# MOBILE ROBOT PROTOTYPE USED TO THE STUDY OF TRAJECTORY CONTROL STRATEGIES AND AUTO-LOCALIZATION

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***Abstract:*** *This paper describes the main characteristics of a differential drive mobile robot prototype built to make experiments oriented to improve the performance of control algorithms developed to deploy a high level trajectory controllers on big structure robotized vehicles. The mobile robot presented in this paper has two servomotors to act on two wheels and therefore to move the structure. The direct control of the servo-motors is executed by an Arduino board. Basically, the objective is to experiment a fuzzy controller to keep a desired orientation of the prototype along its forward displacement. An IMU (Inertial Measurement Unit) has been used to measure the mobile robot orientation and a GPS receiver to know its localization. GPS and IMU lectures are read and processed on the Arduino board and these lectures are sent to an remote computer by Xbee communication and this remote computer computes the control actions using fuzzy controller. The calculated control actions are retransmitted, by Xbee communication, toward the mobile robot in order to be applied on the prototype actuators.*

***Keywords:*** *Differential drive Mobile robot prototype, Fuzzy logic controller, Orientation control.*

## 1. INTRODUCTION

Mobile robot prototypes facilitate the developing of experiments aimed to improve the performance of control algorithms which would be applied on more complex platforms like vehicles and trucks.

Some situations require the projection of high level control strategies like trajectory control, path planning, etc, oriented to drive a big structure mobile robot. So the related experiments would be performed using small platforms to avoid unnecessary energy costs. Thus the prototypes are a good solution to improve the performance of high level control algorithms that once have been approved may be deployed on the real robotized vehicle. For this reason, a differential drive wheeled mobile robot prototype has been built to assume the study of high level trajectory control strategies.

An arduino board has been installed on the mobile robot structure what has been programmed to perform several tasks like the direct control of two servo-motors attached to two wheels; the reading, processing and transmission to an remote computer of lectures provided from an IMU and a GPS. The Communication between the mobile robot and the remote computer is achieved employing the Xbee protocol (Faludi, 2011).

The external computer has been programmed to receive the IMU and GPS lectures from the prototype and to computes the control actions to be applied on the actuator of the vehicle. The computation of the respective control actions is based on a fuzzy controller (Sivanandam et al. 2007; Hakima et al. 2010).

The Remote computer has been programmed to receive (via Xbee communication) the IMU and GPS lectures from the prototype to compute the control actions employing a fuzzy controller (Sivanandam et al. 2007; Hakima et al. 2010). The control actions are communicated to the prototype (via Xbee communication again). These control actions have to be applied on the actuator of the vehicle.

Section 2 provides a basic presentation about the applied general concepts without providing depth, therefore to get more information related to fuzzy logic, GPS, IMU, Xbee and arduino is suggested to follow the following references: (Sivanandam et al. 2007; Hakima et al. 2010; Bajaj et al. 2002; Groves, 2008; Lou et al. 2011; Faludi, 2011; Margolis, 2011). The section 3 presents a mobile robot description and experimental details. Section 4 exposes the reached results. Finally conclusions, agreements and references are presented.

## 2. GENERAL CONCEPTS

### 2.1. Inertial Measurement Unit (IMU)

Inertial sensors comprise accelerometers and gyroscopes, commonly abbreviated to gyros. An accelerometer measures specific force and a gyroscope measures a specific angular rate, both without an external reference. Devices that measure the velocity, acceleration, or angular rate of a body respect to features in the environment are not inertial sensors (Groves, 2008). Most types of accelerometers measure specific force along a single sensitive axis. Similarly, most types of gyros measure angular rate about a single axis. An inertial measurement unit combines multiple accelerometers and gyros, usually three of each, to produce a three-dimensional measurement of specific force and angular rate (Groves, 2008). The IMU measures vehicle states like attitude, orientation, velocity, and position. However, these states are not directly measurable with the current IMU sensors and to achieve the measurement they have to be estimated from a set of correlated states like angular rate by the gyro, linear acceleration by accelerometer and heading angle by magnetometer (Lou et al. 2011).

