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A mechatronic description of an autonomous mobile robot for agricultural tasks in greenhouses

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1. Introduction

Today, greenhouses are one of the main productive sectors of many areas of the world (Spain, the Netherlands, Australia, Morocco, etc.). One extraordinary area is the province of Almería (SE Spain), where production exceeds 2.7 million tn on a surface area of 48000 ha of greenhouses (Cámara Oficial de Comercio, 2007). This constitutes not only economic wealth but also a source of research and innovation.

In recent years, greenhouse techniques have undergone many improvements in irrigation processes, phytosanitary treatments, and climatic-control systems (van Henten, 2006). Nevertheless, many agricultural tasks are conducted manually, such as harvesting, spraying and farming. The environmental conditions inside greenhouses, characterized by high temperatures and humidity, make work harsh and sometimes hazardous for people, especially in applying toxins (pesticides) with little air renewal. This has recently given rise to the development of different automatic machinery to perform greenhouse work.

Some projects and references related to the application of robots in greenhouses have appeared in the literature. On one hand, manipulator robots, usually being controlled by vision systems, have been successfully tested. (Sandini et al., 1990) and (Dario et al., 1994) presented the *Agrobot Project*, a robotic system for greenhouse cultivation of tomatoes. This involved a mobile robot with a colour stereoscopic vision system plus an anthropomorphic arm with a gripper/hand and six degrees of freedom. (Acaccia et al., 2003) described a robotic system (robotic arm and mobile platform) which was able to analyse the plant to evaluate its state of health. (Kitamura and Oka, 2005) presented a robotic system based on vision for navigation control, composed of a cutting system to harvest sweet peppers in greenhouses. (Belforte et al., 2006) presented a fixed-position robot. This was interfaced to a standard belt-conveyor displacement system that provided the robot with pallets containing the crops. The main drawback of this solution was that since the robot remained in a fixed position within a restricted workspace and thus had limited applications.

Another solution is to use automated guided vehicles (AGVs). These vehicles follow a trail fixed on the ground of the greenhouse. (Sammons et al., 2005) described an autonomous spraying robot with navigation control based on inductive sensors which detect metal pipes buried in the soil. (Van Henten et al., 2002) presented an autonomous robot for harvesting cucumbers in greenhouses; it was guided using heating steel pipes. The disadvantage of these types of vehicles is that they require an extensive and costly modification of the greenhouse. Few papers have addressed the autonomous navigation problem of a mobile robot in greenhouses. (Mandow et al., 1996) described an autonomous vehicle (*Aurora*) for spraying tasks. The navigation control of this robot depends on a previous sequence of behaviour established by an operator. (Subramanian et al., 2005) and (Singh et al., 2005) also described a mini-robot to perform spraying activities, for which navigation is controlled by algorithms based on fuzzy logic. The sensorial system uses vision and ladar (laser + radar) sensors. The main drawback of these two autonomous robots is that they have reduced dimensions and a limited power system. For these reasons, they can operate only with a small payload and over small distances. For a complete review of robotic systems in agriculture, see (Kondo and Ting, 1998) and the references therein.

This article presents a project developed at the University of Almeria (Spain) aimed at designing, implementation, and testing a multi-use autonomous vehicle with safe, efficient, and economic operation which moves through the crop lines of a greenhouse and which performs tasks that are tedious and/or hazardous for people, it is called *Fitorobot*. First, it has been equipped for spraying activities, but other configurations have also been designed, such as: a lifting platform to reach high zones to perform tasks (staking, cleaning leaves, harvesting, manual pollination, etc.), and a forklift to transport and raise heavy materials (Sánchez-Gimeno et al., 2006).

The mobile robot developed to operate in greenhouses involves a synergetic integration of mechanical engineering with electronics and automatic control. From the first step of construction to the final tests in greenhouses, all the processes were supervised by a mechanical, electronic, and information technology combination (Isermann, 2003), (Bishop, 2006).

Regarding a mobile platform used to carry on a spraying system, there are some circumstances where it is impossible to maintain a constant velocity due to the irregularities of the soil, different slopes of the ground, and the turning movements between the crop lines. Thus, for work at a variable velocity (Guzmán et al., 2008), it is necessary to spray using a variable-pressure system based on the vehicle velocity, which is the proposal adopted and implemented in this work. This system presents some advantages, such as the higher quality of the process, because the product sprayed over each plant is optimal. Furthermore, this system saves chemical products because an optimal quantity is sprayed, reducing the environmental impact and pollution as the volume sprayed to the air is minimized.

This chapter is organized as follows. An overall mechatronic description is outlined in Section 2, presenting the mechanical, electronic, sensor, and hardware systems. Section 3 examines the control architecture, the navigation control, and the low-level controllers or servocontrollers. Experimental results of sensors, servocontrollers and navigation are reported in Section 4. Conclusions and future works are discussed in Section 5.

2. Mechatronic Description

The mobile robot presented in this work has been designed and built following the paradigm of Mechatronics. According to (Bolton, 2003) a mechatronic system is not just a combination of electrical and mechanical systems and is more than just a control system; it is a complete integration of all of them. For these reasons this project has been supported by engineers of different areas of specialization (Mechanics, Robotics, Automatic Control, Agronomy, Computer Science, and Electronics).

Fig. 1 shows the Mechatronic decomposition of the steps followed:

- *Mechanical systems:* CAD/CAE tools have been employed to design the prototype. The design took into account several requirements, for example the environment conditions, the appropriate position of sensors on the platform, the position of the control system, the maximum desired velocity, the range of pressure of the spraying system, etc. Then the prototype was built and assembled using the CAD planes designed in the first stage.
- *Electronic systems:* Some sensor systems were evaluated, and the most appropriate were acquired. Furthermore, one computer was selected to run the control programs that autonomously govern the vehicle. Coupled with the computer, appropriate input/output cards receive/send commands from/to sensors/actuators.
- *Information technology:* Simultaneously to the previous phases, autonomous navigation strategies and spraying controllers were analysed and studied. These control structures were tested and calibrated when the real vehicle was built.

As detailed in Fig. 1 these three areas are linked. Information technology is related to Mechanics because the design of the mechanical structure of the vehicle has been realized using CAD/CAE tools. This design has taken into account the features and requirements of the physical elements. On the other hand, Information technology is also related to Electronics, because sensors and electronic actuators are required by the controllers implemented in the computer, in order to feedback to the control algorithms and to send the appropriate control signals to the actuators. Finally, Electronics and Mechanics are linked through electromechanical elements such as electronic valves in the track motors, electronic systems to control the hydraulic pressure system, etc. Furthermore, sensors are used to measure these electromechanical systems.

2.1 Mechanical Systems

In the present work, the vehicle works primarily with a spray system but includes such configurations as: a lifting platform (Fig. 2a) to reach high zones to perform special tasks (staking, cleaning leaves, harvesting, manual pollination, etc.), and a forklift (Fig. 2b) to transport and raise heavy materials (Sánchez-Hermosilla et al., 2003), (Sánchez-Gimeno et al., 2006).

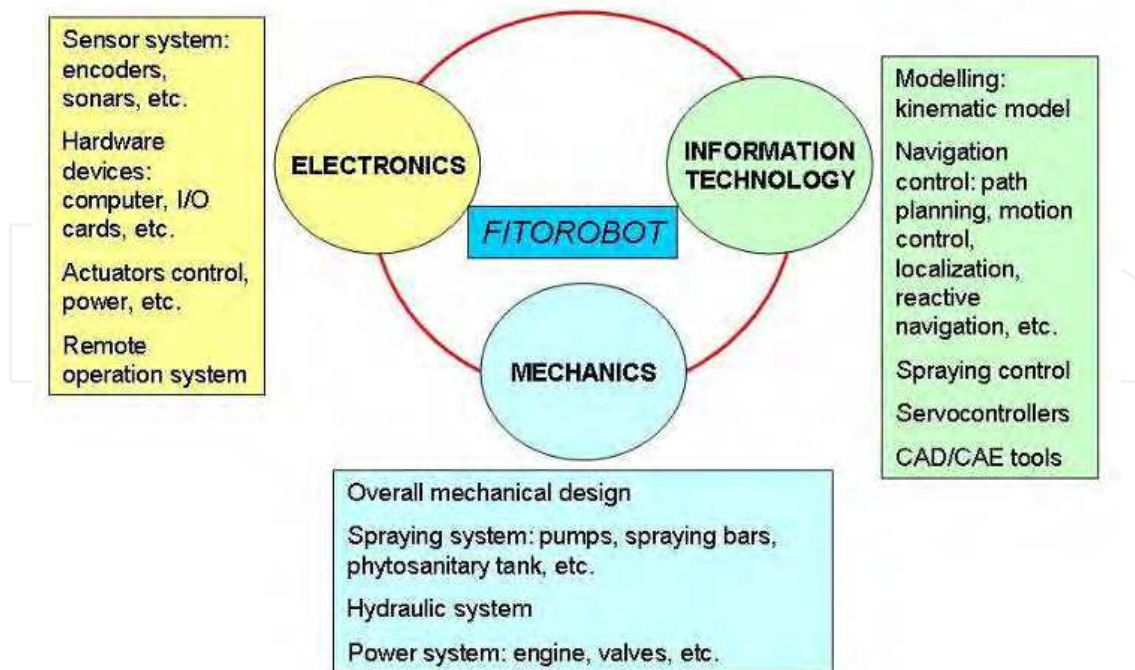


Fig. 1. Mechatronics paradigm followed to develop the *Fitorobot*

The configuration and the position of the greenhouses impose limits to the mechanical structure of the platform:

