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FUZZY CONTROL STRATEGY APPLIED TO ADJUSTMENT OF FRONT STEERING ANGLE OF A 4WSD AGRICULTURAL MOBILE ROBOT

ESTRATEGIA DE CONTROL FUZZY APLICADA AL AJUSTE DE ÁNGULO DE DIRECCIÓN DELANTERA DE UN ROBOT MÓVIL 4WSD AGRÍCOLA

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Abstract. This paper presents the preliminary studies of the control strategy based in fuzzy logic, projected for the steering system of AGRIBOT project that consist of a wheeled autonomous mobile robotic in real scale endowed with four independent steering and driven wheels (4WSD). In this work we present a preliminary fuzzy controller design applied to front steering angle, using a multivariable plant which incorporates simplified linear model of lateral dynamics of a vehicle whose input are linear combination of rear and front steering angles. The fuzzy control strategy was decided because provides flexible way to deploy with embedded systems. Simulations are used to illustrate the designed controller performance. We use Ackerman geometry to trace front steering angle that allows the vehicle to perform correctly a given maneuver preserving a minimum level of stability and maneuverability. The goal is to establish a relationship between steering input commands and the control commands to the actuators so that it is possible to adjust the attitude of the actuators over the movement axis, as the trajectory change.

Keywords: Ackerman geometry, fuzzy controller, Two-Track Vehicle, Lateral dynamics, mobile robot, bike model, steering angle.

Resumen. Este trabajo presenta los resultados preliminares de la estrategia de control basada en lógica difusa, proyectada para el sistema de dirección del proyecto Agribot, que consiste en un robot móvil autónomo con ruedas en escala real dotado de dirección a las cuatro ruedas motrices independientes (4WSD). Se presenta un diseño preliminar de un controlador difuso aplicado a ángulo de dirección frontal, utilizando una planta multivariable que incorpora el modelo lineal simplificado de la dinámica lateral de un vehículo, cuya entrada es la combinación lineal de los ángulos de dirección trasera como delantera. Se eligió como estrategia el control difuso debido a que proporciona una forma flexible para desplegar los sistemas embebidos. Las simulaciones se usan para ilustrar el rendimiento del controlador diseñado. Se acudió a la geometría Ackerman para trazar el ángulo de dirección delantera que permite que el vehículo funcione correctamente en una maniobra dada la preservación de un nivel mínimo de estabilidad y maniobrabilidad. El objetivo es establecer una relación entre la entrada de órdenes de dirección y los comandos de control a los actuadores de modo que es posible ajustar la actitud de los actuadores sobre el eje de movimiento, como el cambio de trayectoria.

Palabras clave: Geometría Ackerman; Controlador difuso; Vehículos de pista; Dinámica lateral; Robot móvil; Modelo de bicicleta.

1. INTRODUCCIÓN

Nowadays is evident the use of a wide range of technological advances in various knowledge fields, which has allowed the adaptation of techniques developed to outdoor mobile robotics in fields as the agriculture or including motorsports, increasing profitability and reducing environmental impacts.

Today, a significant number of research groups in the world are interesting in this area, mainly due to the need of increasing food production and reducing costs. Currently, a keyword in this area is widely known as precision agriculture that encompasses not only the automation of the processes, but also the planting data acquisition, detection and diagnosis of problems (pests, plants malformation, etc.), and customized treatment [1], [2]. The technological application in the precision agriculture crates a scenario when the mobile robots can be applied to optimize some laborious activities, e.g.: harvesting, spraying, seeding, and soil preparation.
Some interesting examples of mobile robots developed for application in agricultural fields can be found in [3], [4], [5], [6]. Nevertheless, many challenges must be overcome in order to become the use of robots economically viable in agriculture. A good example of challenge is the robot navigation system. An agricultural mobile robot needs an onboard path planner that calculates a collision-free trajectory sufficiently precise that enables the robot to execute its tasks without damaging the crop.

