Navigation Techniques for Mobile Robots in Greenhouses

R. González, F. Rodríguez, J. Sánchez-Hermosilla, J. G. Donaire

Abstract. *This article discusses navigation methods for mobile agricultural robots in greenhouses. Today, many dangers of repetitive and hazardous agricultural tasks for humans could be avoided by using robots. The problem of autonomous navigation in greenhouses has been solved using both deliberative and pseudo-reactive techniques. The first one utilizes a map-based algorithm to create a safe, obstacle-free path to circulate throughout the greenhouse. The second technique applies a sensor-feedback algorithm to move through the greenhouse corridors. Furthermore, along the trajectory a sensorial map is built. Both approaches have been implemented and tested in a real environment, with promising results.*

Keywords. *Robotic system, Tracked vehicles, Greenhouses, Spraying.*

Today, agriculture constitutes one of the most important sectors under development in many areas of the world. The province of Almeria (Spain) holds the largest concentration of greenhouses in the world (>27,000 Ha), this type of agriculture is one of the main sources of income of this Spanish region. However, productivity needs to be enhanced, together with product quality and harvest volume, and technology plays an essential role in this adjustment process. Greenhouses require long hours of work, hazardous activities, and repetitive tasks, such as harvesting, spraying, and pruning. These circumstances decrease operational efficiency and could harm the operator's health (García and Gadea, 2004; Nuyttens et al., 2004).

Recent advances in robotics enable the application of mobile robots for greenhouse tasks which can reduce operator's fatigue and workload, improving the efficiency and operational safety. For the successful execution of greenhouse tasks by mobile robots, the first step is to design vehicles appropriate to the structure and to the irregular soil in greenhouses. The second phase is the implementation of navigation techniques that permit the vehicle to move through the corridors between the rows of plants.

To solve the application of mobile robots in greenhouses, different techniques have been studied. On one hand, manipulator robots have been successfully tested, these robots usually being controlled by vision systems (Sandini et al., 1990; Dario et al., 1994; Kondo and Ting, 1998). Recently, Belforte et al. (2006) presents a fixed-position robot. It is interfaced to a standard belt-conveyor displacement system that provides the robot with pallets containing the crops. The main drawback of those solutions is that since the robot is in a fixed position it has a restricted workspace and thus 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) describes an autonomous spraying robot whose navigation control relies on inductive sensors which detect metallic pipes buried in the soil. Van Henten et al. (2002) presents an autonomous robot for harvesting cucumbers in greenhouses. The robot is 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 articles have addressed the autonomous navigation problem of a mobile robot in greenhouse. Ollero et al. (1994b), Mandow et al. (1996), and Martinez et al. (2005) describe an autonomous vehicle (*Aurora*) for spraying purposes. The navigation control of this robot depends on a previous behavioural sequence established by an operator. The sensorial system is composed mainly of ultrasonic sensors. Singh et al. (2004) and Subramanian et al. (2005) also describe 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.

A mobile robot called *Fitorobot* has been developed at the University of Almeria (fig. 1). This vehicle permits movement between lines of crop, and the performance of several greenhouse tasks such as spraying, pruning, and crop transport. In an initial approach, it was equipped for spraying (Sánchez-Gimeno et al., 2006). After the mobile platform was designed, two different approaches for controlling the navigation were examined. First, a map-based technique was tested. This technique uses a map to calculate an obstacle-free path of the greenhouse before the robot moves along it.

Afterwards, an appropriate low-cost sensor system was installed on the platform, and a *pseudo*-reactive technique was implemented to track the greenhouse corridors without the map. This technique is considered *pseudo*-reactive,

Submitted for review in November 2007 as manuscript number PM 7280; approved for publication by the Power & Machinery Division of ASABE in December 2008.

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  ISSN 0883-8542

(a) Lateral view of the mobile robot

(b) Back view of the mobile robot

Figure 1. Mobile robot Fitorobot in a greenhouse.

because the navigation algorithm has been implemented knowing that there are parallel corridors arranged in rows in the greenhouses. Moreover, along the path a sensorial map is built, which will be used by the first technique in subsequent runs.

Objectives

The aim of this article is to present a mobile platform moving autonomously in greenhouses. This work has been undertaken to provide a new way of solving the problem. In this case, two of the most important navigation algorithms in mobile robotics have been implemented and adapted to greenhouse features: reactive and deliberative or map-based ones. Furthermore, promising results with both techniques are discussed.

For this aim, the following tasks were performed:

- Implementation and test of a deliberative and a reactive algorithm to control the mobile robot *Fitorobot*.
- Design of a filter to tolerate peaks in sensor readings.
- Development of an algorithm to build a sensorial map of the environment of operation.

The article is organized as follows. First, the mobile platform *Fitorobot* is briefly described. Second, we discuss the design and the implementation of the deliberative and the pseudo-reactive techniques, together with the mapping process. Next, experimental results are reported to show the performance of the different techniques. Finally, conclusions and suggestions for future work are given.

Materials and Methods

Mobile Robot Fitorobot

As shown in figure 1, the mobile robot *Fitorobot* has a differential-drive mechanism of locomotion. The system is composed of two rubber-tracks, which provide a larger contact surface with the soft ground of the greenhouses, making it more robust and stable (Wong, 2001; Sánchez-Gimeno et al., 2006).

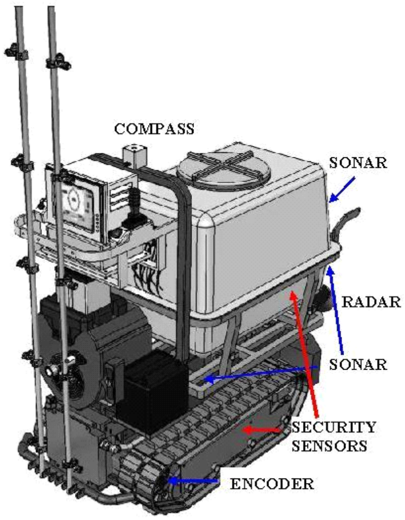
This robot has a mass of 756 kg (with the spray tank full), and it has appropriate dimensions (1.5 m long × 0.7 m wide) for the typical corridors of greenhouses in south-eastern Spain. It is driven by a 20-hp gasoline engine.

It also has a low-cost sensor system (fig. 2), including: six low-distance ultrasonic sensors (three on each side; Sonar Bero M18, Siemens, Munich, Germany), one middle-distance ultrasonic sensor (front of vehicle) (Sonar Bero III, Siemens, Munich, Germany), one magnetic compass (C100, KVH Industries Inc., Kokkedal, Denmark), two incremental encoders (one by each axle; DRS61, SICK AG, Waldkirch, Germany), one radar (Compact II, LH AGRO, Springfield, Ill.), and security sensors (SKL25-40, SafeWork, Barcelona, Spain). Furthermore, for spraying control, one pressure sensor has been installed (ECO1, Wika, Klingenberg, Germany).

