# Virtual Simulator for Dynamics Design for Mobile Robots Navigation Systems

**Leonimer Flavio de Melo, leonimer@uel.br**
**Jose Fernando Mangili Junio, mangili@uel.br**
**Fernando Ciriaco Dias Neto, fciriaco@uel.br**
Department of Electrical Engineering, State University of Londrina(UEL). Londrina - PR - Brazil

***Abstract.*** *The paper presents the virtual environment implementation for design simulation and conception of supervision and control systems for mobile robots, that are capable of operate and adapting in different environments and conditions. The purpose of this virtual system is to facilitate the development of embedded architecture systems, emphasizing the implementation of tools that allow the simulation of the kinematic conditions, dynamic and control, with real time monitoring of all important system points. For this, an open control architecture is proposal, integrating the two main techniques of robotic control implementation in the hardware level: systems microprocessors and reconfigurable hardware devices. The implemented simulator system is composed of a trajectory generating module, a kinematic and dynamic simulator module, and an analysis module of results and errors. All the kinematic and dynamic results obtained during the simulation can be evaluated and visualized in graphs and table formats in the results analysis module, allowing the improvement of the system, minimizing the errors with the necessary adjustments and optimization. For controller implementation in the embedded system, it uses the rapid prototyping which is the technology that allows in set, with the virtual simulation environment, the development of a controller design for mobile robots. The validation and tests had been accomplished with nonholonomic mobile robot models with differential transmission.*

***Keywords:*** *Embedded Control Systems, Mobile Robotic Systems, Virtual Simulator, Opened Architecture Systems, Mobile Robots Navigation.*

## 1. Introduction

Platforms for knowledge consolidation in several teaching and research areas, such as modeling, control, automation, power systems, and sensors, transmission of data, embedded electronics and software engineering are a necessity in teaching and research institutions. The use of the mobile robots for this purpose appears to be quite an attractive solution. It allows the integration of several important areas of knowledge and a low cost solution, which has already been adopted with success by other research institutions. Finally, as each day goes by, it becomes a better solution for practical problems in our society.

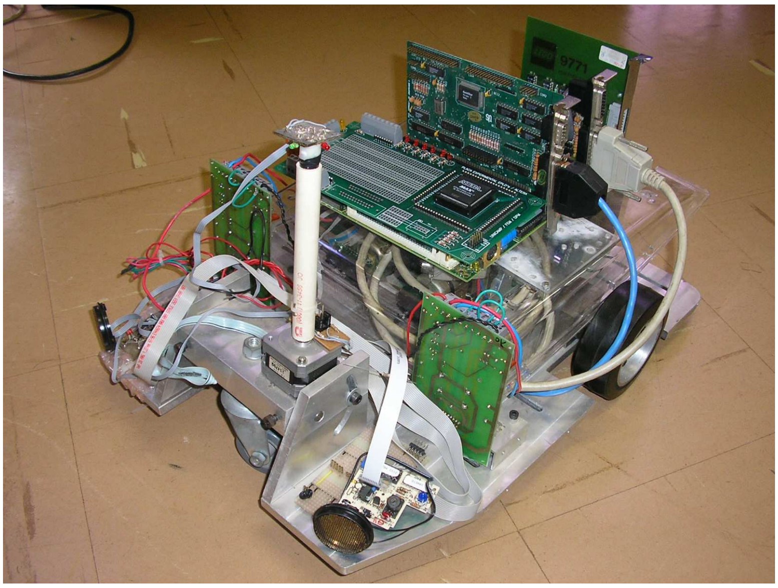


Figure 1. Mobile robot platform prototype.

The proposal and development of this open and generic system aims at supplying this need, having as an emphasis, the control structuring, the supervision and the transfer of information. The development of this system demands the knowledge, in terms of design aspects and integration, that would not be approached if a commercial mobile robot was acquired.