The AgriBOT is a cooperation project between EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), EESC – USP (Escola de Engenharia de São Carlos – Universidade de São Paulo), and Jacto Company with finantial support of FINEP (Financiadora de Estudos e Projetos), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), and COLCIENCIAS (Departamento Administrativo de Ciencia Tecnología e Innovación de la República de Colombia). These institutions have been designed and built a multifunctional and modular robotics platform (the AgriBOT robot prototype) to work in the Precision Agriculture area.

The AgriBOT mobile robot is a vehicle that has as the main power source a 4 stroke cycle turbocharged diesel engine manufactured by Cummins Inc, and has a fuel injection electronic system providing 59.65 kW (80cv) at 2200 RPM. The use of a diesel engine offers autonomy, which in this case can reach up to 20 hours, and ability to refuel quickly. The fuel tank has a capacity of 140 liters of diesel oil. There is also a power system of 12Vcc and 170 Ah, consisting of three batteries connected in parallel, totaling 510Ah, reefed for an alternator set with the diesel engine [6].

This paper presents a fuzzy front steering angle control projected to the AgriBOT mobile robot. This control structure is based on a simplified linear model of the lateral dynamics to control the orientation rate (yaw rate) and the slide slip angle. As was mentioned, the control design is based in the fuzzy logic theory and a multivariable plant which incorporates the model of the lateral dynamics mentioned above and whose input are the linear combination of the rear and front steering angles [7], [8]. The proposed control structure has been applied to design a sideslip and yaw rate controller using an accurate lateral dynamics model of a 4 wheel steering car. This model incorporates the tire force dynamics and the steering actuators. Simulations are used to illustrate the performance of the designed controllers. We present the synthesis and the analysis of a fuzzy controller to adjust the steering angles by acting over the angular position of a respective actuator.

2. AGRIBOT MOBILE ROBOT

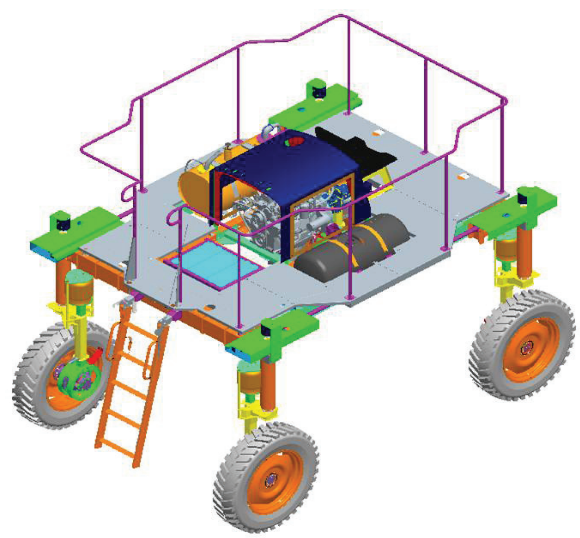

Fig.1. AgriBOT prototype. Pro-Engineer drawing

In Fig. 1 one may observe a Pro-Engineer drawing of the mobile robot platform and in Fig. 2 a photo of the same robot when it was delivered by Jacto Company in December, 2010.

The AgriBOT is a 4WSD vehicle because the basis for the robotic platform is the mobility capability provided by four wheel module mechanism that are powered by a diesel engine, each one of the four

identical wheel modules includes a hydraulic motor actuator for propulsion and other hydraulic motor for the steering, these actuators provides direct drive to create a two-degree-of-freedom system for each module.

Communication between electronics devices and electromechanical actuators is made using the famous Controller Area Network (CAN) protocol. The electronics wheel steering controller is based on a commercial agricultural job computer and handles the local position servo controller for the steering and provides torque control of the driven motor. The driver motor electronics allows speed and current (torque) feedback while the steering servo system provides a steering angle feedback [6].