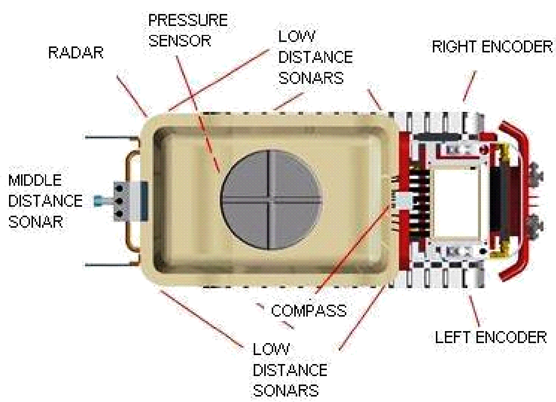
The platform has been equipped with an industrial computer (PCISA-3716E2V-R3, ICP Electronics Inc., Taipei, Taiwan), with one data-acquisition card (PCI-1800L, ICP DAS, Hsinchu, Taiwan) and one counter card (PCI-TMC12, ICP DAS, Hsinchu, Taiwan). Software for data processing and control was developed using the suites LabVIEW (LabVIEW 7.1, National Instruments, Austin, Tex.) and Matlab (Matlab 5.3, MathWorks, Natick, Mass.).

Navigation Techniques

Greenhouses are structured environments where the distribution of plants is at least partially known. As seen in figure 3, plants are usually arranged in parallel straight rows with narrow corridors for the operation of humans and machines. 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). Furthermore, appropriate filters for the sensor readings, and robust navigation strategies should be examined. All the previous requisites are described in this article.



(a) Lateral view of the sensorial system



(b) T op view of the sensorial system

Figure 2. Sensors on the experimental platform.

In mobile robotics, the most dominant paradigms for robot control are deliberative and reactive control. Deliberative techniques use a world model (map) to calculate a safe path between an initial point and a goal point. Models are typically either metric or topological maps. Metric maps explicitly reproduce the metric structure of the environment. Topological maps try to represent the environment as a graph (Siegwart and Nourbakhsh, 2004). On the other hand, reactive techniques do not require a previous environment model. These approaches rely on a sensorial system to determine the states of the vehicle and to execute an action (Dudek and Jenkin, 2000).

The navigation challenge for a robot operating in a greenhouse involves planning a reference trajectory and reacting to unforeseen events (workers, boxes, tools, etc). For this reason, the objective of this project is to develop a hybrid solution (fig. 4). 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, along the path a sensorial map is built, to be employed by the deliberative module in later runs. These layers are discussed in the following section. The two previous approaches utilize a

Figure 3. Real image of a greenhouse.

security layer to avoid collisions. This layer uses on/off sensors. Finally, it has a low-level control or servo control layer. This layer is composed of two PID controllers that regulate the speed of the tracks. This article discusses each method separately, but the combination of both techniques is relatively easy.

Deliberative Technique

Deliberative techniques are based on planning a course of actions that enable the robot to reach a goal position. The main drawback of this solution is that the planned actions are considered off-line, and events in real time are not taken into account. For this reason, deliberative techniques are useful only when the mobile robot is in a structured environment and when the application demands extreme reliability (Siegwart and Nourbakhsh, 2004). Typically, the navigation architecture used in these solutions is composed of three layers (fig. 5). The upper layer is the path planning that involves identifying a free-of-obstacles trajectory that will

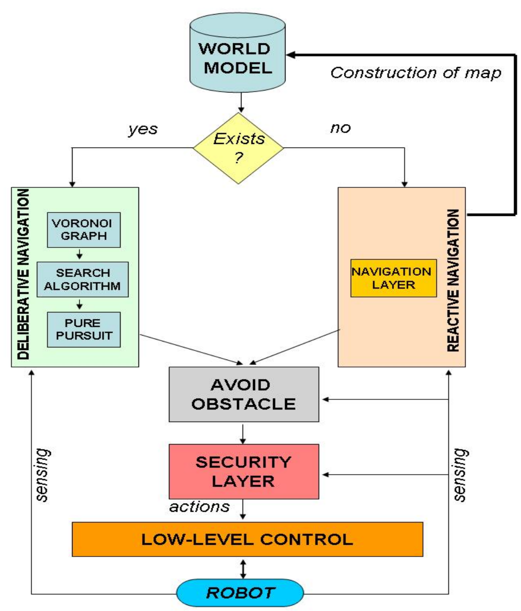


Figure 4. Proposed navigation strategy for the mobile robot.

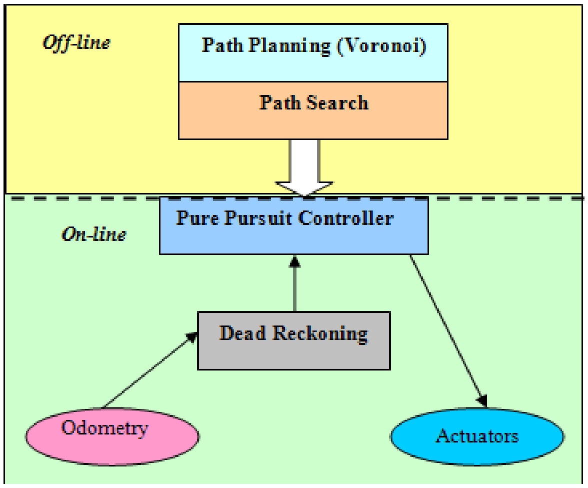


Figure 5. Deliberative control architecture.

cause the robot to reach the goal location. This reference trajectory is determined off-line. Secondly, the executive layer or controller determines the setpoints to the low level actuators. Generally, it uses the error between the current location and the reference trajectory. The selected algorithm has been *Pure Pursuit* (Amidi, 1990). Finally, for the location of the robot a relative location approach has been selected. This is based on the well-known dead-reckoning method using odometry (Borenstein et al., 1996; Siegwart and Nourbakhsh, 2004). Additional to this navigation architecture, a security routine and servo controllers are at the lowest level (as explained in the previous section).

Path-Planning Algorithm

The selected path-planning algorithm is a modified *Voronoi Diagram*. This is defined as the locus of points equidistant from the closest two or more obstacle boundaries, including the workspace boundary. The set of points in the *Generalized Voronoi Diagram* has the useful property of maximizing the clearance between points and obstacles (Choset, 1997). Once the Voronoi algorithm is applied to a greenhouse map, the edges inside of rows of plants must be eliminated to provide an obstacle-free path (fig. 6).

Search Algorithm

The result of applying the Voronoi technique is a graph. This graph represents all possible paths in the greenhouse without obstacles. The mobile robot Fitorobot has to spray all the plants in the greenhouse , as was explained in the introduction. For this reason, the robot could achieve this goal by passing only through appropriate corridors. For

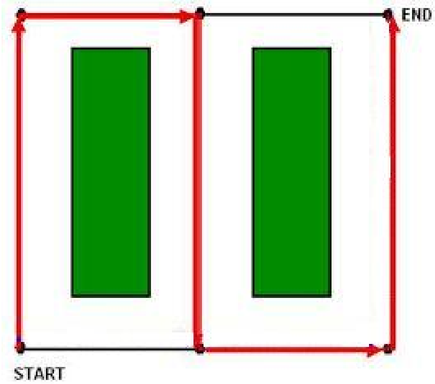


Figure 7. Rows of plants in a greenhouse and tracked trajectory to traverse them.

example, in the distribution presented in figure 7, only the corridors marked with the red bold line must be visited.