- It is necessary for the vehicle to be compact (small dimensions) with high maneuverability in an environment having numerous obstacles and tight spaces.
- The vehicle should have a roller system to guarantee mobility on loose soils and to reduce soil compaction that might harm crop development. Compaction is one of the most important problems to solve in modern agriculture, many studies have determined the negative effect of soil compaction on crop performance (e.g. Kirkegaard et al., 1992, Radford et al., 2001, Hamza and Anderson, 2003, Hamza and Anderson, 2005, Sadras et al., 2005, Chan et al., 2006).
- The vehicle should be autonomous and have sufficient charge capacity for optimal work performance.
- The vehicle should have good flexibility to adapt the work velocity to the requirements of each task.

Satisfying these characteristics, a rubber-track vehicle with differential steering was developed for agricultural tasks in greenhouses. The rubber tracks exert low pressures on the soil (Brown et al., 1992), providing strong traction on uneven ground (Bashford et al., 1999).

CAD/CAE technology was used to design the mechanics of the vehicle, adapting previously established morphology and minimizing volumes and weights (taking into account the manufacturing materials), and optimising the disposition of the elements in its interior. For these tasks the CAD/CAE tool Solidworks (Solidworks Corp., Massachusetts, USA) was used.



(a) Lifting platform.

(b) Forklift.

Fig. 2. Other configurations of the *Fitorobot*

The dimensions of the vehicle were fixed at 0.7 m wide and 1.7 m long. This ensured movement through the crop rows, which in full development leave a free path of approximately 0.8 m, and guaranteed the possibility of turning in the greenhouse lanes, which are normally 2 m wide. A load capacity of 400 kg was established to ensure autonomy and proper work performance.

The rubber tracks were powered with hydraulic fixed-displacement gear motors (TF0204, Parker Hannifin Corp., Cleveland, USA) that were placed in the wheel sprockets. The hydraulic motors are driven by a double variable-displacement axial piston pump (M4PV21, Bondioli & Pavesi, Bologna, Italy) with electronic proportional control. Pump displacement is proportional to the electric current feeding one of the two proportional control electrovalves.

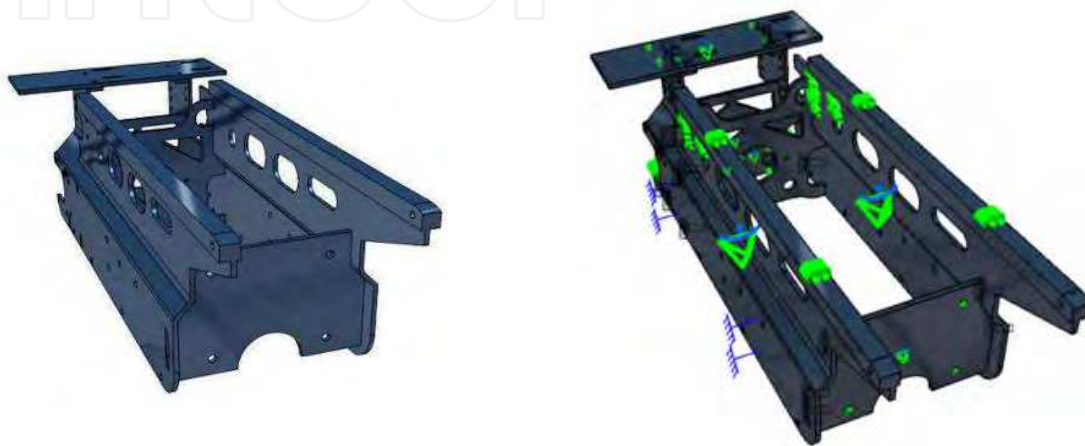
All the energy needed for the vehicle to function comes from a petrol-combustion motor. A 20 HP air-cooled 4-stroke petrol engine (Honda GX 620 K1, Honda Motor Co., Ltd., Tokyo, Japan) was selected, taking into account the vehicle weight (800 kg loaded), a maximum velocity of 2 m/s, under the assumption that the vehicle will be travelling on a sandy surface at a slope of 5°. It was also assumed that the vehicle would have a fixed-volume pump to provide energy for the drive of the attached implement (e.g., sprayer pump of the spraying system).

A maximum velocity of 2 m/s has been considered because this is the appropriate velocity to spray a typical greenhouse with the current tank available in the mobile robot (Guzmán et al., 2004) and this relatively slow velocity permits partially to neglect lateral-slip phenomena (González et al., 2009b).

Steering is accomplished by changing the velocities of the hydraulic gear motors, achieving turning radii of nearly zero. For straight trajectories, the two motors turn at the same velocity. The turn is achieved by reducing the velocity of one of the motors with respect to

the other. Under situations of limited space, turning radii close to zero can be achieved by making the two motors turn in opposite directions.

A chassis was designed to joint the different elements that form part of the vehicle and that should support the different actions that are generated during the functioning. It is constituted by different pieces in 8-mm steel sheeting (Fig. 3a). On the lower part it fits into the rubber tread which makes up the roller system. The upper part is equipped with a system to transport and connecting accessory equipment, characterized by rectangular guides and self-locking pins. Furthermore, in order to study the robustness and stability of the chassis, a finite element analysis (FEA) of the chassis was made (Fig. 3b).



(a) Front view of the chassis

(b) FEA analysis of the chassis

Fig. 3. Chassis of the vehicle

The rest of the main elements making up the vehicle are indicated in Fig. 4. This figure also includes the spraying system designed for the vehicle, composed of:

- A 300-litre fibreglass-reinforced polyester resin tank (92x61x60 mm)
- A 26.75 l/min spray tank (Comet MP30, COMET S.p.A. Reggio Emilia, Italy), 15 bar maximum pressure.
- A vertical boom sprayer with ten nozzles (Teejet DG 9502 EVS, Spraying Systems, Co., Wheaton, Ill.).
- A frame made of hollow rectangular steel tubes of 30x30x1 mm

The arrangement of the different elements gives the vehicle a wide zone to transport equipment; the connection and disconnection of the equipment proves easy, as the guides of the transport system are situated near the soil level (approx. 50cm).

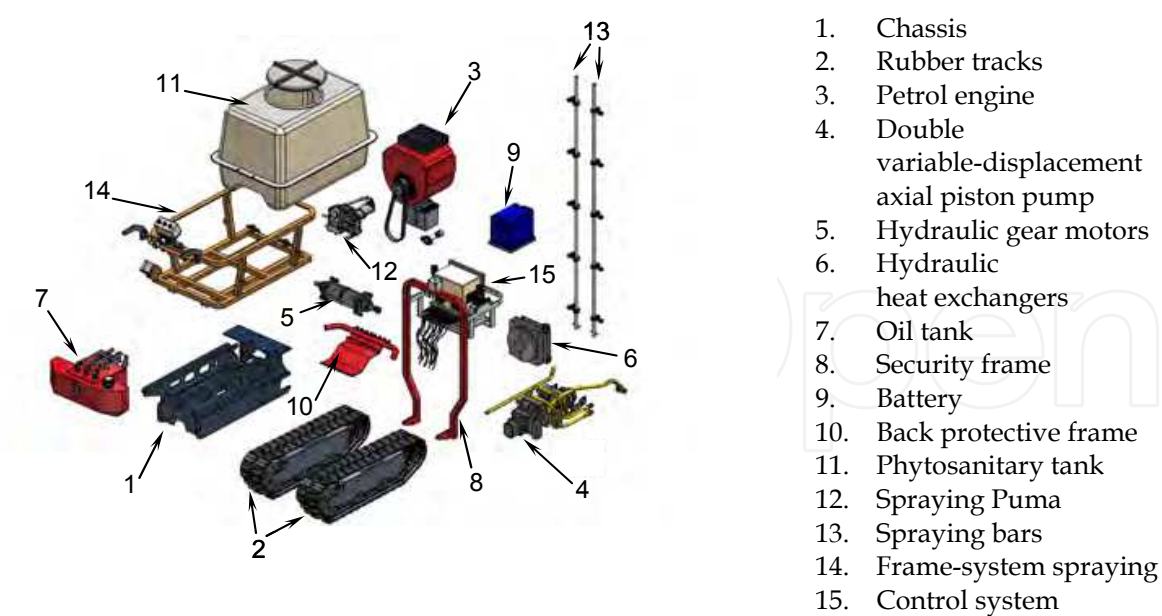


Fig. 4. Exploded drawing of the prototype

2.2 Electronic Systems

2.2.1. Sensors

Autonomous control and operation of the mobile robot relies heavily on external sensor information. Therefore, the performance of the navigation and spraying controller will depend heavily on the installed sensors on the platform. For this, several sensors are installed on the platform; some sensors are redundant for the purpose of testing different configurations, and thus, in a future commercial version of the mobile robot, only the most useful and appropriate sensors will be installed. The position of each sensor has also been studied, in order to determine the best location of the sensors depending on the mechanical structure and the environment.