The 4WSD configuration was introduced in order to provide a flexible platform the research, but the improved mobility also supplies a number of more practical benefits. By using 4WSD configuration, it is possible to produce parallel displacement of the vehicle during turns because it decouples adjustments in position from adjustments in orientation. It also allows both the front and rear of the vehicle to follow a specific path precisely and may maintain a fixed orientation relative to the crop rows. Steering on all wheels also minimizes side slip of the wheels resulting in reduced wear on the vehicle and less damage to the field.

Fig. 2. AgriBOT prototype. Photo of the robot when it was delivered by Jacto company in December 2010

3. SIMPLIFIED LATERAL DYNAMICS

The development of chassis control schemes has been a major area of study for automotive control engineers over the past 30 years. The volume of published literature is large, exceeding 1000 papers. Of this literature, there are 250 examining yaw and sideslip control [9].

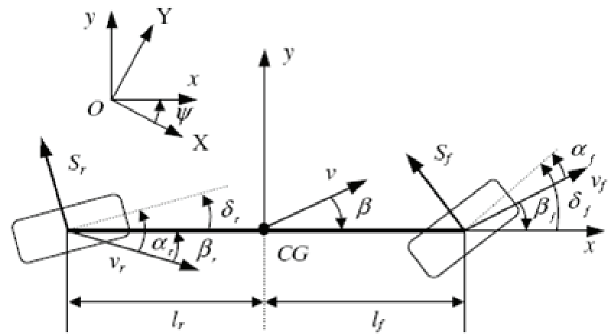

Fig. 3. Single-track model of a 4-wheel steering car.

Dynamics of 4-Wheel Steering Car Throughout this paper it is assumed that the essential features of the lateral dynamics of the car can be described using the single-track model show in [7], [8]. In the single-track model, the two front wheels are lumped into a single imaginary wheel located at the center of the respective axle; the same is done with the two rear wheels. The resulting front and rear wheels are interconnected by a one-dimensional rigid element with the car as show in Fig. 3 where the set of reference axes CG-xy, with origin at the centre of gravity CG, is fixed to the vehicle and O-XY is an inertial reference frame; v is the velocity of the vehicle with respect to O-XY; v_f and v_r are the velocities at the front and rear axle, respectively, with respect to O-XY; ψ is the yaw angle and β is the sideslip angle. It is assumed that the front (and respectively, rear) steering angle of the single-track model, δ_f and respectively, δ_r in Fig. 3, corresponds to the steering angle at the two front and rear wheels. In this paper we are not concerned with the longitudinal motion of the single-track model; due to this we only consider tire-road interaction forces perpendicular to the wheel plane, i.e. cornering forces. The force S_f and S_r in Fig. 3, are the lateral tire forces on the front and rear wheels respectively.

In order to derive the equations governing the linearized lateral dynamics of the single-track model, assume that the front and rear steering angles are small, which in turn results in the angles β, β_f, α_f, β_r and αr (as shown in Fig. 3) also being small. Under this premise, the application of the equations of motion of a rigid body to the single-track model results in:

$$\dot{\beta} = \psi - \frac{S_f+S_r}{mv_x}\beta = \psi - \frac{S_f+S_r}{mv_x} \quad (1)$$

$$\dot{\psi} = \frac{S_f l_f+S_r l_r}{I_{zz}}\psi = \frac{S_f l_f+S_r l_r}{I_{zz}} \quad (2)$$

Where m is the mass of the vehicle, I_{zz} is its moment of inertia with respect to the vertical axis, l_f (and respectively, l_r) is the distance from the center of gravity to the front (and respectively, rear) axle and v_x is the projection of the velocity vector along the CG – x axis, i.e. the vehicle longitudinal velocity, which we hereafter refer to as the vehicle speed. For small α_f and α_r values, S_f and S_r can be approximated by the following equations [7, 8]:

$$S_f = K_f\alpha_f S_f = K_f\alpha_f \quad (3)$$

$$S_r = K_r\alpha_r S_r = K_r\alpha_r \quad (4)$$

The constant K_f is the result of modifying the combined stiffness of the two front tires to take into account the caster effect of the steering system at the front axle. Since no caster effect is generated at the rear axle, the constant K_r is simply the cornering stiffness [7], [8]. We have to consider the caster effect as it is assumed that the front steer-by-wire function is integrated with a conventional steering system.

