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Virtual Simulator for Design of Mobile Robot Control and Navigation Systems

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1. Introduction

The development of control systems for independent mobile robots has appear as a great challenge for the researchers until the current days. Different platform for the project of control system for independent mobile robots come being used in diverse research areas. Per many years the researchers have constructed control systems that present an intelligent behavior in controlled environments, with ideal situations, but that normally does not keep the same performance in the real world. Innumerable systems of control exist to be used in the real world, but generally these systems are limited and they do not present an independent or intelligent behavior.

Diverse possible applications for the mobile robots already exist. In the transport, monitoring, inspection, cleanness of houses, space exploration, aid the physical deficient, among others. However, the independent mobile robots had not yet caused much impact in domestic or industrial applications, mainly had the lack of a system with robust, trustworthy and flexible control that it would allow these robots operated in dynamic environments, less structuralized, and inhabited by human beings. The development of a mobile robotic model system with open architecture and flexible control, with robust control system, that incorporates what exists of modern in terms of embedded hardware technology and that makes possible the operation of a mobile robotic systems in a real world environment is one of the motivations of this work.

The locomotion planning, under some types of restrictions, is a very vast field of research in the area of the mobile robotics (Graf, 2001). The basic planning of trajectory for the mobile robots imply the determination of a way in the space-C (*configuration space*) between an initial configuration of the robot and a final configuration, in such a way that the robot does not collide with no obstacle in the environment, and that the planned movement is consistent with the kinematic restrictions of the vehicle. In this context, one of the boarded points in this work was development of a trajectory calculator for mobile robots.

One of the main motivations of this work is to propitiate a virtual environment that facilitates the development of archetypes of embedded systems, emphasizing the implementation

of tools that allow the simulation of the kinematic, dynamic and control conditions, with real time monitoring of all important points of the system. In this way, the proposal of a virtual simulator of mobile robotic systems is presented together with techniques of rapid prototyping.

2. The Mobile Robot Platform

Platforms for knowledge consolidation could be used in several educational and research areas, such as modeling, control, automation, power systems, sensors, transmission of data, embedded electronics and software engineering. In fact, the use of the mobile robots as base for knowledge consolidation, has been successful adopted in many educational and research institutions mainly because they appear to be a quite attractive low cost solution that allow the integration of several important areas of knowledge. Mobile robots also become a better solution for practical problem in modern society. These appointments shows a large applicability of mobile robots and a crescent request in the modern world. The proposal of this project is developing a generic open system for control a mobile robot and supply this need. The system emphasizes the control structure, the supervision and the transfer of information. In a context of educational and research aims the project aspects and integration solution compose the desired know-how acquired during the development of the system, which one certainly would not to be approached if a commercial mobile robot was acquired.

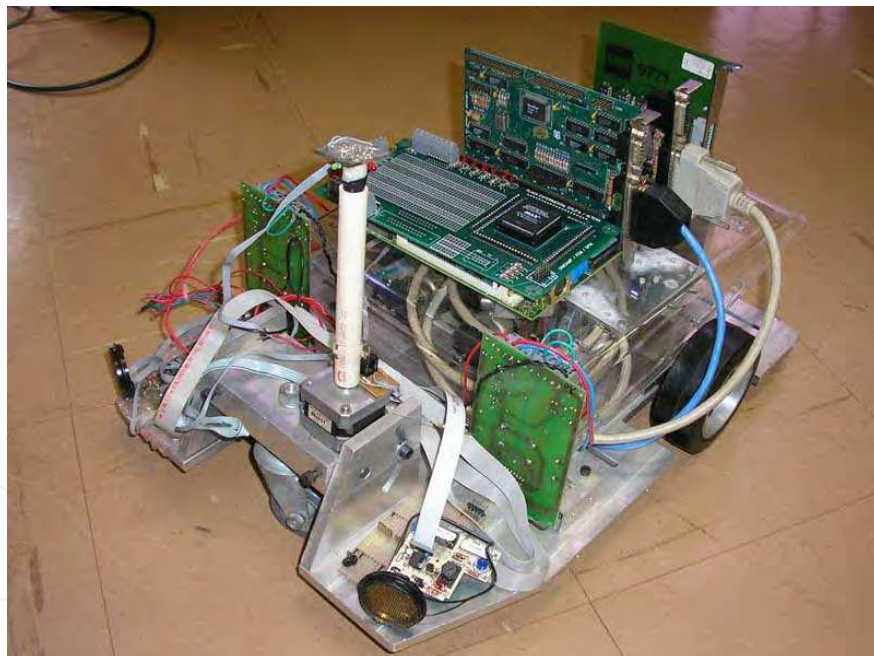


Fig. 1. Mobile robot platform prototype.

An embedded processor, with a dedicated control software, to be used on a platform mobile robotics, is considered. In addition to this platform another one, a commercial platform, coupled to a communication net, is analyzed. The set of platforms, whose objectives are making use of the existing communication interfaces and providing an embedded user interface alternative in the mobile robot, allows the creation of a powerful link with the external world. The objective of this platform is to make use of the existing communication interfaces, as well

as to provide an embedded user interface alternative in the mobile robot. Another aspect considered, is the flexibility of the hardware project, which allows the expansion of mobile robot facilities. New sensor combinations should be used. Different supervision and control models should equally be used to carry out the mobile robot tasks.

This work aim to presents the implementation of a virtual environment for project simulation and conception of supervision and control systems for mobile robots and focus on the study of the mobile robot platform, with differential driving wheels mounted on the same axis and a free castor front wheel, whose prototype used to validate the proposal system is depicted in Fig. 1 and Fig. 2 which illustrate the elements of the platform.

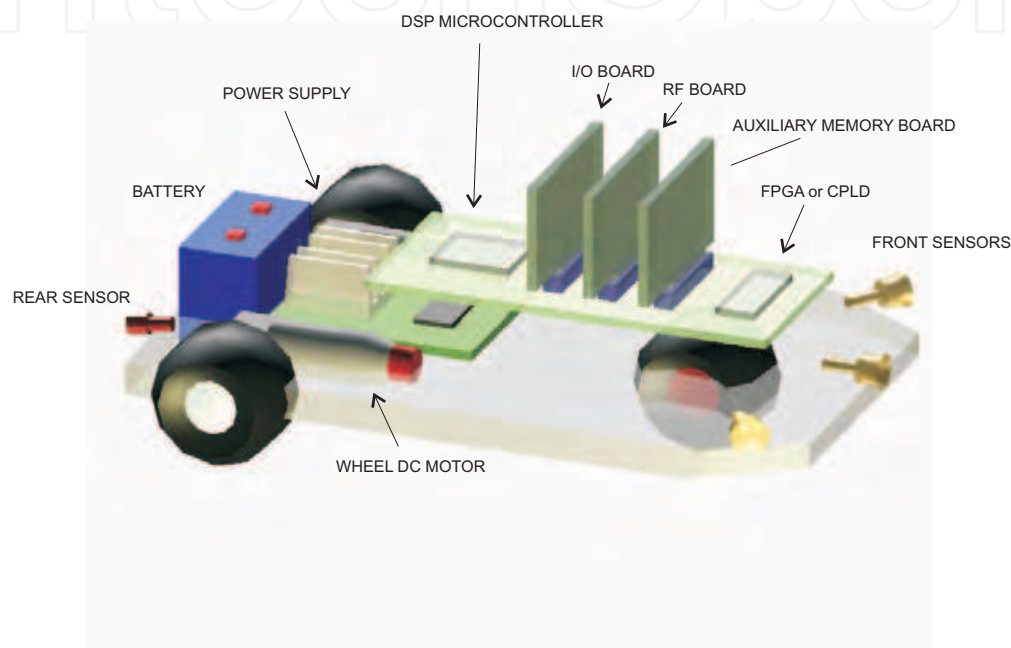


Fig. 2. Mobile robot platform and elements.

3. Mobile robot modeling

It's necessary to make the mobile robot mathematics modeling in order to extract the equation and algorithms that will be used in the simulator's blocks. This section due with that, observing the fact our physics model is a mobile robot with differential driving wheels with nonholonomic restrictions.