To solve this issue, a traversal algorithm should be implemented. The objective of this algorithm is to determine the reference path that the mobile robot should follow. The solution proposed here is a technique based on the so-called depth-first search (O'Rourke, 1998; Sedgwick, 2002). The procedure is as follows: first, to visit a vertex, mark it, then (recursively) visit the next vertex that is adjacent to it and has not yet been marked and has the maximum distance. This process determines an ordered vector with the vertices that traverse the graph. The edges between vertices represent the greenhouse corridors. Finally, these points should be interpolated to define the reference path. Figure 8 shows an example of the previous solution. It shows a typical distribution of plants (rectangles), and the graph determined using *Voronoi*. The distance between vertices in the longitudinal direction is 30 m and in the lateral direction 2 m. Figure 8b shows the ordered vector with the vertices that traverse the graph.

Pseudo-Reactive Technique

Reactive navigation strategies focus on control of the robot's trajectory using information provided by its sensors during robot motion. Classical reactive navigation algorithms such as Bug, Tangent Bug and Potential Fields are not well suited to solve navigation in greenhouses. The main drawback of previous algorithms is that they become unstable easily, for example, with a narrow corridor, with noisy sensor readings, etc. (Siegwart and Nourbakhsh, 2004).

Thus, a new pseudo-reactive algorithm has been developed to avoid this problem. The architecture of control is composed of four layers (fig. 9). The first one (build map)

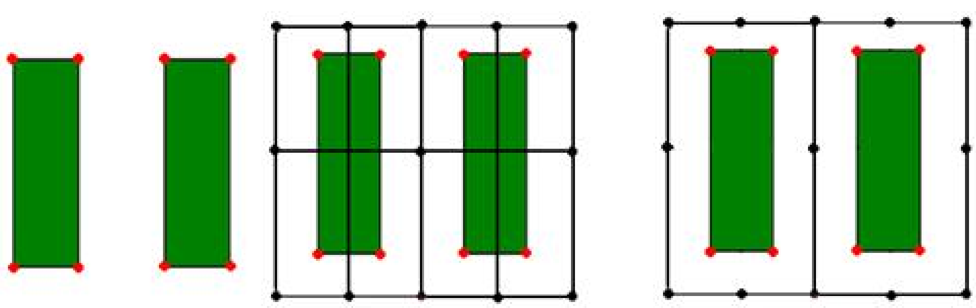
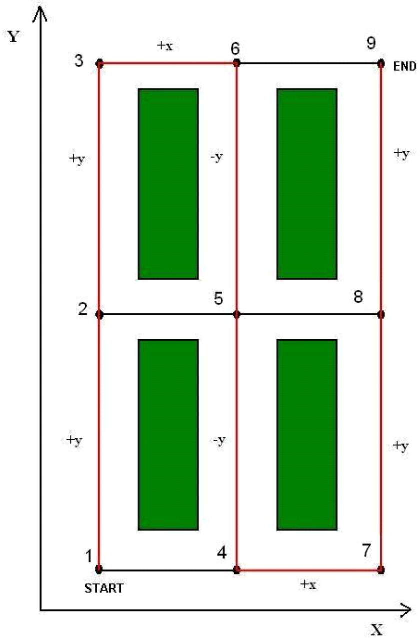
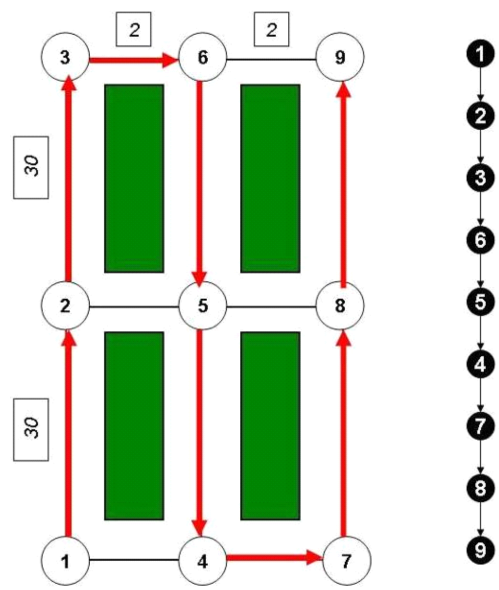


Figure 6. Voronoi's algorithm applied to a greenhouse.



(a) Paths in a greenhouse



(b) Graph-view of paths in a greenhouse

Figure 8. Traverse algorithm to obtain the reference trajectory.

corresponds to the module that builds a sensorial map. The following layer (navigation) is responsible for filtering the sensor readings, determining the location of the mobile robot using the dead-reckoning method, and generating the setpoints to the low-level servo controllers. Finally, the bottom layer (avoid obstacles) is responsible for detecting and solving special events in the greenhouse, such as: centering the robot and curved corridors. Additionally, for this navigation architecture, a security routine and servo controllers are at the lowest level (as explained in previous section). Faults in sonar readings are detected comparing the three sonars on each side. When one of them presents data

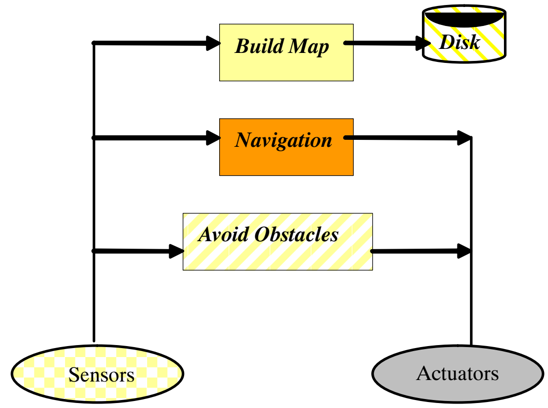


Figure 9. Pseudo-reactive control architecture.

different from the next sonar, the navigation algorithm does not take this sensor into account.

Navigation Strategy

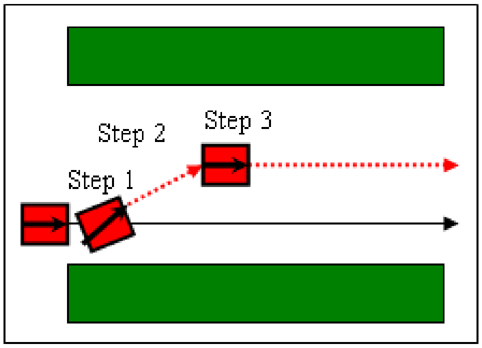
As mentioned previously, a greenhouse is a structured environment and therefore *a priori* knowledge can be added to the reactive navigation strategy. For example, when the mobile robot is at the end of a corridor, it could turn to the left or to the right side. This decision will be made relying on 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.

