A New Design of a Robot Prototype for Intelligent Navigation and Parallel Parking

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Abstract:

Nowadays, the design of industrial vehicles and movable cars is based on the automation of their different tasks, which are currently handled by humans. These tasks, such as maneuvering robots in complex environments, require high level of precision that cannot be guaranteed by humans. Manual operations are likely to produce errors of computation and optimization of navigation and manoeuvre (left, right, veering…). In this paper, a novel prototype of a well-structured robot for intelligent navigation and parallel parking applications is presented. The robot have two axels, the front one is composed of two wheels that are manoeuvred by a stepper motor, and a pinion rack system for controlling the rotation of the wheels, and also the orientation of the robot. The driving wheels are mounted in the rear axle of the robot and are commanded by two DC motors. The design allows modification of the robot structural components whenever required. In addition to the mechanical components, the prototype is equipped with a DC power supply, three infra-red sensors, one ultrasound sensor, and control modules composed of an FPGA card, microcontroller card and two cards which are responsible for commanding actuators. The parameters of the mechanical and electronics components are optimised to perform multiple tasks for training and instruction applications. A mathematical model that describes the dynamics of the robot prototype is also developed. Simulation, experimental and theoretical investigations were carried out consisting in navigation and parallel parking manoeuvres. It was confirmed that the experimental and theoretical results agree well in both applications.

Keywords: *autonomous vehicles, embedded design, and mobile robot.*

1. Introduction

Creating autonomous robots is one of the main up-to-date research activities. Real-world mobile robots operate in an environment that is not engineered for a particular robot. In other words, prior knowledge of the environment is limited and unreliable because of the complexity and unpredictable dynamics of the surroundings. Consequently, the ability of a robot to plan its motion autonomously is of vital importance. In the literature, several research studies addressed the problems of navigation and intelligent car parking, obstacle avoidance and target tracking control of mobile robots. The control of a mobile robot in dynamic and unstructured environments typically requires efficient processing of data/ information to ensure precise navigation and intelligent parallel parking.

1.1. Motivation

The present study aims at developing a novel approach of obstacle avoidance for a mobile robot that uses a hierarchical control for autonomous navigation in an unknown environment. A new configuration of hybrid architecture for intelligent parallel parking with the use of a PC for command is also developed. For control purposes, an RF module installed on the chassis of the robot is used. A mathematical model, which describes the robot kinematics, is incorporated into the proposed design to control the robot within its unknown environment. The collected sensors information regarding this environment is processed to guide the mobile robot to its target while avoiding collisions. For example, when more than two parking lots with different widths are available, the robot measures the width of each lot, and thus, selects the suitable place for parking. Using the information's of the sensors, the robot parks while avoiding obstacles in all directions (forward, backward, right and left). To confirm its efficiency, the proposed control approach is implemented on a robot prototype. Software for the microcontroller is developed in order to acquire the sensor data and perform algorithms and functions that control the speed of the two rear DC motors and the direction of the mobile robot.

Both scale and weight of the platform are optimised during the manufacturing stage of the robot prototype. The prototype addresses the safety issues and incorporates the interfacing modules and troubleshooting of the software with the hardware. Algorithms for autonomous navigation or intelligent parking are implemented.

This paper is structured as follows. Section II presents the description of the mobile robot in its new design. Section III discusses the proposed architecture of the robot prototype. In section IV the mathematical model describing the kinetic behaviour of the mobile robot is presented. Section V presents the proposed control approach. Section VI provides simulations and real-time implementation results as well as their comparison with the experimental results. The last section of the paper concludes the work with suggestions for future studies.

1.2. Background/Literature review

Recently, there has been a growing interest in parallel-parking problems of car-like mobile robots for navigation [5, 9-15]. Lyon [13] formulated the parallel-parking problem of curvilinear path generation for a car with nonholonomic constraints, where the slope and curvature constraints are used to derive a fifth-order polynomial equation denoted as the parallel-parking path. The relationship between the rear-path curvature and the steering angle was also developed.

Reactive type-2 fuzzy architecture, for the real-time control of mobile robots navigation in dynamic unstructured indoor and outdoor environments, is one of many research activities in mobile robots that use interval type-2 Fuzzy Logic Controller (FLC) to implement the basic navigation behaviours and their coordination to produce a type-2 hierarchical FLC [1]. Simon [2] developed an embedded fuzzy controller for a nonholonomic mobile robot that was built based on the behaviour-based artificial intelligence, where several levels of competences and behaviours were implemented. A hybrid learning approach for a neuro-fuzzy system applied to obstacle avoidance of a mobile robot was suggested by Meng and Deng [3] to prove that the simulation environment is supervised via learning. Using the hybrid learning approach, an efficient and compact neuro-fuzzy system can be generated for obstacle avoidance of a mobile robot in the real world.

Many other studies investigated the computing-based-embedded design of an intelligent wall/lane following vehicle. For unstructured environments, soft computing techniques for vehicle control systems were modelled using highly non-linear differential equations. Using these techniques, two intelligent controllers based on fuzzy logic and artificial neural network were designed for performing a wall following task [4]. These controllers were contrasted for hardware resource requirements, operational speed, and trajectory tracking errors. Many others problems were encountered in testing forward navigation and the direction control module of the platform [6].

Typical autonomous vehicles employ conventional controllers that generally require the use of complex mathematical models [16-17]. However, these controllers are prone to many issues such us modelling uncertainties in real-world environment and processing of noisy sensor information. Yang and Meng [18] presented a real-time collision-free motion-planning algorithm using a Neuronal-Network (NN) based approach. Unlike conventional NN models, dynamics of each neuron is characterized by a shunting or an additive equation derived from Hodgkin and Huxley's [19] membrane equation. Weights are predefined at the stage of NN design, eliminating the need for a learning procedure. The proposed algorithm demonstrated effectiveness in parallel parking and navigation applications. Zalama *et al.* [20] designed an NN model for navigation. Reinforcement learning is employed in which the control system learns the appropriate action through a credit and punishment system that assigns rewards and penalties according to the correctness of the control action. The goal is to maximize the long-term reward. Based on this technique, the control system successfully learnt collision avoidance, wall following, and goal-reaching behaviours.

In terms of computing medium, many researches utilize microprocessors and FPGA (Field Programmable Gate Array) based hardware. The design and implementation of a real-time fuzzy logic based parallel parking system was proposed with two control units consisting of a main controller and a secondary fuzzy logic controller [5]. The latter is employed for realizing the wall following task, which plays a key role in the parking system. Based on performance and flexibility considerations, the control units were implemented onto a reconfigurable hardware platform. Krohling *et al.* [21] used an evolutionary algorithm, implemented on FPGA, to provide navigation for an autonomous robot in unknown and changing environments. Fakhfakh *et al.* presented a work that show different analysis (Numerical and Experimental) of a Gear System with Teeth Defects [22].

Few papers were interested on the kinetic behaviour of the mobile robot influenced by the driving system and the environments constraints.

Also the optimization of the manoeuvring operation such as changing direction is not well tested in literature.

In the other hand, existing mobile robots have specific operations objectives, which are induced by their limited design.

The present work intends to design and implement a new generation of robots able to solve manoeuvring operations in complex situations using an original driving system and orientation mechanism.

