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Fuzzy Control for Navigation of a Mobile Robot Using Real Time Computational Vision

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Abstract: This study presents the methodology used to develop a navigation system for autonomous robotic vehicles using fuzzy control techniques and the application of computational vision algorithms for tracking a particular mobile object in real time. The developed system consists of a robot of two wheels of differential traction of which its kinematic model is presented, controlled remotely through a closed loop of control. The computer vision technique is used for the perception of the environment through the camera embarked on the vehicle. The technique of fuzzy control is implemented in the system to interpret and make the decisions of action of the robot during navigation in a poorly structured environment in addition to the uncertainties associated to the tracking of the objective through the image. Through, the validations made for the fuzzy control, the desired results are obtained that in this case corresponds to the monitoring of a given objective in real time.

Key words: Autonomous navigation, fuzzy logic, computer vision and distributed system, obtained, environment, uncertainties

INTRODUCTION

The process of control and navigation of autonomous robots is based on the conception that the system is able to act efficiently in new situations, supported by some specific knowledge. Miranda Neto (Miranda, 2007) consider an unstructured environment in which there are variations of the illumination, factor of the images as well as the influence of unknown factors such as mobile and fixed elements not captured in the first Acquisitions of the navigation scene where using the vision as the only system input sensor, becomes a difficult task for the selection of ideal movements for the displacement, leaving the system unstable. In this way, applications must be generated that are composed of a system "intelligent" enough to command the mechanical structure during its displacement when facing unstructured environments.

The implementation of artificial intelligence algorithms is based on fuzzy inference systems. Such algorithms have shown their effectiveness in various environments as presented below. By Liang (2011), the design of a classical PID controller is presented which is improved by using a parallel control action based on a fuzzy controller. At the industrial level, fuzzy control applications offer advantages over the system model where due to its complexity, an alternative identification is required, so as by Wang and Wang (2011) the design of a fuzzy controller for controlling a tank level in a boiler system is presented.

In the field of intelligent cities, the benefits of fuzzy systems are evident, especially to operate on complex and non-linear models such as vehicular traffic in this way, the development of fuzzy inference algorithms to implement traffic controllers through the intelligent traffic light scheme is presented by Moreno *et al*. (2013).

As the system presented in this paper operates with imprecise information, i.e., answers that are within ranges of values and not an exact answer, a flexible system of control is required with an approximate processing of the human mind which associates intelligence algorithms to fuzzy inference systems such as those proposed by Zadeh (1965).

To contextualize the work presented here, Fig. 1 illustrates the general view of the entire developed system where the focus of this article centers on the navigation

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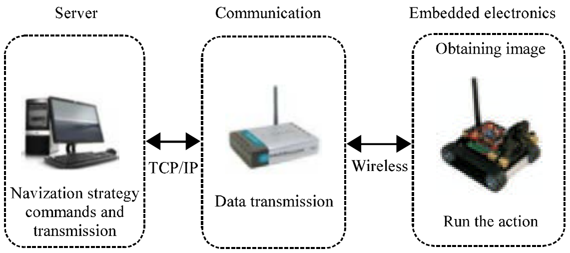

Fig. 1: Functional system architecture

strategy for robot movement. As shown in the functional architecture of the staged system (server, communication and embedded electronics) each stage is responsible for a given task as explained by Vitor (2010). In this way, embedded electronics has the function of obtaining the perception of the environment through the capture and processing of images that allows the robot to interact with the environment in which it is. The communication stage is responsible for regulating the traffic of information between the server and the robot. Finally, the server stage contains the software required to implement the artificial intelligence responsible for generating the orientation and speed commands that the robot must execute to meet its objective. The union of these stages forms a distributed processing that is executed in real time.

MATERIALS AND METHODS

Kinematic modeling: The differential-mobile robot used has the characteristic of being non-holonomic, i.e., it does not have the ability to move in all its directions but it is restricted so that its displacement is only on the Y-axis as shown in Fig. 2. For the first analysis, it must be assumed that the robot is a rigid body whereby movement is only possible in the plane (x_0, y_0). According to Campian (Moreno *et al*., 2013) the position of the robot can be described by a generalized coordinate vector $q = (x, y, \theta)^T$. In the inertial reference $F_0(x_0, y_0)$ system, generalized coordinates define the position and orientation of the robot. The position of the robot is defined by the coordinates (x, y) with respect to its center of mass 0_1, point at which the origin is defined of the local reference system $F_1(x_1, y_1)$ in addition the orientation of the robot is defined by the coordinates θ which represent the rotation of F_1 in relation to F_0.