Within the proposal of platform mobile robotics, the use of an embedded processor, with control software especially developed for the necessary applications is considered. Together with this, a commercial platform is analyzed, which coupled to a communication net, 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 design 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 paper presents the virtual environment implementation for design 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 illustrate the elements of the platform.

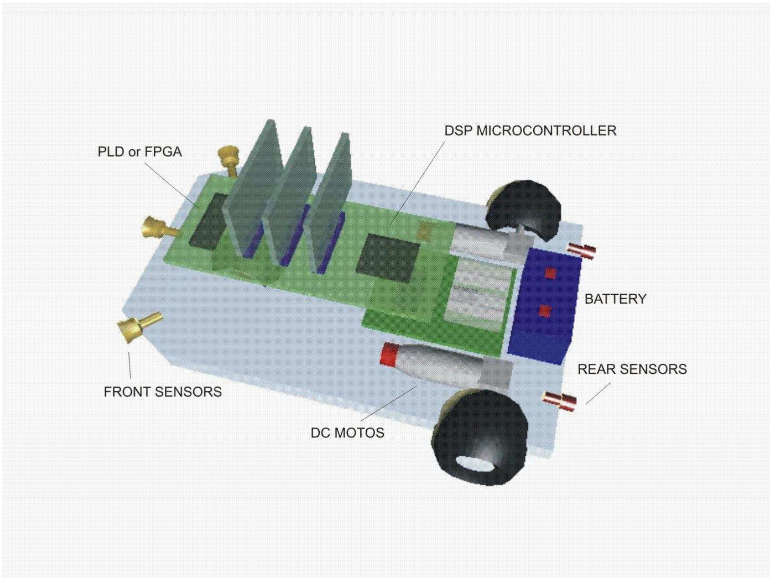



Figure 2. Mobile robot platform and elements.

## 2. Mobile robot modeling

Suppose that the robot is at some position $(x, y)$ and "facing" along a line making an angle $\theta$ with the $x$ axis (Fig. 3).

Through manipulation of the control parameters $v_e$ and $v_d$, the robot can be made to move to different poses. Determining the pose that is reachable given the control parameters is know as the forward kinematics problem for the robot. Because $v_e$ and $v_d$ and hence $R$ and $\omega$ are functions of time, is straightforward to show (Fig. 3) that, if the robot has pose $(x, y, \theta)$ 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

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

For better equation write, we can simplifying $ICC = I$, $\cos(\omega\delta t) = C$ and $\sin(\omega\delta t) = S$, then, at time $t \rightarrow t + \delta t$, the pose of the robot is given by

$$\begin{bmatrix} x' \\ y' \\ \theta' \end{bmatrix} = \begin{bmatrix} C & -S & 0 \\ S & C & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - \text{I}_x \\ y - \text{I}_y \\ \theta \end{bmatrix} + \begin{bmatrix} \text{I}_x \\ \text{I}_y \\ \omega\delta t \end{bmatrix}. \tag{2}$$

Equation 2 describes the motion of a robot rotating a distance $R$ about its ICC with an angular velocity given by $\omega$ [1]. Different classes of robots will provide different expressions for $R$ and $\omega$ [2].

The forward kinematics problem is solved by integrating equation 2 from some initial condition $(x_0, y_0, \theta_0)$, 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