2. Description of the mobile robot

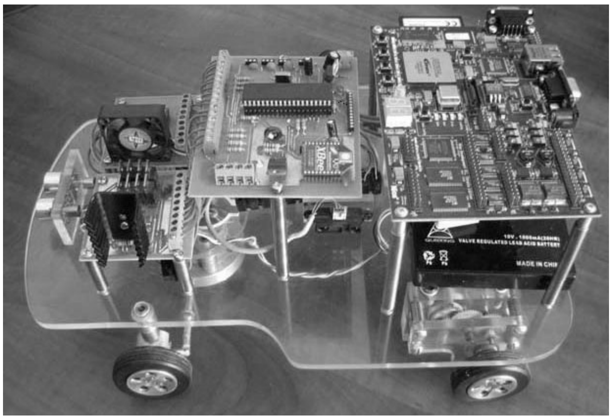

Fig. 1. Autonomous mobile robot.

A structure of a mobile robot (Fig. 1) is developed for navigation control and intelligent parallel parking in a dynamic environment. The robot is of length 350 mm, width 240 mm and weight 2,840 kg. The hardware and software of the proposed robot prototype were developed in the Micro Electro Thermal Systems Laboratory of the National School of Engineers in Sax, Tunisia. The prototype was properly designed to address the concerns of automobile manufacturers raising problems of intelligent parallel parking and navigation that require scheduled tasks with/without human intervention in a complex environment. The robot is trained to use artificial vision and is programmed to follow trajectories in its environment by acquiring information from the positioning sensors. It is also talented to move autonomously in its unknown environment, to avoid obstacles, and to perform intelligent parallel parking using four sensors mounted on the chassis of the robot. As it detects obstacles in its environment, the robot measures its position with respect to the parking place. This prototype, illustrates many types of smart applications, such as universal and didactic applications [23].

The developed mobile robot consists of the following modules (Fig. 2):

- Four positioning sensors S_1-S_4 responsible for detecting obstacles,
- An electronic card ($Card_1$) for controlling the stepper motor (M3), and the DC motors (M_1 and M_2),
- A micro controller ($Card_2$) for database acquisition,
- An F.P.G.A card ($Card_3$) for processing the data supplied by the three infrared sensors and the ultrasonic one,
- Front and rear axles,
- Four wheels w_1-w_4, battery, one rack in front axle for manoeuvring, and two reducers R_1 and R_2.

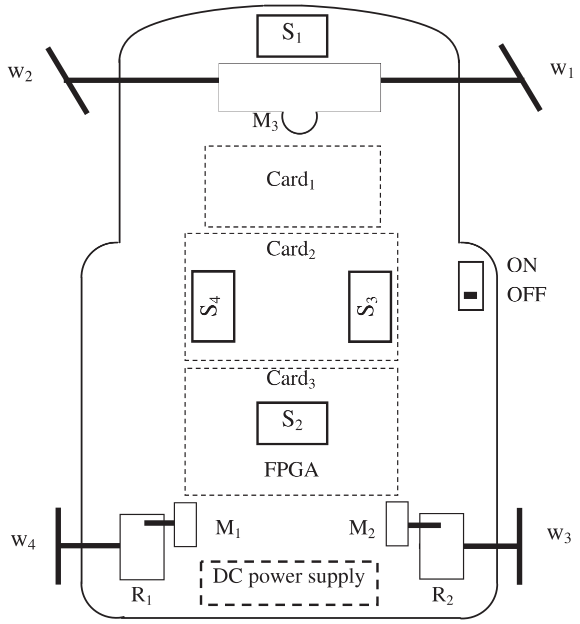

Fig. 2. Schematic of the mobile robot.

Figures 3 and 4 show the components of the front and rear axles, respectively. The front axle consists mainly of two wheels, a pinion rack system for manoeuvring the robot during navigation, and a stepper motor. To change the direction, the DC motors operate at different angular velocities. The rear axle consists mainly of two gearboxes independently mounted on the chassis driven by two DC motors. This driving system is essentially used for the system motion and also for the direction changing manoeuvres.

3. Proposed Architecture of the Robot Prototype

The architecture design of the proposed prototype is valid for various fields of application that use FPGA cards for intelligent parking in different working conditions. In fact two mains design levels for the robot prototype are encountered in literature [7]: the global and physical levels. The global level is defined by a set of exteroceptif sensors and the physical level by the mechanical system where the proprioceptif sensors are integrated. For planning tasks, the exteroceptif sensors:

- compute the shortest track between two memorized locations,
- accomplish short cuts to unexplored zones within the working environment,
- memorize the robot trajectory, and
- foresee a trajectory between the two locations.

The robot prototype integrates hybrid controllers for building intelligent algorithms using an FPGA card for navigation and parallel parking applications. [7-8] The different tasks of planning and obstacle detection by the proprioceptif sensors in the proposed platform are converted into data that are processed by the FPGA card to activate the actuators without disruption during other decisions. The development system allows the integration of multi-tasks operation for navigation in unknown environments Two basic application concept of the proposed robot in an unfamiliar environment containing fixed or movable barriers were developed. In the first one, the robot navigates in this environment while detecting the distances that separate the robot platform from barriers. The decision to change direction (right or left) depends on the distance that separates the platform of the detected obstacle. In the second application, several parking stations are available and the robot have to select the suitable one, which fits its width, to travel through it.

4. Kinematics model of the robot

In order to describe and realize its motion, we develop expressions for the kinematics of the robot prototype. A stepper motor geared to a rack commands the front axle, represented in Fig. 5. As the motor rotates, the rack moves to the right or to the left depending on the direction of rotation. On each side of the front axle, a wheel mechanism composed of three joints ensures the rotation

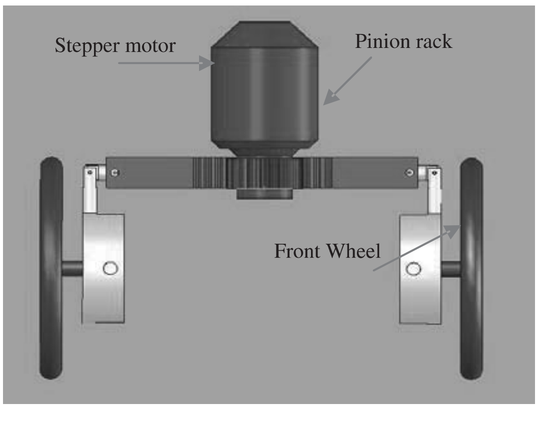

Fig. 3. Front axle of the mobile robot.

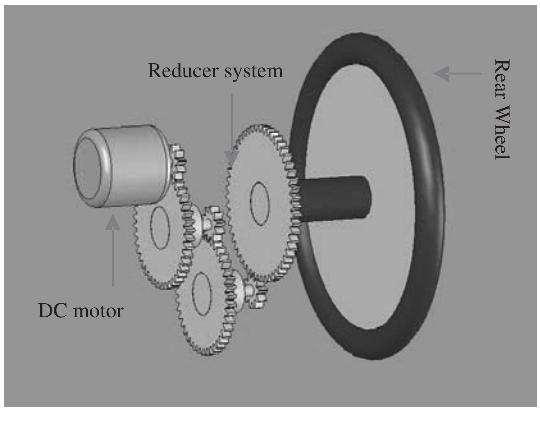

Fig. 4. Rear axle of the mobile robot.

of the wheels (Fig. 6).

The configuration of the mobile robot during navigation is shown in Fig. 7. We distinguish three position vectors R , R_r and R_l that locate the centres of the front axle, right and left wheels, respectively. L is the distance that separates the centres of front and rear wheels, E is the axle length, R is the radius of gyration, and α is the steering angle such that sin $\alpha = L/R$. For a given steering angle, the rack displacement is characterized by the arc length AA'.