Suppose that a robot is in a position (x, y) and "facing" along a line making an angle θ with the x axis (Fig. 3). Through manipulation of the control parameters v_e and v_d , the robot can moves to different positions. Determining the positions that is reachable at given control parameters is know as the forward kinematics problem for the robot (Siegwart & Nourbakhsh, 2004). Because of v_e , v_d and hence R and ω are functions of time, is straightforward to show (Fig. 3) that, if the robot has position (x, y, θ) at some time t , and if the left and right wheels have ground-contact velocities v_e and v_d during the period $t \rightarrow t + \delta t$, the ICC (Instantaneous Center of Curvature) is given by

$$\text{ICC} = [x - R \sin(\theta), y + R \cos(\theta)]. \quad (1)$$

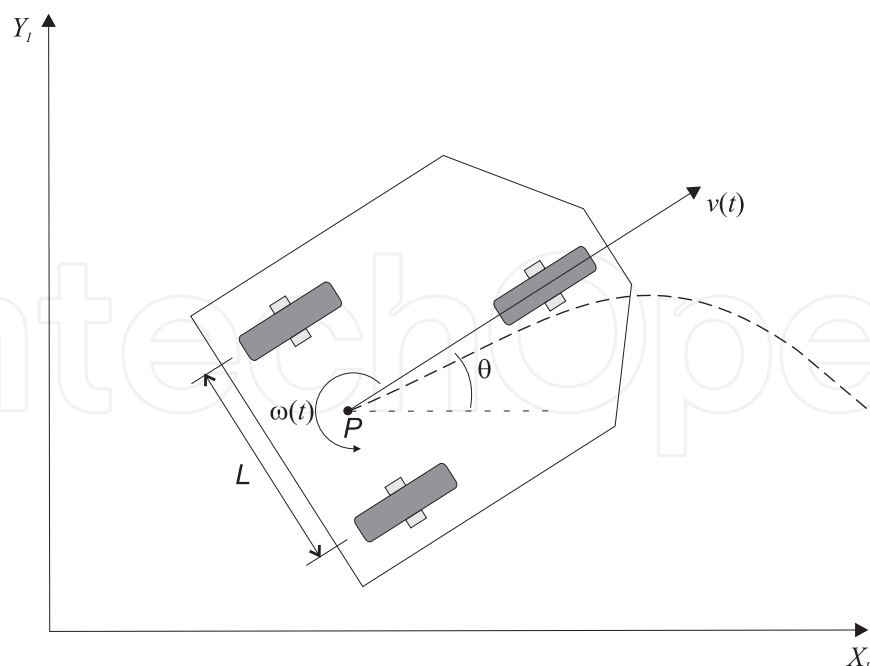


Fig. 3. Forward kinematics geometry.

For better comprehension of the equation, it's possible to simplify $ICC = I$, $\cos(\omega\delta t) = C$ and $\sin(\omega\delta t) = S$, then, at time $t \rightarrow t + \delta t$, the position of the robot is given by

$$\begin{bmatrix} x' \\ y' \\ \theta' \end{bmatrix} = \begin{bmatrix} C & -S & 0 \\ S & C & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - I_x \\ y - I_y \\ \theta \end{bmatrix} + \begin{bmatrix} I_x \\ I_y \\ \omega\delta t \end{bmatrix}. \quad (2)$$

The Eq. (2) describes the motion of a robot rotating a distance R about its ICC with an angular velocity given by ω (Dudek & Jekin, 2000). Different classes of robots will provide different expressions for R and ω (Shim et al., 1995).

The forward kinematics problem is solved by integrating (2) from some initial condition (x_0, y_0, θ_0) , it is possible to compute where the robot will be at any time t based on the control parameters $v_e(t)$ and $v_d(t)$. For the special case of a differential drive vehicle, it is given by

$$\begin{aligned} x(t) &= \frac{1}{2} \int_0^t [v_d(t) + v_e(t)] \cos[\theta(t)] dt, \\ y(t) &= \frac{1}{2} \int_0^t [v_d(t) + v_e(t)] \sin[\theta(t)] dt, \\ \theta &= \frac{1}{L} \int_0^t [v_d(t) - v_e(t)] dt. \end{aligned} \quad (3)$$

A question more interesting, and at same time more difficult to answer, is: How can the control parameters could be selected in a way the robot obtain a specific global position or follow a specific trajectory? This is known as the task of determining the vehicle's *inverse kinematics*: inverting the kinematic relationship between control inputs and behavior. It is also related to the problem of trajectory planning.

3.1 Inverse kinematics for differential drive robots

The Eq. (3) describe a constraint on the robot velocity that cannot be integrated into a positional constraint. This is known as a *nonholonomic constraint* and it is in general very difficult to solve, although solutions are straightforward for limited classes of the control functions $v_e(t)$ and $v_d(t)$ (Zhao & BeMent, 1992). For example, if it is assumed that $v_e(t) = v_e$, $v_d(t) = v_d$ and $v_e \neq v_d$, then (3) yields

$$\begin{aligned} x(t) &= \frac{L}{2} \frac{v_d + v_e}{v_d - v_e} \sin \left[\frac{t}{L} (v_d - v_e) \right], \\ y(t) &= -\frac{L}{2} \frac{v_d + v_e}{v_d - v_e} \cos \left[\frac{t}{L} (v_d - v_e) \right] + \frac{L}{2} \frac{v_d + v_e}{v_d - v_e}, \\ \theta(t) &= \frac{t}{L} (v_d - v_e), \end{aligned} \quad (4)$$

where $(x, y, \theta)_{t=0} = (0, 0, 0)$. Given a goal time t and goal position (x, y) . The Eq. (4) solves for v_d and v_e but does not provide a solution for independent control of θ . There are, in fact, infinity solutions for v_d and v_e from Eq. (4), but all correspond to the robot moving about the same circle that passes through $(0, 0)$ at $t = 0$ and (x, y) at $t = t$; however, the robot goes around the circle different numbers of times and in different directions.

4. Control Architecture System

The control architecture system can be visualized at a logical level in the blocks diagram of Fig. 4.

The system was divided into three control levels, organized in different degrees of control strategies. The levels can be described as:

- **Supervisory control level:** This represents a high level control. In this level it was possible to carry out the supervision of one or more mobile robots, through the execution of global control strategies.
- **Local control level:** In this level the control was processed by the mobile robot embedded software implemented in a 8 bits microcontroller. The control strategies allowed decision making to be done at a local level, with occasional corrections from the supervisory control level. Without communication with the supervisory control level, the mobile robot just carried out actions based on obtained sensor data and on information previously stored in its memory.
- **Interface control level:** This control level is restricted to strategies of control associated with the interfaces of the sensor and actuators. The strategies in this level were implemented in hardware, through PLD (Programmable Logic Devices).

The hardware architecture, from the point of view of the mobile robot, was organized into several independent blocks, connected through the local bus which is composed by data, address and control bus (Fig. 5). A master manager block operates several slave blocks. Blocks associated with the interfaces of sensors and actuators, communication and auxiliary memories were subjected to direct control from the manager block. The advantage of using a common bus was the facility to expand the system. Despite of the limitations of resources, it was possible to add new blocks, allowing an adapted configuration of the robot for each task.