The movement of the robot can be characterized by the velocities of translation v and rotation w over the center of mass of the robot. The translation system that enables the movement of the robot is formed by two independently driven wheels. The wheels of radius r are separated by a distance b, so that, the kinematic model of the mobile is determined by Eq. 1-3:

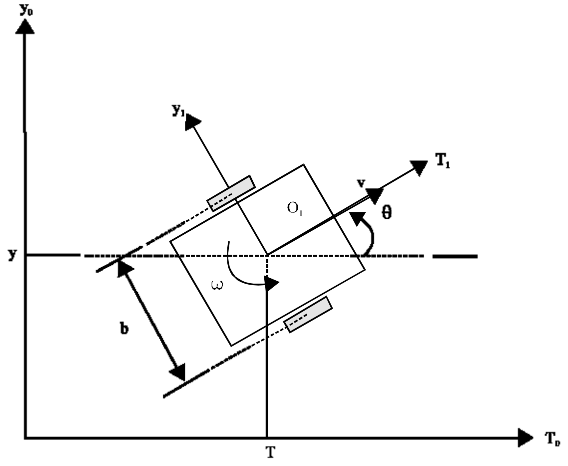

Fig. 2: Schematic of the mobile robot

$$\dot{x} = v\cos\theta \tag{1}$$

$$\dot{y} = v\,\text{sen}\theta \tag{2}$$

$$\dot{\theta} = w \tag{3}$$

The kinematic Model does not take into account the slippage in the wheels which can be solved by considering the relationships of robot speeds v and w with wheel speeds, denoting v_ι and v_r as each speed associated with the right and left wheel yields:

$$v = r\frac{v_\iota + v_r}{2} \tag{4}$$

$$w = r\frac{v_r - v_\iota}{b} \tag{5}$$

The linear velocities of the non-slip wheels can be related to their angular velocities as shown by Zadeh (1965) obtaining the following:

$$v_\iota = rw_\iota \tag{6}$$

$$v_r = rw_r \tag{7}$$

To obtain the mathematical model of the robot, Eq. 6 and 7 are replaced in Eq. 4 and 5:

$$v = r\frac{w_\iota + w_r}{2} \tag{8}$$

$$w = r\frac{w_r - w_\iota}{b} \tag{9}$$

Expressing Eq. 1-3 in rotation matrices and subsequently replacing in Eq. 8 and 9 is obtained:

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\cos\theta & 0\\ \text{sen}\theta & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}v\\ w\end{bmatrix} \tag{11}$$

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\cos\theta & 0\\ \text{sen}\theta & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}r\dfrac{w_l+w_r}{2}\\ r\dfrac{w_r-w_l}{b}\end{bmatrix} \tag{12}$$

In order to concretize the matrix kinematic model, the movement of the robot can be determined by Eq. 13.

Fuzzy modeling: According to Vitor (2010) fuzzy logic is characterized as the logic that supports rationing models that are approximate rather than exact. Fuzzy modeling and control techniques are used to treat qualitative information rigorously (Campion *et al*., 1996). In the conception of Zadeh (Wang and Xu, 2003) basically, it is a logic of imprecision and approximate rationing. The fundamental idea of this work is the ability of human beings to solve processes based on approximate information where they are generally expressed in linguistic terms such as “man is tall” or “we are almost close”.

The theory of fuzzy sets and the concepts of fuzzy logic can be used to translate in mathematical terms such inaccuracies by sets of linguistic rules. Its result will be a rule-based inference system in which fuzzy set theory and implemented logic argue the mathematical tool to study this problem. The general proposal of the modeling starts from the rationing stages for the inference process which are presented by Wang and Wang (2011).

The different applications of fuzzy logic are well established in various fields of action where it can be found in the literature base, both set theory, system modeling and fuzzy control applications (Chien, 1990; Zadeh, 2008; Tanscheit, 2004; Feng, 2010).