Considering the kinematics of the single-track model as a rigid body, the angles α_f and α_r are obtained as follows:

$$\alpha_f = \delta_f + \beta - \frac{l_f\dot{\psi}}{v_x}\alpha_f = \delta_f + \beta - \frac{l_f\dot{\psi}}{v_x} \quad (5)$$

$$\alpha_r = \delta_r + \beta - \frac{l_r\dot{\psi}}{v_x}\alpha_r = \delta_r + \beta - \frac{l_r\dot{\psi}}{v_x} \quad (6)$$

$$\begin{aligned} \dot{x} &= Ax + Bu\dot{x} = Ax + Bu \\ y &= Cx + Duy = Cx + Du \end{aligned} \quad (7)$$

$$A = \begin{bmatrix} -\frac{K_f+K_r}{mv_x} & \frac{K_f l_f - K_r l_r}{mv_x^2} + 1 \\ \frac{K_f l_f - K_r l_r}{I_{zz}} & -\frac{K_f l_f^2 + K_r l_r^2}{I_{zz} v_x} \end{bmatrix},$$

$$B = \begin{bmatrix} -\frac{K_f}{mv_x} & -\frac{K_r}{mv_x} \\ \frac{K_f l_f}{I_{zz}} & -\frac{K_r l_r}{I_{zz}} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ and } D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

This construction allows for the introduction of a safety management system that reverts to normal steering in case of failure of the steer-by-wire function.

Equations (1), (2), (3), (4), (5), and (6) can be rearranged into the state-space representation of a linear time-invariant system with two inputs (δ_f and δ_r) and two outputs (β and ψ). The resulting state-space representation is given is show in (7).

The linear time-invariant system introduced above describes the lateral dynamics of the single-track model around the trajectory given by zero sideslip, zero yaw rate, zero steering angles and constant vehicle speed [7, 8].

4. FUZZY LOGIC GENERALITES

The Fuzzy Logic tool was introduced in 1965, also by Zadeh, and is a mathematical tool for dealing with uncertainty. It offers to a soft computing partnership the important concept of computing with words. It provides a technique to deal with imprecision and information granularity. The fuzzy theory provides a mechanism for representing linguistic constructs such as many, low, medium, often, few. In general, the fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities. On the contrary, the traditional binary set theory describes crisp events, events that either do or do not occur. It uses probability theory to explain if an event will occur, measuring the chance with which a given event is expected to occur [10].

Real world situations are too complex, and this complexity involves the degree of uncertainty – as uncertainty increases, so does the problem complexity. Traditional system modeling and analysis techniques are too precise for such problems (systems), and in order to make complexity less daunting we introduce appropriate simplifications, assumptions, etc. (i.e., degree of uncertainty or Fuzziness) to achieve a satisfactory compromise between the information we have and the amount of uncertainty we are willing to accept. In this aspect, fuzzy systems theory is similar to other engineering theories, because almost all of them characterize the real world in an approximate manner. For more details about the concepts related to fuzzy logic and its application with Matlab™, you should follow the following reference [10].

5. CONTROL SYSTEM ARCHITECTURE

The utility of fuzzy sets lies in their ability to model uncertain or ambiguous data, so often encountered in real life. It is important to observe that there is an intimate connection between Fuzziness and Complexity. As the complexity of a task (problem), or of a system for performing that task, exceeds a certain threshold, the system must necessarily become fuzzy in nature. Zadeh, originally an engineer and systems scientist, was concerned with the rapid decline in information afforded by traditional mathematical models as the complexity of the target system increased.