### 2.2. Global Positioning System (GPS)

GPS consists of a network of 24 satellites in six different 12-hour orbital paths spaced so that at least five are in view from every point on the globe. The satellites continuously transmit military and civilian navigation data on two L-band frequencies. Five monitor stations and four ground antennas located around the world passively gather range data on each satellite's exact position. The system relays this information to the master control station at Schriever Air Force Base in Colorado, which provides overall coordination of the network and transmits correction data to the satellites. Each satellite emits radio signals that a receiver (a miniature device installed on a vehicle or carried by hand) uses to estimate the satellite's location as well as the distance between satellite and receiver. The receiver can roughly determine its position by locking on to the signals of at least three satellites, a technique commonly known as triangulation but more precisely called *trilateration*. With four or more satellites in view, the receiver can determine the user's latitude, longitude, and altitude. Once it has calculated the user's 3D position, the receiver can calculate other useful information such as speed, bearing, track, trip distance, distance to destination, and sunrise and sunset time.
To obtain an accurate fix on a moving object or person, GPS determines how long it takes a satellite signal to reach a receiver, which generates its own signal. Assuming that the signals are synchronous, GPS compares the satellite signal's pseudorandom number code—a digital signature unique to each satellite—with the receiver's PNC to determine the signal's travel time. The system multiplies this value by the speed of light to compute the satellite's distance from the receiver. Because the satellites are nearly 11,000 miles away, miscalculating signal travel time by even a few milliseconds can cause a location error measuring as much as 200 miles. Satellites therefore use extremely precise—and expensive—atomic clocks. A receiver's clock doesn't need to be as accurate because it measures the distance to a fourth satellite to synchronize its PNC with the satellites and correct for any timing offset (Bajaj et al. 2002)

### 2.3. Fuzzy Logic

The Fuzzy Logic tool was introduced in 1965 by Zadeh and it is a mathematical tool for dealing with uncertainty. The fuzzy theory provides a mechanism for representing linguistic constructs such as many, low, medium, often and few. In general, the fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities. 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 are introduced 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 applications you should follow the following reference (Sivanandam et al. 2007; Hakima et al. 2010).

## 3. MOBILE ROBOT DESCRIPTION AND EXPERIMENTAL DETAILS

### 3.1. Structure

The employed prototype to make experiments corresponds to a differential drive wheeled vehicle which is showing in Fig. 1. The mobile robot has two circular platforms with 15 cm of diameter each one and its height is 33 cm. On the lower platform has been installed two batteries of 4.7 Vd.c used to provide energy for the actuators and electronic circuits deployed on the vehicle. Below the lower platform had been assembled a caster wheel and two servo-motors (model SM-S4303R). The two vehicle wheels have been attached to each one of the servo axles. Onto the higher platform were installed the deployed electronic circuits.

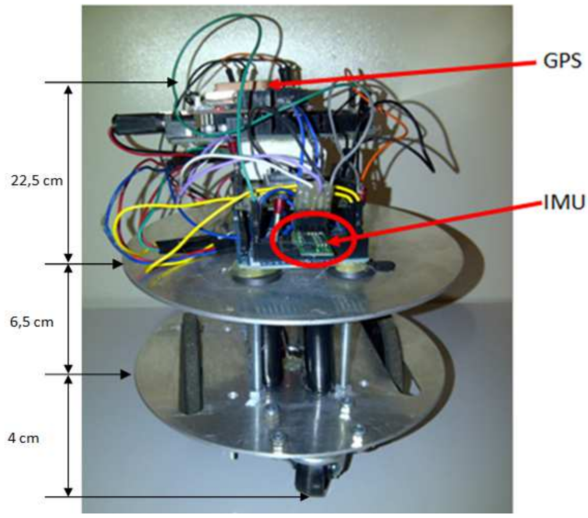



Figure 1. Prototype Picture

### 3.2. Hardware

An Arduino board (model Mega 2560), an EM-406A GPS receiver, an mini IMU and a Xbee interface have been installed on the mobile robot structure.

The robot maneuverability is generated by two continuous rotation servos which requires a PWM (Pulse Wide Modulated) signal to be controlled, this signal have to be applied to a specific available input. Figure 2 shows a general diagram of the servo and its dimensions.