Implementation of the proposal: Derived that the final function of the system is to follow a moving target, the strategy to achieve this task by the robot is based on fuzzy modeling which will be presented in this section. It is noteworthy that the feedback system to validate and guarantee the correct execution of the movements sent to the robot as well as the control for its navigation are structured according to the information generated by machine vision tools. Figure 3 shows the procedures adopted to develop the fuzzy controller.

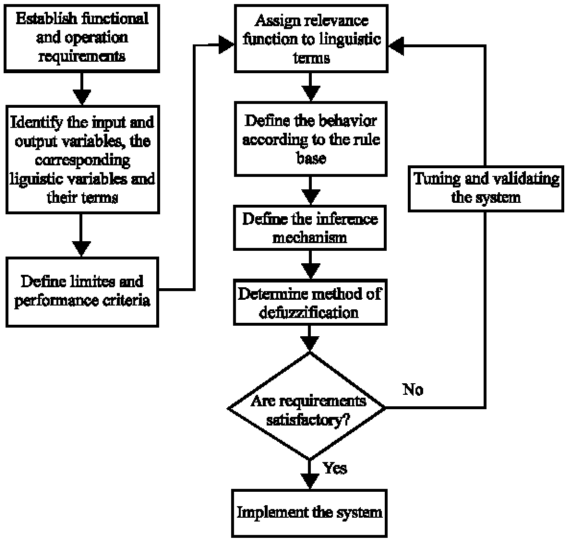

Fig. 3: Algorithm of fuzzy modeling

The principle used for the modeling of the control strategy was based on the displacement of depth and lateral displacement of the robot. The depth refers to the “forward” and “back” movements characterizing the distance relationship between the robot and the target and the lateral displacement references the "left" and "right" movements. In order to elaborate such displacement commands in function of a rule base, some calculations made with the information provided by computer vision are required.

The navigation information corresponds to the target zone (A) and the Representative Point (PR) the first step for modeling the strategy is to define the point. This central point will serve as a basis for verifying the variation in the axes (X, Y) of the reference target to the center of the image. This central point called PC is obtained in Eq. 14 where iw and ih are the horizontal and vertical dimensions of the image:

$$PC = \left(\frac{iw}{2}, \frac{ih}{2}\right) \tag{14}$$

Defining the central point PC and the variation of PR referring to the PC, VP is called as:

$$VP = PR\text{-}PC = \left(PR.x\text{-}PC.x, PR.y\text{-}PC.y\right) \tag{15}$$

With the obtaining of the VP values in relation to the two axes, the rule base is then created as a function of each displacement. With respect to the horizontal displacement, it is possible to determine the movements of “left” and “right” following the information of VPx, so,

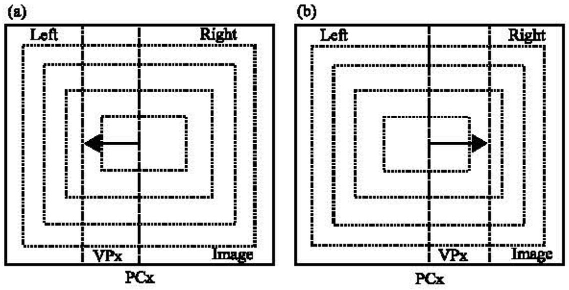

Fig. 4: Commands for horizontal displacements

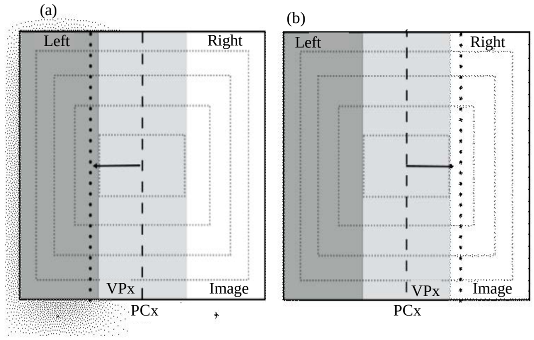

Fig. 5: Areas of membership for the VPx variable

if the value of VPx is negative, "left" command will be given in case it is positive, then "right" command will be given according to Fig. 4.