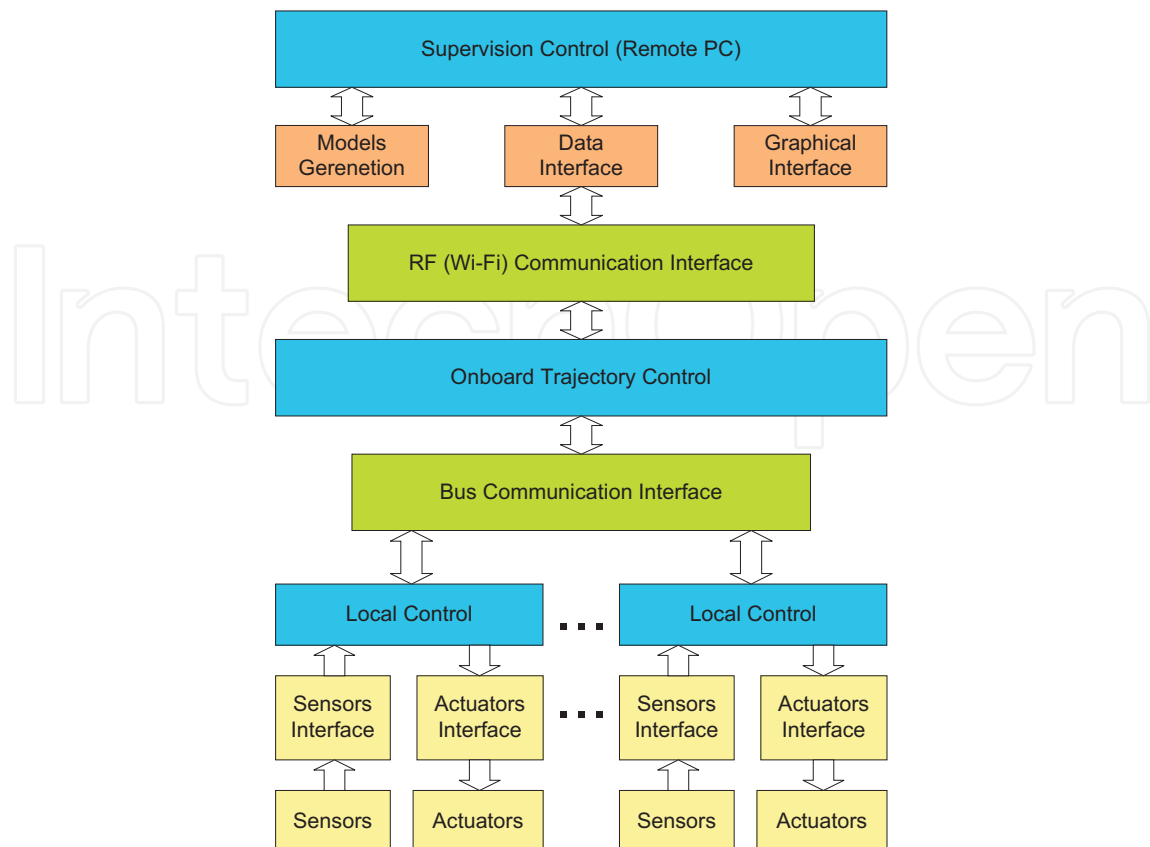


Fig. 4. Different control levels of the proposed system.

4.1 Description of Blocks

- Supervisory control block:** Is the highest level of control. In this block, the supervision of one or more mobile robots is managed through the execution of global control strategies. It is implemented in an IBM PC platform and is connected with the local control level, in the mobile robot, through Ethernet wireless WI-FI link. This protocol uses IEEE 802.11a standard for wireless TCP/IP LAN communication. It guarantees up to 11 Mbps in the 2.4 GHz band and requires fewer access points for coverage of large areas. Offers high-speed access to data at up to 100 meters from base station. 14 channels available in the 2.4 GHz band guarantee the expansibility of the system with the implementation of control strategies of multiple robots.
- Master manager block:** It is responsible for the treatment of all the information received from other blocks, for generation of the trajectory profile for the local control blocks and for communication with the external world. In communication with the master manager block, through a serial interface, a commercial platform was used, which implemented external communication using an Ethernet WI-FI wireless protocol. The robot was seen as a TCP/IP LAN point in a communication net, allowing remote supervision through supervisory level. It's implemented with Texas Instrument TMDSDSK6416 DSP board Kit that uses the TMS320C6416 DSP, a 1 GHz device delivering up to 8000 million instructions per second (MIPs) with highest performing.
- Sensor interface block:** It is responsible for the sensor acquisition and for treatment of data in digital words, to be sent to the master manager block. The implementation of

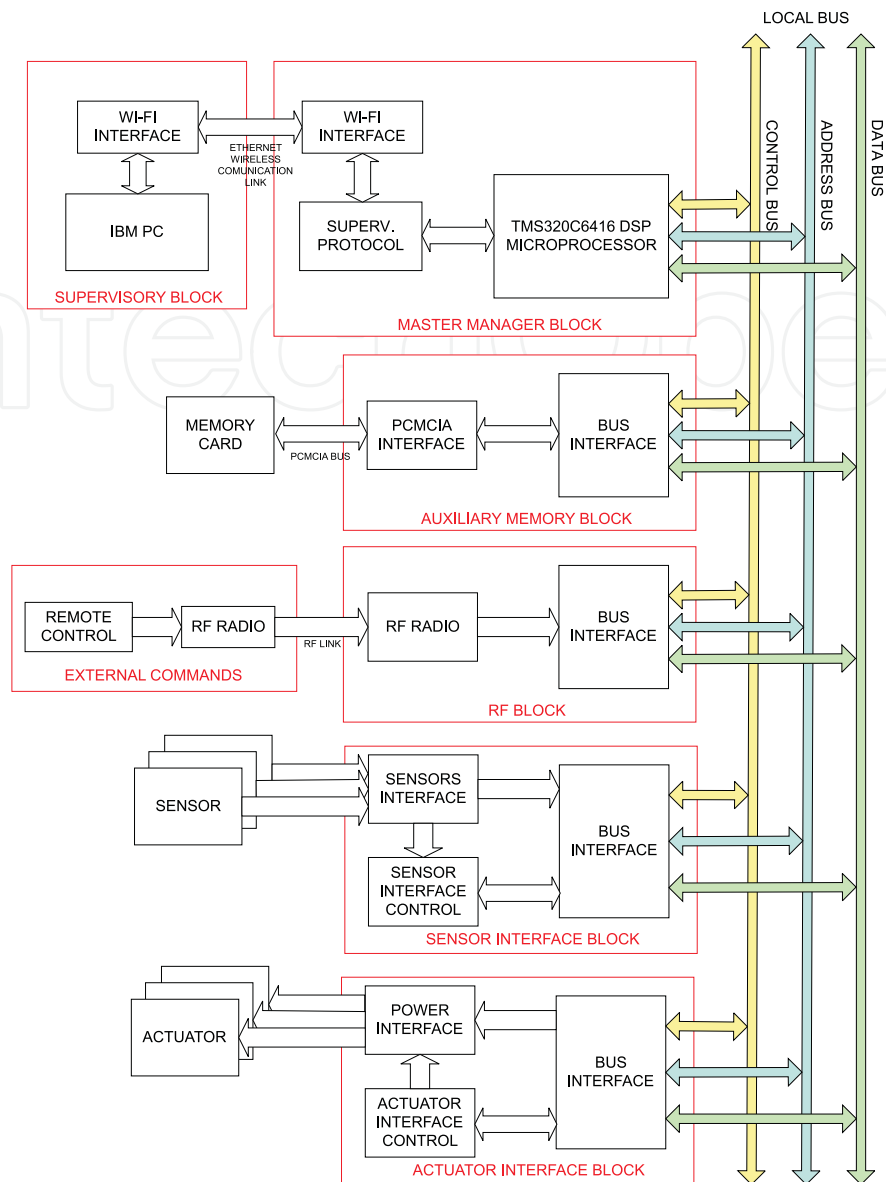


Fig. 5. Hardware architecture block diagram of the proposed system.

that interface through PLD allowed the integration of information from sensors (sensor fusion) locally, reducing manager block demand for processing. In same way, they allowed new programming of sensor hardware during robot operation, increasing sensor treatment flexibility.

- **Actuator interface block:** This block carried out speed control or position control of the motors responsible for the traction of the mobile robot. The reference signals were supplied through bus communication in the form of digital words. Derived information from the sensor was also used in the controller implemented in PLD. Due to integration capacity of enormous hardware volume, PLD was appropriate to implement state machines, reducing the need for block manager processing. Besides the advantage of the integration of the hardware resources, PLD facilitated the implementation and debug-

ging. The possibility of modifying PLD programming allowed, for example, changes in control strategies of the actuators, adapting them to the required tasks.

- **Auxiliary memory block:** This stored the information of the sensor, and operated as a library for possible control strategies of sensors and actuators. Apart from this, it came with an option for operation registration, allowing a register of errors. The best option was an interface PCMCIA, because this interface is easily accessible on the market, and being well adapted for applications in mobile robots, due to low power consumption, low weight, small dimensions, high storage capacity and good immunity to mechanical vibrations.
- **RF communication Block:** It allows the establishment of a bi-directional radio link for data communication. It operated in parallel with the commercial platform WI-FI link. The objective of these communication links was to allow the use of remote control. The remote control has a high trajectory priority from other blocks, like supervisory control block, and can take the control of the mobile robot to execute, for example, emergency necessary movements or stop. To implement this block was used a low power UHF data transceiver module BiM-433-40.