One middle-range sonar and four short-range sonars have been located in front and in each side of the platform, respectively. These sensors enable to the robot to sense the environment and the greenhouse corridors. Odometry establishes the position and velocity of the robot, using two incremental optical encoders attached to the axle of rotation of the track motors. One radar and one magnetic compass measure the linear velocity and orientation of the vehicle, respectively. It is protected from unexpected obstacles in the environment by a security sensor composed of four tactile bars around the vehicle. Finally, a pressure sensor has been installed in the spraying hydraulic system to regulate the spraying controllers. The main features of these sensors are summarized in Table 1 and their positions on the platform are shown in Fig. 5.

Sensor	Mark, Model	Range	Precision / Resolution	Signal Output
Pressure	WIKA, ECO-1	0-250 bar	0.50%	0-10 VDC
Sonar (middle dist.)	Siemens, Bero III	40-300 cm	2.5 %	0-10 VDC
Sonar (short dist.)	Siemens, Bero M18	15-100 cm	1.5 %	0-10 VDC
Magnetic Compass	KVH, C100	0-360°	0.1°	0.1-1.9 VDC
Radar	LH Agro, Compact II	0.08-17.3 m/s	128.4 pulse/m	Pulse
Encoders	Sick, DRS61	0-360°	1024 pulse / rev.	Pulse
Security sensor	SafeWork, SKL25-40	On-off	-	Digital (0-1)

Table 1. Features of the installed sensors.

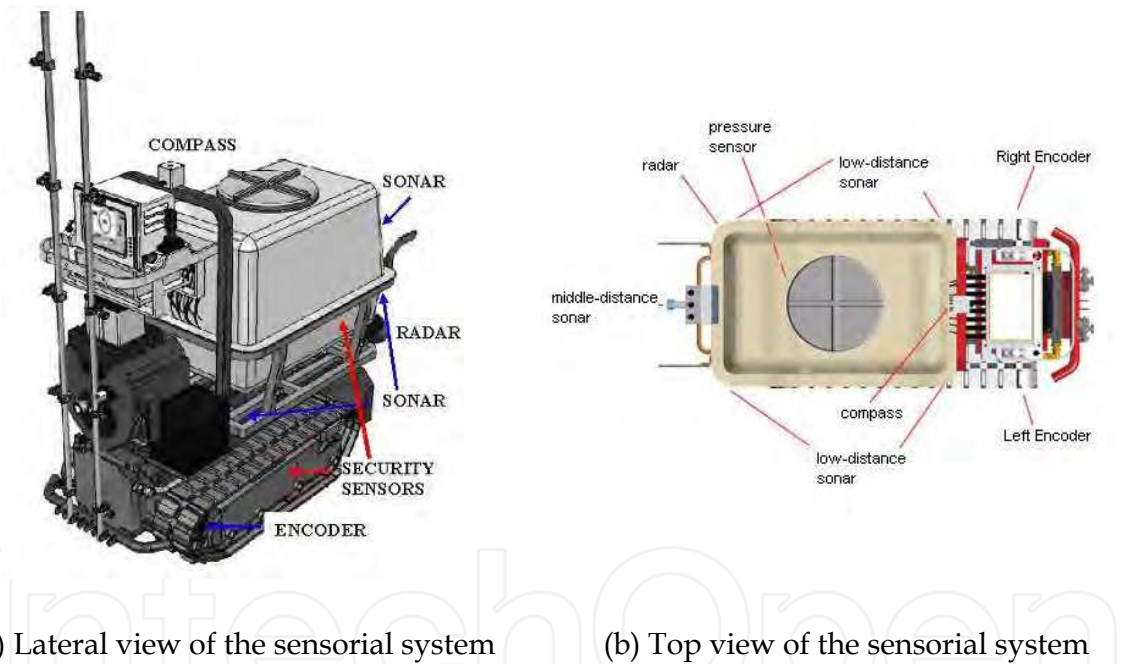


Fig. 5. Sensors on the experimental platform

2.2.2 Hardware devices

The mobile robot is governed by an embedded system based on the PC-104 standard (PC-104 Embedded Consortium, 2008) (PCM-9371, Advantech, Irvine, USA). This system is based on the ISA specifications to work in embedded devices. The main reasons of why PC-104 system has been selected are: It has reduced dimensions; low power supply and, ease to integrate new input/output cards. The main characteristics of our PC-104 are summarized in Table 2.

Feature	Description
CPU	Intel Pentium III – 933 MHz
Memory	Compact Flash of 1 GB
Cache	512 KB
Chipset	VIA PN133T (133 MHz FSB)
Interfaces	USB, Ethernet, Audio, Serial, PS2
Graphic Card	VIA VT8606
Power	12 VDC
Temperature	0 - 60°

Table 2. Main characteristics of PC-104

Some input/output digital/analogue boards have been connected to the PC-104 bus, so that the signals of the different sensors onboard the vehicle can be read and commands can be sent to the actuators of the vehicle. An analog input board (PCM-3718H, Advantech, Irvine, USA) with digital outputs is used for sonar, compass, and pressure sensing; furthermore, the digital output data determine the rotation of the tracks (forward or backward); a counter board (PC104-3126, Nagasaki IPC, Taiwan) with digital inputs governs the security sensors, encoders and radar; two analog outputs boards (PCM-3712, Advantech, Irvine, USA) are used for the track engines and spaying valves. The composition of the system is shown in Fig. 6.

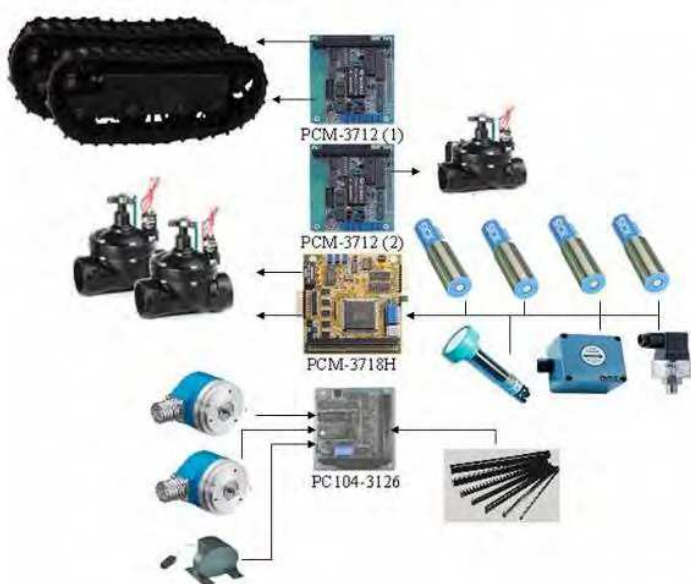


Fig. 6. Input/Output boards

The system is completed by a tactile screen (7" LCD Screen, Nagasaki IPC, Taiwan) connected to the PC-104. This monitor permits to the user to define the parameters and options of the programs to make the desired tests. Fig. 7 shows a real image of the hardware system.

The software used to develop the control and supervision programs is LabVIEW® of National Instruments® and Matlab® of MathWorks®. These programs were selected for their simplicity and familiarity with program control algorithms, as well as their

appropriate connection with real systems: input/output boards, engines, etc. Furthermore, they have appropriate graphic interfaces, facilitating the use of their programs.



(a) Front view

(b) Top view

Fig. 7. PC-104 on *Fitorobot*

2.2.3 Remote operation system

The mobile robot *Fitorobot* can also be controlled remotely by a teleoperation system in complex situations. The remote operation system is composed of two segments (Fig. 8a). One segment is the user keypad or user interface that provides to the operator the remote control of the vehicle's position and velocity (Fig. 8b). The operator can also regulate the pressure of the spraying system and open/close the spraying bars. The keypad has a selection switch that establishes the velocity program (maximum velocity, joysticks functioning, etc.) and the working pressure. Data communications are implemented via an RS-232 serial link, half-duplex radio modem operating at the free band of 868 MHz. The second part is defined by a program running in the computer installed on the mobile robot. This program interprets the messages sent by the user keypad and sends the appropriate signals to the actuators.

2.3 Spraying Systems

As commented above, the mobile robot is equipped with some spraying devices for autonomous spraying tasks to be controlled by programs running in the main computer. As shown in Fig. 9, the spraying system is composed of a tank containing the chemical treatment, vertical bars with several nozzles, two on/off electrovalves to activate each spraying bar, a proportional electrovalve to regulate the output pressure, and a pressure sensor to close the control loop. This arrangement of the bars and the nozzles was established in previous studies (Guzmán et al., 2004; Guzmán et al., 2008).