However, since, the PR value has a variation caused by the variation of luminosity over time, this may generate undesired movements in the robot. In case the value VPx varied near the value of PCx, it can generate oscillatory movements like "left", "right", "left" along the acquired images. To avoid this, areas of membership are created on the horizontal axis of the image in order to avoid those movements. Three areas with the respective names of "Left", "Standing" and "Right" were determined where the movement of the robot is given in relation to these areas as shown in Fig. 5.

The rules of the movements referring to the orientations in the horizontal axis were developed according to the previous explanation. Thus, there is the universe of displacement in X varying between [-160.160] (dimension of the image in the horizontal direction) given by Fig. 6 with respective membership functions.

Following this, the strategy was developed for the depth movements in the environment, noting that, since, this project is working with mono-vision, the depth information of the scene is lost in the construction of the image. To perceive when the target is shifting in the depth axis, two aspects can be extracted as information, the variation of PR in the Y-axis given by VPy and the area of objective A. Obtaining the displacement of the target by the variation given by VPy is characterized by the optical axis EO of the camera, since, it is not parallel with the Z-axis of the environment. Therefore, the displacement of the target on the Z-axis of the environment will be reflected on the Y axis of the camera as shown in Fig. 7.

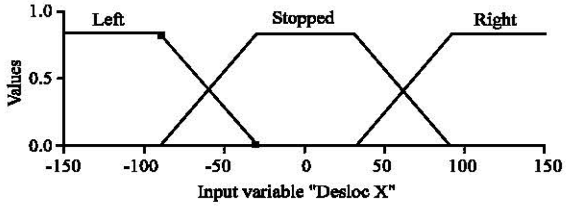

Fig. 6: Membership functions for lateral displacement

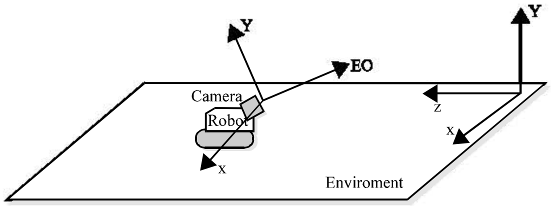

Fig. 7: Camera reference, optical axis is not parallel to the Z-axis of the environment

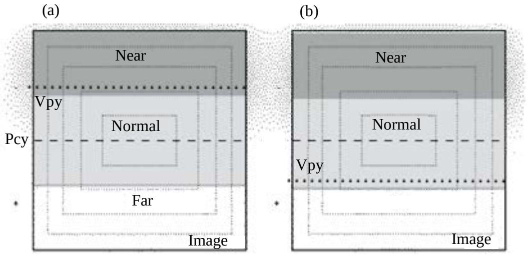

Fig. 8: Membership area for the VPy variable

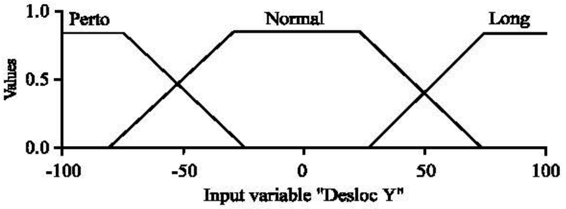

Fig. 9: Membership functions for vertical displacement

Thus, the first depth information for the motion rule is obtained through the relationship of the axes presented. For this, the areas of membership for the variable VPy named "Near", "Normal" and "Far" are created in the image as shown in Fig. 8. For each reference area, the respective movement of "back", "Stop" and "Forward" was generated as illustrated in Fig. 9.

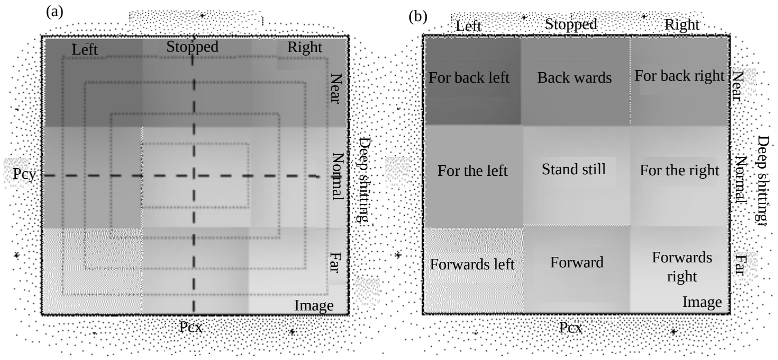

Fig. 10: Rule base for the displacement: a) Relation of the areas of membership and b) Table of movements associated with the areas