The norm of the position vector locating the centre of joint A can be expressed by

$$a = \overline{OA} = \sqrt{OD^2 + AD^2} \tag{1}$$

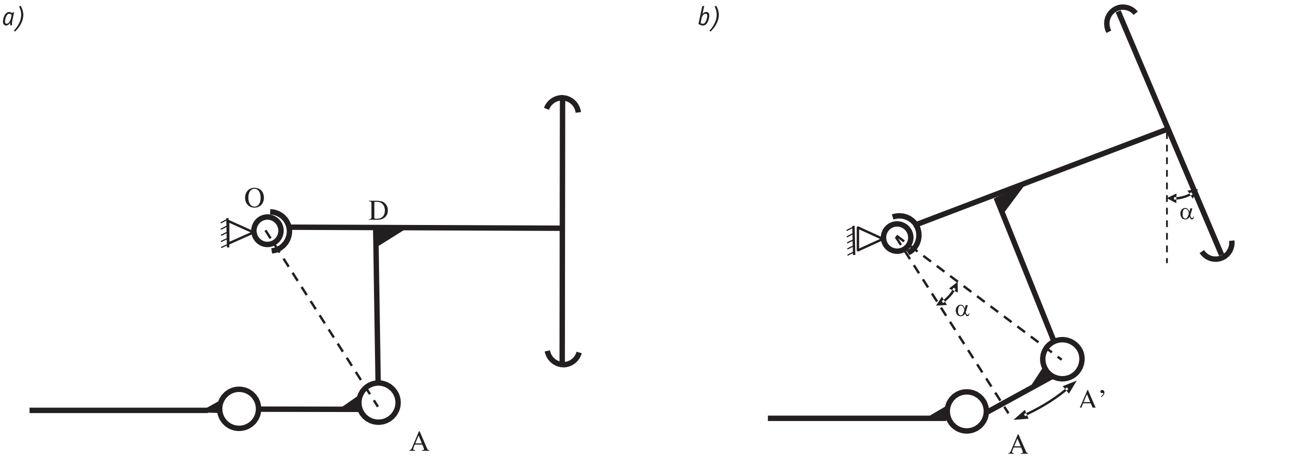

Fig. 5. Schematic of the front axle.

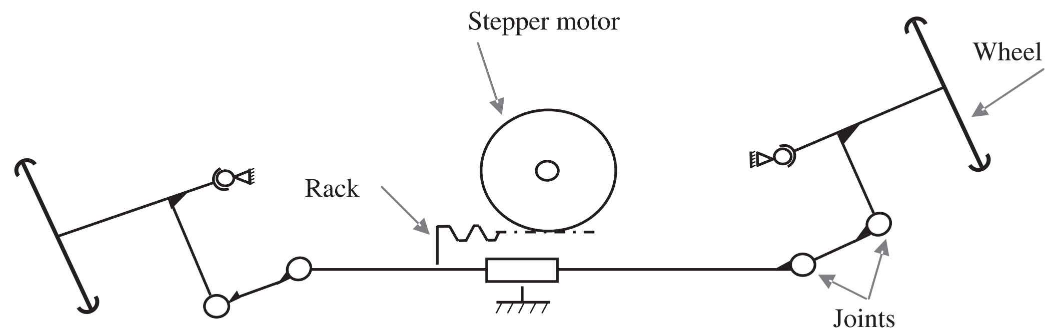

Fig. 6. Wheel mechanism (a) non-rotated (b) rotated through and angle.

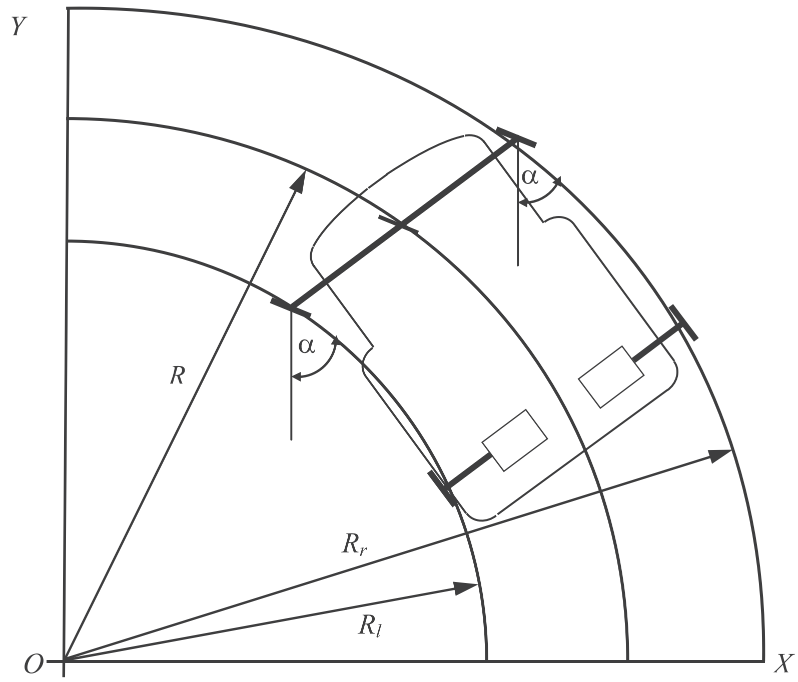

Fig. 7. Robot configuration during curving motion.

Thus, the arc length travelled by this joint is as follows:

$$d = \alpha a \quad (2)$$

Where d represents the translation distance of the rack, hence, the angular rotation of the pinion and then of the stepper motor is given by

$$\psi = \alpha d_p / d = \pi m Z_p / d \quad (3)$$

Where d_p is the pinion pitch diameter, m is the module, and Z_p is the pinion tooth number. In case of a left turn, the left wheels of the front and rear axles travel a shorter distance as opposed to the right ones. This can be justified by the fact that R_r is less than R_l. For example a rotation of 90° corresponds to the following distances travelled by the right rear and front wheels respectively:

$$d_r = R_r \theta = \left(R + E/2\right)\frac{\pi}{2} \quad (4)$$

In the absence of a differential gears system at the rear axle, the DC motors are operated independently to regulate the angular velocities of the left and right wheels. The time to travel a gyration angle of 90° can be expressed by:

$$t = \frac{d_l}{V_l} = \frac{d_r}{V_r} = \frac{R(\pi/2)}{V} \quad (5)$$

Where V_l and V_r are respectively the linear velocities of the left and right wheels, and V is the linear velocity at the robot centre line. Hence, V_l and V_r can be expressed by

$$V_l = V\frac{2d_l}{R.\pi} \quad \text{and} \quad V_r = V\frac{2d_r}{R.\pi} \quad (6)$$

Consequently, in order to ensure a regular gyration of the robot, the angular speeds of the left and right wheels have to be reduced by

$$100\left(1 - \frac{2d_l}{R.\pi}\right)\% \quad \text{and increased by} \quad 100\left(\frac{2d_r}{R.\pi} - 1\right)\%$$

respectively. Robot navigation for intelligent parking with a gyration angle of 90° requires the computation of the steering angle, the distance travelled by the rack, the angular rotation of the stepper motor, and the speeds of the DC motors. This enables precise parking by commanding the two DC motors with independent speeds.

A model for the kinematics associated with the rear axle is represented in Fig. 8, where C_m and C_w denote the torques associated with the motor and wheel, respectively. The robot torque is regulated by a control law, which is automatically constructed by intelligent algorithm.

k_θ - is the torsional stiffness of the different shafts and the gear mesh between the different gears.
$k_g(t)$ - is modelled by a time varying mesh stiffness in order to take into account the mesh process.
J_i $(i=1\ldots..6)$ are the inertia moments of the gears.
θ_i $(i=1\ldots..6)$ are the different angular rotation of the gears.