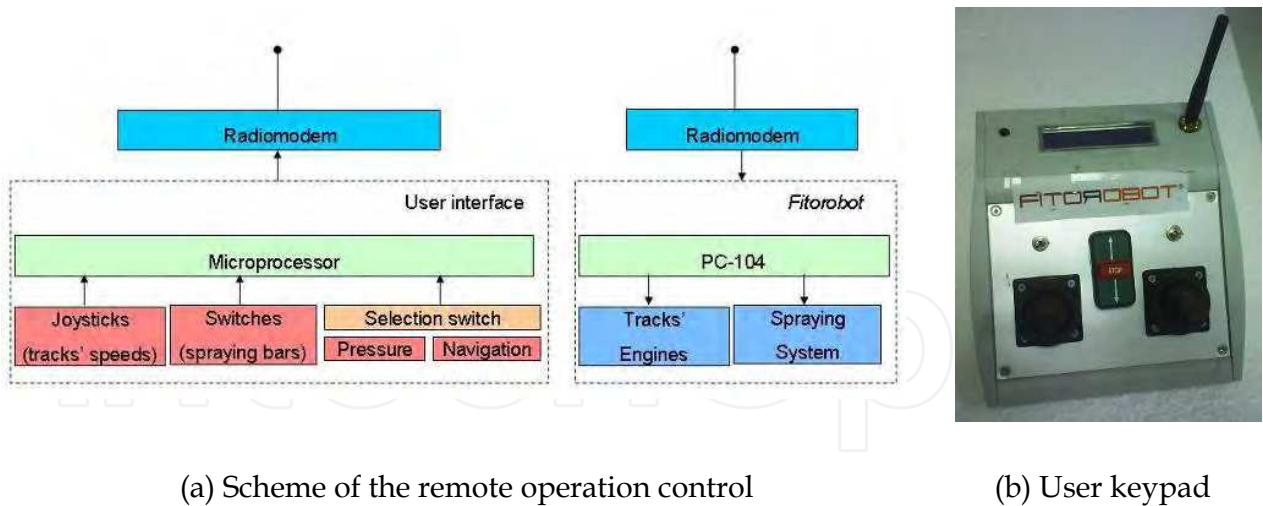


Fig. 8. Remote operation system

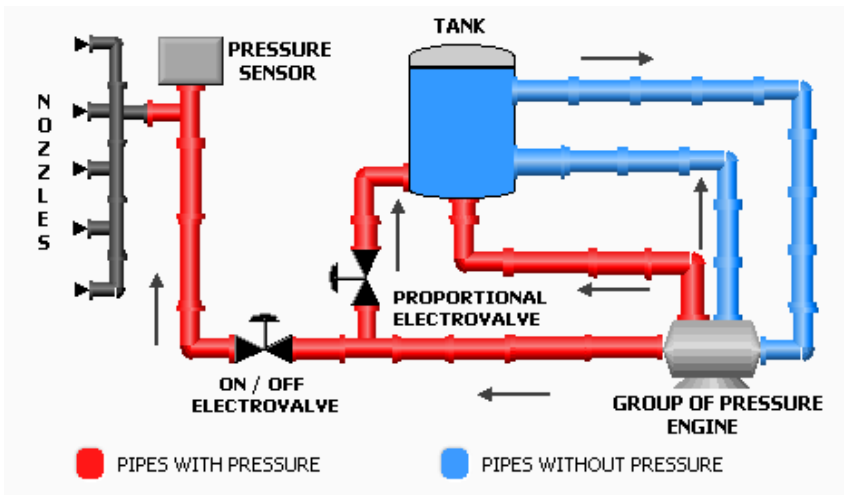


Fig. 9. Spraying system used to control the output pressure

3. Control System

3.1 Modes of operation

The vehicle can be operated on three different modes: autonomous control, remote operation, and manual control. As commented above, remote human operation is performed by radio communication. The platform can be manually controlled using two joysticks directly connected to the two valves that move each track. In the case of autonomous control, the motion of the vehicle is governed by controllers running on a computer.

The control architecture of the mobile robot is studied in (González et al., 2009a) and it is detailed in (Fig. 10). Greenhouses are built using digital maps, which can be used by robotic navigation algorithms to control and steer the vehicle. Deliberative approaches are based on these maps to construct an obstacle-free path which will act as the reference path that the robot will follow in real time. On the other hand, reactive navigation strategies focus on

controlling the robot's trajectory using information provided by its sensors during robot motion. One navigation algorithm of each technique has been implemented in the mobile robot *Fitorobot*. The main results are discussed in (González et al., 2009a).

The architecture follows a hierarchical decomposition on five layers (Fig. 10). The function of each layer is the following:

- The *user layer* is composed of the interface by which the user can calibrate the program; for example, selecting between reactive or deliberative navigation algorithms.
- The *path-planning level* generates path following from the map information (this map will be built using the reactive algorithm) and gives instructions to the motion-control layer and spraying controller.
- The *motion control level* gives the setpoints to the servo layer depending on the current position of the vehicle. Furthermore, it sends the setpoints to the spraying controller, depending of the vehicle's velocity. Additionally, in this layer a new filter has been added for the sonar readings.
- The *spraying controller level* consists on an appropriate robust controller which controls the pressure of the bars (Guzmán et al, 2008). Motion control and spraying controller are related because the spraying pressure should be appropriate to the velocity of the vehicle.
- The *servo level* is composed of two PI controllers that ensure that the actuators (tracks) follow the setpoints given by the motion-control level.

3.2 Path-planning level

Greenhouses are structured environments where the distribution of plants is at least partially known. The plants are usually arranged in parallel straight rows with narrow corridors for the operation of humans and machines. The navigation challenge for a robot operating in a greenhouse involves planning a reference trajectory and reacting to unforeseen events (workers, boxes, tools, etc).

In order to solve this problem, a hybrid solution has been developed, using the most dominant paradigms for robot control (Fig. 10) (González et al., 2009a):

- *Deliberative strategies*. This technique uses a map to calculate an obstacle-free path of the greenhouse before the robot moves along it. In this work, the selected path-planning algorithm is a modified Voronoi Diagram, obtaining a graph with all the possible paths in the greenhouse without obstacles. Based on the task that the robot must do (spraying, transport, etc.), one of this paths is selected. Once the path is chosen, a navigation control strategy is used to follow it. The navigation control strategy used in this work will be described in the next section.
- *Reactive strategies*. This technique focus on control of the robot's trajectory using information provided by its sensors during robot motion. As previously mentioned, a greenhouse is a structured environment and therefore a priori knowledge can be added to the reactive navigation strategy. For example, when the mobile robot is at the end of a corridor, it could turn to the left or to the right side. This decision will be made relying on the sensorial system and on the previous turn. The key idea is that the second turn will be to the same side as the

previous one. When it has turned two consecutive times, the next two turns will be to the opposite side. This can be seen as a zigzag movement, but taking into account that the robot can react to unexpected events and to different configurations of greenhouses where zigzag is not appropriate. Really, this technique should be considered pseudo-reactive, because the navigation algorithm has been implemented knowing that there are parallel corridors arranged in rows in the greenhouses.