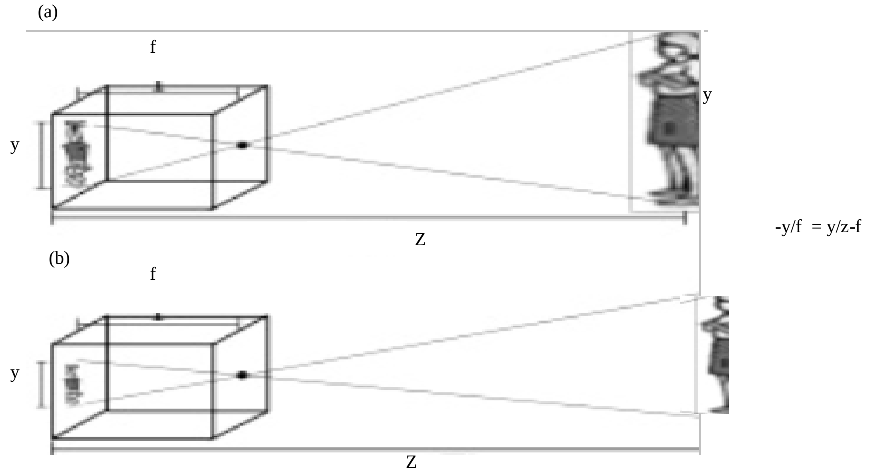

Fig. 11: Extraction of depth information: a) Perspective projection for different distances in Z and b) Perspective model

Noting that all rule bases so far were created on the same image domain in this way, there is a relationship between the rules Fig. 10a that will provide more orientation of the movement as "back/left", "back/right", "Forward/left" and "forward/right", according to Fig. 10b.

The second aspect for extracting the auxiliary information from the depth is obtained in area A. This is characterized by the perspective projection in the formation of the image which can be deepened by Jantzen (2007), Passino *et al.* (1998), Kulkarni (2001), Ramirez-Cortes *et al.* (2011) and Hossen *et al.* (2017). In general, the existing geometric relationship can be presented by the stereometrics camera giving origin to the perspective model as shown in Fig. 11.

In this way, it can be concluded that given a central area called AC, characterizing y = AC of the target in the image relative to a distance Z, the variation of area A denoted by VA in relation to the central area AC, at time t which will indicate the displacement on the Z axis. As shown in Eq. 16, the variable A also, oscillates with the illumination, generating different values along the time referenced by A. To minimize this problem, two strategies were implemented being the first in the modeling of the value of the central area AC and the second based on the relation of the areas of membership previously seen.

The first strategy to determine the value of AC was modeled in order to find an average value over time which represents the fixed value of the area using the system when it is at rest. For this strategy to be applied, it is necessary to place the system at rest through the PR information, i.e., for the selected target region anywhere in the image, the PR data will be used to centralize this target and then start the AC calculation. The purpose of this calculation is to centralize it close to the values of PR that is within the area of membership of the "stopped" movement. This action implies that the robot and the target are probably standing, characterizing that any variation of area A, during that time "Stop" represents the same area A. This condition is replicated to obtain AC using Eq. 16 where td is defined as the trigger time td = t where n is a constant given by 100 and t is the acquisition number of the image over the time.