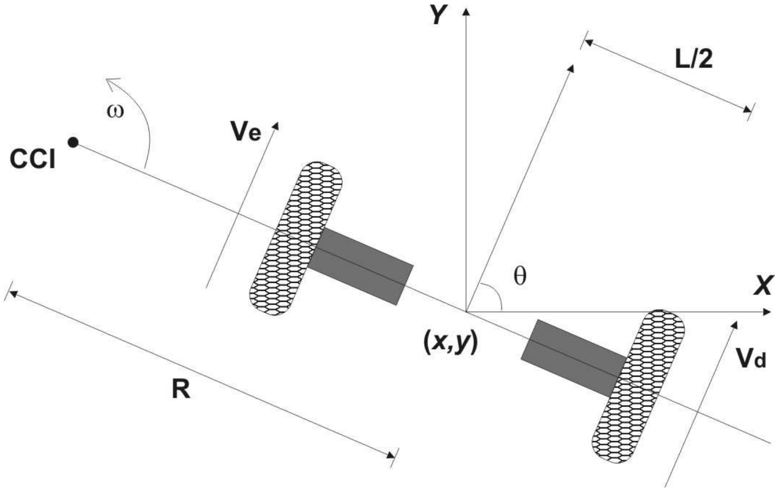



Figure 3. Forward kinematics geometry.

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

A more interesting question, and one somewhat more difficult to answer, is how can the control parameters be selected so as to have the robot obtain a specific global pose or follow a specific trajectory. This is known as the task of determining the vehiclet's *inverse kinematics*: inverting the kinematic relationship between control inputs and behavior. It is also related to the problem of trajectory planning.

### 2.1 Inverse kinematics for differential drive robots

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

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

where $(x, y, \theta)_{t=0} = (0, 0, 0)$. Given a goal time $t$ and goal position $(x, y)$. Equations 4 solves for $v_d$ and $v_e$ but does not provide for independent control of $\theta$. There are actually infinitely many solution for $v_d$ and $v_e$ from equations 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.

## 3. 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 the form of different degrees of control strategies. The levels can be described as:

- **Supervisory control level**: This represents a high level of 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.

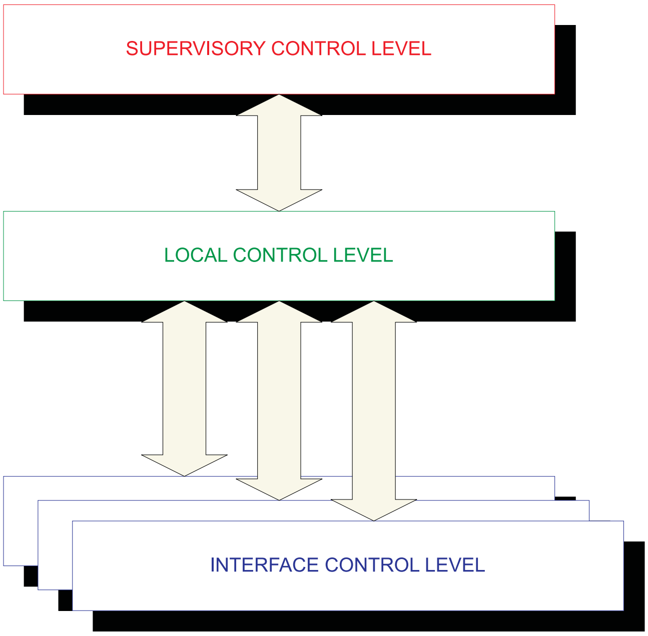



Figure 4. Different control levels of the proposed system.

- **Local control level**: In this level 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 was 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).

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

### 3.1 Description of Blocks

- **Supervisory control block**: Is the high level of control. In this block, the supervision of one or more mobile robots is managed through the execution of global control strategies. 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**: Responsible for the treatment of all the information received from other blocks, for the generation of the trajectory profile for the local control blocks and for the 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**: Is responsible for the sensor acquisition and for the treatment of this information in digital words, to be sent to the master manager block. The implementation of that interface through PLD allowed the integration of information from sensors (sensor fusion) locally, reducing manager block demand for processing. In

