A HYBRID OPENED ARCHITECTURE WITH HARDWARE RECONFIGURABLE CONTROL APPLIED IN NONHOLONOMIC MOBILE ROBOTS

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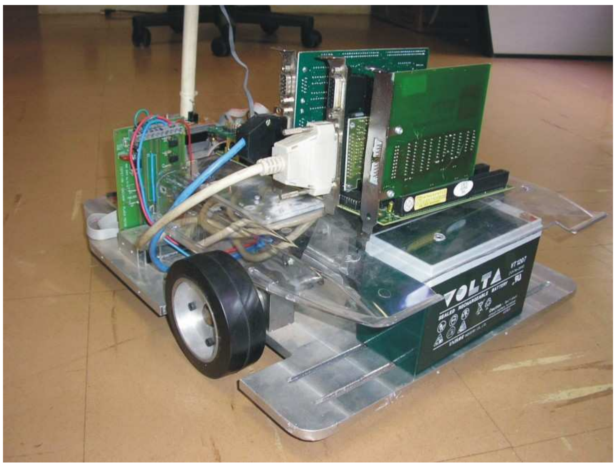
Abstract. *With the fast innovation of the hardware and software technologies in embedded systems area, with application in the robotics and automation, more and more it becomes necessary the development of applications based on methodologies that facilitate future modifications, updates and increments in the original projected system. In this way, this article presents a system of opened architecture, distributing the several control actions in growing levels of complexity and using resources of reconfigurable computing proposal oriented to embedded systems implementation. Software and the hardware are structuralized in independents blocks, with connection through common bus. Is presented the functional blocks where the use of DSP processor board is illustrated for local control level. The supervisory control level is implemented in an IBM PC platform and is connected with the local control level, in the robot, through Ethernet WI-FI link. Also are seen the control blocks that use reprogrammable logic components (FPGA) hardware projected for sensors fusion control interface and actuators controllers and the study and applications of new structures control that possibility good performance in relation to the parameter variations. The sensors, actuators, RF transceiver unit, and others necessary peripheral components for the project implementation with their implementation blocks are listed in the article.*

Keywords: *Embedded Systems, Reconfigurable Systems, Mobile Robotic Systems, Opened Architecture Systems.*

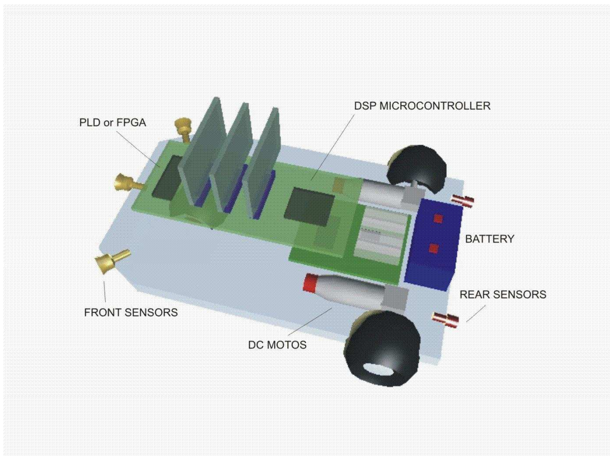
1. INTRODUCTION

Platforms for knowledge consolidation in several teaching and research areas, such as modelling, 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 (Barros, 1999).

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 project aspects and integration that would not be approached if a commercial mobile robot was acquired.



(a) Mobile robot platform prototype.



(b) Mobile robot elements.

Figure 1. Mobile robot platform prototype and elements.

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 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 paper focuses 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(a). Fig. 1(b) illustrate the elements of the platform.

2. MOBILE ROBOT MODELLING

Suppose that the robot is at some position (x, y) and “facing" along a line making an angle θ with de x axis (Fig. 2).