5. Mobile Robot Simulator

The use of the system has beginning for the captation of main points for generation of the mobile robot trajectory. The idea is to use a system of photographic video camera that catches the image of the environment where the mobile robot navigates. This initial system must be able to identify the obstacles of the environment and to generate a matrix with some strategic points that will be good for input data for the system of trajectory generation. Figure 6 presents a general vision of the considered simulator system.

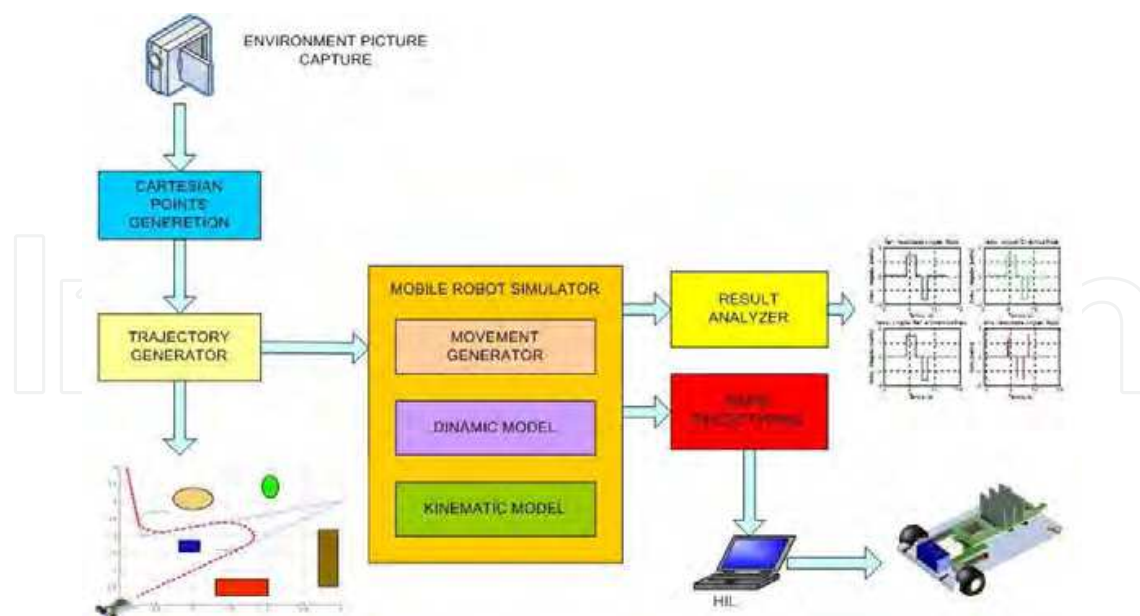


Fig. 6. General vision of the simulator system.

Fig. 7 illustrates an example of an environment with some obstacles where the robot must navigate. In this environment, the robot is located initially in the P1 point and the objective

is to reach the P4 point. The generating system of initial cartesian points, must supply to the module of trajectory generation, with the cartesian points P1, P2, P3 and P4, that are the main points of the traced route.

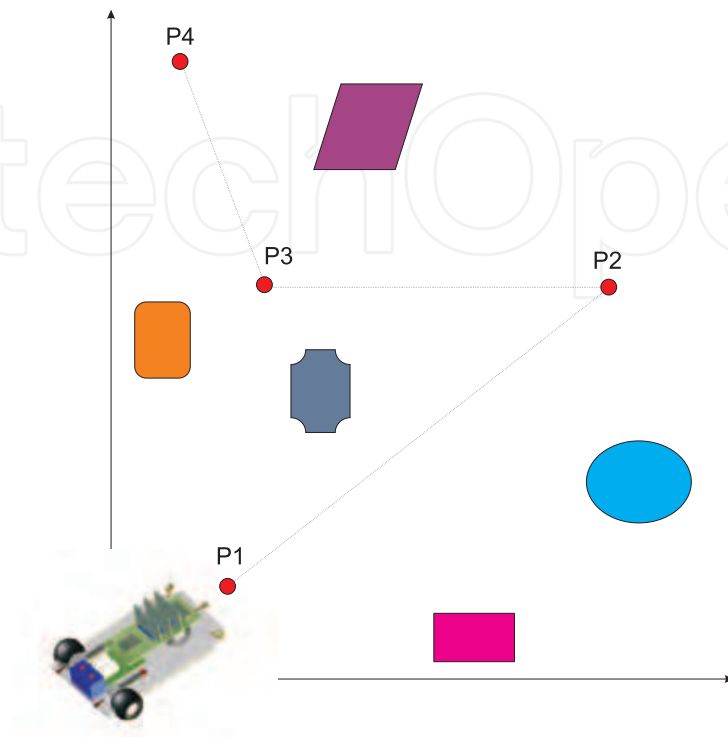


Fig. 7. Example of an environment with some obstacles where the robot must navigate.

This system is particularly interesting and can be used, for example, in robotic soccer games, where the navigation strategies are made from images of the environment (soccer field) and the obstacles are the other robots players. As it's described follow, with this system, the best trajectory can be defined and traced, respecting always the kinematics holonomic or nonholonomic constraints of the robotic systems in question, and to make all the simulation of the system foreseeing imperfections and analyzing results before the final implementation of the control system in the mobile robot (Melo & Rosario, 2006).

5.1 Mobile Robot Control Structure

The tasks carried through for the mobile robots are based on the independent movement of each degree of freedom, coordinated from a trajectories plan based in its kinematic model. In the most of the cases, the tasks programming is planned with anticipation and a map of the environment is loaded in the robot memory board. The mobile robot accomplish the trajectory with sequence of independent movements of each axle, until reaching the desired final position. From the knowledge of these articulated positions, easily is implemented a generator of references (profile of speeds) based in the kinematic characteristics of each joint.

For accomplishment of tasks in level of cartesian coordinates system and for generation of the reference signals for the position controller of each robotics joint of the mechatronics system in study, the establishment of mathematical model based in the kinematics of the system becomes necessary, what is described in section 3. Therefore, the control of a robot needs procedures to transform the data of positioning reference, such as the linear speed and the bending

radius, in cartesian coordinates, when it is desired to realize the control through a cartesian referential. The Fig. 8 illustrates the mobile robot structure of control with the representative blocks of the trajectory generation, dynamic and kinematic model of the system.

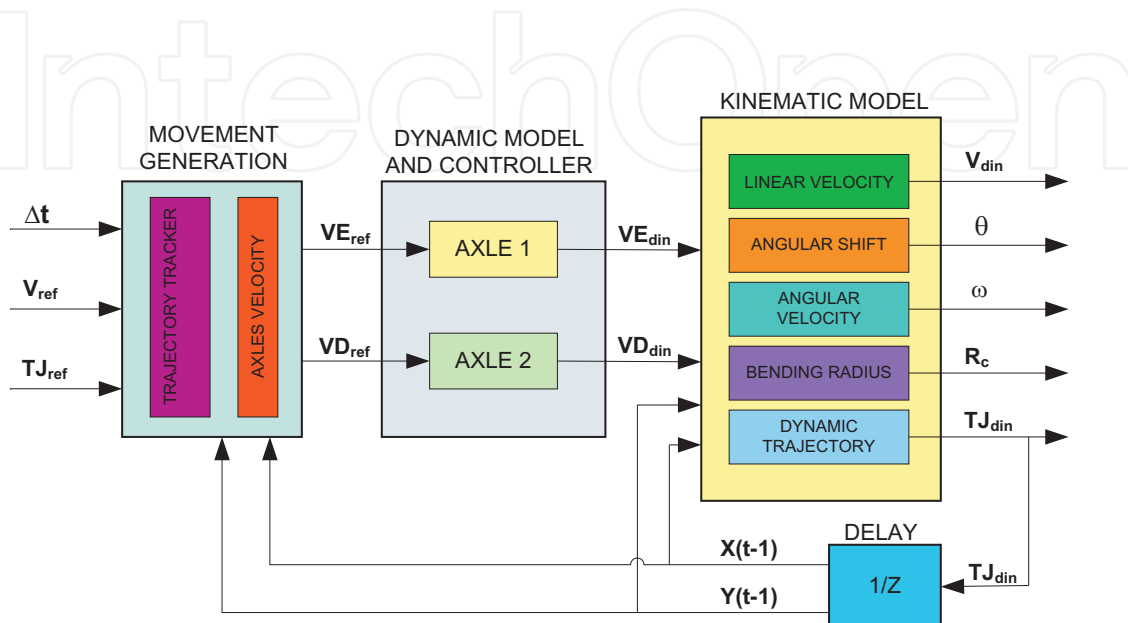


Fig. 8. The mobile robotic control structure.