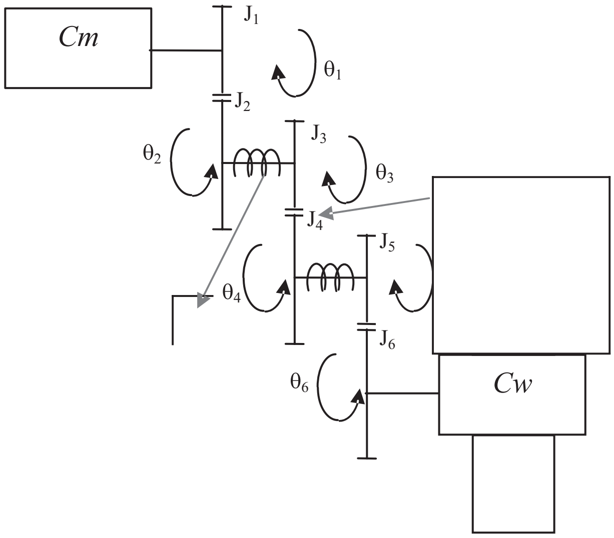

Fig. 8. Kinematics of the rear axle.

The front wheels and the gearboxes mounted on the rear axle constitute the principal mechanism for navigating the mobile structure in its working environment. As the robot detects an obstacle, it makes a turn, as depicted by Fig. 9. We allow a moving frame (O, X, Y) to be attached to the centre point of the front axle.

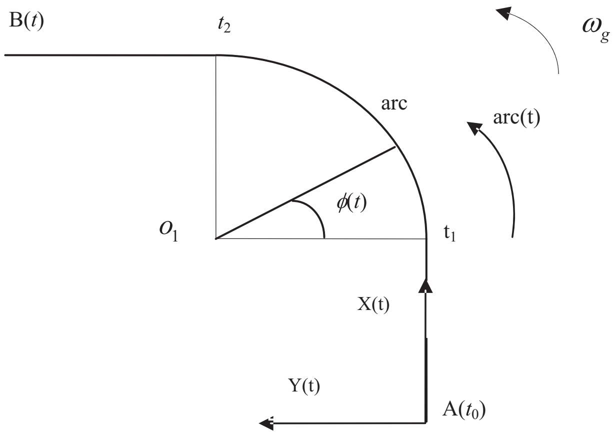

Fig. 9. Trajectory of the robot for obstacle avoidance.

During an angle turn $\phi(t)$ with respect to the Y axis, the coordinates of the centre point of the front axle are

$$X(t) = X(t_1) + \frac{r_w \phi(t)\left[1 - \cos\omega_g(t - t_1)\right]}{\omega_g(t - t_1)} \quad (7)$$

$$Y(t) = \frac{r_w \phi(t)\sin\omega_g(t - t_1)}{\omega_g(t - t_1)} \quad (8)$$

where r_w is the wheel radius, ω_g is the angular velocity of the robot around o_1, and $\phi(t)$ is the angular position of the rotating wheel. In all cases, the computed trajectories must start and finish at zero-curvature configuration.

5. Proposed control Approach

We propose the use of classical and hybrid control strategies for intelligent navigation and parking, respectively. Fig. 10 displays the global and physical levels of each of these control strategies.

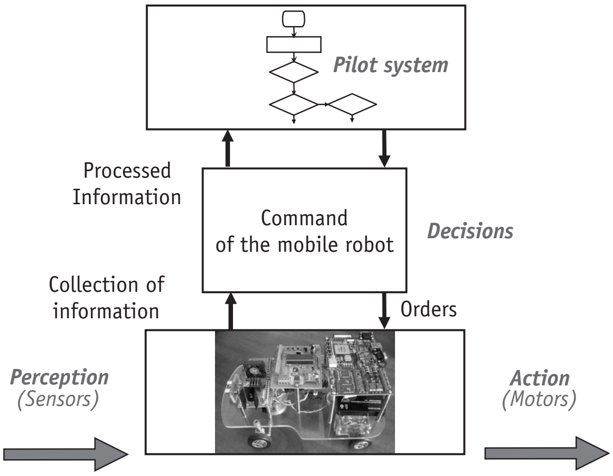

Fig. 10. Proposed control approach.

Starting from the perception by the sensors at the global level, the data is processed in a sequential way to operate the actuators at the physical level. The perception phase collects the information and processes it by a pilot system, as shown in Fig. 10. This process is characterized by sequential decisions for the control of actuators that obey the orders and instructions of the algorithm. Consequently, this approach follows the bottom-up/top-down design approach. The proposed approach is characterized by control tools of a hierarchical nature, where we use the classical approach to validate the robot prototype. After the design of the mechanical components, we simulated and tested the navigation application and simulated the parking application. These applications are commanded at distance by a PC since the prototype is equipped with an RF module. Therefore, the proposed approach constitutes a phase of real actions are simulated.

6. Computer simulations and real-time implementation results

In order to show the efficiency of the proposed approach, the intelligent navigation and parking applications are simulated in this section.

6.1. Navigation

Fig. 11 configures a navigation application in which the prototype has to avoid a set of obstacles within its working environment. The navigation control approach consists of an algorithm for detecting an obstacle and veering to avoid a collision without making any stop. When the robot detects an obstacle, it measures the distances on its right and left, and veers at an angle of 90° to the left or to the right, depending on the longest distance from the obstacle. In classical robot navigation, the robot stops in front of the obstacle, measures the distances on the right and left, and then resumes its motion. Let us show a real example of this experience.

An example of this navigation process is presented in Fig. 12, where Snapshots of the prototype location and orientation are associated with phases 1, 2 and 3.

Figures 13a-c present simulations of this navigation case. The robot prototype starts moving along the X-axis and then makes a right turn as it detects an obstacle, which is either predictable or unpredictable. In the second phase, we notice that the translation in the X-Y plane is accompanied with a vibratory motion. This latter is mainly due to the flexibility of the gears mounted on the rear axle. As the robot navigates along either the X-axis or Y-axis, these vibrations become negligible, and due to the torsional kinematics model it is not possible to get representation of these vibrations in the X-Y plane. However, during the veering phase the dynamics of the rear axle induce important vibrations to the rigid-body motion. Fig. 13c shows the controlled trajectory of the mobile robot in X-Y plane. These simulation results illu-