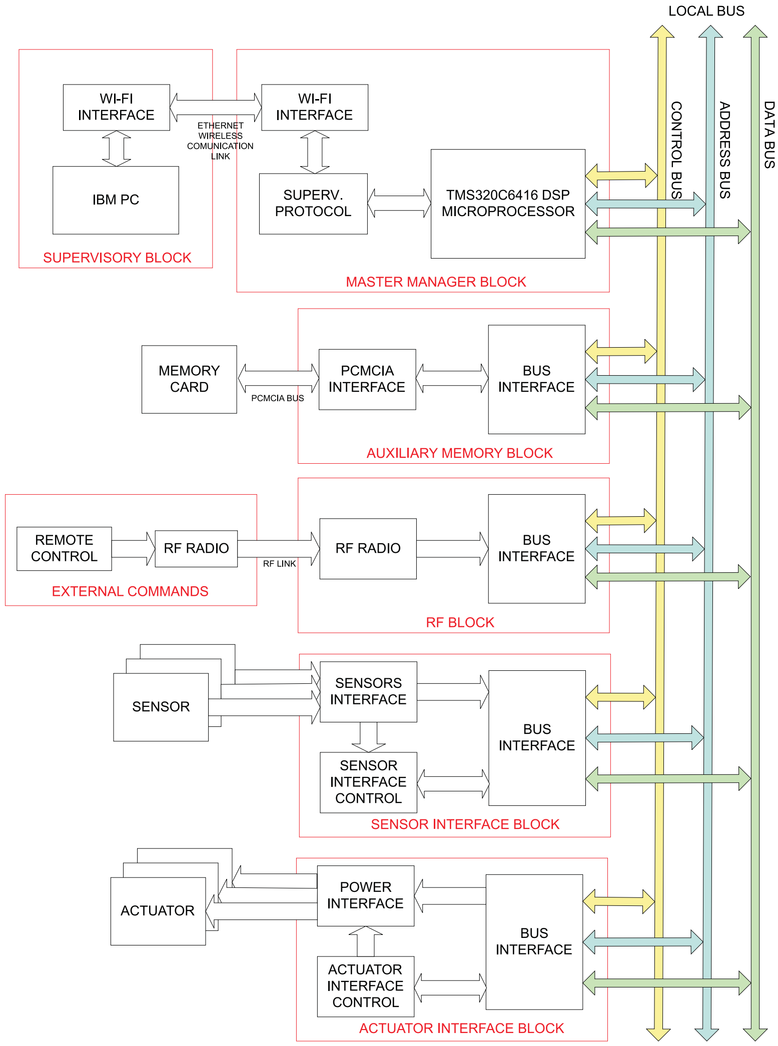



Figure 5. Hardware architecture block diagram of the proposed system.

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 debugging. 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 a well adapted for applications in mobile robots, due to low consumption, little weight, small dimensions, high storage capacity and good immunity to mechanical vibrations.

- **RF communication Block**: It allowed 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.

## 4. Mobile Robot Simulator

Figure 6 presents a general vision of the considered simulator system. The use of the system starts getting the main