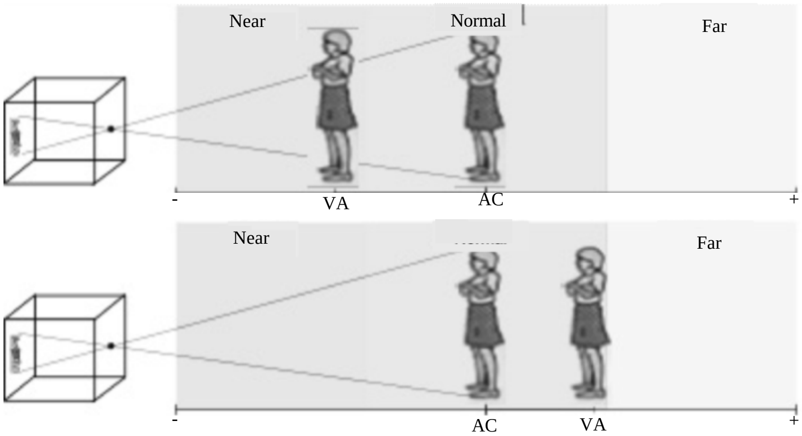

Fig. 12: Membership area for the VA variable, evaluating on the Z-axis

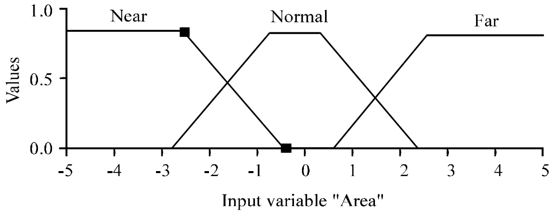

Fig. 13: Membership functions for the area

$$AC = \frac{1}{n}\sum_{t=td}^{td+n} At \qquad (16)$$

Defining the central area AC, the variation of A, referring to the AC is given by VA by:

$$VA = \left(\frac{AC\text{-}At}{AC}\right) \qquad (17)$$

Finding the value of the variation of the VA area, the second strategy is to model the area of membership for that variable. As this value also, characterizes the displacement in the Z-axis, the nomenclature of the areas of membership was maintained in "near|", "normal" and "Far" as well as the movements "back", "stopped", "forward" as shown in Fig. 12 and 13.

At this point, the two depth information represented by the variables (VA and VPy) theoretically will have to result in the same information of the environment which in practice does not occur due to the noises generated in the system (internal and external factors). An example of this discrepant phenomenon would be that the value of VP.y was in the membership area "Close" of the image and the variable VA with a positive value within the membership area "far" where the control and navigation strategy would be in conflict. To solve this problem, a ru base was implemented that considers this type of conflicting relationships. For the development of fuzzy arithmetic, it is used the t-norm (and) characterized by the product, the s-norm (or) defined as the probabilistic sum, the implication made by the product, the aggregate by the addition and defuzzification by the centroid method. The fuzzy logic modeling was implemented in the MATLAB® fuzzy toolbox where relationships were defined according to Fig. 14, however, the implementation of the fuzzy inference systems was performed in C language within the electronics of the mobile robot.

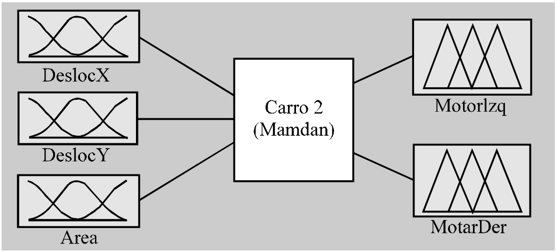

Fig. 14: Scheduling of the fuzzy system relating the inputs and outputs through the MATLAB® fuzzy toolbox

Following the relations to make the inference of the fuzzy system, the graphs that compose the membership functions for the desired outputs are obtained as shown in Fig. 15.

In this way the proposed system consists of the output of the fuzzy controller which is given by the intensity required for the speed of each motor. After modeling the fuzzy control, the next stage consisted of the synchronization of the proposed model with the plant which for the case is the robot SVR1.