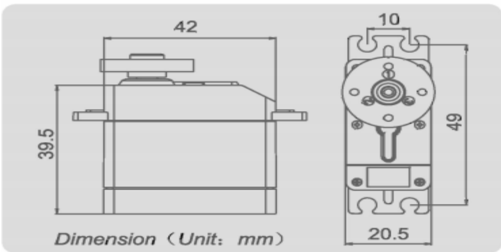



**Figure 2. Servomotors dimensions**

The Arduino board performs several tasks which are: To receive the control information sent from a remote computer via Xbee communication; To drive directly the servos; To capture and to process the IMU and GPS lectures and transferring these lectures to the remote computer via Xbee communication.

### 3.3. Fuzzy Controller

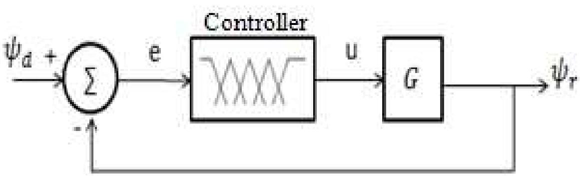


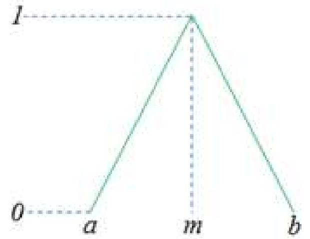

**Figure 3. Block Diagram of Control System.**

This paper exposes the physical and conceptual necessary elements so that a mobile robot prototype be able to keep a desired orientation along its forward locomotion. In order to reach this purpose has been deployed a control system whose architecture is represented in Fig. 3 where the input ($\psi_d$) corresponds to the desired orientation (Yaw angle). $\psi_r$ is a signal related to the real instantaneous orientation that is measured using an IMU. $\psi_d$ and $\psi_r$ are compared in order to get an error ($e$) signal like is shown in Eq. (1). The error signal is the input of a controller block which calculates an appropriate control action ($u$) which will be applied to the actuators of the mobile robot represented by the block (G) in Fig. 3.

$$e = \psi_d - \psi_r \tag{1}$$

The deployed control strategy is based on the SISO (*Single Input Single Output*) closed loop control systems and fuzzy logic. The projected control system has a fuzzy controller of one input and one output (Sivanandam et al. 2007; Hakima et al. 2010). As has been mentioned, the controller input is the error signal ($e$) and the controller output is the control signal ($u$) which is transferred to the robot actuators in order to induce a vehicle steering.

The development fuzzy controller requires the definition of the fuzzy input and output sets, also is required to define rules to relate these sets. During the fuzzy sets definition process has been defined five triangular pertinence functions according to the definitions shown in Fig. 4 (Yu and Zhang, 2008). Fuzzy sets are represented in Fig. 5. Equations (2) to (6) show mathematic expressions of the fuzzy sets *Mn*, *n*, *z*, *p and Mp* respectively.




$$\mu(x) = \begin{cases} 0, & if\ x \le 0 \\ \dfrac{x-a}{m-a}, & if\ a \le x \le m \\ \dfrac{b-x}{b-m}, & if\ m \le x \le b \\ 0, & if\ x \ge b \end{cases}$$

**Figure 4. Triangular form definition**

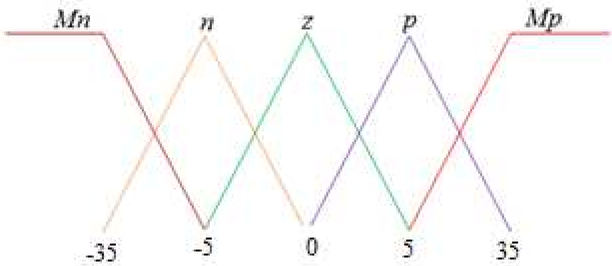



**Figure 5**. **Input Fuzzy Logic sets**

$$Mn = \begin{Bmatrix} 1, & if\ e \le -35 \\ \dfrac{-5-e}{-5-(-35)}, & if\ -35 \le e \le -5 \end{Bmatrix} \tag{2}$$