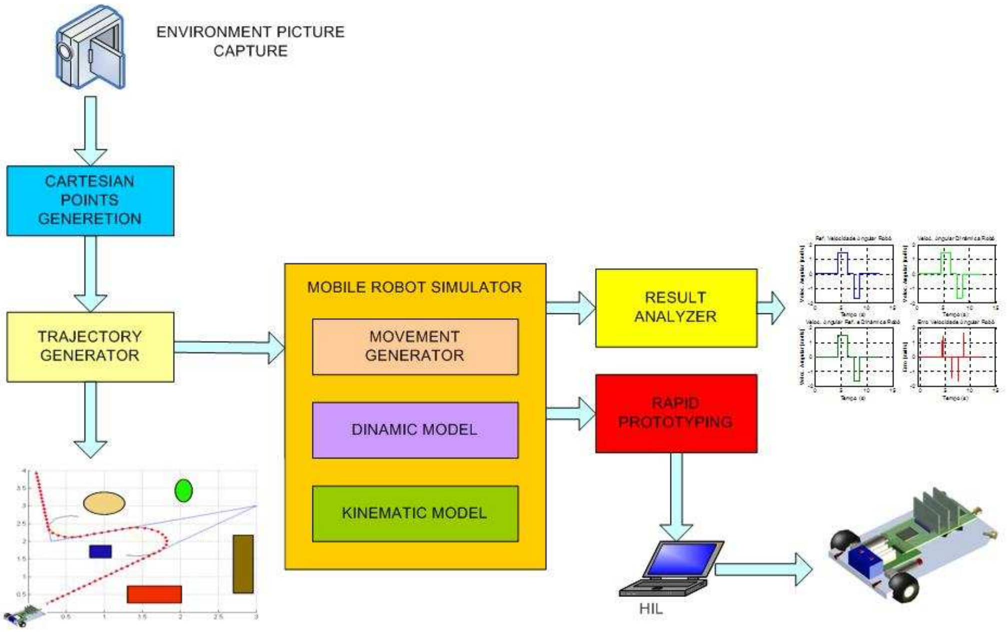



Figure 6. General vision of the simulator system.

points for generation of the mobile robot trajectory. The idea is to use a system of photographic video camera that captures the image of the environment where the mobile robot navigate. This initial system must be capable to identify the obstacles of the environment and to generate a matrix with some strategical points that will serve of entrance for the system of trajectory generation.

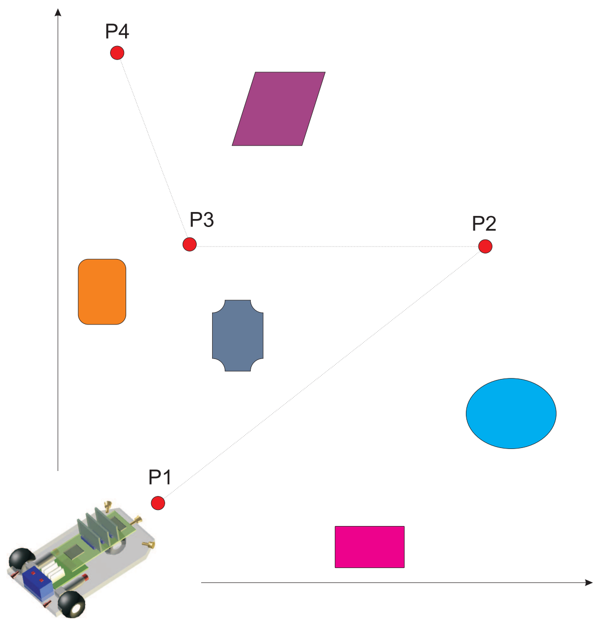



Figure 7. Example of an environment with some obstacles where the robot must navigate.

The figure 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 then supply to the module of trajectory generation, the cartesian points P1, P2, P3 and P4, that are the main points of the traced route.

The virtual simulator system of the mobile robot is formed by three main blocks. The first one is called movements generation block. The second is the block of the controller and dynamic model of the mobile robot. Third is the block of the kinematic model. Figure 8 illustrates the mobile robot simulator implemented into Matlab Simulink blocks.