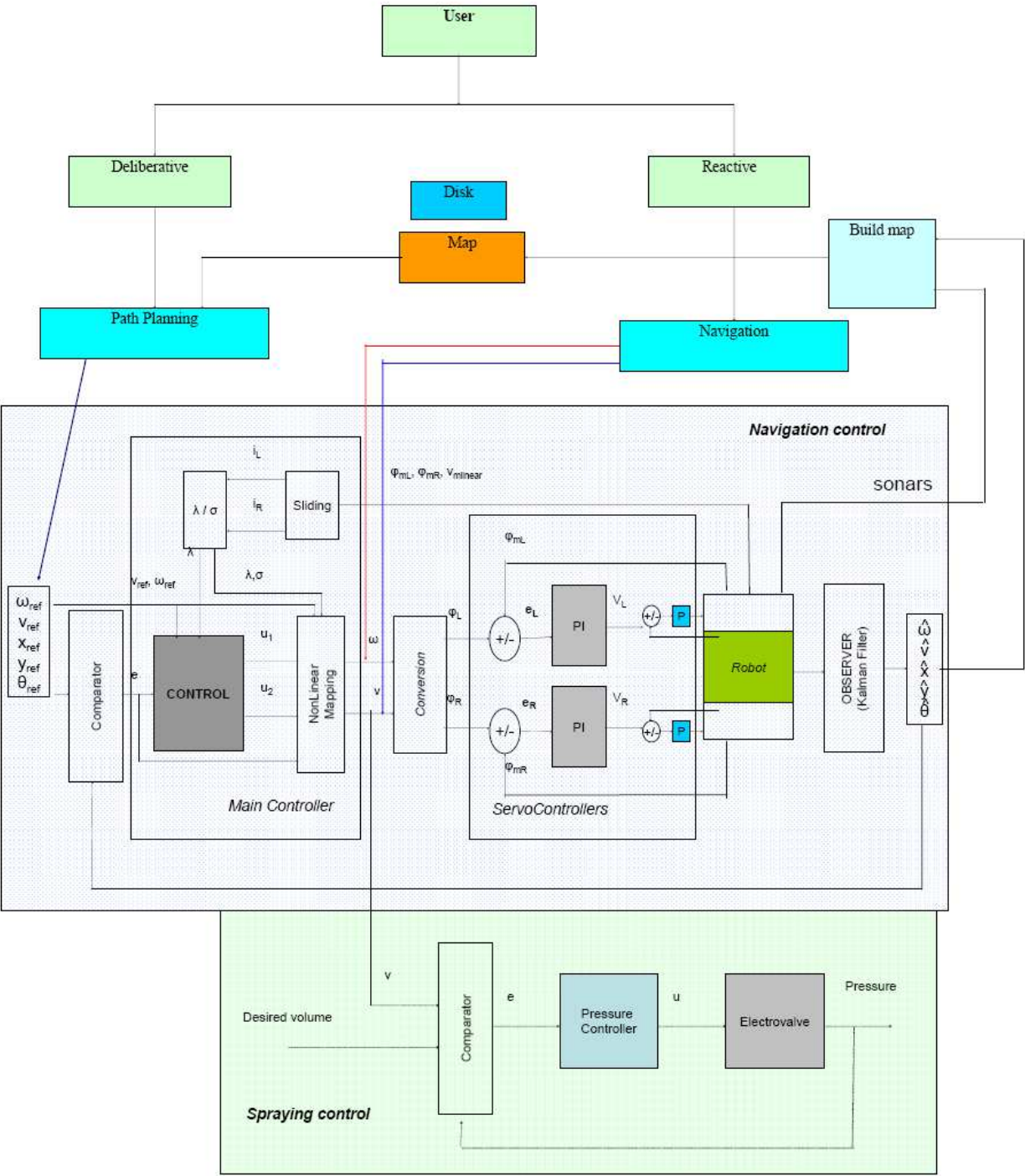


Fig. 10. Motion-control architecture

Therefore, the first time that the robot navigates the greenhouse if a map exists, it is employed by a deliberative method. On the other hand, when there is no map, a pseudo-reactive method is used. Moreover, a sensorial map is built along the path to be employed by the deliberative module in later runs.

The two previous approaches utilize a security layer to avoid collisions. The main obstacle to the movement of mobile robotics in greenhouses is related to the fact that navigation algorithms should take into account unexpected events (humans working in the greenhouse). This layer uses on/off sensors.

3.3 Navigation control

As discussed above, when a deliberative strategy is used and a fixed path is selected, a control strategy must be used to follow this path. In order to address this navigation control problem of the mobile robot, we have used the trajectory tracking problem which consists that a robot must follow a *virtual mobile robot* representing the desired positions and velocities. Hence, the objective is to find a feedback control law (Canudas et al., 1997), such that, the error between the desired location and the real location of the mobile robot is close to zero (regulation problem). For that purpose, the kinematic model (KM) of a differential-drive mobile robot has been extended with a parameter which weights the slip factor of the terrain (González et al., 2009b). In our case, we suppose that the mobile robot will operate at low velocities, and we only consider longitudinal slip. As stated in (Le, 1999), lateral slip is zero for straight line motions and it can be neglected when the vehicle turns “on the spot” or at low velocities. However, longitudinal slip is an unavoidable effect of pneumatic tire compression / reaction to soil shearing due to the own characteristics of wheeled / tracked locomotion (Wong, 2001).

As detailed in (González et al, 2009b) the KM under longitudinal slip can be expressed as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos \theta & 0 \\ \sin \theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_m \\ \omega_m \end{bmatrix} - \begin{bmatrix} \cos \theta & 0 \\ \sin \theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \sigma \\ \lambda \end{bmatrix}, \quad (1)$$

where (x, y) is the position of the robot, θ is the orientation, v_m is the linear or translational velocity, ω_m is the angular or rotational velocity of the vehicle, and σ and λ are terms depending of slip,

$$\sigma = \frac{v_r \dot{i}_r + v_l \dot{i}_l}{2}, \quad (2)$$

$$\lambda = \frac{v_r \dot{i}_r - v_l \dot{i}_l}{b}, \quad (3)$$

where v_r and v_l are the linear velocities of the right and left track, respectively; i_r and i_l are the longitudinal slip of the right and left track, respectively, and b is the distance between the track centers.

This formulation of the kinematic model is used into the trajectory tracking problem (González et al., 2009b) to defined a new control law which is based on the work of (Canudas et al., 1997) but now including the additional terms compensating the slip effects (which affect to the tracked vehicles in sandy soils),

$$\begin{aligned} u_1 &= -k_1 e_x, \\ u_2 &= -k_2 \text{sign}(v_{ref}) e_y - k_3 e_\theta. \end{aligned} \quad (4)$$

This control law tries to reduce the error in the driving or forward direction (e_x) using a gain (k_1), the orientation error (e_θ) can be efficiently manipulated using gain k_3 , and finally, the error orthogonal to the driving direction can be reduced using the gain k_2 . The controller gains (k_1, k_2, k_3) are determined using the procedure described in (Canudas et al., 1997) and adding new parameters to compensate for the slip effects, as is discussed in (González et al., 2009b), it holds

$$\begin{aligned} k_1 &= 2\delta_c (\omega_{ref}^2 + \beta_c v_{ref}^2)^{\frac{1}{2}}, \\ k_2 &= \beta_c |v_{ref}| + \omega_{ref} \lambda, \\ k_3 &= 2\delta_c (\omega_{ref}^2 + \beta_c v_{ref}^2)^{\frac{1}{2}}, \end{aligned} \quad (5)$$

where $\beta_c > 0$ and $\delta_c > 0$ are constants that are used to determine the desired closed-loop behaviour of the system; v_{ref} and ω_{ref} are the linear and angular reference velocities, respectively.

3.4 Servocontrollers

PI controllers are used at the lowest level; the objective is that the main controller gives the setpoints to the low-level controllers. The function of these PI controllers is to control the valves which regulate the track motors. Due to saturation of the actuators, an anti-windup strategy has been implemented (Åström and Murray, 2008). As a means of determining the parameters of the controllers, a step-response test was made to characterize the valves as well as to obtain the empirical model of the valves. Then, the method of cancellation of poles (Åström and Murray, 2008) was used for tuning the PI parameters.

3.5 Spraying Controllers

A robust control system aimed at regulating the output pressure of the spraying system has been implemented (Guzmán et al., 2004; Guzmán et al., 2008). The pressure setpoints are calculated based on the actual velocity of the vehicle at each sampling time and on a predefined volume of pesticides to apply based on the crop-growth state, and are then used in a feedback loop for pressure control, where the controller accounts for uncertainty in the system. Quantitative Feedback Theory (QFT) is used as a robust control technique to cope

with system uncertainties. This is a methodology to design robust controllers based on frequency domain (Horowitz, 2001), enabling the design of robust controllers which fulfil some minimum quantitative specifications considering the presence of uncertainties in the plant model and the existence of perturbations. With this theory, the final aim of any control design must be to establish an open-loop transfer function with the suitable bandwidth in order to sensitize the plant and reduce the perturbations (Guzmán et al., 2008). As shown in Fig. 11, the spraying-control system is divided into two steps. In the first one, the pressure reference is calculated based on the vehicle velocity and the desired spray volume (algebraic relationship). The second phase consists of performing the necessary actions to control the pressure in order to reach the desired set point in a robust way. The typical profile for the pressure references calculated in the first stage is given by combinations of ramps. When the robot starts to move or to break, the pressure must go up or down, respectively, and while the robot velocity remains constant the pressure set point also does (Guzmán et al., 2008).