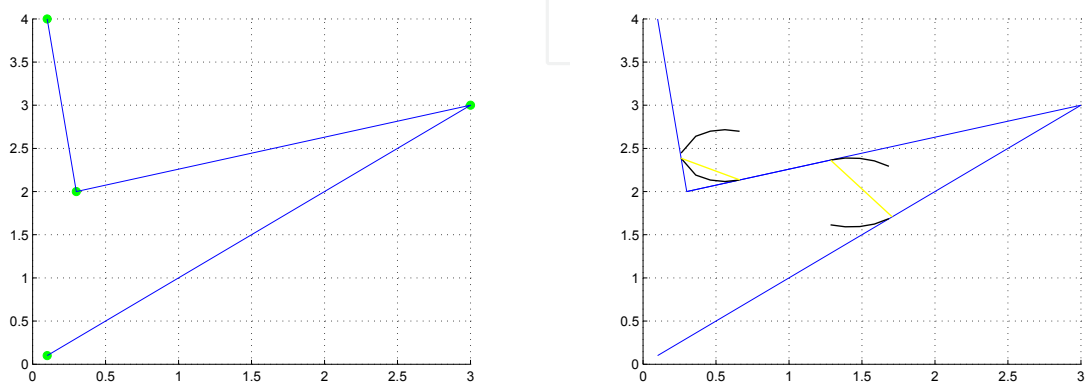
The trajectory generator receives the references data, such as the positioning vector $\mathbf{X}_{ref} = [x_{ref}, y_{ref}, \theta_{ref}]$, the robot reference linear speed V_{ref} and the robot instantaneous trajectory radius R_{curv} , that are converted into VE_{ref} (linear speed of the left wheel) and VD_{ref} (linear speed of the right wheel). These differentiated speeds are received by the controller, and in the dynamic model of the system, they are sent to the respective wheels of the robot, through its actuators. Then are generated by the controller the vectors VE_{din} (dynamic linear speed of the left wheel) and VD_{din} (dynamic linear speed of the right wheel). Into the block of the kinematic model, these data are converted into the vector final positioning of the robot $\mathbf{X} = [x, y, \theta]$.

5.2 Trajectory Generation Block

The Trajectory Generation Block of trajectory, receives some important points from the camera system so that the trajectory can be traced to be realized by the mobile robot. These points form a cartesian matrix containing more or less points, depending on the complexity of the environment. For a reason or purpose tests and for validation of the system, the number of points to be fed the system was fixed in four. Nevertheless, the number of points can be increased depending on the complexity of the environment where the mobile robot will navigate. Another data important to be used by the system have relation with the holonomics constraints of the modeled mobile robot. The bending radius must be informed to the system to be performed in the trajectory. A time that, for a reason or purpose tests, was fixed in four the number of cartesian input points, must also be supplied the radius of the two curves to be

executed for the robot. The information of distinct radius makes the system more flexible, being able the trajectory to be traced with different bendings depending on the angle of direction displacement and on the restrictions of the robot.

The graphic of the Fig. 9(a) illustrates the initial points for the trajectory generator. In this example, it was captured from the camera system and transmitted for the simulator the vector $\mathbf{x} = [1 \ 3 \ .3 \ .1]$ and the vector $\mathbf{y} = [1 \ 3 \ 2 \ 4]$, with the bending radius for first and the second semicircle given by the vector $\mathbf{r} = [4 \ .3]$. All the measures are in meters.



(a) Initial points given to trajectory generation.

(b) Assay to the delineated trajectory.

Fig. 9. Initial points given by camera system and Assay to the delineated to trajectory.

In the Fig. 9(b) it's possible to see the tracing of the straight lines, the semicircles and an intermediate segment of straight line indicating the start and the end of the tracing of each circular movement to be executed by the mobile robot.

The final tracing of the mobile robot trajectory can be observed in the Fig. 10, represented by red spots.

5.3 The Virtual Simulator Implementation

Now are presented the main characteristics of a simulator of mobile robotic systems. It was implemented from the kinematic and dynamic model of the mechanical drive systems of the robotic axles, for the simulation of different control techniques in the field of the mobile robotics, allowing to deepen the concepts of navigation systems, trajectories planning and embedded control systems. This simulator, designed in modular and opened architecture, as presented in section 4, allows the direct application of some concepts into of the mobile robotics area, being used for its validation, and as main objective of this study, the model of an prototype of mobile robot with nonholonomic kinematic constraint and differential drive with two degrees of freedom (movement of linear displacement and rotation).

For the simulator development, the constructive aspects of the mobile robot prototype had been considered, including the kinematics and dynamics modeling of drive and control systems. The simulator presents the trajectories generating module that is the first block of the system and was implemented with the functionality to generate a trajectory for the mobile robot from a matrix of points supplied initially. Another presented block is the controller, implemented in the PID traditional form.

Fig. 11 shows the initial page of the Virtual Mobile Robot Simulator. The user can choose one of the captured trajectory for analyzing, take a look in the graphical results of the simulation

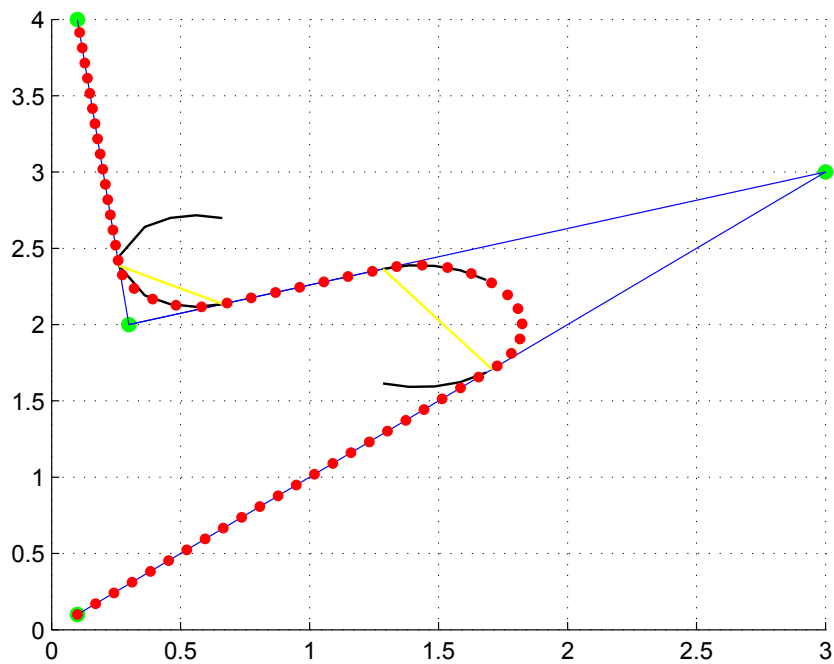


Fig. 10. The final tracing of the mobile robot trajectory.

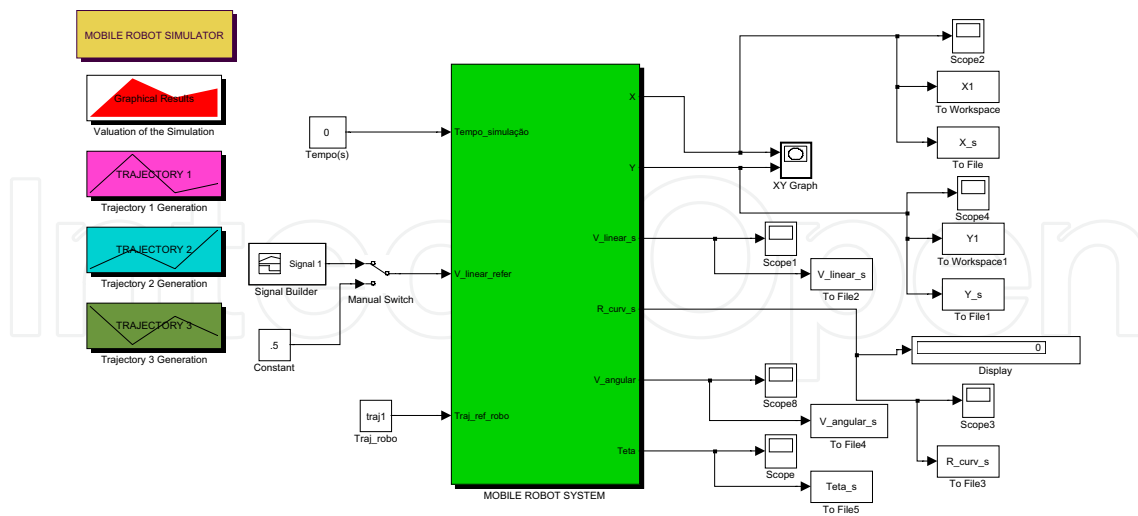


Fig. 11. The Virtual Simulator first page.

or implement changes in the robot model, by clicking on the mobile robot system (green main block).