Because the sensors are used to make decisions, their function requires explanation. The sensor employed for feedback to the controller in the turns is the magnetic compass and the robot completes the turn when the value of the compass is between $[90-\tau, 90+\tau]$ degrees. The value of the τ-parameter is experimentally established depending of the accuracy of the compass readings. The front sonar is used to adjust the vehicle speed, in order to avoid sudden stops. Lateral sonars are employed to detect the plants and the corridors.

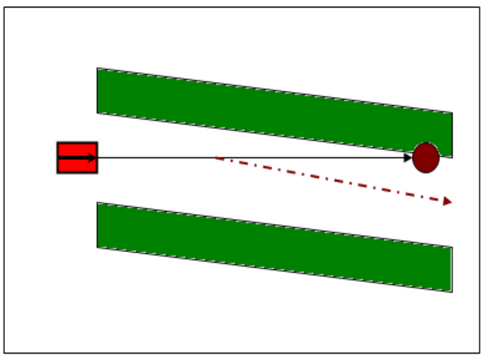
It is important to note that the real corridors of greenhouses are not perfectly straight and vary in width. Therefore, a centering process and a curved-corridor detection-correction process have been implemented. These processes will enable the robot to work in greenhouses of different layouts.

The centering process is represented in figure 10a. First, the situation is detected with lateral sonar. If $|sonars_{\text{Right}} - sonars_{\text{Left}}| > \lambda$ the robot is outside of the centerline; λ will be established depending of the width of the corridor. Then the robot turns to the side with the higher lateral sonar value (step 1), it later goes straight (step 2), and finally turns to the opposite side of the previous turn (step 3). These steps are made at a fixed low speed.

In a greenhouse some corridors may not be parallel to the greenhouse walls, making a "curved" corridor. This situation is shown in figure 10b. This situation appears when the front lateral sonars have different values from the back lateral sonars. Mathematically, if $|sonar_{\text{FrontRight}} - sonar_{\text{FrontLeft}}$



(a) Centering process



(b) Curved -corridor detection-correction process

Figure 10. Routines implemented to avoid obstacles.

$| > 0$ and $|sonar_{RearRight} - sonar_{RearLeft}| < 0$ the robot will turn to the right side; otherwise, it will turn to the left side. This process will be followed at a fixed low speed.

Filter Designed for Sonars

Figure 11 shows that the rows of plants present holes, because the leaves of the plants are heterogeneous. As expected, in the first experiments in greenhouses, the analysis of sonar readings reveals that sometimes these data had peaks or outliers. These peaks were caused because the sonar beam penetrates holes in the vegetal mass.

To solve this drawback some filters were reviewed. Filters based on statistics such as the *Kalman Filter* (Maybeck, 1977; Welch and Bishop, 2001), are not appropriate because the peaks do not follow any probability distribution. Other similar filters such as mean filter and low-pass filters are not appropriate, because they only attenuate the signal and do not remove the peaks.

On the other hand, the problem of the outliers cannot be solved using a fixed threshold because the distance between the robot and the rows of plants can vary.

Although these data are quite attenuated combining readings of all sensors, a filter to flatten the peaks has been designed and implemented. This filter is based on comparing the current reading with a window of previous values and, if the current one differs by a quantity greater than a threshold with respect to the majority of the values of the window, the current reading changes its value to the one for which the difference is greatest (eq. 1).

Figure 11. Detail of the holes in a row of plants (superimposed red lines).

$$\xi = \left[\sum_{i=k-1}^{k-n} \Gamma[(s_k - s_i) < \varepsilon] \right] > \frac{n}{2} \tag{1}$$

where Γ is {true, false} $\rightarrow$ {0,1}, ε is a threshold established heuristically, n is the window size, s_k the current data, s_i the window, and ξ is the condition change. If ξ is false the current reading is correct, else it is a peak.

Map-Building Algorithm

One of the main problems working in greenhouses is that the layout changes over production periods. Furthermore, farmers rarely have updated digital maps of their greenhouses. For this reason, an algorithm to build a sensorial map was implemented. This algorithm is based on combining sensor readings with the localization of the robot (Dudek and Jenkin, 2000; Fujimori et al., 2002). In the future, this sensorial map should be manipulated in order to be used by the deliberative approach. Furthermore, this work can be a start toward implementing SLAM (Simultaneous Localization and Mapping) techniques in greenhouses (Leonard and Durrant-Whyte, 1991; Durrant-Whyte and Bailey, 2006).

To build the sensorial map, the sonars are employed to determine the distance to the objects in the environment. First, sonar readings should be translated to distance (this has been determined experimentally). Next, the location of the robot is calculated using the dead-reckoning method. Finally, sonar readings are expressed in the global reference system. The equations used to change the reference system are equations 2 and 3; θ_{Sonar} is the angle that a sonar takes with respect to the platform (see fig. 12) and d_{Si} is the calculated distance to the obstacle.

$$x^{SRrobot} = x_{robot} - [d_{Si} \sin(\theta_{Sonar})] \tag{2}$$

$$y^{SRrobot} = y_{robot} - [d_{Si} \cos(\theta_{Sonar})] \tag{3}$$

where (x_{robot}, y_{robot}) are the current location of the robot. The values ($x^{SRrobot}$, $x^{SRrobot}$) build a bi-dimensional matrix which constitutes the sensorial map.

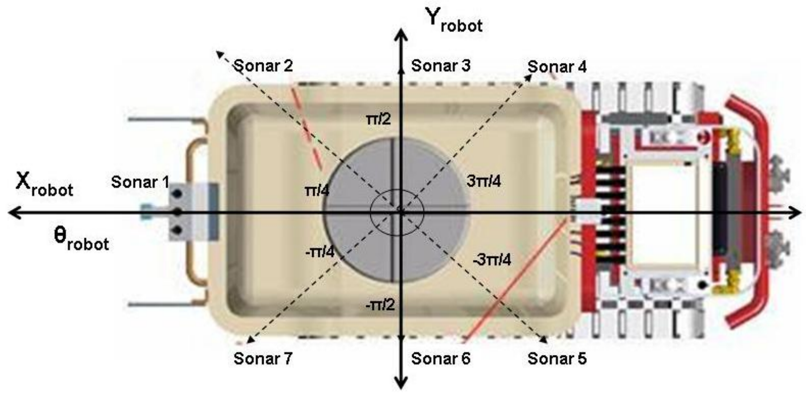


Figure 12. Position of the sonars on the Fitorobot.

RESULTS AND DISCUSSION

Before navigation was attempted, several experiments were made to calibrate and to test the proposed filter. Later, the two navigation techniques were tested in an experimental greenhouse using the mobile robot Fitorobot. Both techniques were successfully tested in a greenhouse of the Experimental Centre "Cajamar - Las Palmerillas" in Almeria (Spain). Figure 13 shows the mobile robot during the tests and the dimensions of the experimental greenhouse. Because the greenhouse is only for experimentation its dimensions are relatively small, having an area of 450 m^2. Other experiments will be made in larger greenhouses soon.