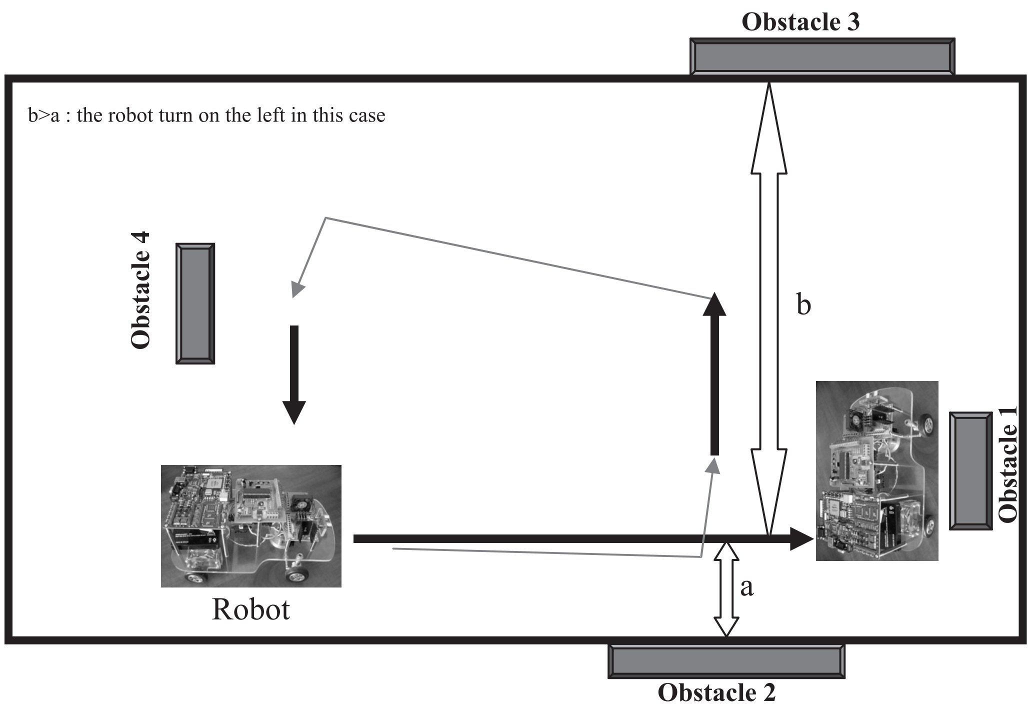

Fig. 11. Configuration of a navigation in an unknown environment.

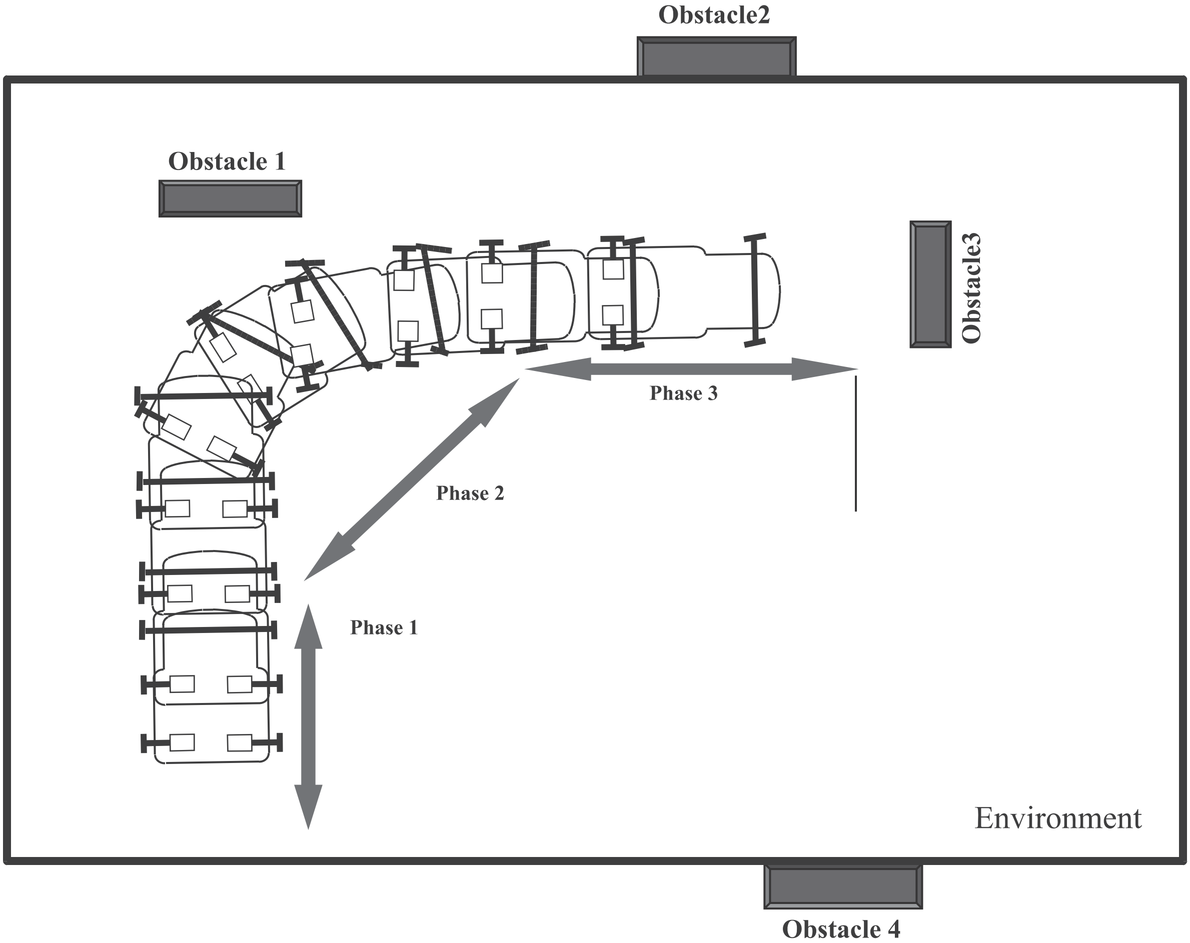

Fig. 12. Implementation experimental results of navigation.

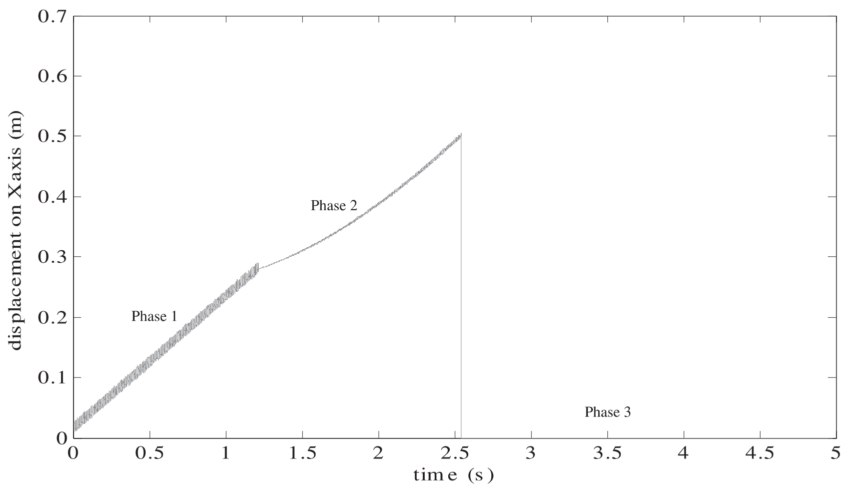

Fig. 13a. Simulation results: Phases (1, 2).

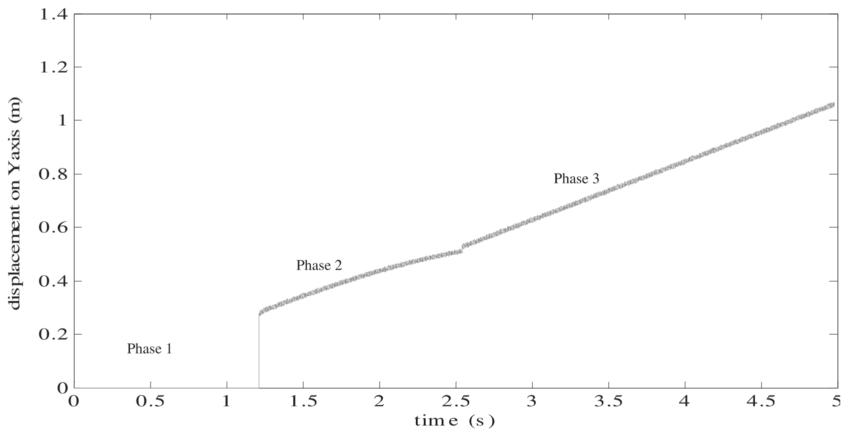

Fig. 13b. Simulation results: Phases (2, 3).