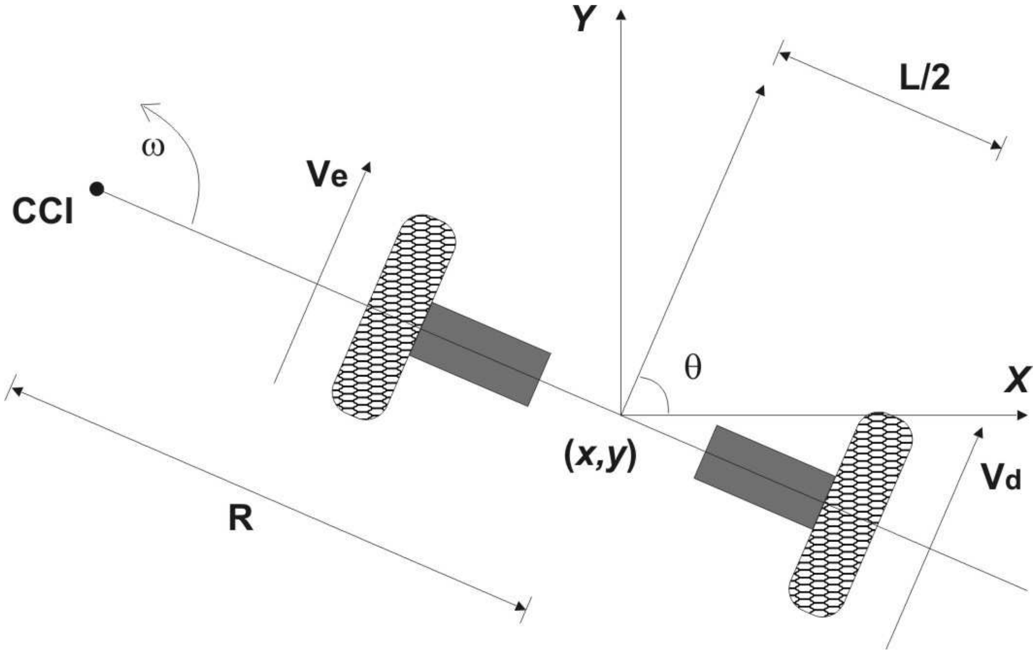


Figure 2. Forward kinematics geometry.

Through manipulation of the control parameters v_e and v_d, the robot can be made to take on 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 ω are functions of time, is is straightforward to show (Figure 2) that if the robot has pose (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 $t \rightarrow t + \delta t$, then the CCI (Instantaneous Center of Curvature) is given by

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

and at time $t \rightarrow t + \delta t$ the pose of the robot is given by (Dudek and Jenkin, 2000)

$$\begin{bmatrix} x' \\ y' \\ \theta' \end{bmatrix} = \begin{bmatrix} \cos(\omega\delta t) & -\sin(\omega\delta t) & 0 \\ \sin(\omega\delta t) & \cos(\omega\delta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - \text{CCI}_x \\ y - \text{CCI}_y \\ \theta \end{bmatrix} + \begin{bmatrix} \text{CCI}_x \\ \text{CCI}_y \\ \omega\delta t \end{bmatrix} \qquad (2)$$

Equation 2 describes the motion of a robot rotating a distance R about its CCI with an angular velocity given by ω. Diferente classes of robots will provide different expressions for R and ω (Shim, 1995).

By integrating Equation 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 $v_d(t)$, the is, to solve the forward kinematics problem for the vehicle. For the special case of a differential drive vehicle, it is given by

$$x(t) = \frac{1}{2}\int_0^t [v_d(t) + v_e(t)]\cos[\theta(t)]dt$$

$$y(t) = \frac{1}{2}\int_0^t [v_d(t) + v_e(t)]\sin[\theta(t)]dt \quad (3)$$
$$\theta = \frac{1}{L}\int_0^t [v_d(t) - v_e(t)]dt.$$

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 an behavior. It is also related to the problem of trajectory planning.

2.1 Inverse kinematics for differential drive robots

Equation 3 describe a constraint on the velocity of the velocity of the robot 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 $v_d(t)$ (Zhao and 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 Equation 3 yields

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

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

The proposed system can be visualized at a logical level in the blocks diagram in Fig. 3.