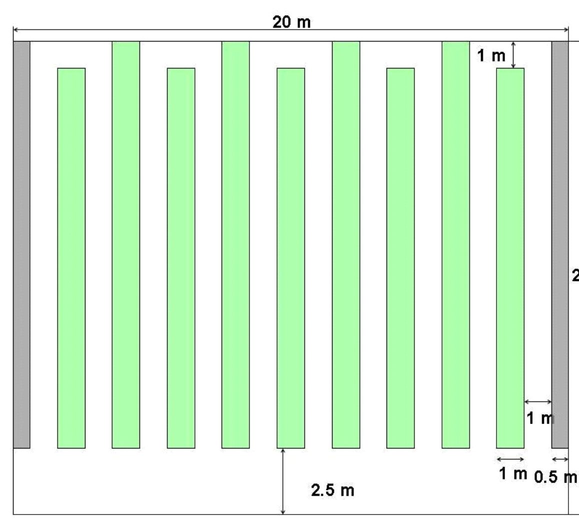
We have tested many trajectories (for three years), but this article summarizes two of the most frequent and representative trajectories in a greenhouse: a straight trajectory in a corridor between plants and an S-shaped trajectory which corresponds to the typical path of spraying activities.

The programs were executed at a sampling time of 100 ms. Speeds in the experiments were between 0.3 and 1.2 m/s. The position of the robot was determined using a relative localization technique (dead-reckoning). The initial position of the mobile robot was always the point (0, 0).

TESTS OF THE DESIGNED FILTER

Figure 14 shows the result of applying different filters to the raw data from sonars. The filters compared are: a mean filter with 30 values, a threshold filter with a threshold of 3.5 V, and a low-pass filter with gain 1 and time constant 1. Figure 14a and 14b show the data of a test in which the mobile robot started outside of the corridor and later entered in it. This experiment shows that threshold filters are not appropriate because the robot always would detect corridor, as shown in the instants of time between 0 and 6 s. Mean and low-pass filters are not appropriate for this application because they could modify the dynamic of the system and only attenuate the peaks. The implemented filter has a good result and peaks are well tolerated. The peak at time instant 18 s is due to transitory bad raw data. Figure 14c and 14d show the data of a test in which the robot goes through a corridor; in this case the implemented filter also has a quite appropriate behavior. In this case threshold filter is again unacceptable. The rest of the filters only attenuate the peaks.

(a) Mobile robot during the tests



(b) Plan view of the greenhouse

Figure 13. Tests in the Experimental Centre "Cajamar – Las Palmerillas."

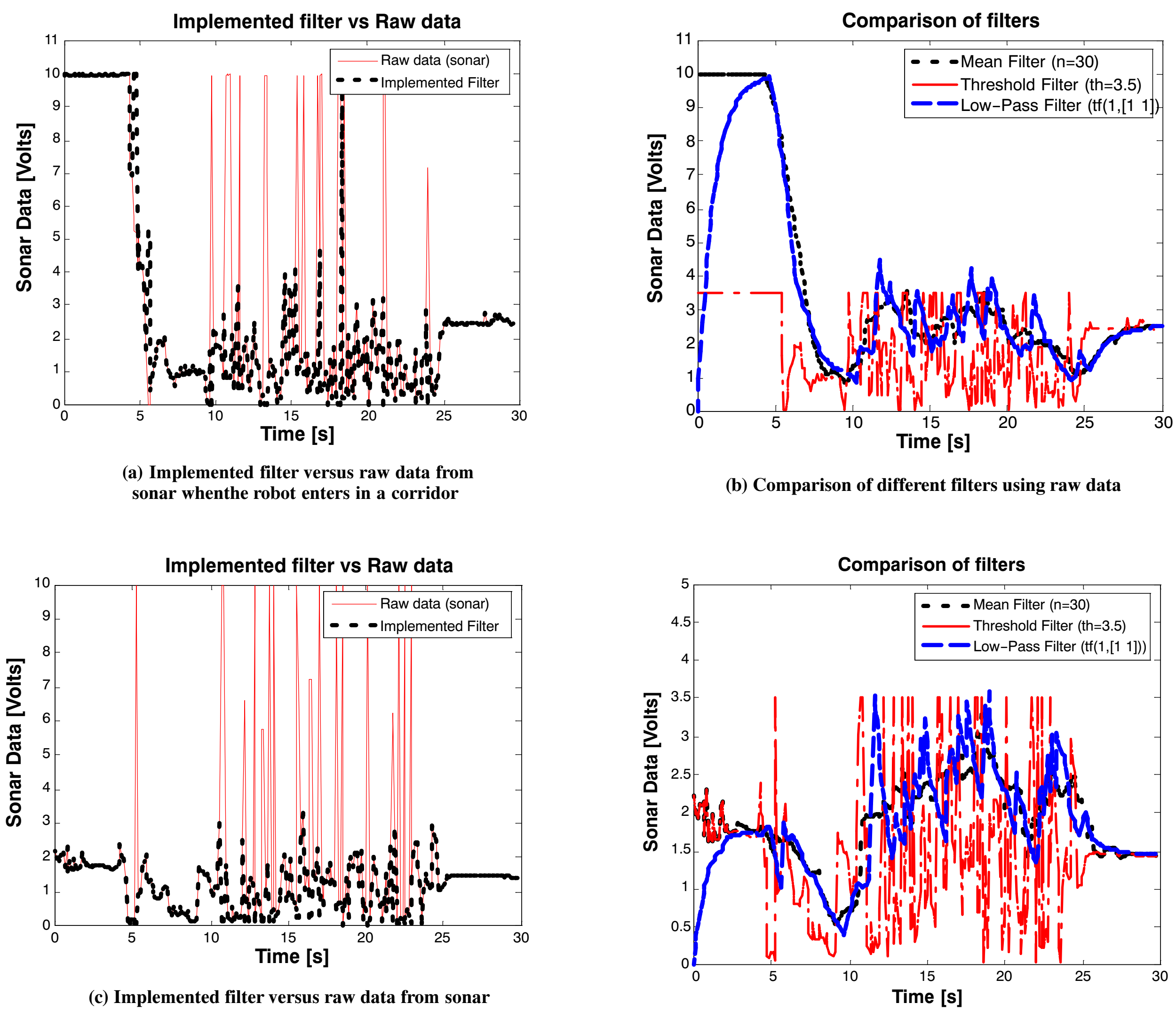
Pseudo-Reactive Navigation and Mapping

Figure 15 shows the path followed in a straight corridor. The continuous line represents the path tracked by the mobile robot using the dead-reckoning method. The asterisks represent the sensorial map built. The superimposed boxes represent the true position of the plants in the greenhouse. The right box represents the wall at the end of the corridor. As explained in the previous section, this sensorial map was built using sonar readings. The sensorial map fits quite appropriately the line of plants. As is reflected in this figure, the average error between the tracked path and the center of the corridor is small (lesser than 0.15 m). However, the trajectory is not perfect because in this strategy the vehicle does not try to follow a reference trajectory, that is, the navigation control is in open-loop mode because the robot *apriori* does not known that reference. In this case, this average error is an approximation to the center of the corridor.