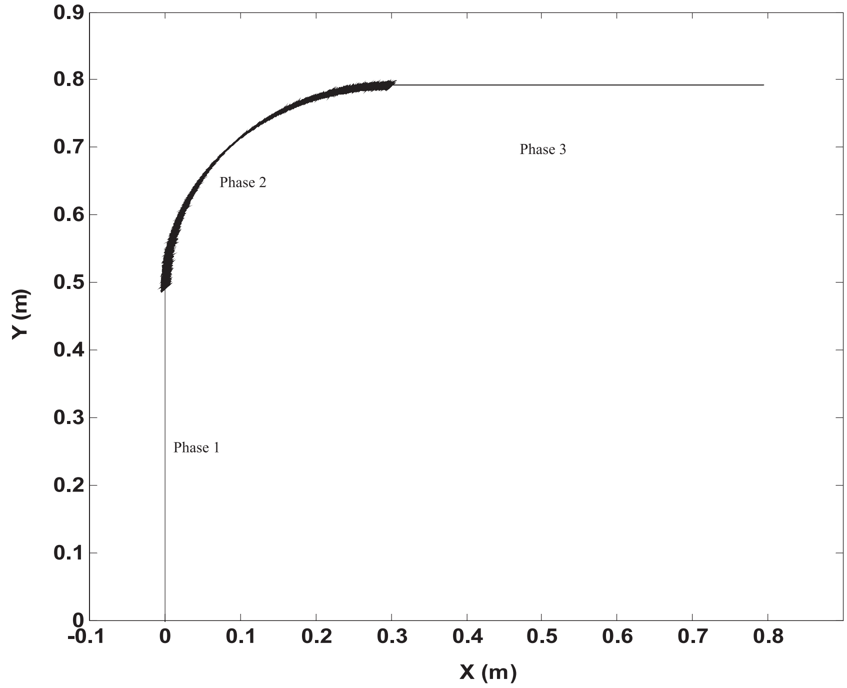

Fig. 13c. Comportment of the mobile robot in the X and Y axis.

strate the efficiency of the proposed control algorithm when the mobile robot confronts obstacles. Fig. 14 shows 3D representation of the mobile robot position as a function of time.

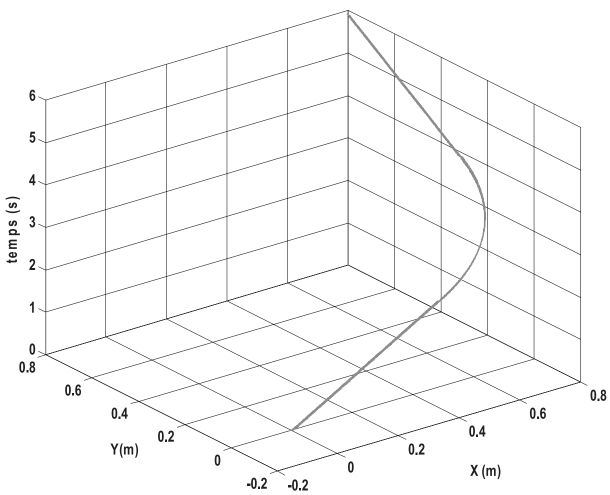

Fig. 14. 3D representation of the commanded navigation.

6.2. Parallel parking

In order to show the feasibility of the proposed algorithm for navigation, we consider the parallel parking application. A algorithm is implemented for this purpose to handle different situations. Figures 15a and 15b configure two different parallel parking applications. In the first one, the robot, whose width is 240 mm, moves on a straight path while inspecting on its right side the sizes of two parking lots (150 and 300 mm). This inspection yields decision of the correct lot where the prototype is to be parked. The mobile robot goes back a distance of 275 mm to take a turn to the right followed by a straight line leading to the selected parking lot.

An example of these two operations of parallel-parking process is presented in Fig. 16a and 16b, where Snapshots of the prototype location and orientation are associated with phases 1, 2, 3 and 4 in the two appli-cations.

Figures 17a and 17b display the simulated trajectories along the X and Y axes for application 1 presented in Fig. 15a. The commanded trajectory of the prototype in the X-Y plane is shown in Fig. 17c. Once more, we observe that the flexibility of the gears mounted on the rear axle induces important vibrations.

Figures 18a and 18b are simulations of the commanded displacements along the X and Y axes, respectively, associated with application 2 represented in Fig. 15b.

These simulations illustrate the efficiency of the proposed control algorithm when the mobile robot confronts obstacles. The results of both applications confirm the efficacy of the proposed control algorithm for commanding intelligibly the mobile robot, equipped with an RF module, at distance using a PC.

7. Conclusions and Future Studies

In this paper a novel design of an autonomous mobile robot for navigation and parallel parking applications is manufactured and implemented. The proposed robot is equipped with an FPGA card, a microcontroller module, an electronic driver module, an ultrasonic sensor and infrared sensors. These robot present real advantages: it offers optimised manoeuvring operation allowed by the novel mechanism and hardware design. In order to show the viability of the proposed design, we considered one case of navigation and two cases of parallel parking. For each case, we implemented an intelligent algorithm for obstacle avoidance. It was found that the simulated trajectories of the commanded robot show similar performance with real navigation applications. The main outcome of this research was to develop an electromechanical system that is commanded at a distance and navigates intelligently in a working environment with predictable and unpredictable obstacles. The proposed design can be easily implemented in industrial environments, such as carrying objects. It can also be used in vehicles

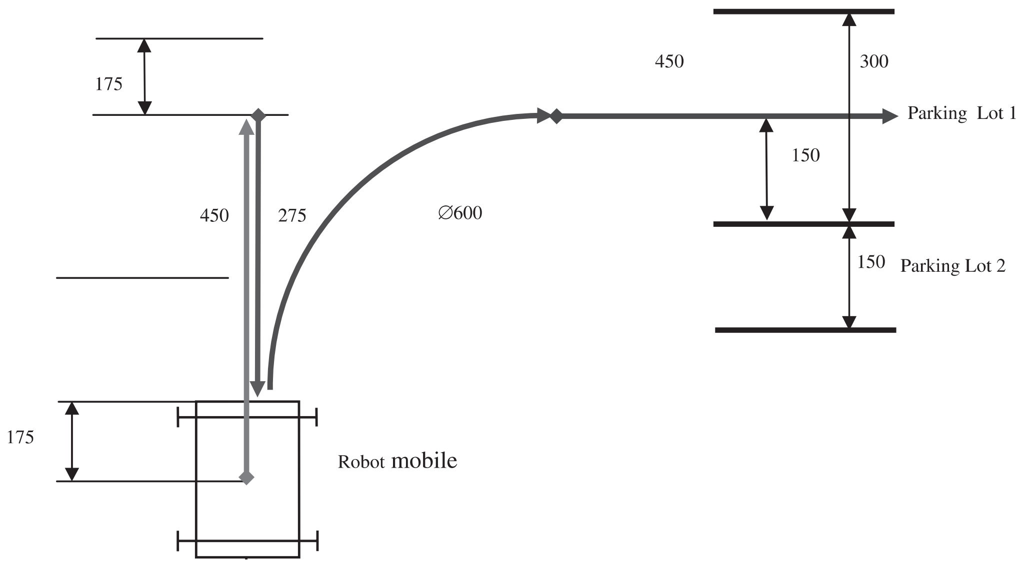

Fig. 15a. Parallel parking: application 1.

