although the Arduino can act fast enough to correct the trajectory of the vehicle, but its actuation rate is at the limit for proper correction. In this way, if a problem occurs in the data communication and/or processing, the controller probably will lose some performance and the vehicle trajectory possibly will not be corrected with the same efficiency.

Finally, was concluded that the method of configuring the fuzzy controller parameters by the GA optimization proved to be effective. The designed control was able to act on the vehicle model and correct its trajectory. Moreover, in future work, the developed control will be implemented in a vehicle prototype, and experimentally evaluated regarding its time response.

6. ACKNOWLEDGEMENTS

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