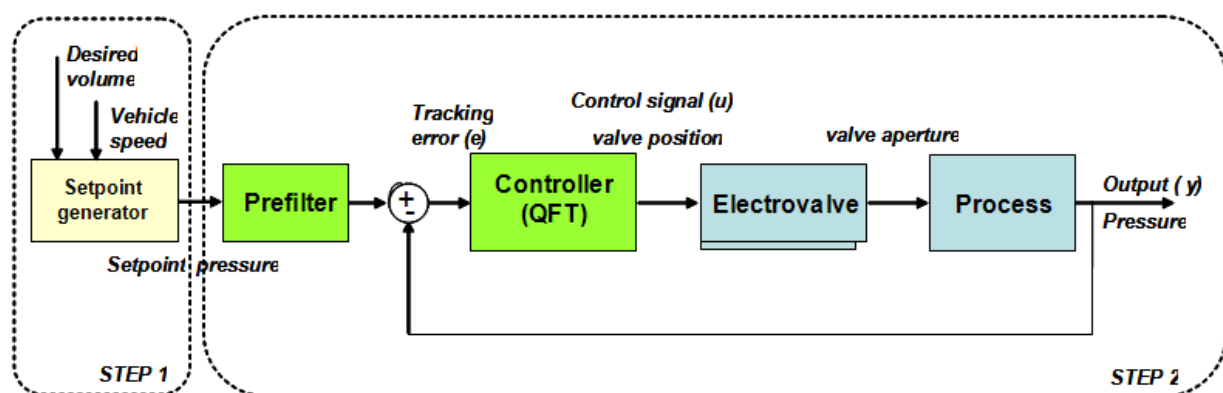


Fig. 11. Full spraying-control system taking into account the velocity and volume

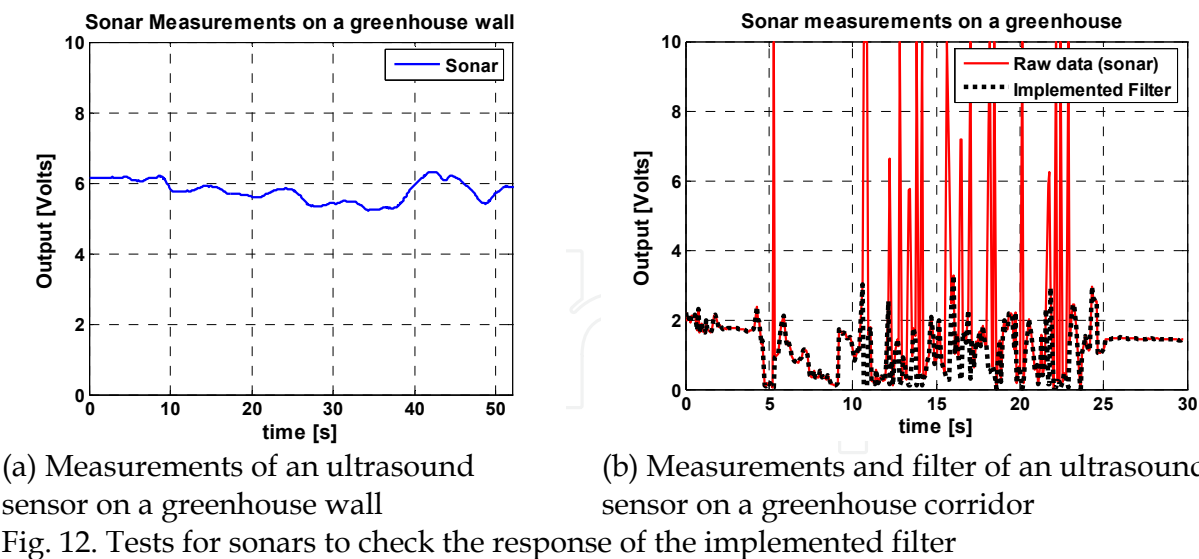
4. Results and Discussion

Before the navigation techniques were attempted, several experiments were made to calibrate and test the sensor system and the low-level or servocontrollers. Later, two navigation strategies were tested in a real greenhouse (deliberative and reactive navigation strategies). Afterwards, the motion controller with slip compensation was also tested through simulations. A comparative with the original controller is discussed.

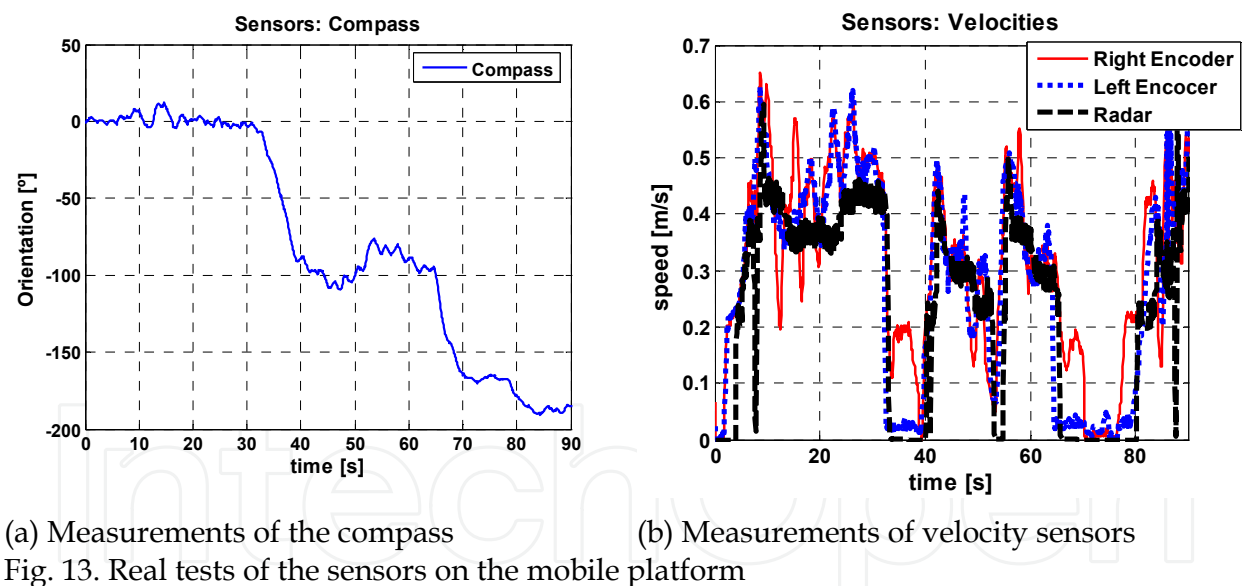
4.1 Sensor system validation

Several experiments were carried out to test the sensor system, and sonars were checked to obtain a right filter. These tests allowed us to design and calibrate an appropriate filter. As shown in Fig. 12a the sonar readings are homogeneous on greenhouse wall (plastic film).

On the other hand, when the sonar works on a greenhouse corridor their measurements are very heterogeneous due to the irregularity in the shape of plants. Fig. 12b shows the good performance of the implemented filter. It is advised that raw data presents multiple peaks due to the previously discussed holes in the plants. The implemented filter cleans these undesirable peaks and attenuates the rest of the rough data.



Additionally, some compass experiments were made. As example, Fig. 13a shows a test in which two consecutive 90° turns were made. It is possible to see the low noise of this sensor. In the same experiment the measurements of encoders and radar were recorded (Fig. 13b). This figure shows the effect of slip, because the velocity measured with radar is less than that of the encoders, and the difference determines the slip online (González et al., 2009b).



4.2 Experimental tests of the Servocontrollers

The low-level controllers or servocontrollers have also been tested in several experiments. In this case, we discussed two experiments to check the single PI and the PI with the anti-windup improvement. Experiments were sampled at 50 ms, and the parameters of the PI controllers were: gain (K_p) = 2 m/s/V, constant time (τ_i) = 0.58 s, and anti-windup constant time = 0.76 [s]. These values were determined using the procedure previously described in Section 3.4.

Fig. 14 shows the velocity and voltage of a track controlled with the PIs. It is possible to check the appropriate behaviour of the controllers. The peak at instant time 12 s is due to a fault in the encoder readings, because the mobile robots traversed a bump on the ground.

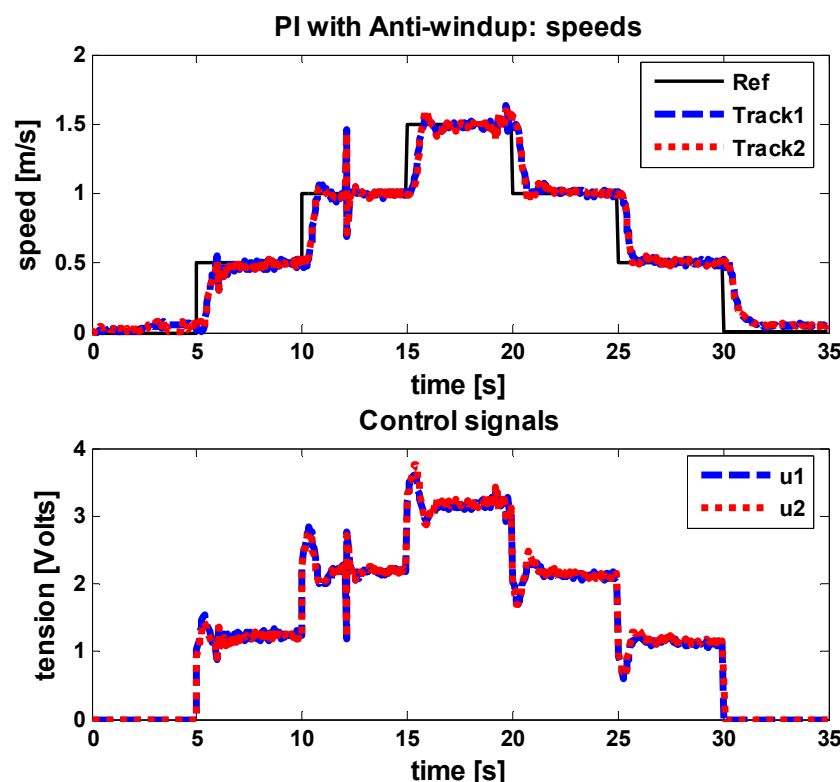


Fig. 14. Servocontroller test with Anti-windup

4.3 Navigation tests

Several real tests were performed in a greenhouse of the Experimental Centre “Cajamar -Las Palmerillas” in Almeria (Spain). Fig. 15 shows the mobile robot in the greenhouse. The greenhouse is only for experimentation its dimensions are middle-size, having an area of 450 m². Future new experiments will be made in larger greenhouses. The programs were executed at a sampling time of 100 ms. Velocities in the experiments were between 0.3 and 1.7 m/s. The position of the robot was determined using a relative localization technique (odometry). The initial position of the mobile robot was always the point (0, 0).