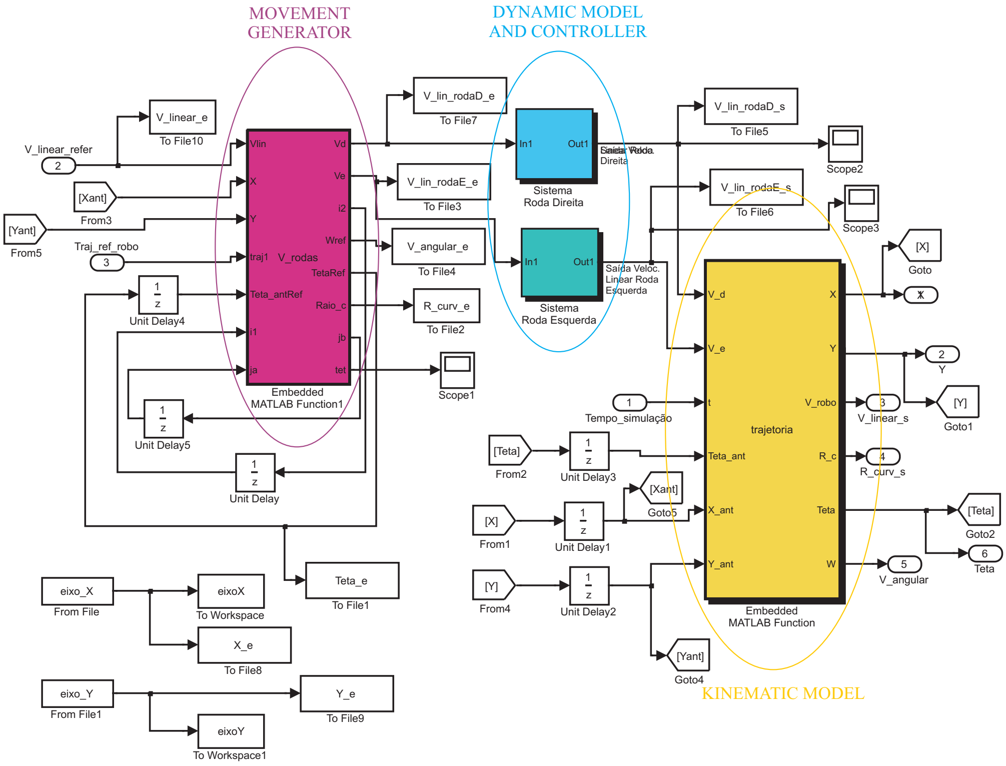



Figure 8. Mobile robot simulator implemented into Simulink.

## 4.1 Results Graphical Analyzer

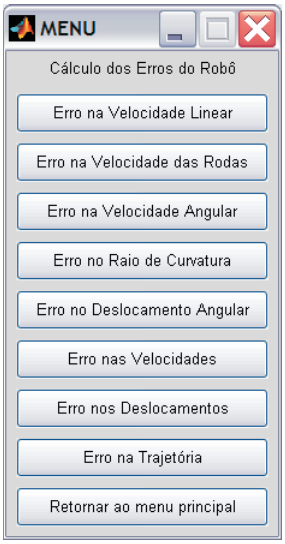
The simulator implemented in Simulink® environment allows the visualization of the inputs and outputs of the system in study. For better understand and analyze the behavior of the system the implementation of a results graphical analyzer becomes essential. In this way, after realizing the simulations 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 Figure 9 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 with relation to the linear displacement of the robot in axles X and Y. Through the Figure 10, can be seen then, which the dynamic behavior of the robot with regard to these parameters, as well as the presented errors.

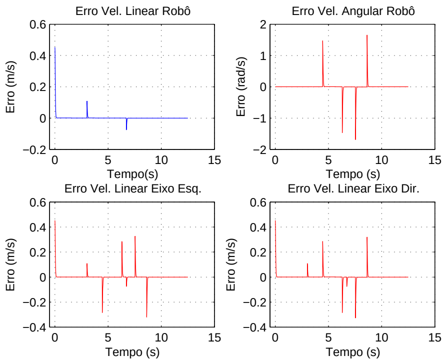
Another important graphic generated for the system, in the *cartesian trajectory* sub-menu, is the graphic of the cartesian trajectory kinematics and dynamics of the mobile robotic system in plan XY. The Figure 11(a), shows the dynamic tracing of reference and of the trajectory of the mobile robot. The Figure 11(b) illustrates the graphic of the trajectory error.

## 5. 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 is opened and flexible in the way of effecting the necessary modifications for system optimization. A proposal of open architecture is then presented in this work [4]. 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




(a) Robot errors analyzer submenu.




(b) A robot speeds errors graphics.