The control signals and the performance of this strategy cannot be considered quantitatively because the robot does not follow any reference trajectory or any reference velocity. The user specifies only a maximum speed for forward motion and, a maximum speed for turns. The pseudo- reactive algorithm determines the reference speed depending on the reading of the sonars in real time.

In order to check one of the improvements to the basic navigation algorithm, a "curved" corridor was tested. Figure 16 shows the result. At the beginning of the test, the robot followed a straight trajectory, but as displayed in the plot, with the use of sonar readings the corridors are not parallel to the greenhouse structure. As in the previous figure, the real position of the corridor is superposed. This figure checks the accuracy of the "curved" corridor detection-correction process.

Finally, figure 17 shows the mapping of a typical spraying trajectory in a greenhouse. In the figure, the top corridor is the wall of the greenhouse, the rest of the corridors are plants. This figure permits to checking the accuracy of our mapping algorithm. In the first turn, it is possible to see whether the algorithm detects the wall of the greenhouse (asterisks). At the second turn, nothing appears because as observed in the plan view of the greenhouse (fig. 13b), the distance between



(a) Implemented filter versus raw data from sonar whenthe robot enters in a corridor

(b) Comparison of different filters using raw data

(c) Implemented filter versus raw data from sonar when the robot goes through a corridor

(d) Comparison of different filters using raw data

Figure. 14. Comparison of different filters for sonar data.

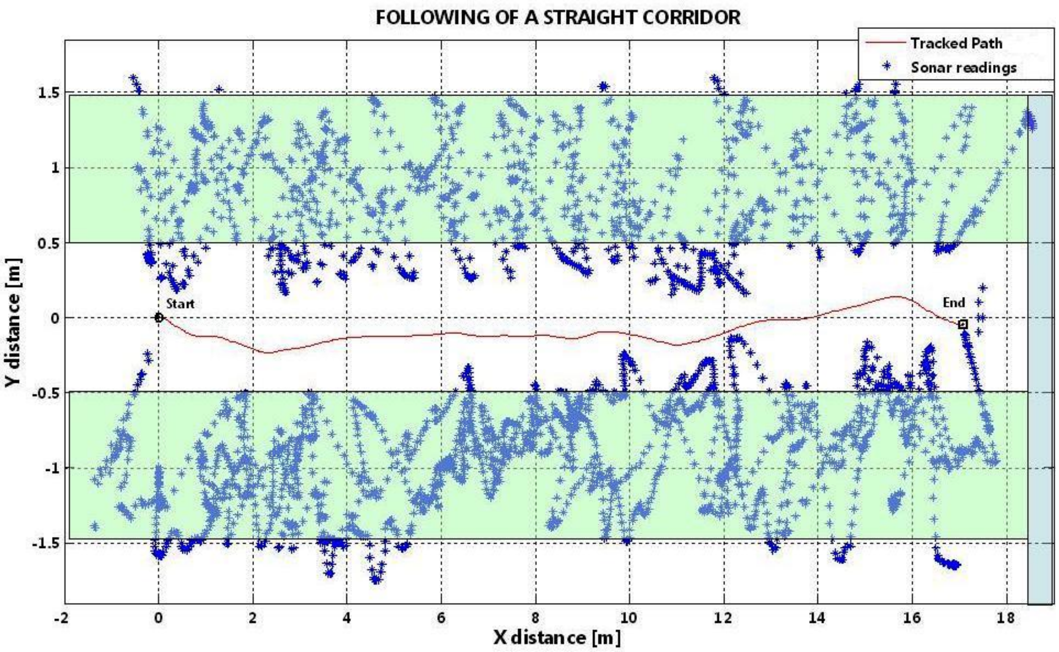


Figure 15. Straight trajectory in a corridor using the pseudo-reactive navigation algorithm and sensorial map.

the wall of the greenhouse and the end of the corridors is greater than the resolution of the sonars.

Deliberative Navigation

After the previous experiments were completed, the deliberative algorithm was tested by using a map of the greenhouse. As in the previous experiments, two types of trajectories were tried: a straight line and an S-shaped trajectory. The look-ahead distance used in the Pure Pursuit controller was two sampling positions.

Figure 18a shows the straight corridor test. The reference trajectory is the bold line and the path tracked by the mobile robot is represented by the dashed line. The position of the plants and the greenhouse wall are superposed. The reference speed was 0.5 m/s. As shown in figure 18b, the error between the reference and the tracked path can be considered negligible, with a maximum deviation of 15 cm. The mobile robot has a small oscillatory behaviour. This behavior is due to the look-ahead distance of the Pure Pursuit. The main disturbances are irregular soil and noisy data from odometry. Figure 19 shows the control signals (speed of each track) determined by the Pure Pursuit and the current speeds. These speeds were controlled by the PID at the servo level. As expected the reference setpoints are almost constant.

Finally, figure 20 shows the result of applying the *Pure Pursuit* algorithm to an S-shaped trajectory. This plot reflects the bad behaviour of the controller, particularly in the turns. As shown in errors-plot, the main deviation is in the first turn, where the robot goes out 0.7 me. The reason is that this algorithm depends strongly on the look-ahead parameter and odometry is not quite fine to those conditions. Some studies to improve this behaviour can be found in Ollero et al. (1994a) As in figure 18 the response of the controller in straight corridors is appropriate. Figure 21 shows the performance of the PID servo controllers. This figure confirms that the Pure Pursuit has a fast response to changes in the trajectory. These fast changes imply that PID controllers cannot completely ensure the references at these instants: for example, the right track at instants 25 and 53 s.

Conclusions

This article addresses the work of preparing a mobile robot to navigate successfully and safely through a greenhouse. On one hand, a deliberative algorithm was presented; this requires a map of the greenhouse in which the mobile platform will operate. On the other hand, a pseudo-reactive navigation algorithm was described together with a sensorial-map-building process. This sensorial map will be used by the deliberative technique in future runs. Finally, the algorithms were tested on a real mobile robot, called Fitorobot, developed at the University of Almeria, and in real greenhouses. The conclusions obtained from the tests are that

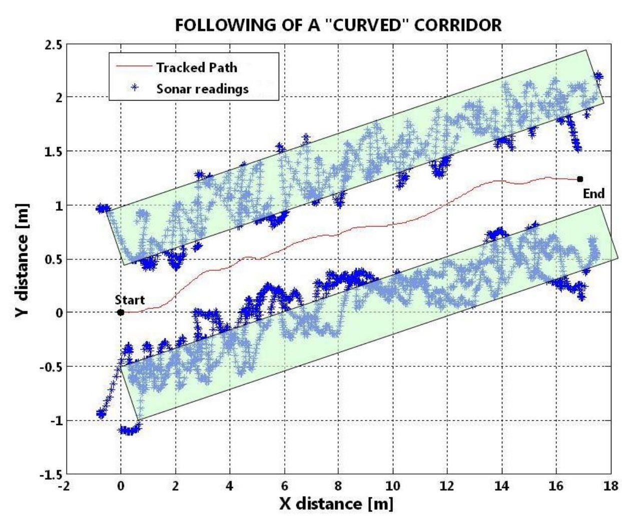


Figure 16. “Curved” trajectory in a corridor using the pseudo-reactive navigation algorithm and sensorial map.