First, we tested the reactive navigation strategy. In this case, we show a test on a greenhouse corridor of 20 m length.

Fig. 16 display the sensorial map built (blue asterisks) and the real trajectory followed by the mobile robot (solid red line). In this figure, it is possible to discern the heterogeneous distribution of plants and the slight curvature of the corridor. Furthermore, the trajectory followed is quite appropriate because the mobile robot moves approximately in the centre of the corridor. For that reason, the plants are sprayed uniformly at each side.



(a) Entering in a corridor (b) Between lines of crop
Fig. 15. Mobile robot *Fitorobot* during tests

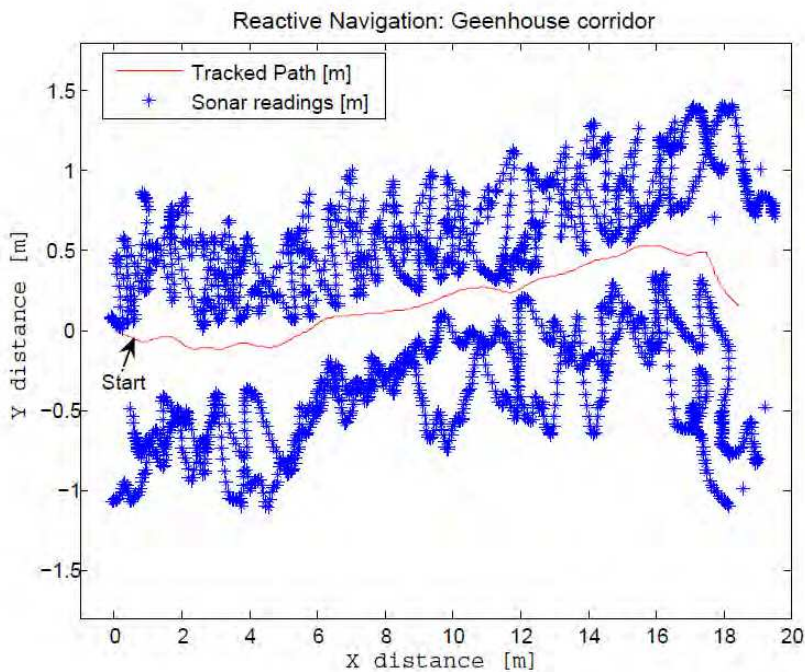


Fig. 16. Reactive navigation test in a greenhouse corridor and sensorial map built

After several experiments with the reactive navigation strategy, we also checked the deliberative approach. As commented in previous works (González et al., 2009a), we used for the motion control a simple controller, *Pure Pursuit*. For that reason, in Fig. 17a the trajectory followed by the mobile robot is slightly different from the reference, above all, in the turns. It can be checked in the errors plots (Fig. 17b) where the maximum error is close to

0.7 m. Furthermore, in Fig. 17c and Fig. 17d is possible to observe the appropriate behaviour of the low-level PI controllers, which assure that the tracks follow the set-points.

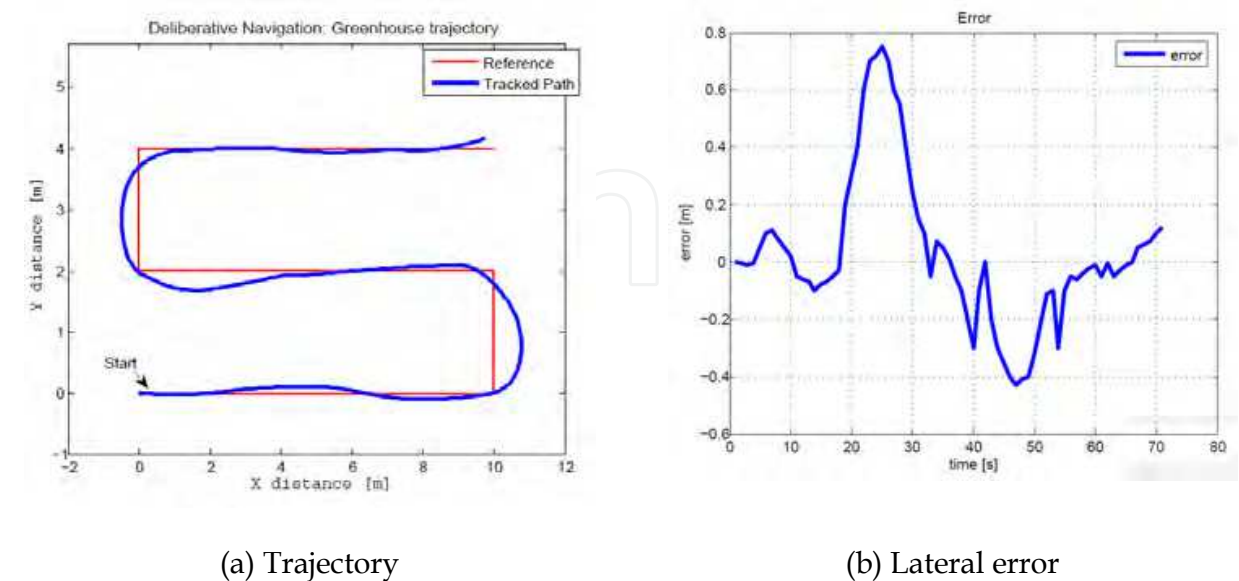


Fig. 17. Deliberative navigation test in a greenhouse

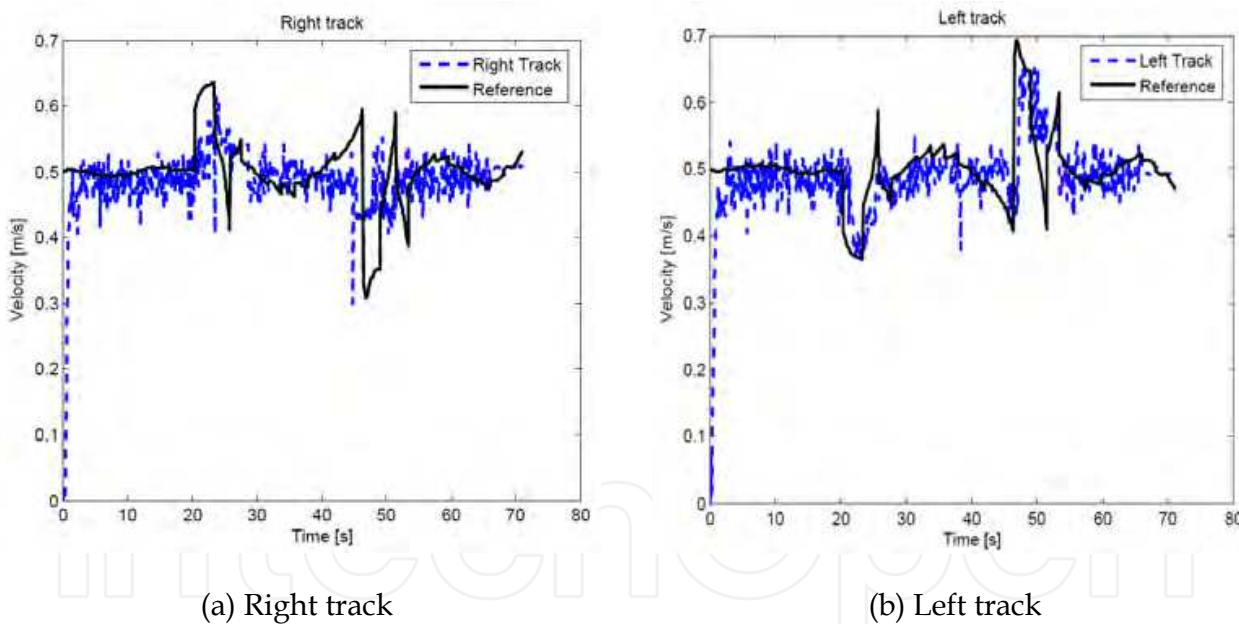


Fig. 18. Reference velocities and measured velocities from the navigation test

Finally, the control approach with slip compensation was simulated and compared with the original controller. In this case, we have simulated a typical greenhouse trajectory (Fig. 19a). The controller parameters were set $\beta_c = 5$ and $\delta_c = 0.6$ to reach a soft overdamped closed-loop behavior (Canudas et al., 1997). For this test, the slip varies between 10-30 %. Furthermore, in order to do more realistic the simulations a small random noise has been added to the position estimation of the robot. Fig. 19b, c, d plot the errors. As expected, the controller with slip compensation achieves smaller errors than those obtained with the original controllers. Longitudinal, lateral and orientation errors are close to zero.