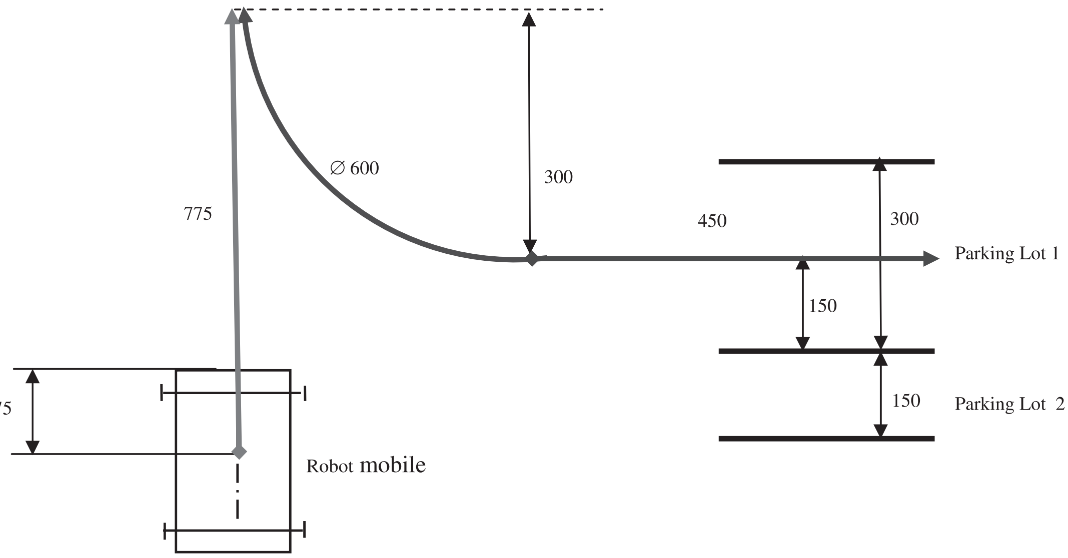

Fig. 15b. Parallel parking: application 2.

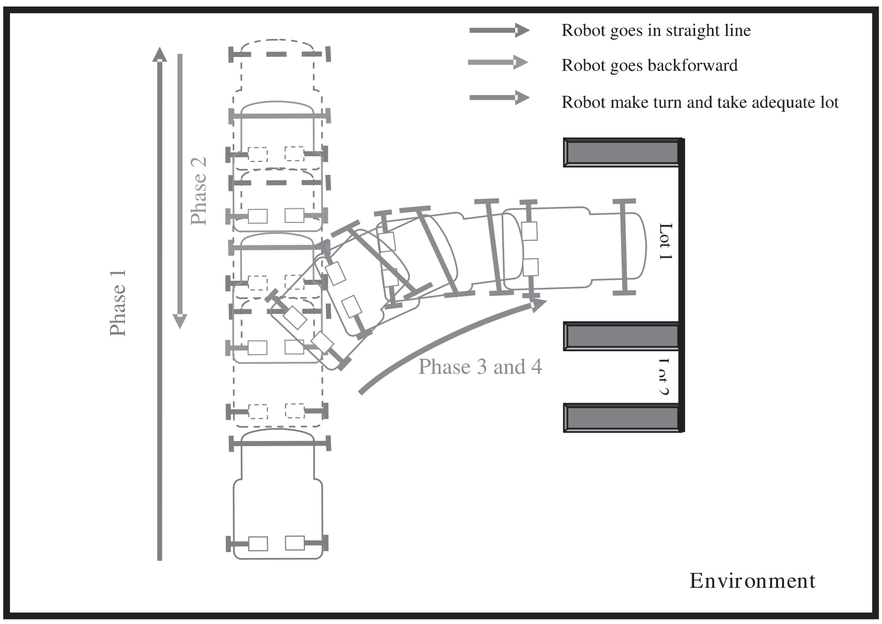

Fig. 16a. Implementation experimental results (parallel parking: application 1).

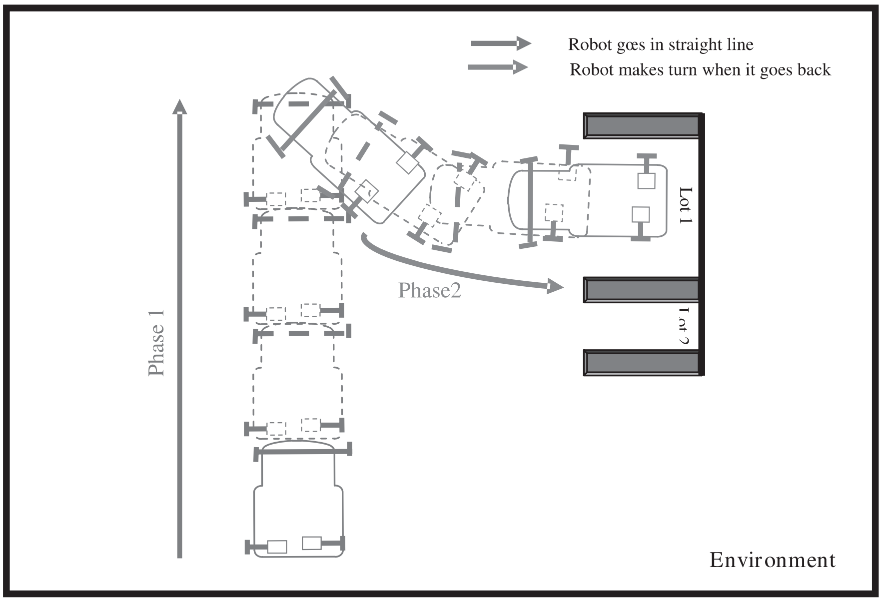

Fig. 16b. Implementation experimental results (parallel parking: application 2).

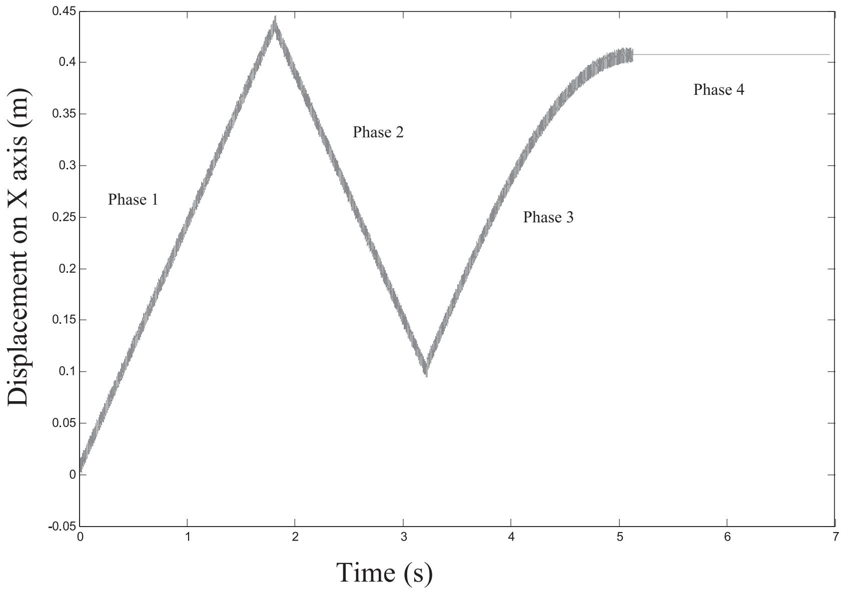

Fig. 17a. Displacement along the X-axis (parallel parking: application 1).