5.1 The FUZZY Controller Design and Preview Results

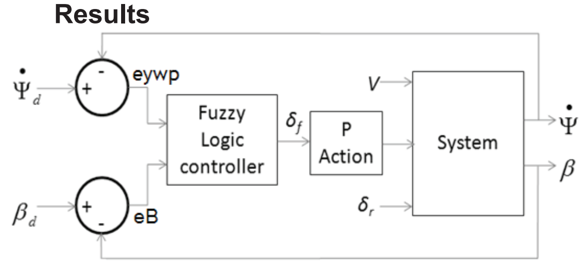

Fig. 4. Control system architecture.

Fuzzy logic is a new and innovative technology being used to enhance control engineering solutions. It allows complex system design directly from engineering experience and experimental results, thus quickly rendering efficient solutions. Fig. 4 shows a blocks diagram of a general control system where the controller is a fuzzy logic block. For our case, the plant corresponds to the state space expression (eq. 7) and we know that the inputs to the system are the front and rear steering angles $u = [\delta_f \delta_r]'$ and if we want to achieve the path tracking of a straight line, for this goal is desirable to maintain an orientation of zero and likewise for the steering angles. I this work we are assuming that the system has the necessary sensors to provide the immediate information about the orientation, steering and side-slip. Thus, if we have some desired behavior, as we can see in fig. 4 the fuzzy controller must provide the necessary signal to the plant for achieve the desired behavior and error zero.

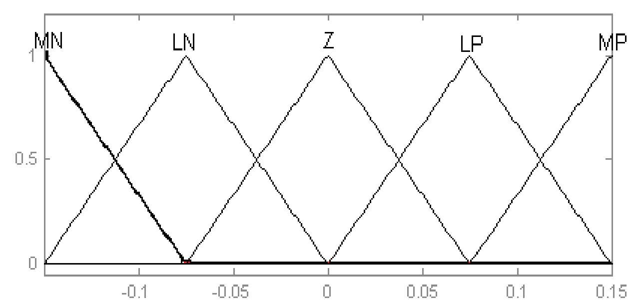

Fig. 5. Membership functions for the slide slip angle error (eB).

For the problem in this paper the synthesis of the fuzzy controller is based on the fuzzy logic theory and implemented for simulation with the fuzzy Logic toolbox of Matlab™ [10]. The scheme shown in the Fig. 4 represents the control architecture used in this work [11]. For the deployment control system the inputs are desired orientation rate ($\dot{\psi}\psi_d$) and the desired slip angle (β). Is possible to see that *eB is* representing the sideslip angle error and it is the difference between desired sideslip angle and the real measured sideslip angle. In this order, ***eywp*** represents the orientation rate error. The block named system represents the dynamic model expressed with the equation shown in eq. 7 and for this model we have the velocity (V), the front steering angle and the rear steering angle as inputs of the vehicle model. The fuzzy controller receives the information respective to the error in the orientation rate and the sideslip angle error and acts providing the front steering angle action to a proportional controller. The proportional controller output is applied to the front steering angle input of the dynamic model. Is very important to note that was assumed that rear wheel was considered fixed with zero steering angle.

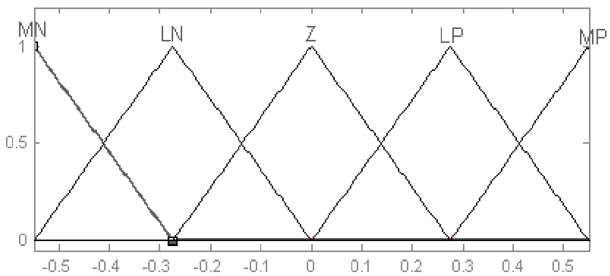

Fig. 6. Membership functions for the yaw angle rate error.

The development of the fuzzy controller requires the definition of the membership functions for the inputs and outputs of our system, thus, for this work the inputs are the error of orientation angle and the error of the slip angle. Fig. 5 shows a basic representation of the fuzzy logic controller with membership functions for "*eB*".