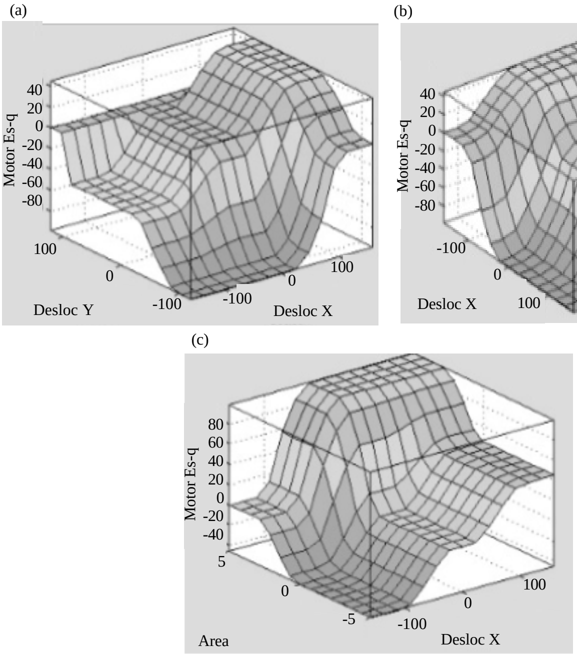

Fig. 15: Surface graph generated by the rule compositions: a) Relation between the displacements in X and Y for the left motor; b) Relation between the displacements in X and Y for the right motor and c) Relation between the area and the horizontal displacement for the left motor

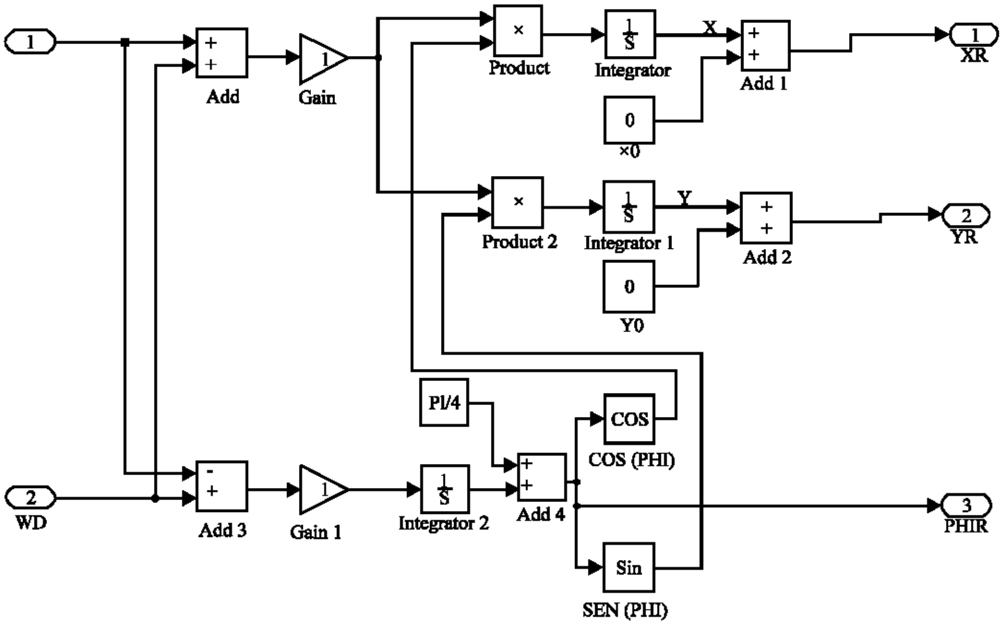

Fig. 16: Kinematic model implemented in simulink

RESULTS AND DISCUSSION

The experiments were based on the simulation developed in Simulink of MATLAB® as presented in Fig. 16 where the kinematic model determined by Eq. 13 was validated, it is also sought to validate the fuzzy algorithm for tracking a target on favorable terms, i.e., that the area to be detected is always constant being in the normal region but the displacement of the target along the