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.
- **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. 4). 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 is managed the supervision of one or more mobile robots, 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

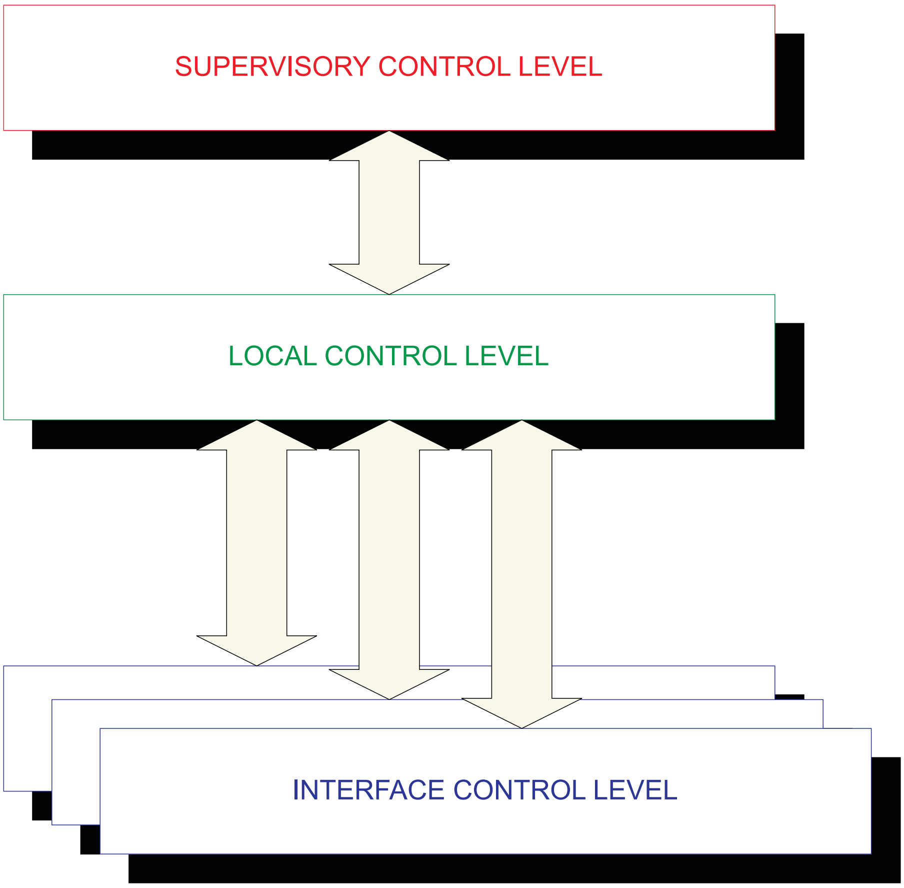


Figure 3. Different control levels of the proposed system.

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. The C6416 is based on the high performing TMS320C6400 DSP platform designed to needs of high-performing memory intensive applications such as networking, video, imaging, embedded systems controllers and most multi-channel systems.

- **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 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.