The virtual simulator system of the mobile robot is composed of three main blocks. The first one is called movements generation block. The second one is the block of the controller and dynamic model of the mobile robot and the third one is the block of the kinematic model. The Fig. 12 illustrates the mobile robot simulator implemented into Matlab Simulink® blocks.

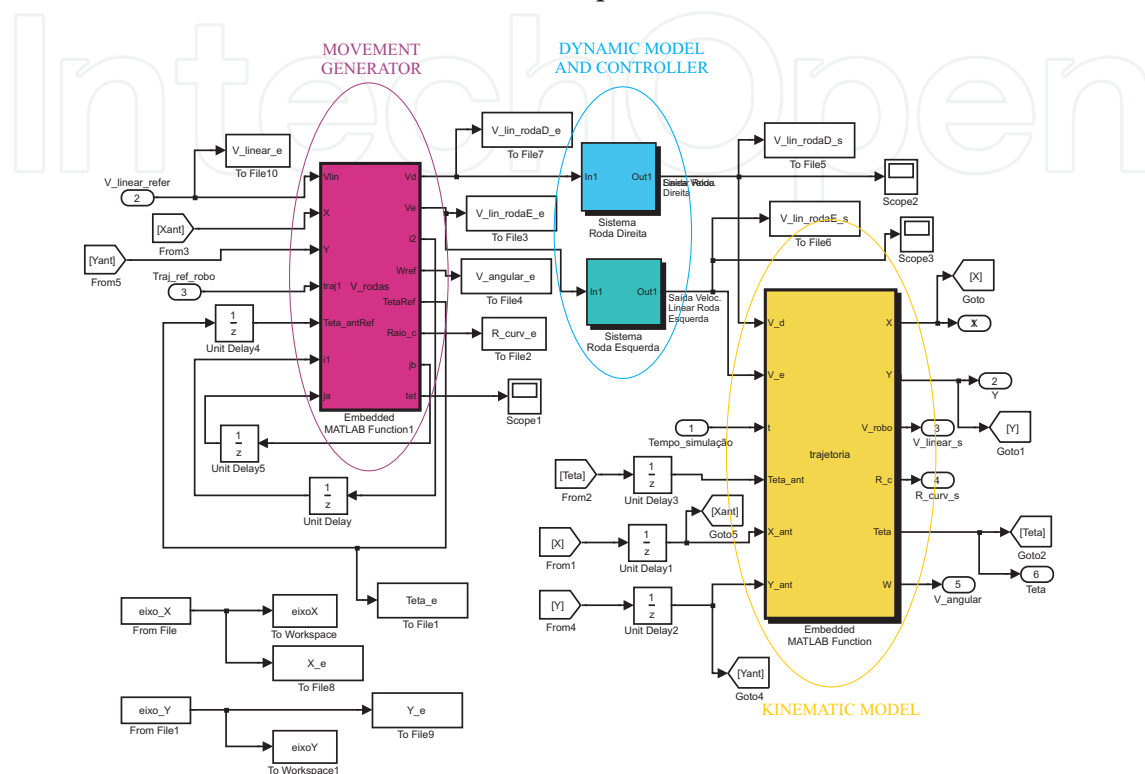


Fig. 12. Mobile robot simulator implemented into Simulink®.

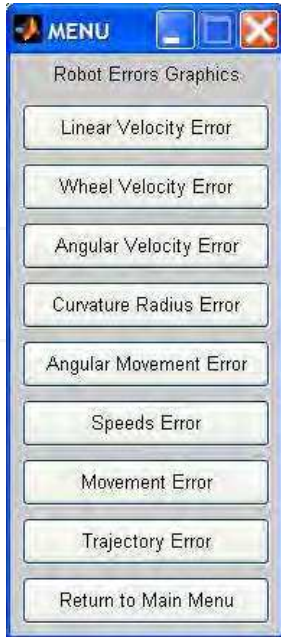
5.4 Results Graphical Analyzer

The simulator implemented in Simulink® environment allows the visualization of the inputs and outputs of the system in study.

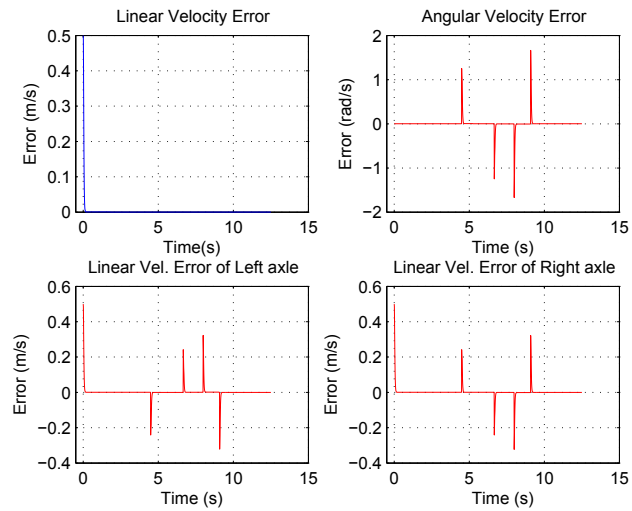
For a better understand and analysis of the behavior of the system the implementation of a results graphical analyzer becomes essential. In this way, after realizing the simulations in the domain of the time, timings data archives are got corresponding to the study variables (angular and cartesian position, linear and angular speed and control signals), that after convenient treatment, becomes possible to verify important results for better analysis of the system behavior. The Fig. 13 illustrates a menu of the graphical analyzer of the mobile robotic system in study with an example of generated graphic.

One kind of analysis that is made is in relation to the linear displacement of the robot in axis X and Y. In Fig. 14, the dynamic behavior of the robot with regard to these parameters, as well as the presented errors is illustrated.

Another important graphic generated for the system, in the *cartesian trajectory* sub-menu, that is the graphic of the cartesian trajectory kinematics and dynamics of the mobile robotic system



(a) Robot errors analyzer submenu.



(b) A robot speeds errors graphics.

Fig. 13. Submenu of the mobile robot graphical analyzer with an example of generated graphic.

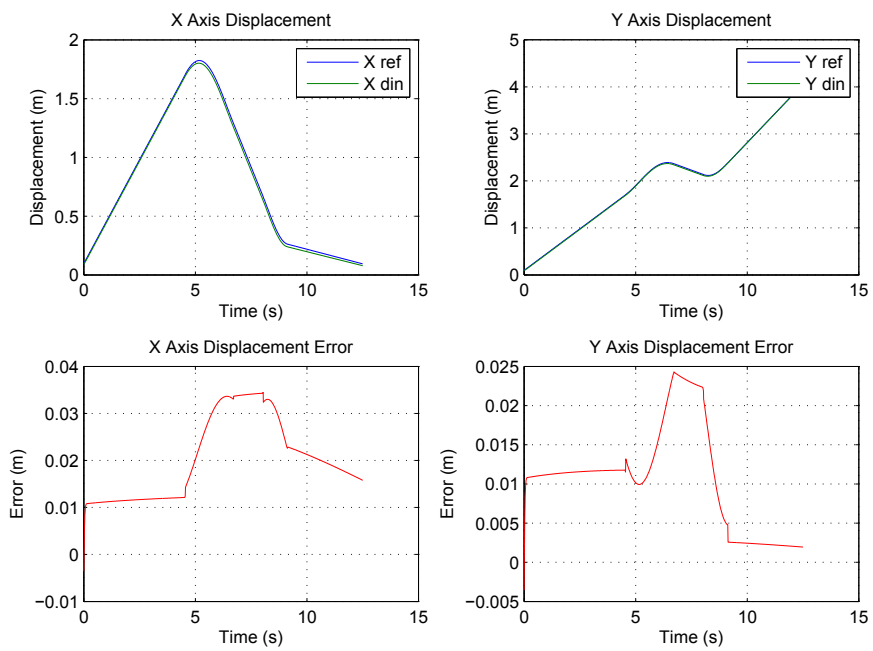


Fig. 14. Dynamic behavior graphics of the robot in the X and Y axis with their errors.