Figure 9. Submenu of the mobile robot graphical analyzer with an example of generated graphic.

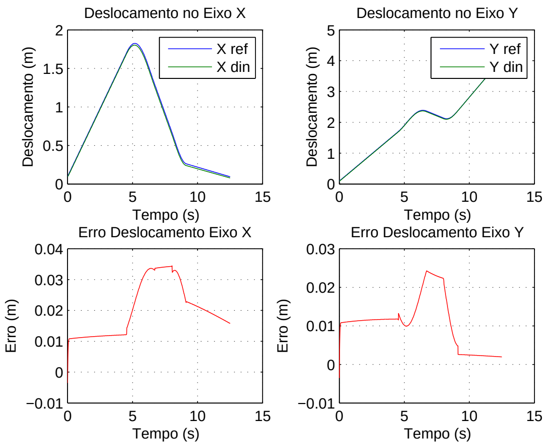
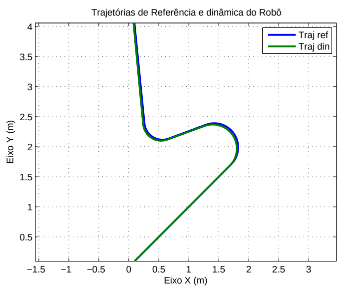
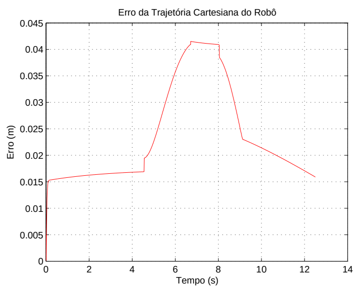



Figure 10. Dynamic behavior graphics of the robot in the X and Y axles with their errors.




(a) Graphic of the cartesian trajectory kinematics and dynamics of the mobile robotic.




(b) trajectory error.

Figure 11. Trajectory kinematics and dynamics of the mobile robotic with error presented.

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 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, validating first all the model virtually for later to operate the physical implementation of the system.

### 5.1 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 complexity 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.

The Figure 12 illustrates the use of the HIL simulation technique for real time simulation of the considered mobile robotic system.

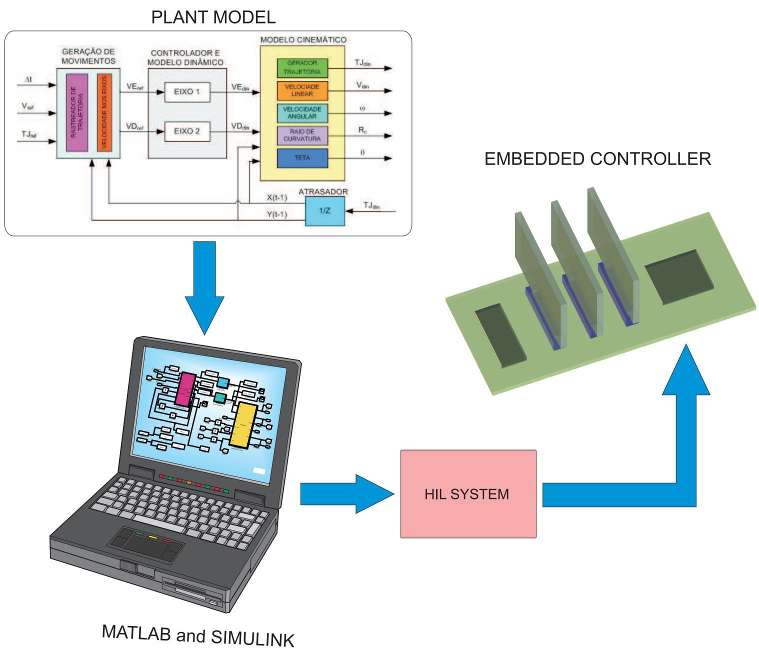



Figure 12. HIL simulation for mobile robot system.