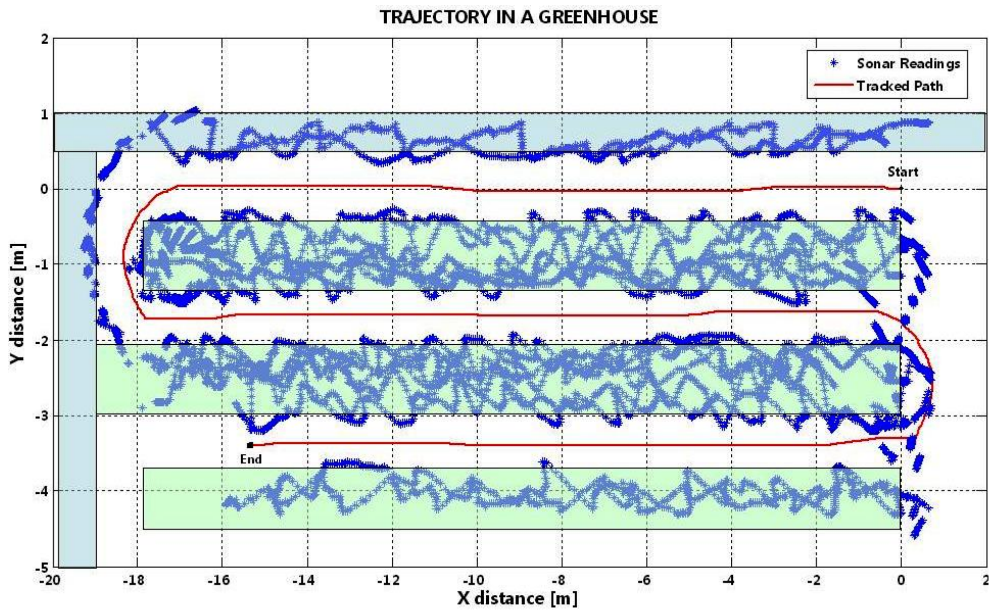
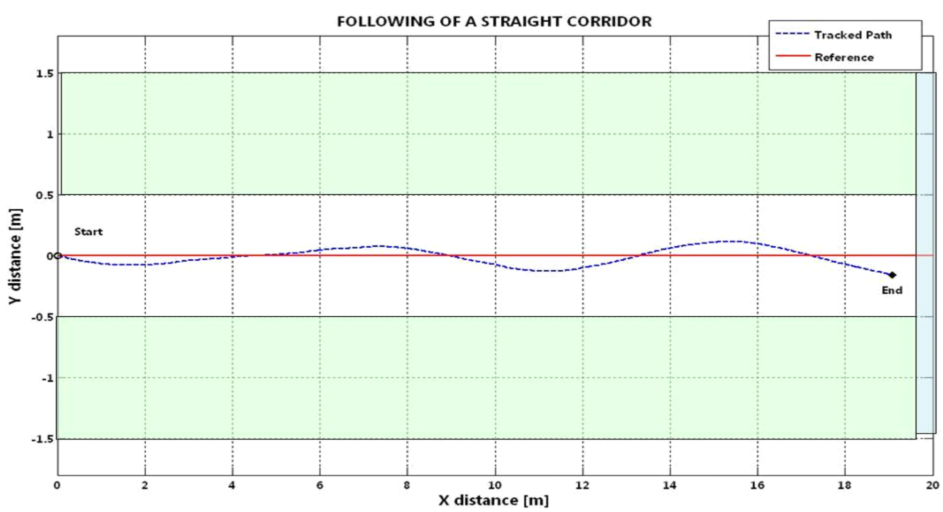
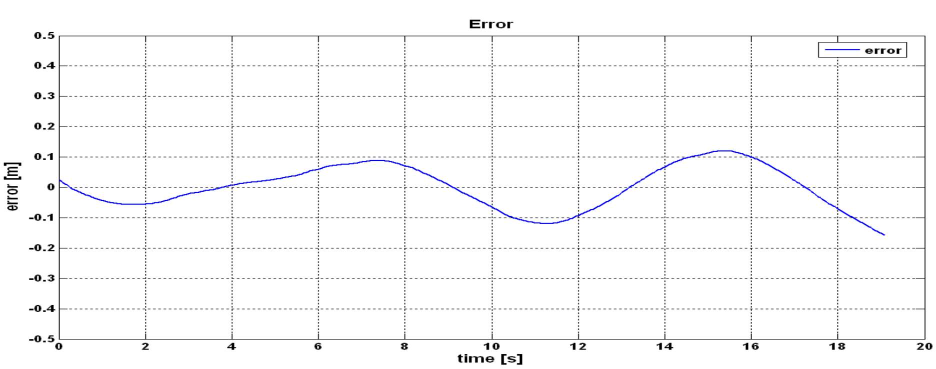


Figure 17. Typical trajectory in a greenhouse using the pseudo-reactive navigation algorithm and sensorial map.