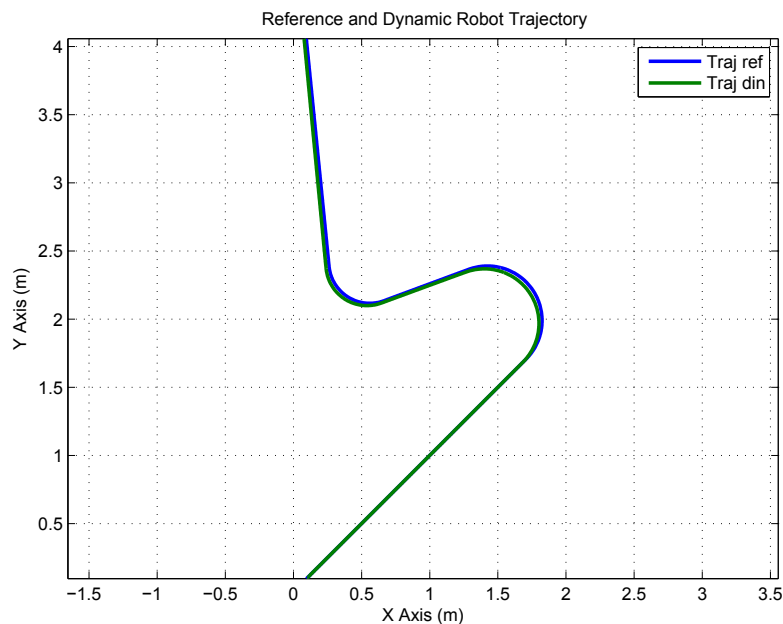


Fig. 15. Cartesian trajectory kinematics and dynamics of the mobile robotic.

in plan XY. The Fig. 15, shows the dynamic tracing of reference and of the trajectory of the mobile robot.

The Fig. 16 illustrates the graphic of the trajectory error.

6. Mobile Robot Rapid Prototyping

The use of the rapid prototyping technique in mobile robotic systems differs from the traditional target used in mechanics engineering and enters in new field of research and development for projects of mobile robots mechatronics systems. In this way, the rapid prototyping of these systems is associated not only with the project of the physical system, but mainly with the experimental implementations in the fields of *hardware* and *software* of the robotic system. It is fundamental that the architecture of *hardware* of the considered system be opened and flexible in the way of effecting the necessary modifications for system optimization. A proposal of open architecture system was presented in (Melo *et al.*, 2003). The *software* of the embedded control system of the mobile robot, in the context of the rapid prototyping, can be elaborated in simulators and tested all the parameters for adjustments that makes necessary in accordance with the physical system to be implemented, the hardware architecture, the actuators and the sensors. In this way, in the context of this work, the rapid prototyping is then the methodology that allows the creation of a virtual environment of simulation for the project of a controller for mobile robots. After being tested and validated in the simulator, the control system is programmed in the control board memory of the mobile robot. In this way, a economy of time and material are obtained, sooner validating all the model virtually and later operating the physical implementation of the system.

6.1 HIL (Hardware-in-the-loop) Simulation

The HIL technique of simulation is used in development and tests for real time embedded systems. HIL simulations provide a platform accomplish of development for adding the com-

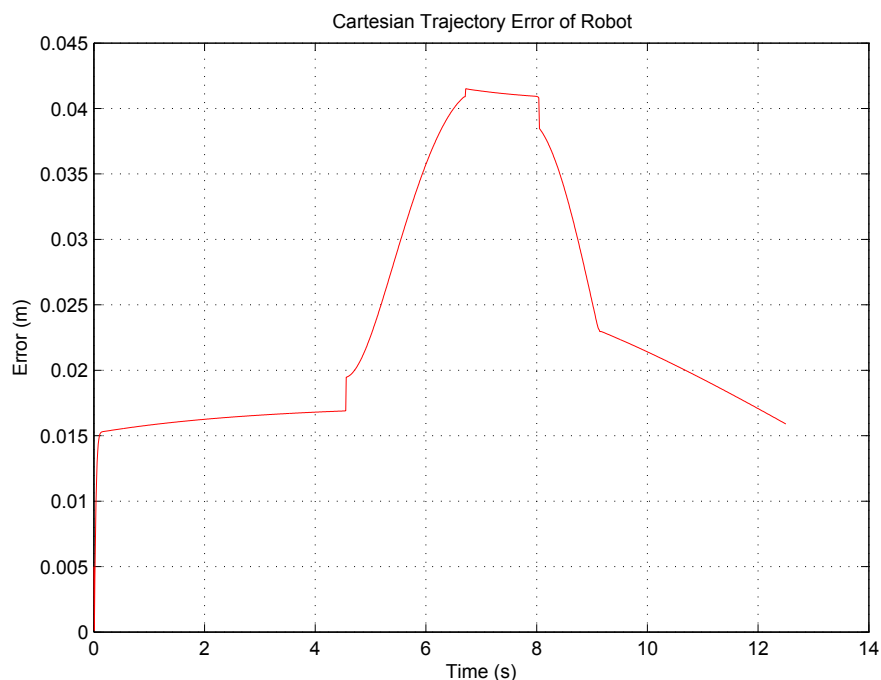


Fig. 16. Error of the kinematics and dynamics trajectory of the mobile robot.

plexity of the plant under control to the tests platform. The control system is enclosed in the tests and developments through its mathematical models representations and all the respective dynamic model (Melo & Rosario, 2006).

The Fig. 17 illustrates the use of the HIL simulation technique for real time simulation of the considered mobile robotic system.

7. Experimental Validation

The Aedromo, a didactic experimental environment for mobile robots, is an ambient used to test and validate the trajectory virtual simulator, the onboard robot control and the rapid prototyping system, all of them describe above. This environment is utilized for many others applications, like robotic soccer game, two or more robots interaction, etc. The supervision and the robots movements coordination are made through a close loop architecture based in a satellite camera over the arena. The information supplied for a video camera is sent for one or two computers for processing. The data obtained from this process are used to generate a sequence of instructions that are sent for the robots. The robots receive the instructions and carry through the actions obeying the predetermined tasks. The instructions are results of developed programmers strategies to execute the tasks and to realize the robot navigation into the environment. The Fig. 18 depicts this environment.

The trajectory to be executed by the robot, from trajectory generation software, is illustrated on Fig. 19. This trajectory allows to get parameters of comparison between the real system, represented by de robot prototype, and the virtual system. On the onboard control of the mobile robot was implemented a dynamic and kinematic strategy, in order to find best trajectory, avoiding obstacles on the way, like can be seen in Fig. 7.

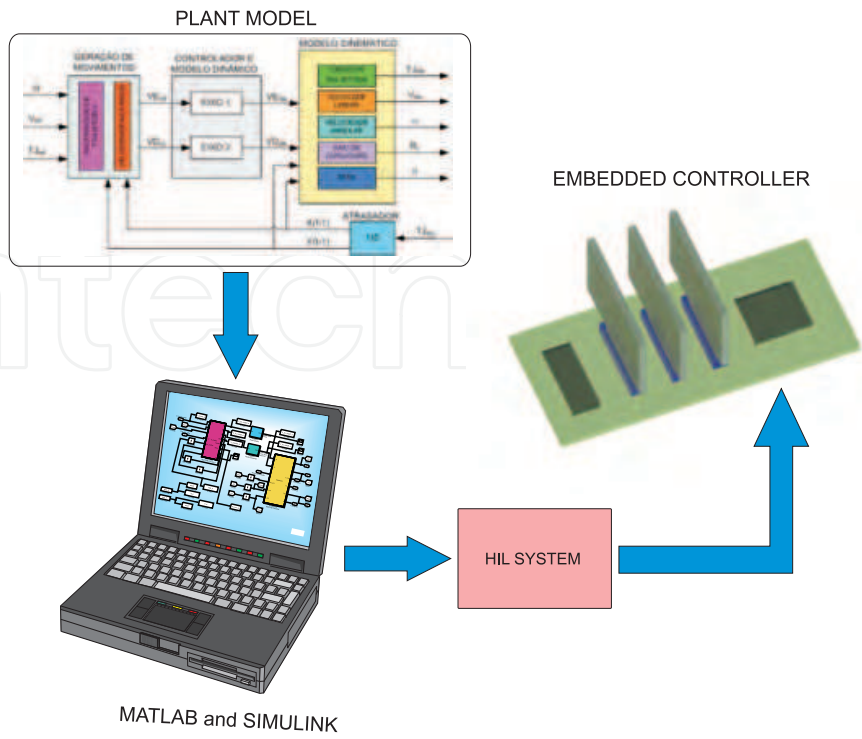


Fig. 17. HIL simulation for mobile robot system.