$$n = \begin{Bmatrix} 0, & if\ e \le -35 \\ \dfrac{e-(-35)}{-5-(-35)}, & if\ -35 \le e \le -5 \\ \dfrac{0-e}{0-(-5)}, & if\ -5 \le e \le 0 \\ 0, & if\ e \ge 0 \end{Bmatrix} \tag{3}$$

$$z = \begin{Bmatrix} 0, & if\ e \le -5 \\ \dfrac{e-(-5)}{0-(-5)}, & if\ -5 \le e \le 0 \\ \dfrac{5-e}{5-0}, & if\ 0 \le e \le 5 \\ 0, & if\ e \ge 5 \end{Bmatrix} \tag{4}$$

$$p = \begin{cases} 0, & if\ e \le 0 \\ \dfrac{e-(0)}{5-(0)}, & if\ 0 \le e \le 5 \\ \dfrac{35-e}{35-5}, & if\ 5 \le e \le 35 \\ 0, & if\ e \ge 35 \end{cases} \tag{5}$$

$$Mp = \begin{cases} \dfrac{e-5}{35-5}, & if\ 5 \le e \le 35 \\ 1, & if\ e \ge 35 \end{cases} \tag{6}$$

Figure 6 allows explaining how the error signal (***e***) is fuzzified for two different input values. Fig. 6 (a) shows that the respective (*e*) magnitude generates the $\mu_n\,(e)$ and $\mu_{Mn}\,(e)$ values. Fig. 6(a) shows that when a different input (*e*) is being applying, then obtained fuzzy values are $\mu_p\,(e)$ and $\mu_z\,(e)$.

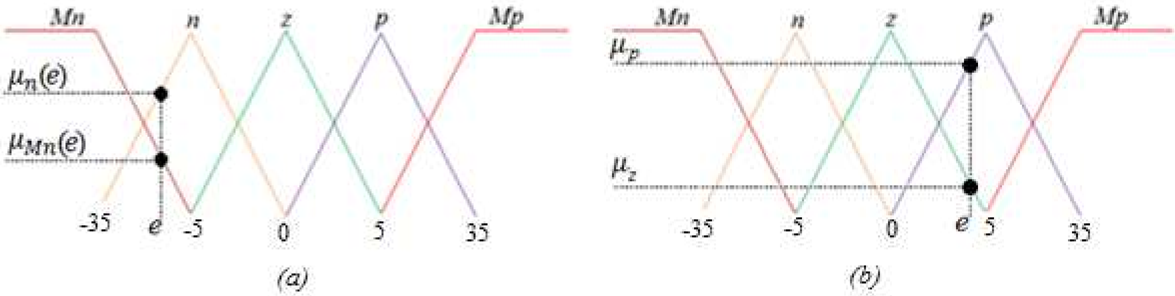



**Figure 6. Fuzzy values relative to two different situations for the error input signal (*e*)**

The desirable controller performance requires the definition of rules relating the input signal (***e***) and the fuzzy input and output sets, so these rules were defined according to the representation of Fig. 7 and Eq. (7), Eq. (8) and Eq. (9).

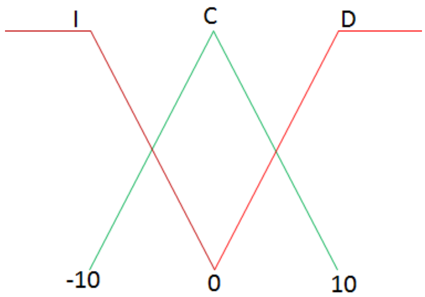



**Figure 7. Fuzzy sets**

$$I = \begin{cases} 1, & if\ y \le -10 \\ \dfrac{0-y}{0-(-10)}, & if\ -10 \le y \le 0 \end{cases} \tag{7}$$

$$c = \begin{cases} 0, & if\ y \le -10 \\ \dfrac{y-(-10)}{0-(-10)}, & if\ -10 \le y \le 0 \\ \dfrac{10-y}{10-0}, & if\ 0 \le y \le 10 \\ 0, & if\ y \ge 10 \end{cases} \tag{8}$$

$$D = \begin{cases} \dfrac{y-0}{10-0}, & if\ 0 \le y \le 10 \\ 1, & if\ y \ge 10 \end{cases} \tag{9}$$