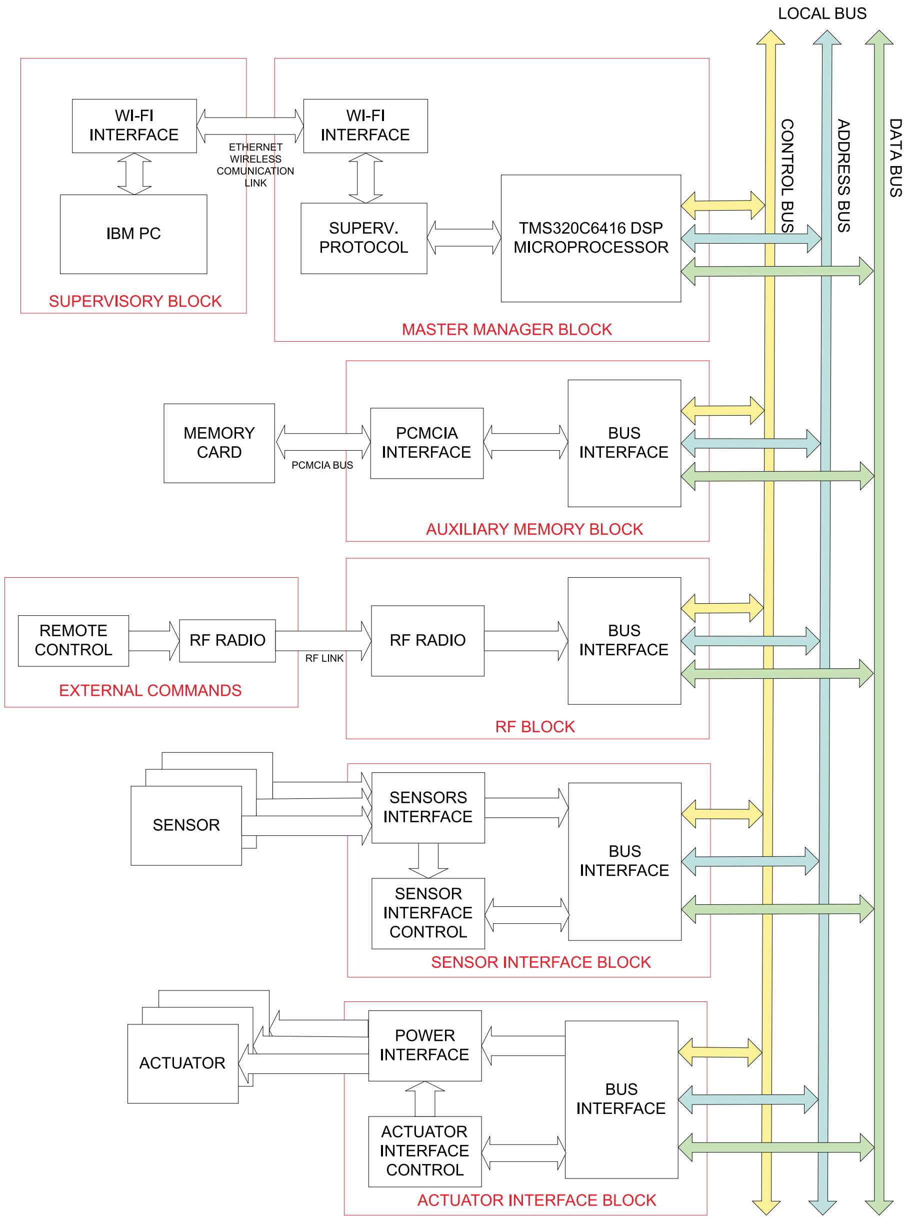


Figure 4. Hardware architecture block diagram of the proposed system.

- **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 is used for the mobile robot to receive operation commands, allowing the learning of trajectories, for example. 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. All the commands executed from the remote control are analyzed from master block manager to guarantee the best trajectory strategy. 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. It is a miniature UHF radio module capable of half duplex data transmission at speeds up to 40 kbit/s over distances of 30 meters "in-building" and 120 meters open ground. The module was chosen because it integrates a low power UHF FM transmitter and matching super- heterodyne receiver together with the data recovery and TX/RX change over circuits to provide a low cost solution to implementing a Bi-directional short-range radio data link.

4. MOBILE ROBOT SIMULATOR

The complete simulator system for the wheeled mobile robot, including motor drives, gears, kinematics and dynamics model, and controllers can be modelled in the same diagram using blocks from the Electric Drives library and SIMULINK libraries.

The purpose of the following experiments is to implement a simulator robot position control, based in This architecture was sufficiently generic to be used with several models of mobile robots. As an initial validation, the use of a platform with a differential drive configuration was proposed (Astrom and Wittenmark, 1989). A great number of sensors could equally been used, but two types were initially considered:

- **Position sensor**: Two encoders responsible for the odometer information.
- **Range finder sensor**: Responsible for the distance measured to obstacles in front and on the side of the mobile robot.

4.1 Platform Model Proposed

At the platform model proposed (Fig. 5), the encoders were coupled directly to the axis of the motor, allowing for a larger resolution in odometer measurements. The range finder sensors were distributed to cover the probable areas of collision.