## 6. Experimental Validation

The experimental validation of the proposed system was implemented as a didactic experimental environment for mobile robots, is an environment of small dimensions constituted of two independent mobile robots, with independent drive systems and local control. The supervision and coordination of movements of these robots are carried through a close loop architecture based in a satellite camera on the environment. The information supplied for a video camera model *WebCam* are sent for one or two computers for processing. the information 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 do the tasks and to realize the navigation of the robot into the environment. Figure 13 depicts this environment.

## 7. 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. 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 gather 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 were:

- Flexibility: there was a great variety of possible configurations in the implementation of solutions for several problems associated with mobile robots.

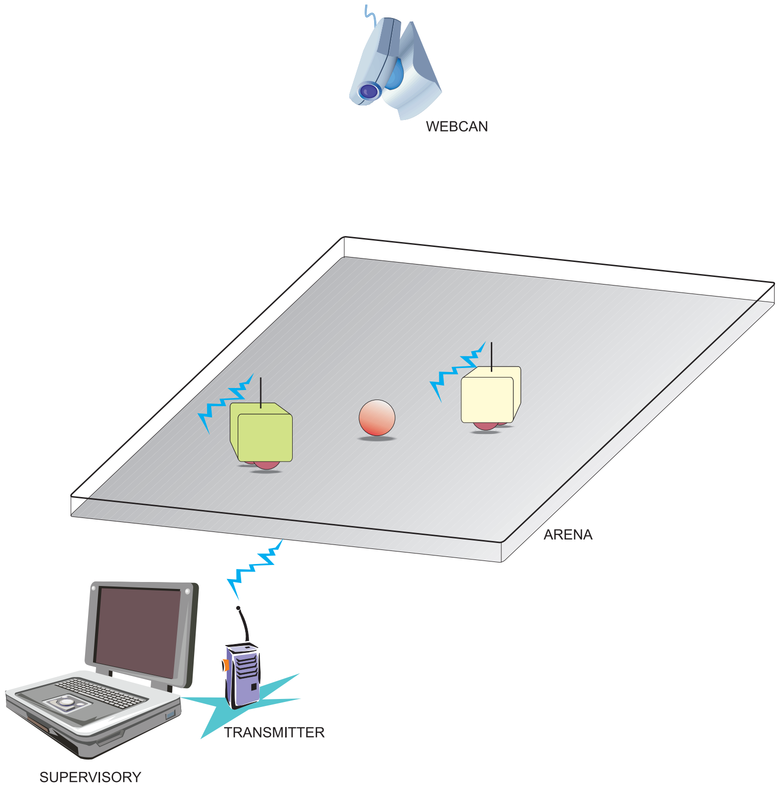



Figure 13. The experimental environment.

- Great capacity of memory storage allowing implementation of sailing strategies for maps.
- Possibility of modification of control strategies during the operation of the mobile robot in special mechatronics applications.

## 8. References

G. Dudek and M. Jenkin, *Computational Principles of Mobile Robotics, Cambrige*, UK: Cambridge University Press, 2000.

H.-S. Shim, et al, *Variable structure control of nonholonomic wheeled mobile robot*, IEEE International Conference on Robotics and Automation, vol. 2, pp. 1694-1699, Nagoya, Japan, May 1995.

Y. Zhao and S. L. BeMent, *Kinematics, dynamics and control of wheeled mobile robots*, IEEE International Conference on Robotics and Automation, vol. 1, pp. 91-96, May 1992.

Melo, L. F.; Lima, C. R. E.; Rosario, J. M. *A Reconfigurable Control Architecture for Mobile Robots*. MuSMe 2005-2nd. Internacional Symposium on Mutibody and Mechatronics, Uberlândia, MG. Proceedings of MUSME 2005. NY: IEEE. v. 1. p. 1-8, 2005.

## 9. Responsibility notice

The author(s) is (are) the only responsible for the printed material included in this paper