The rules deployed are represented in Eq. (10):

$$\begin{array}{ll} if\ e = Mn, & then\ y = D \\ if\ e = n, & then\ y = D \\ if\ e = z, & then\ y = C \\ if\ e = p, & then\ y = I \\ if\ e = Mp, & then\ y = I \end{array} \tag{10}$$

According to Fig. 8 and rules defined in Eq. (10), the error value (*e*) determines two fuzzy values associated to the fuzzy input sets. Like is shown in Fig. 8 $\mu_n(e)$ and $\mu_z(e)$ determine the maximum value for each one fuzzy output sets. Thus as $\mu_{Mn}(e) = 0$ then *D* is limited to be *0;* simultaneously as $\mu_n(e) = \mu_n$, then *D* is limited to be $\mu_n$ at $Z_d$; like $\mu_z(e) = \mu_z$, then *C* is limited to be $\mu_z$ at $Z_{ci}$ and $Z_{cd}$; as $\mu_p(e) = 0$, then *I* is limited to be 0; finally as $\mu_{Mp}(e) = 0$, then *I* is limited to be 0. Like "*D*" has the suggested limiters *0* and $\mu_n$, then the chosen value is the largest value. Like "*C*" and "*D*" has the suggested limiters $\mu_z$ and $\mu_n$, then the chosen value is $\mu_n$. The output set limiters are used to define the defuzzified output (Sivanandam et al. 2007; Hakima et al. 2010).

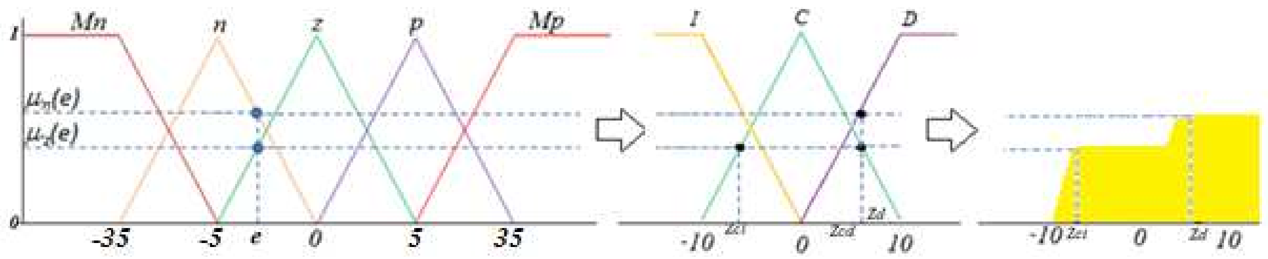



**Figure 8. Obtained fuzzy output representation from a determined (*e*) value**

In order to calculate the defuzzified output (Z*) has been decided to employ the centroid method whose mathematical expression is shown in Eq. (11).

$$Z^* = \frac{\sum_{i=1}^{n} (z_i)(\mu_i)}{\mu_i} \tag{11}$$

Where *i* corresponds to the quantity of fuzzy outputs generated. *Z* is the abscissa value corresponding to each one of the fuzzy outputs; $\mu_i$ corresponds to fuzzy values obtained from the fuzzication of the input (***e***). The defuzzified output (*Z**) is employed to decide the necessary commands to be applied. Eq. (12) shows how the mobile robot steering commands are defined according to the *Z** value. Steering commands shown in Eq. (12) are sent to the Arduino board which translates them to a differential drive acting over the servo-motors

$$\begin{array}{lll} if\ Z^* < -5, & then & u = turn\,left; \\ if\ \ -5 < Z^* < 5, & then & u = turn\,right; \\ if\ \ -5 < Z^* < 5, & then & u = go\,ahead; \end{array} \tag{12}$$

### 3.4. Software Application

The fuzzy controller described in section 3.3 was developed in Visual Studio 2010 employing the Visual Basic programming language. The graphical user interfaces are shown in Fig. 9 and Fig. 10.