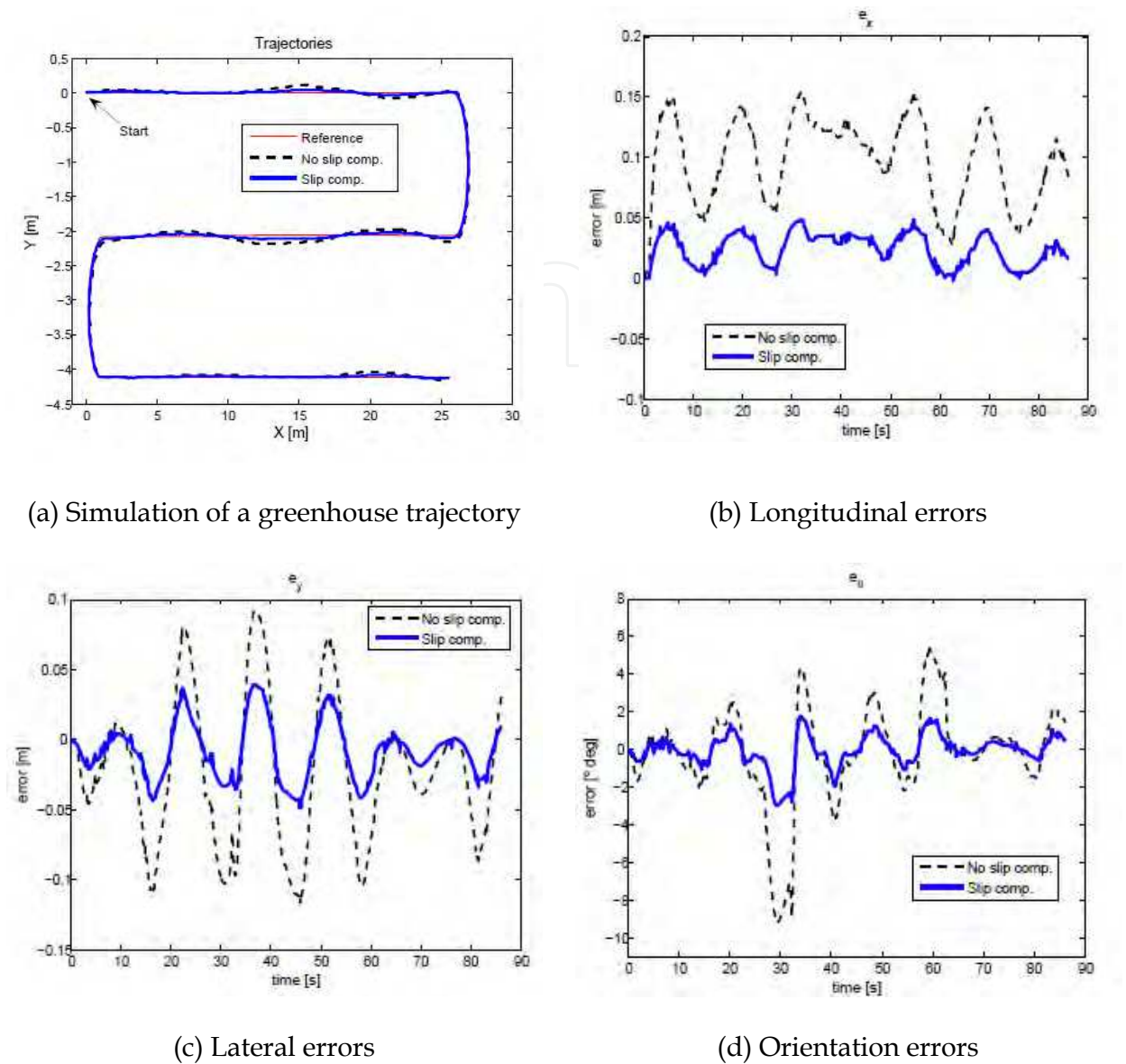


Fig. 19. Simulation in a typical greenhouse trajectory of the controller with slip compensation and the original controller

4.4 Spraying tests

The spraying system was tested under a combination of ramps and steps along different operating points. In this way, the system was validated in order to handle all kinds of possible input data. Fig. 20 (Guzmán et al., 2008) shows that the system responds correctly at the different operating points faithfully following the proposed *setpoint* profile. The robust-control system developed has presented a good disturbance rejection in these cases, modifying the control signal in order to help the system track the desired reference.

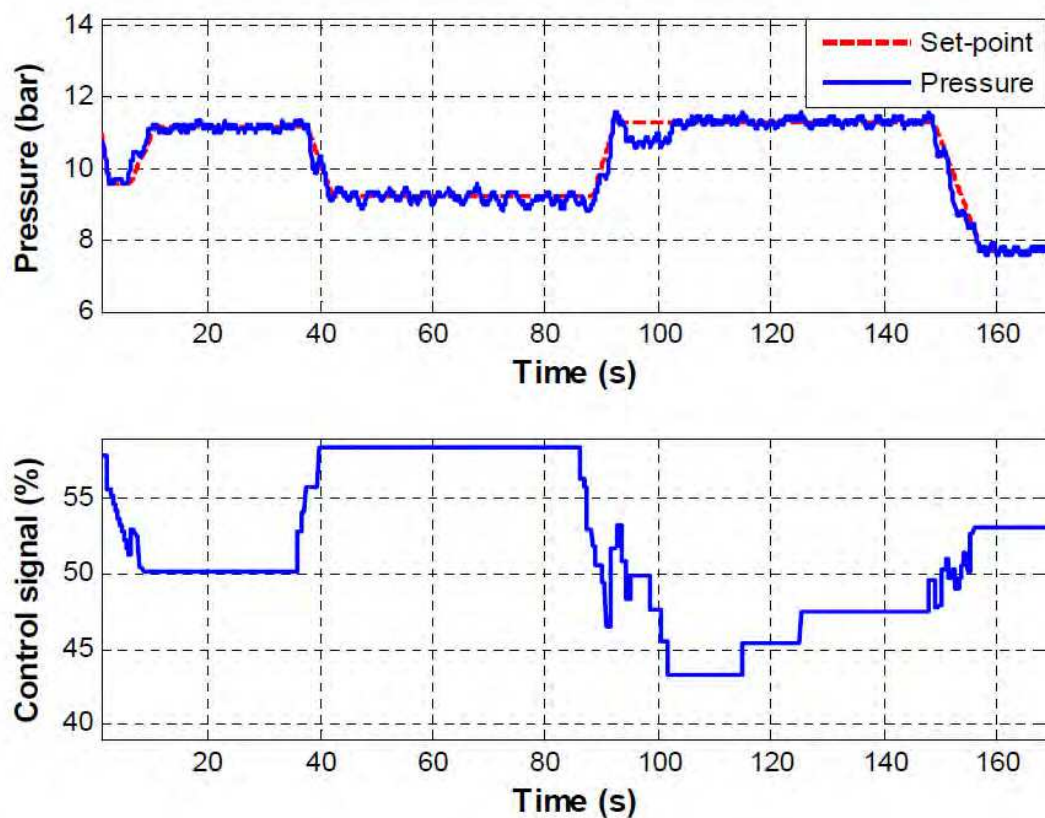


Fig. 20. Spraying control of the test (Guzmán et al., 2008)

5. Conclusions and Future research

This chapter presents a mechatronic description of an autonomous mobile robot for agricultural tasks in greenhouses. The mobile robot developed to operate in greenhouses has been supported by a synergetic integration of mechanical engineering with electronics and automatic control.

As commented above, few vehicles exist which navigate autonomously in greenhouses, many of these being static manipulators or semiautonomous vehicles. Because the importance of the greenhouse sector a whole mobile robot has been developed which has been designed for realize some of the most important tasks in greenhouses.

The mechanical design of the mobile robot has been carried out using CAD/CAE technologies in which the main features of greenhouses, the electronic components have been considered. Later some types of sensors were installed on the platform. These sensors are used by the spraying and navigation controls. Finally, navigation and spraying control strategies were implemented in order to govern the vehicle. Successful results have been obtained using this mobile robot, along four years of the project. In this chapter, some real tests have shown the appropriate behaviour of the vehicle working in greenhouses.

Future works involve a dynamic model which will be tested in order to model and control the vehicle. This model is intended to provide better performance of the navigation control.

Finally, we will try advanced navigation control techniques as adaptive and predictive control policies.

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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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