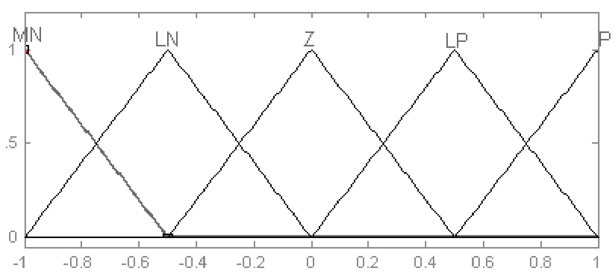

Fig. 7. Membership functions for the front steering angle command.

In this paper was desired use the vehicle parameters provided in [8] without forget the importance of the AgriBOT parameters in future works. These parameters are understood by the following values [8]: m = 1573; I_{zz} = 2873; L_f = 1.1; L_r = 1.58; K_f = 80000; K_r = 80000 and was assumed a constant velocity of 10m/s.

1. If (eB is Z) and (e_yawp is MP) then (deltaF is P) (1)
2. If (eB is Z) and (e_yawp is LP) then (deltaF is P) (1)
3. If (eB is Z) and (e_yawp is Z) then (deltaF is Z) (1)
4. If (eB is LP) and (e_yawp is MN) then (deltaF is MN) (1)
5. If (eB is Z) and (e_yawp is MN) then (deltaF is MN) (1)
6. If (eB is LN) and (e_yawp is LN) then (deltaF is LN) (1)
7. If (eB is Z) and (e_yawp is LN) then (deltaF is LN) (1)
8. If (eB is Z) and (e_yawp is MN) then (deltaF is MN) (1)
9. If (eB is LP) and (e_yawp is MN) then (deltaF is MN) (1)
10. If (eB is LN) and (e_yawp is MN) then (deltaF is MN) (1)

Fig. 8. Rules defined to Fuzzy Logic Controller.

Fig. 6 shows the definition of the membership functions to yaw angle rate error (eywp). Fig. 7 shows membership functions definition for the front steering angle command.

The membership functions of slide slip angle error and the orientation rate error are between small values because the goal of control is maintain these small values provided for the side slip angle and yaw rate.

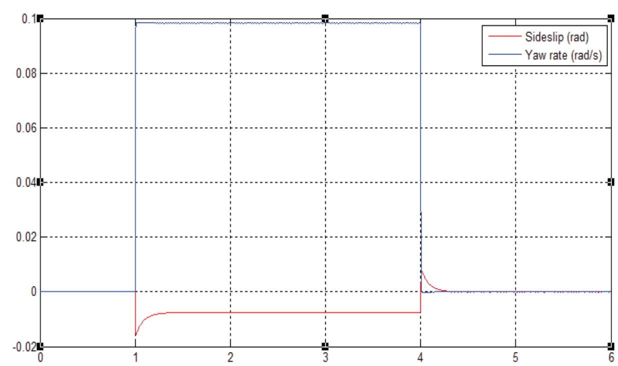

Fig. 9. Response of the controller to the desired inputs.

The membership functions was defined as MN (very negative), PN (little negative), Z (zero), PP (little positive), MP (very positive). In this simulation was defined also the rules for the fuzzy controller, in Fig 8 are shown this rules defined with the Matlab™ Fuzzy logic toolbox. The inference components are the eB (slide slip angle error), eywp (orientation error) and with the Mamdani method is decided is generate a magnitude to act on the operating front steering angle. Mamdani Fuzzy inference method is the most commonly used in applications, due to its simple structure of 'min-max' operations [10].

6. EVALUATION OF THE RESULTS

To illustrate the performance of the designed controller, the response of the controlled vehicle to a given control task has been simulated. The simulations have been carried out using the state expression of eq. 7 and the fuzzy controller developed in the previous section with a constant speed of 10 m/s. The control task considered consists of tracking a yaw rate reference signal in the shape of a single rectangular pulse of 0.1 rad/s amplitude and 3s width while maintaining zero sideslip. The respective results are shown in Fig. 9, the red trace corresponds with the orientation rate (yaw rate) and the blue trace corresponds to the slip angle. As can be seen for the desired inputs the system has an acceptable response due to the work performed by the fuzzy controller.