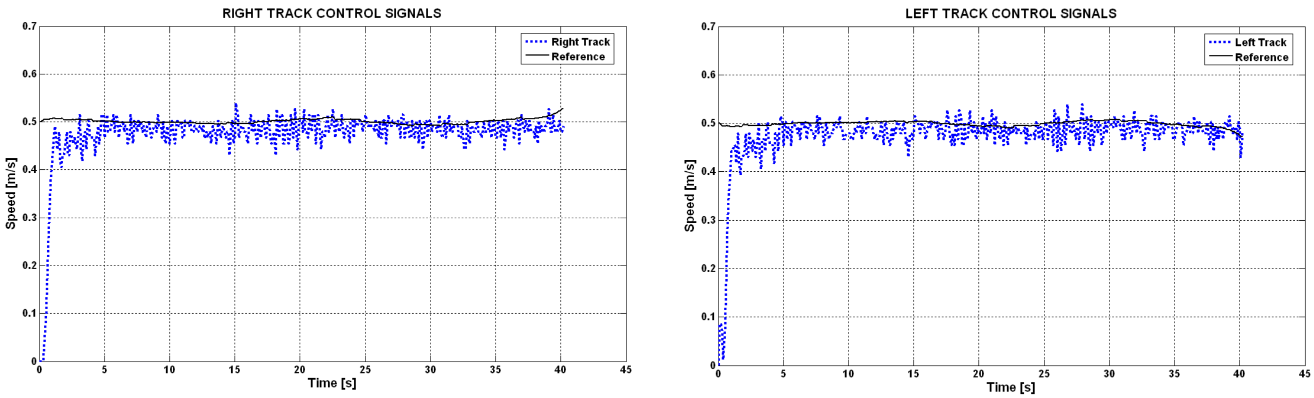


(a) Straigtht-line trajectory



(b) Error along the trajectory

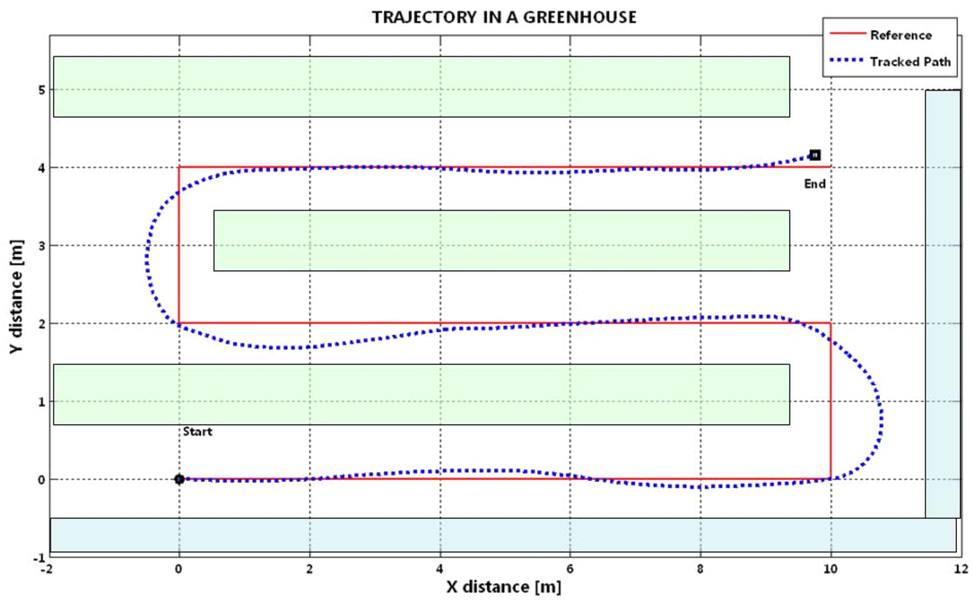
Figure 18. Straight trajectory in a corridor using the deliberative navigation algorithm versus reference trajectory (center of the corridor).



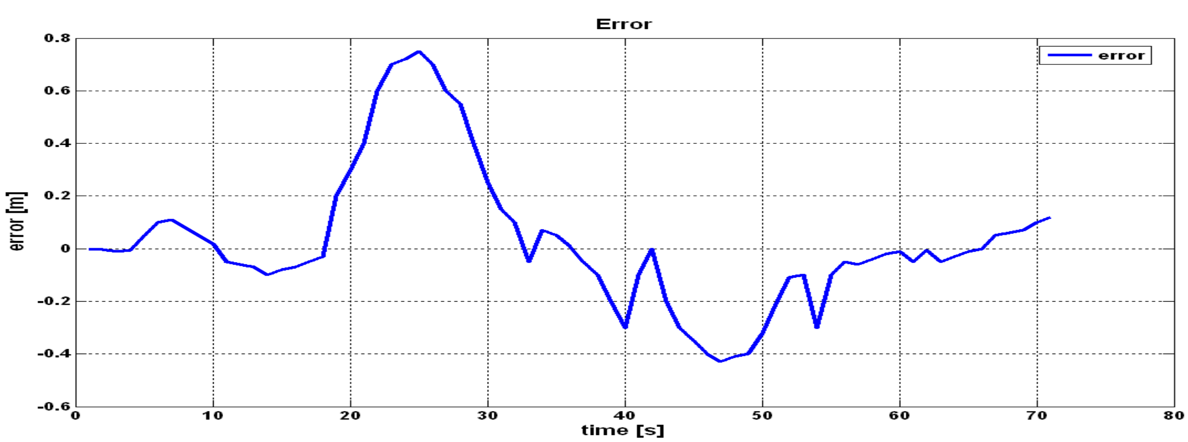
(a) Right track

(b) Left track

Figure 19. Control signals generated from the deliberative navigation algorithm.

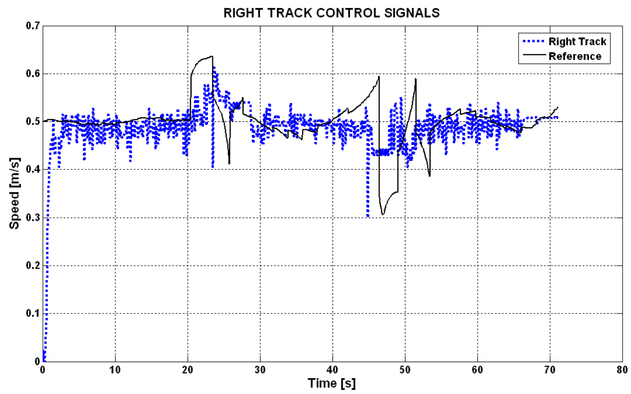


(a) Trajectory in a greenhouse

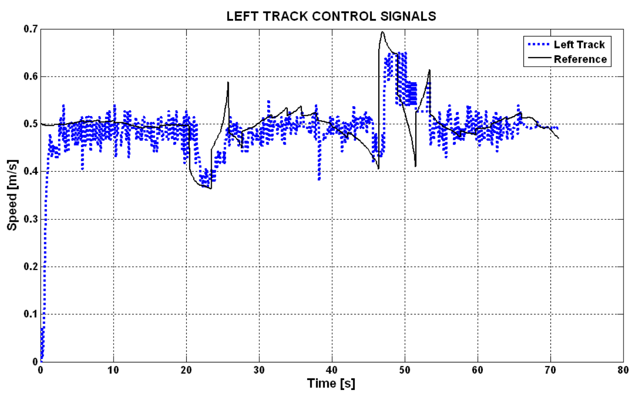


(b) Error along the trajectory

Figure 20. Trajectory in a greenhouse using the deliberative navigation algorithm vs. reference trajectory (centre of the corridors).



(a) Right track



(b) Left track

Figure 21. Control signals generated from the deliberative navigation algorithm.

the most appropriate architecture of control should be a hybrid approach. This approach would employ the deliberative technique to establish an obstacle-free path and in real time it would take into account the decisions of the reactive strategy.

Future work will involve advanced techniques of control such as predictive control and adaptive control, to overcome the problems of the Pure Pursuit controller. A preliminary step is discussed in González et al. (2008). Furthermore, the use of SLAM (Simultaneous Localization and Mapping) techniques will be also explored to navigate unknown greenhouses and to construct maps (Leonard and Durrant-Whyte, 1991; Durrant-Whyte and Bailey, 2006).

Acknowledgements

This work has been supported by the Spanish CICYT under grants AGR2002-00982 and AGR2005-00848. The authors are also grateful to the Experimental Centre "Cajamar - Las Palmerillas" for allow us to practice in their installations. The authors further wish to thank the professors M. Berenguel, J.L. Guzmán, and A. Corral at the University of Almeria for their comments.

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