**Figure 9. Initial Form of the Visual Basic Application.**

Figure 9 shows the initial application form which has the logotypes of São Carlos Engineer School (EESC) from Sao Paulo University (USP) and the EESC-USP Mechatronics Group. Figure 9 also shows the "Projeto Pinky" button which is employed to open the project form shown in Fig. 10. The "Sair" button allows to exit the application.

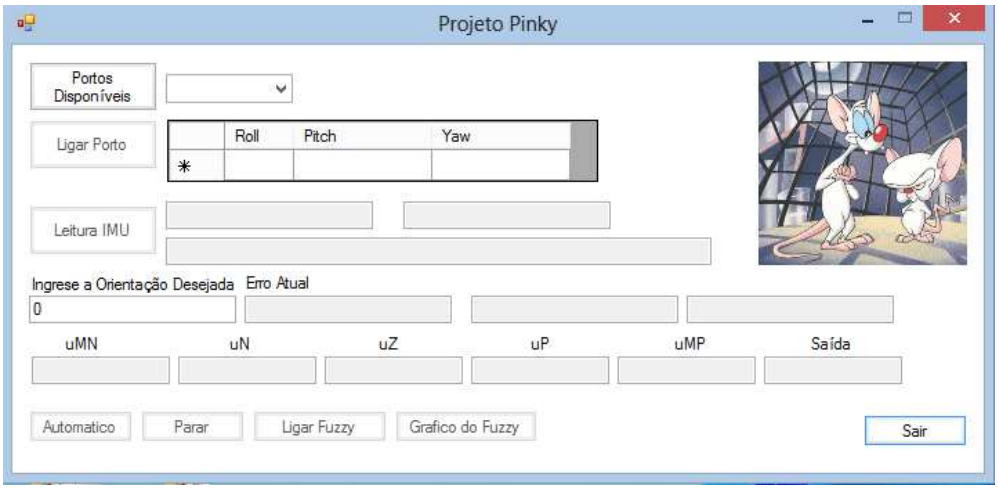



**Figure 10. Project Form of the Visual Basic Application.**

According to Fig. 10, the button "*Portas Disponíveis*" searches and reports the available computer serial ports. If some serial port is available, then "Ligar Porto" button is enabled what allows choosing a serial port to be opened, what enables "*Leitura IMU*" button to start a timer component.

Once the timer remains activated the "Automatico", "Parar", "Ligar Fuzzy" and "Grafico do Fuzzy" buttons are available to be clicked. The serial port reading is performed every 20 milliseconds in order to capture the lectures from the GPS receiver and the IMU unit. The installed IMU provides measurements of roll, Pitch and Yaw angles (Rajamani, 2005), so has been necessary to extract the yaw angle because such is the magnitude of interested which corresponds to the heading orientation of the vehicle and it will be processed in order to control the prototype orientation.

The "*Automatico*" button starts an operation mode in which has been established a small range related to the mobile robot heading orientation (*Yaw angle*) along its forward displacement. This operation mode corresponds to a kind of on-off trajectory control. When the button "*Parar*" is clicked, the robot stops and waits for a new command in order to start a new trajectory based on some desired orientation which is ente red by the "*Ingrese la orientação deseada*" text box.

The "*Ligar Fuzzy*" button starts a timer that runs every 50 milliseconds activating the fuzzy controller described in Section 3.3. In concordance to the application, fuzzy values "*uMN*", "*uN*", "*uZ*", "*uP*","*uMP*" and the controller output "*Saída*" are published in TextBoxes like is shown in Fig. 7. The controller output is sent to the mobile robot using Xbee communication. The captured lectures from the GPS receiver and the IMU unit are sent to an excel book to generate a database which includes data from each one of the performed tests. "Grafica do Fuzzy" button allows showing the input fuzzy sets and the fuzzy controller output graphs which will show in section 4. If "Sair" button is clicked, then the previous selected serial port and the fuzzy controller are left to exit the application.

## 4. RESULTS

Orientation (yaw) control has been performed over the built mobile robot which already has been described in section 3.1 and shown in Fig. 1 employing the fuzzy controller and the application expounded in the section 3.3 and 3.4 respectively.