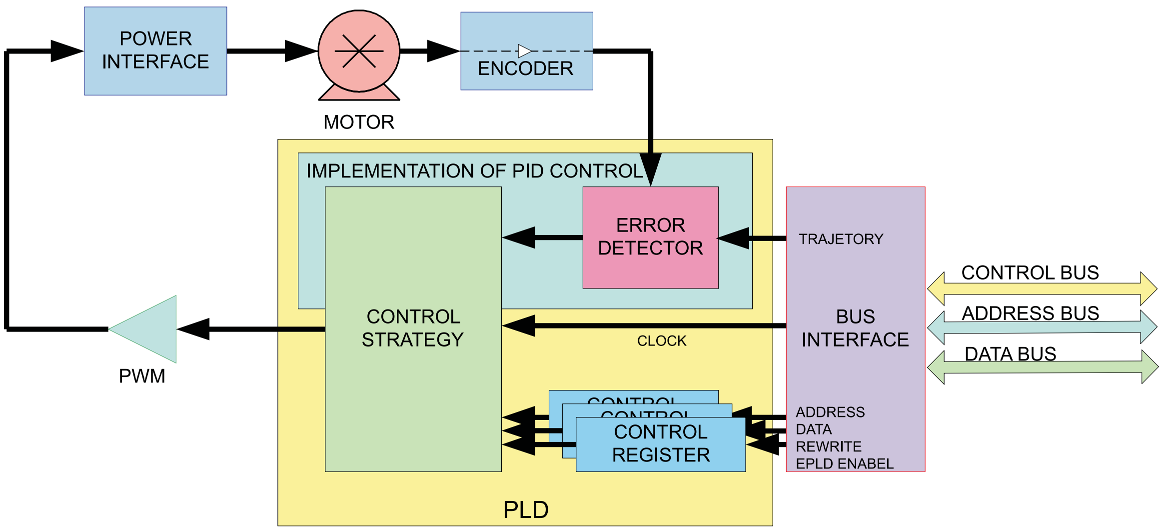


Figure 5. Motor controller blocks - Diagram of the mobile robot.

An example of flexibility provided by FPGA was illustrated in the speed and position control of the traction axis of the mobile robot, the aim of which is a DC motor control powered by a PWM drive. This programmable controller worked directly with digital signals generated by the encoder coupled to the motor and generated by the local control level, representing a trajectory. Fig. 6 represents the proposed controller, with the various proposed control levels. PLD allowed this controller to be implemented in different ways, applying different control strategies. The controller can be, for example, a PID, an adaptive controller (Astrom and Wittenmark, 1989) or a predictive controller (Boucher and Dumur, 1995). In this case, information coming from the encoder direction or from the range finder sensor can be used as additional signal to the controller. The implementation of digital controller (RST form) is realized using libraries built for algebraic manipulation in VHDL.

4.2 Axis Control Architecture

One advantage of the virtual environment is the possibility to implement and test advanced axis control strategies, in particular Generalized Predictive Control, well known structure providing improved tracking performances. This philosophy aiming at creating an anticipative effect is using the explicit knowledge of the trajectory in the future (Boucher and Dumur, 1995), (Pimenta at al, 2001).