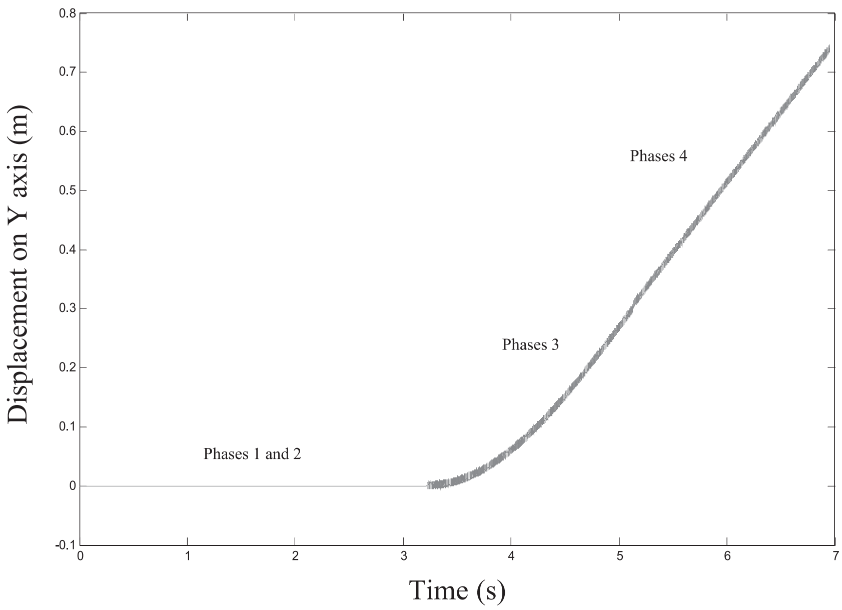

Fig. 17b. Displacement along the Y-axis (parallel parking: application 1).

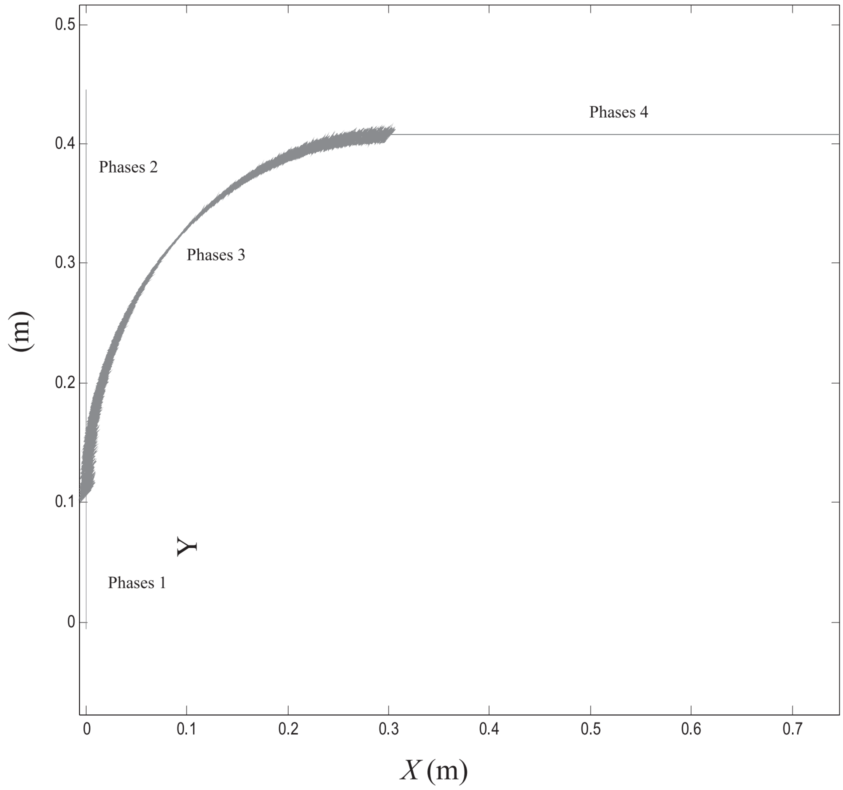

Fig. 17c. Robot trajectory on the X -Y plane (parallel parking: application 1).

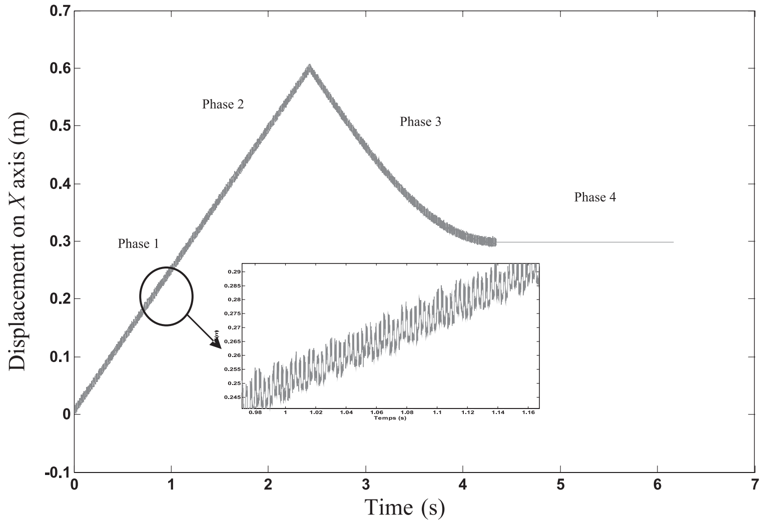

Fig. 18a. Displacement along the X-axis (parallel parking: application 2).

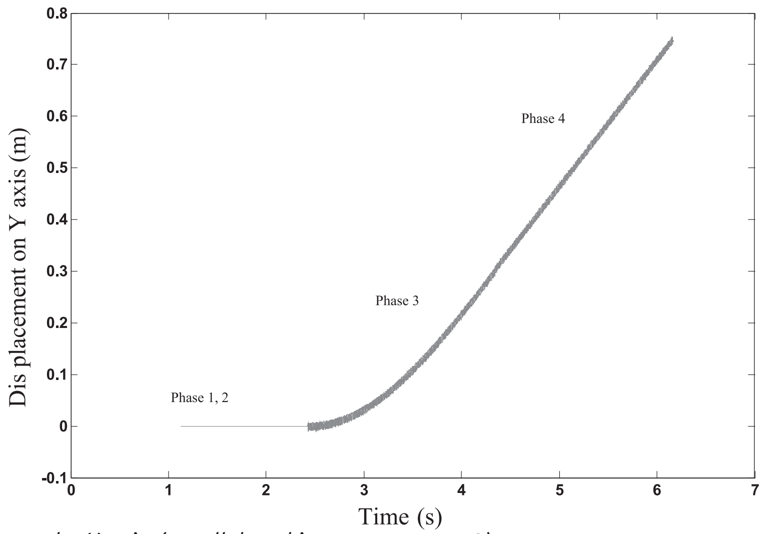

Fig. 18b. Displacement along the Y-axis (parallel parking: application 2).

for intelligent parallel parking. In addition, the prototype will be used for educational and research purposes at undergraduate and graduate laboratories in the Department of Electrical Engineering of the National Engineering School of Sfax.

Future research will emphasize the integration of a mobile camera, instead of a set of sensors, into the mobile robot for intelligent navigation and obstacle avoidance. This camera is used not only for detecting obstacles but also for positioning the robot within its working environment. The implementation of intelligent control approach based on genetic algorithms with the use of an FPGA module card will be also investigated.

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