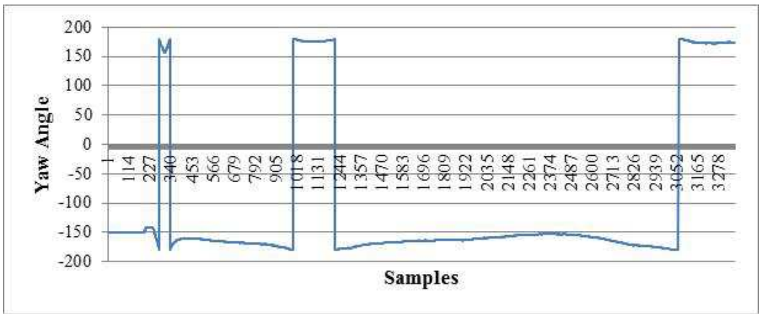



**Figure 11. Result of a test in open loop without controller**

Initial tests have been done using an on-off trajectory controller to act on the vehicle steering when the desired orientation along its forward displacement was -150°. In this case has been established an orientation range from -160° as lower limit to -140° as the upper limit. Fig. 11 shows the Yaw angle value variation during a period of time. Each Yaw angle value sample was read every 20 milliseconds and the test has been carried out during 65 seconds. The graph shows some Yaw values outside of the range, this effect allows concluding that the developed controller requires to be improved.

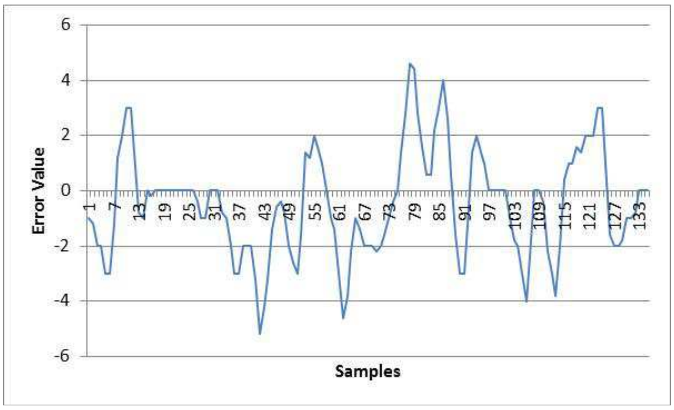



**Figure 12. Result of a test of the control system with the fuzzy controller.**

Once the first tests were finished, the fuzzy control system described in section 3.3 was deployed. Figure 12 shows results of a test done locating the vehicle on a regular surface to assume the absence of perturbations. In this test the error values along the vehicle displacement were inside a selected range. Each error value sample was read every 200 milliseconds and the test has been performed during 14 seconds because the route was a short line on an initial geographic coordinate (latitude = -22.0062751 and longitude = -47.8966941) and the final geographic coordinate (latitude = -22.0062923 and longitude = -47.8967128). The graph in Fig. 12 shows points near to the error value limits (lower limit = desired error - 5° and upper limit = desired error + 5°). In the case of the described experiment, the desired error value was 0° and the desired orientation was 25°.