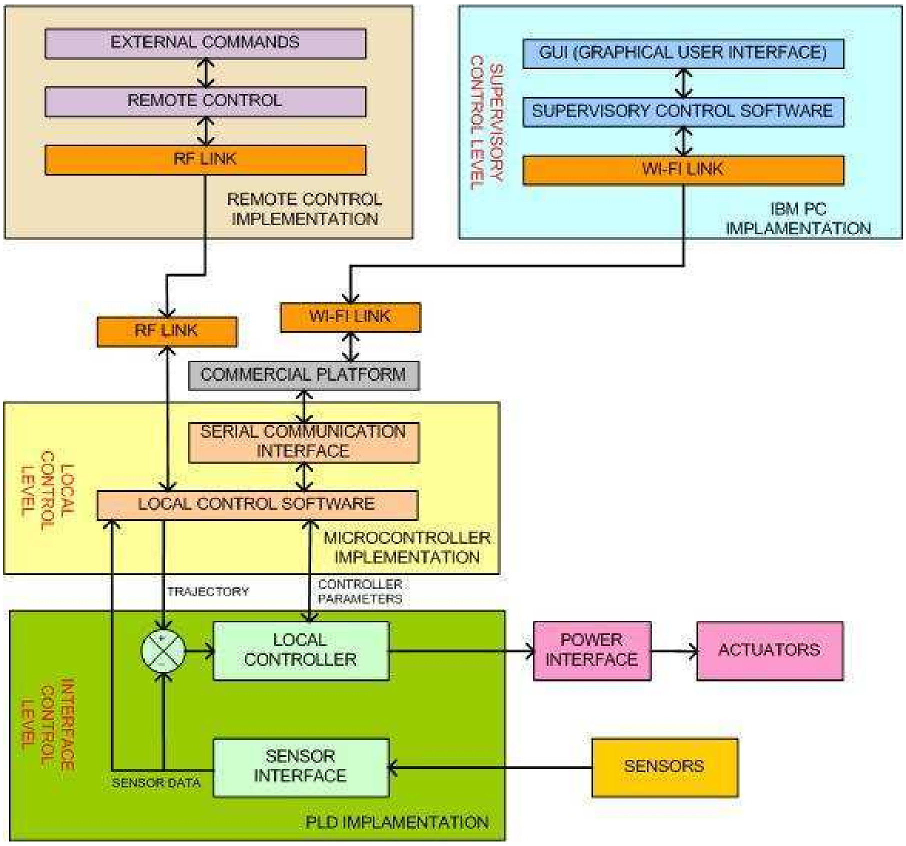


Figure 6. Blocks diagram representing the control levels structure of the mobile robot.

4.3 Generalized Predictive Control (GPC)

The Generalized Predictive Control (GPC) has shown to be an effective strategy in many fields of applications, with good time-domain and frequency properties (small overshoot, improved tracking accuracy and disturbance rejection ability, good stability and robustness margins), able to cope with important parameters variations.

5. SIMULATION RESULTS IN THE VIRTUAL ENVIRONMENT

Previous sections have described the whole virtual environment related to the mobile robot device, including motor drives, kinematics and design of the proposal control system architecture for mobile robots.

5.1 Actuator parameters

The system considered here, used for supervision and control implementation, includes the wheels DC motors, a 1:100 gear box (N), a ball screw transmission and incremental encoders (Table 1).

Table 1. Motor parameters.

parameters	*value*
J_m - Inertia (kgm^2)	0.71×10^3
Weight (kg)	8
Mechanical time constant (ms)	1.94
Voltage constant (V/rad/s)	0.807
Torque constant (Nm/A)	1.33
L - Inductance (mH)	14.7
R - Resistance (Ω)	1.44

5.2 Simulation results

Figure 7 and 8 shows the resulting position errors obtained with PID and GPC axis controllers, respectively. The previous PID was tuned as best as possible, showing a slower disturbance rejection dynamics and a more unstable behavior compared to GPC. Tracking performances offered by GPC laws are clearly emphasized on Fig. 8, with very small tracking errors.