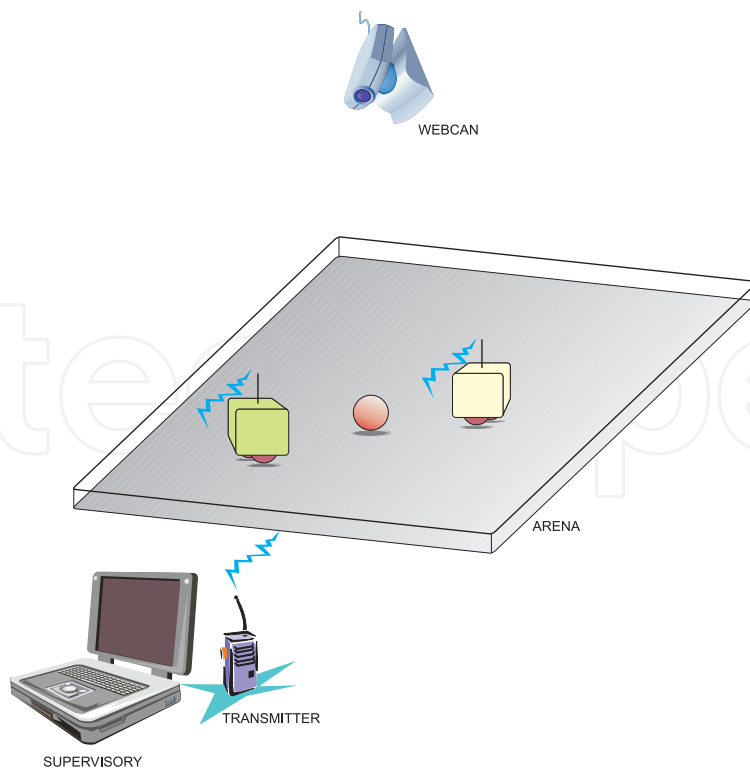


Fig. 18. The Aedromo environment.

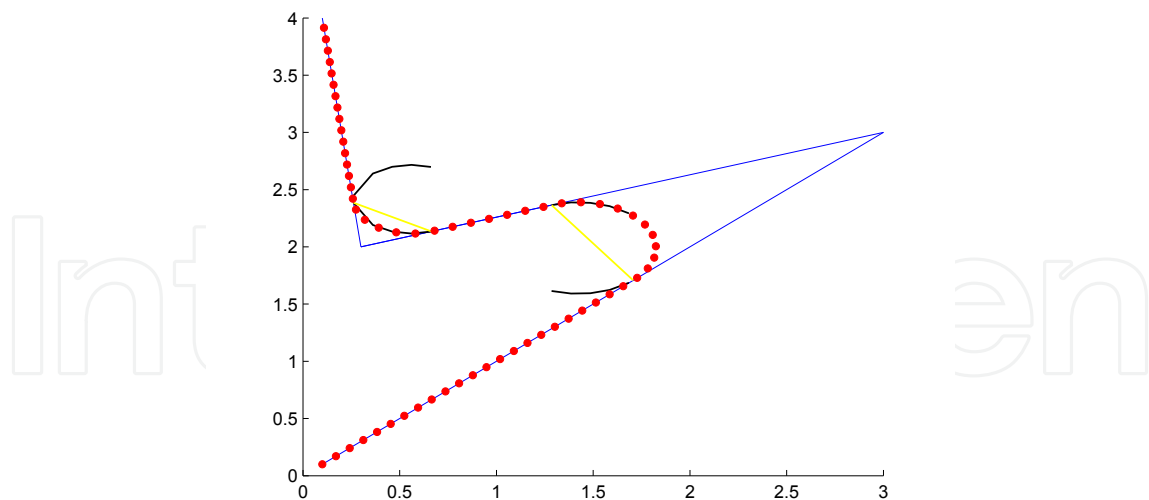


Fig. 19. Best trajectory to be executed by the robot.

The graphic presented on Fig. 20 illustrates the difference of the reference trajectory, showing by the slim line with square blocs (violet) and the dynamic trajectory executed by the robot, showing by the thick line (blue).

Even so the robot executes the proposed trajectory with success, we can see errors between the two trajectory, mainly on curves. It was foreseen on simulator of the cartesian trajectory kinematics and dynamics of the mobile, depicted on Fig. 15 with the trajectory error on Fig. 16. These errors are predictable for the simulator because of the intrinsic dynamic characteristic of nonholonomic mobile robotics systems with differential drive wheels, which the prototype are made, and for the PID close-loop controller of wheels velocity axes. It's demonstrated, in this example, the necessity and efficacy of the virtual system, proposed by this work.

8. Conclusion

The main objective of this work was to propose a generic platform for a robotic mobile system, seeking to obtain a support tool for under-graduation and graduation activities. In this way, it presents the virtual environment implementation for simulation and design conception of supervision and control systems for mobile robots, that are capable to operate and adapting in different environments and conditions. This came from encountering the growing need to propose to the research that integrates the knowledge acquired in several domains that stimulates teamwork in order to reach a result. Another objective was to improve knowledge in the mobile robotic area, aiming at presenting practical solutions for industrial problems, such as maintenance, supervision and transport of materials. Some promising aspects of this platform and simulator system are:

- Flexibility: there are a great variety of possible configurations in the implementation of solutions for several problems associated with mobile robots.
- Great capacity of memory storage allowing implementation of sailing strategies for maps.
- The use of the rapid prototyping technique in mobile robotic systems.

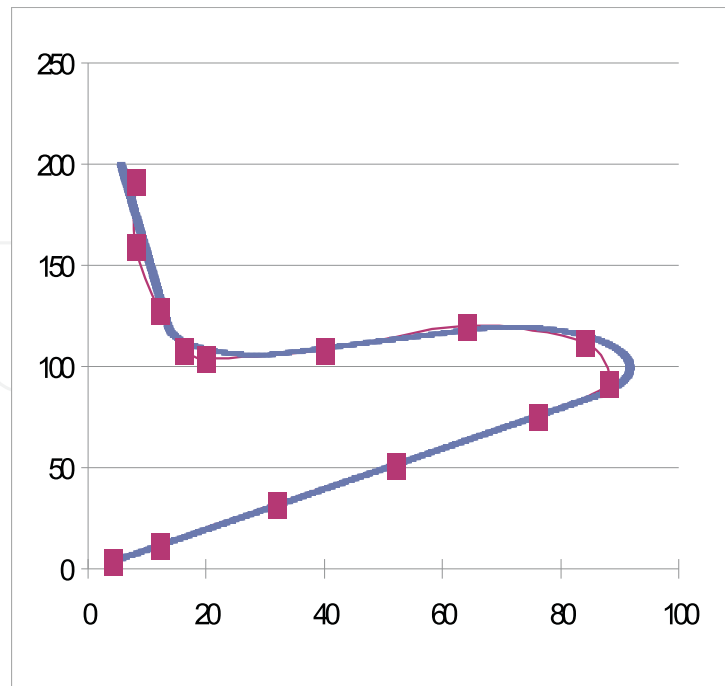


Fig. 20. Reference and dynamic trajectory executed by the robot.

- Possibility of modification of control strategies during the operation of the mobile robot in special mechatronics applications.

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Mobile robots navigation includes different interrelated activities: (i) perception, as obtaining and interpreting sensory information; (ii) exploration, as the strategy that guides the robot to select the next direction to go; (iii) mapping, involving the construction of a spatial representation by using the sensory information perceived; (iv) localization, as the strategy to estimate the robot position within the spatial map; (v) path planning, as the strategy to find a path towards a goal location being optimal or not; and (vi) path execution, where motor actions are determined and adapted to environmental changes. The book addresses those activities by integrating results from the research work of several authors all over the world. Research cases are documented in 32 chapters organized within 7 categories next described.

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