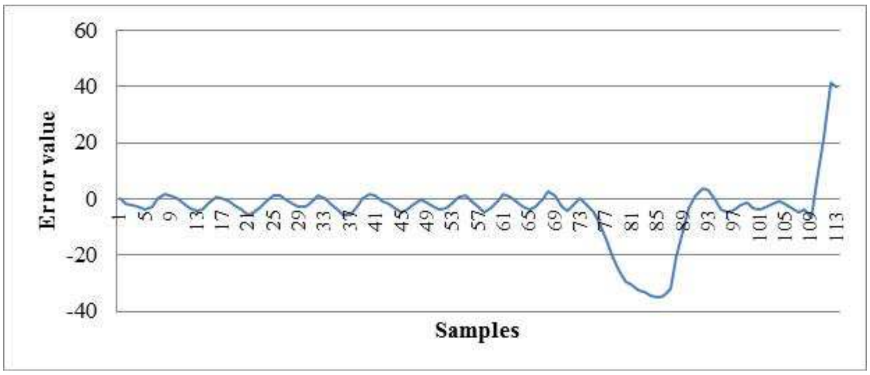



**Figure 13. Second test result of the control system with the fuzzy controller.**

The variations of error values are strong because the robot steering was strong. To improve this problem, the robot steering was enhanced by changing the servomotor control signals in order to modify the servo-motors acting toward lower differential speeds resulting on the behavior plotted in Fig. 13. In this test the vehicle was located on a regular surface with some irregular regions to induce some perturbations during the mobile robot locomotion. In concordance to Fig. 13, the error values variation were within the established limits (lower limit = desired error - 5° and upper limit = desired error + 5°). The desired error value was 0° and the desired orientation was -107°. Whenever a perturbation was induced the vehicle was forced to lose its path, but the fuzzy controller reacted fast to stabilize the mobile robot orientation without losing the desired vehicle heading angle. In this experiment each error value sample was read every 50 milliseconds and it has been executed along 22 seconds.

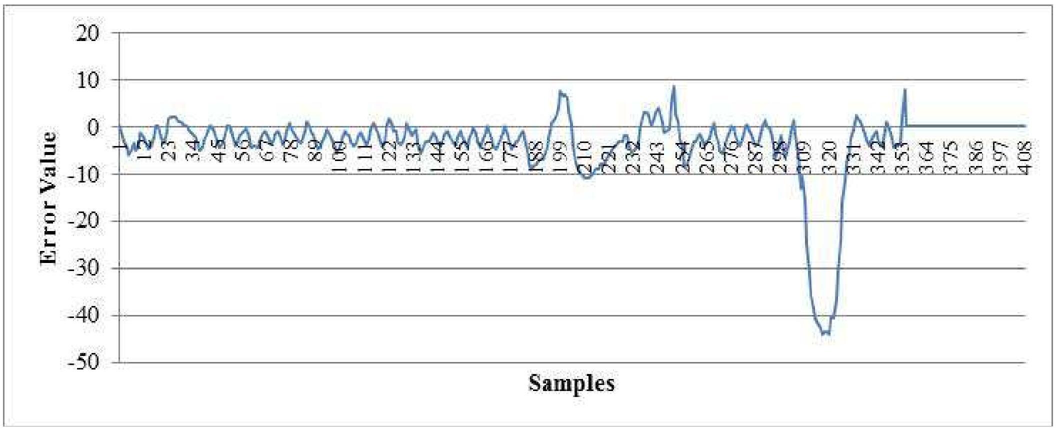



**Figure 14. Final test of control system.**

Fig. 14 shows results obtained from a final test. The chosen route was a regular surface on a right line among the initial geographic coordinate (latitude = -22.0061492 and longitude = -47.8967590) and the final geographic coordinate (latitude = -22.0062408 and longitude = -47.8967132). The chosen route had some irregular regions in order to induce some perturbations. The desired orientation was -108° and the desired error value was 0°. According to results shown in Fig. 14, the error lower limit value was -113° and the error upper limit value was -103°. The test has been performed during 100 seconds.

## 5. CONCLUSIONS

Taking into account that in the case of the locomotion systems for mobile robots, usually is required to develop a stage for high level control and another stage corresponding to low level control where the low-level control is related to the actuators direct control and high-level controller is related to the complete robotic system.

A vehicle like the AgriBOT (Sampaio et al. 2011; Archila et al. 2013) claims a unnecessary high energy expenditure in order to make experiments aimed to improve algorithms like exposed in this document in section 3.3, therefore, the exposed mobile robot prototype is a good platform to facing the study and experimenting of high level control strategies without making a big effort and facilitating its improving. In this way the experimental results might be collected and may be projected improvements employing the prototype in order to, subsequently, deploy an improved algorithm on the real robot. Basically a considerable quantity of experiments might be made on a simple prototype before to do a big effort experimenting on a complicated platform.

Has been concluded that fuzzy controller had a good performance according to the demanded requirements. Along the vehicle forward locomotion, when some perturbations were induced, the fuzzy control system was able to reassume a desired mobile robot orientation.

## 6. ACKNOWLEDGEMENTS

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