Fig. 10. Expanded form of the behavior of the yaw rate when is desired track a yaw rate of 0.1 rad/s.

In the Fig. 10 is show the expanded form of the behavior of the yaw rate basically when is desired track a yaw rate of 0.1 rad/s, this figure is included for evaluate the acceptable performance of the fuzzy controller about the required orientation variability during the respective time.

The Fig. 11 show the expanded form of the behavior of the slip angle basically when is desired track a yaw rate of 0.1 rad/s, also, this figure is included for evaluate the acceptable performance of the fuzzy controller about the required slip angle during the respective time.

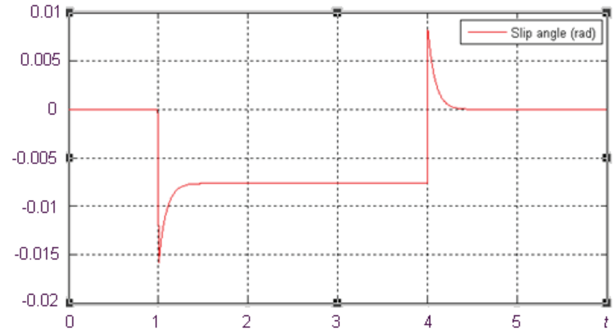

Fig. 11. Expanded form of the behavior of the slip angle when is desired track a yaw rate of 0.1 rad/s.

The Fig. 12 shows the performance of the system under the change of the desired yaw rate. In this case during 1s the desired yaw rate is zero; on the second 2 the desired yaw rate is 0.1rad/s during 3s, after during 1s the required yaw rate is zero, subsequently, the yaw rate is -0.1rad/s during 4s. Again is possible to evaluate the acceptable performance of the controller.

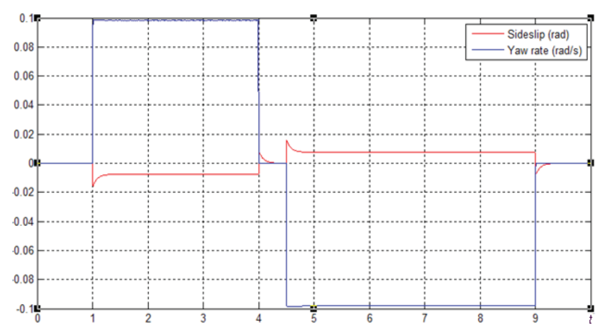

Fig. 12. Response of the controller to the desired inputs

Is necessary to mention that the response is acceptable, but the has a small steady-state error and in other works as [12], the results achieved are better and is proved that the appropriate definition of the membership functions help to improve the performance of a fuzzy controller, for this appropriate definition is possible use tools derived of the artificial intelligence.

7. CONCLUSION AND FUTURE WORK

In this work we presented the results of the design of an initial fuzzy controller applied on the stabilization problem of the yaw rate and sideslip angle in a 4WSD

Autonomous Vehicle. Based on tests described in the literature and in previous works was made a preliminary study that is a good basis that must be improved for its direct deployment on the AgriBOT mobile robot. It's sure that this previews controller needs more evaluations to decide to use it in the real deployment.

When it comes to future works, is a research group interest the deployment of the controller in an embedded processor. We want to evaluate the performance for controlling the AgriBOT mobile robot. As the AgriBOT prototype has mobility similar to holonomic mobile robot, and it was designed to work in the outdoor environments like farm fields, the vehicle model parameters can vary. Due to this, we consider essential the implementation of intelligent control systems that can deal with this.

The controller proposed integrates the slip angle and the yaw rate that is relatively easy using fuzzy logic, the dynamic model used in this work use parameter obtained in vehicle dynamics bibliography. Is desired assume dynamic models for off road vehicles.

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