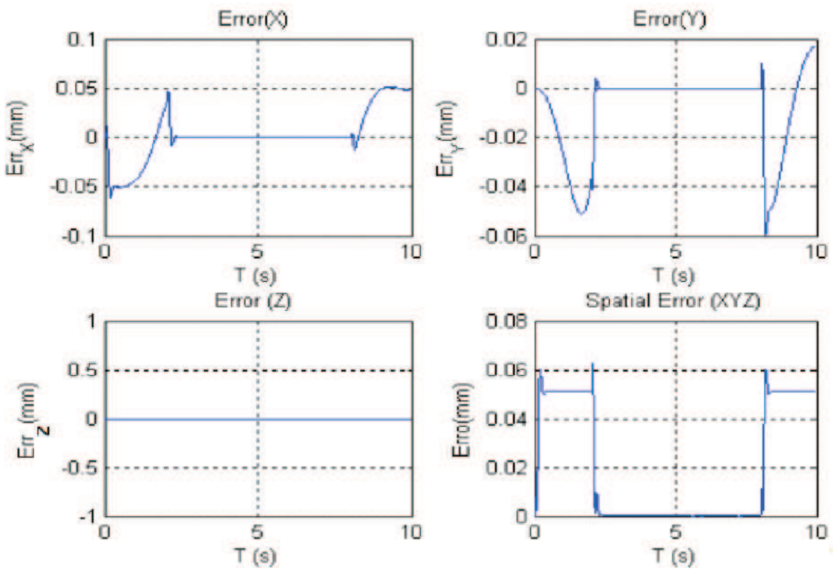


Figure 7. PID case with disturbances.

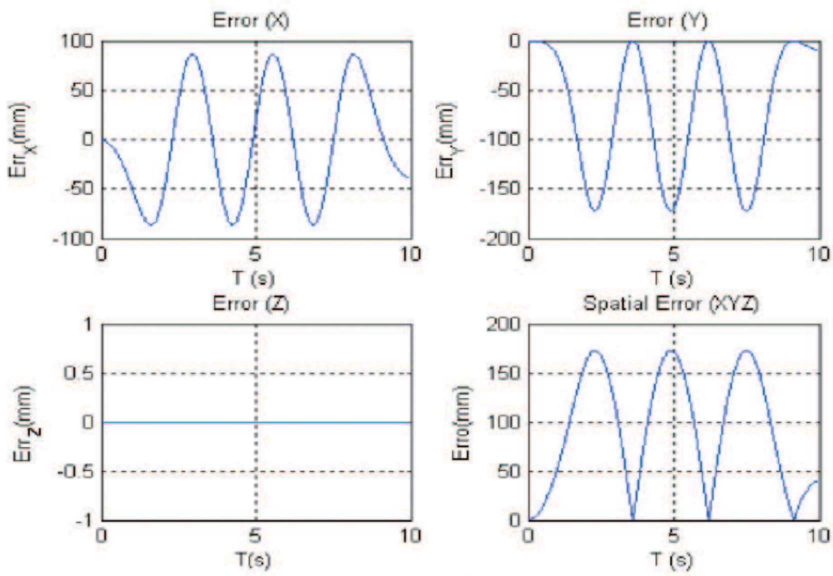


Figure 8. PID and GPC case with disturbances.

Globally, the results analysis shows that the anticipative effect of the GPC law can provide better performances, even if the controllers were designed neglecting the coupling effect between each axis. In this direction, GPC is less sensitive to inertia variations (appearing as every axis acts on the other ones) than PID. This significant simulation shows the robustness of GPC, so that the inertia variation can be considered as a disturbance performing on the system.

6. 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.
- 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.

7. REFERENCES

Astrom, K. and Wittenmark, B., 1989, “Adaptive Control", Addison-Wesley Editions.
Barros, E.A., 1999, “A test bed applied to Mobile Robot Navigation”, XV Brazilian Congress of Mechanical Engineering, Sao Paulo, Brazil.
Boucher, P. and Dumur, D., 1995, “Predictive Motion Control”, J. Syst. Eng., Special Issue on Motion Control Systems, Vol. 5, pp.148-162, Springer-Verlag London.
Dudek, G. and Jenkin, M., 2000, Computational Principles of Mobile Robotics, Cambrige, UK: Cambridge University Press.
Pimenta, K.B. at al, 2001, “Control of Robotic Joints with Generalized Predictive Control (GPC)”, RaddŠ2001, Vienne, Austria.
Shim, H.-S. et al, 1995, “Variable structure control of nonholonomic wheeled mobile robot", IEEE International Conference on Robotics and Automation, vol. 2, pp. 1694-1699, Nagoya, Japan, May.
Zhao, Y. and BeMent, S.L., 1992, “Kinematics, dynamics and control of wheeled mobile robots", IEEE International Conference on Robotics and Automation, vol. 1, pp. 91-96, May.

8. Responsibility notice