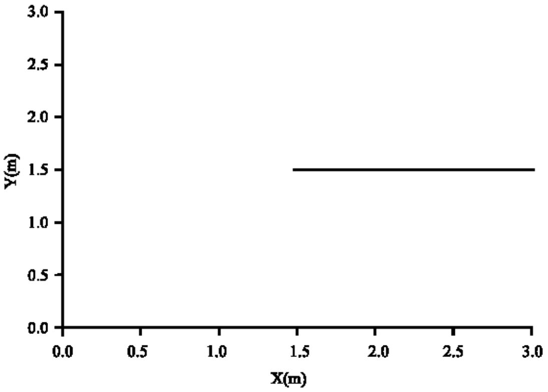

Fig. 17: Simulated target tracking in a straight line

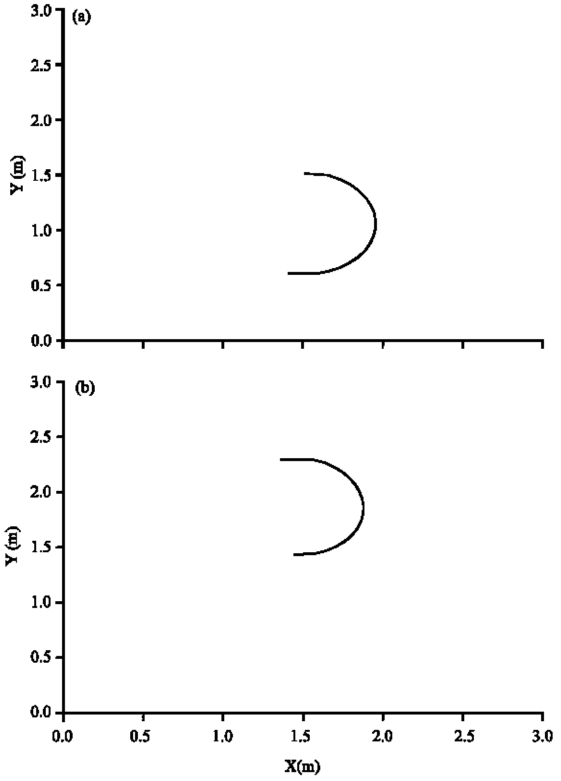

Fig. 18: Simulated tracking of the robot with respect to the object towards the right and left respectively

plane (X, Y) with variations according to the positions of the object as forward, back, right and left is evaluated.

The first validation is done with the movement of the object in a straight line where the robot follows it, according to the parameters established as illustrated in Fig. 17.

In the same way, the behavior of the robot is analyzed when the object moves to the right and to the left as shown in Fig. 18a, b.

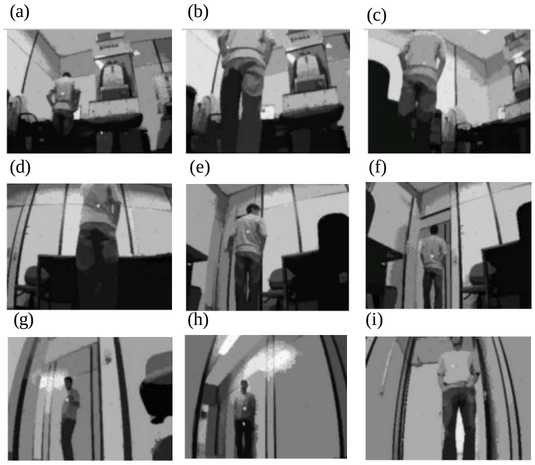

Fig. 19: Simulation on indoor environment, “robot vision”

Subsequently, these parameters were implemented in the real system where the experiments done involving the entire monitoring and navigation system are presented below.

The first case deals with an internal environment where monitoring and navigation is performed through the view of the robot as shown in Fig. 19. At first the robot is at certain distance from the target which is selected. The sequence of images shows that the robot is following the target which moves from the interior of a room to a narrow corridor. It is observed that although the objective shows a good deal with the background in some images the influence of the luminosity of the lamps affects the tracking of the objective in relation to the tonalities of the color of the objective, hence, generating instability in the data sent for navigation and fuzzy control. The video generated from this experiment clearly presents the behavior of the system in relation to the displacement of the target versus the movement performed by the robot.

CONCLUSION

When analyzing the sequence of the figures of the experiment, it can be noticed that there is still a deficiency in the synchronization of the projected membership functions. This is due to the fact that there are still output currents for the motors that do not exactly match the angle the robot must take to center the target.

The modeling of a fuzzy control system has the advantage of a coherent response to the movements of the object to be followed in an unstructured environment. Through the use of a natural language corresponding to the fuzzy algorithm, it is sought to avoid the use of rigid rules constraining a conventional control system which in turn facilitates the development of the robotic controller implementation.

According to what was presented, the fuzzy control modeling represents in a satisfactory way the complex system that relates the robot and an unstructured environment, observing that this theory implicitly finds a simplicity in the development of the algorithm making it quite flexible for future improvements and adaptations. It is also important to note the existence of a possible tuning to improve the response in the environment.

ACKNOWLEDGEMENTS

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