Building a Mobile Robot for a Floor-Cleaning Operation in Domestic Environments

Jordi Palacín, *Member, IEEE*, José Antonio Salse, Ignasi Valgañón, and Xavi Clua

***Abstract*—Domestic robots are one of the new industrial challenges. In this paper, a floor-cleaning robot specifically designed for this function is proposed. Aspects such as sensor placement, motor control, robot control, and safety are considered toward an optimal implementation of this helpful robot.**

***Index Terms*—Acoustic applications, acoustic devices, mobile robot motion-planning, mobile robots, robot sensing systems.**

I. Introduction

CLEANING is usually a tedious, boring, and repetitive task and thus a clear candidate for the application for robotics. Researchers in artificial intelligence and robotics have made huge efforts, but it is still an open problem because of the unstructured environment of the cleaning operation. In this paper, a new robot for floor-cleaning operations in a household environment is proposed (Fig. 1) [1]. There are a huge number of articles dealing with different problems associated with mobile robots, most of which are applicable to the floo-cleaning problem. However, there are a small number of papers dealing specifically with floor-cleaning robots. These tend to be rather specialized, with the coverage algorithm as the main subject of interest [2]–[6]. Conversely, this paper describes the integrated use of different competencies oriented toward the design of a complete floor-cleaning mobile robot, the most feasible domestic robotic operation.

In the following sections the basic mechanical robot design, discussions about safety, details of motor control and robot control, and some functional tests are presented. The test stage is centered on the sensorial system and on the robot control by means of the University of Michigan Benchmark (UMB) test [7]. This paper ends with the main conclusions.

II. Robot Mechanical Design

Fig. 1 shows the proposed robot design. The practical implementation of a cleaning robot is an interdisciplinary problem but in this paper, the attention is focused on the actuators, sensors, and electronics and their usability.

The mechanical design of a cleaning machine for domestic use must be ergonomic and small enough to move around the typical obstacles in a household room and as well as light enough for easy transportation in case of unexpected problems. In its design, several different problems have to be solved: the efficiency of the cleaning device, the placement of the motorized wheels, the on-board sensors, and the battery recharge operation.

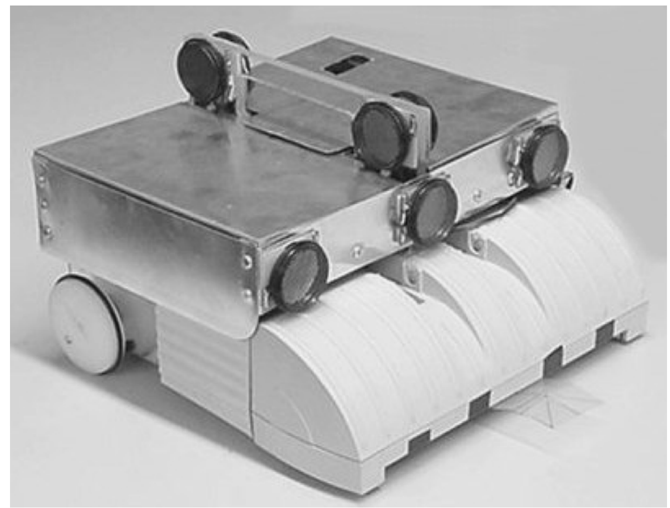

Fig. 1. Proposed cleaning robot: 28 $\times$ 27cm wide, 23 cm brush width, and 14 cm height (19 cm with the handle).

A. Cleaning Principles and Robot Structure

Most cleaning robots use a vacuum as the principle cleaning device [8], [9], but in our case, the cleaning device has been adapted from a commercially available electric broom manufactured by Karcher [10] because the aim of this paper is to focus on the mobile robot problem. The cleaning principle of the original machine is based on a battery-powered roller brush that is ideal for a robotic application. Depending on the surface type, the roller brush can be very effective because it cleans by friction and the rotation itself also generates a suction airflow that avoids dust generation. Moreover, its design is very simple and cheap, having only three parts: a roller brush, a dustpan, and a broomstick.

Therefore, the proposed design (Fig. 1) includes the original cleaning elements. The original dustpan has been extended with a box for the motors in the back. An additional upper box contains the electronics and sensors and a handle for easy transportation. This demonstration prototype was built in aluminum for rapid prototyping but plastic materials are planned for more advanced prototypes. Finally, the dustpan cleaning is done in the same way as the original cleaning machine, by manually removing the brush.

B. Wheels and Motors Placement

Two dc geared motors with the wheel attached to the gear axis are used for driving the robot. The best placement for the

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wheels is on the central axis of the robot, beside the brush or the dustpan. However, this placement is not compatible with the original cleaning parts, and the motors were placed at the back. This configuration is expected to be more complex to control, and the robot maneuvering will require a large area. However, the direct connection between the motors and the wheels without any chain or additional gears reduces odometry errors due to twisting angles in the mechanical parts. In addition, a third wheel (self-cleaning ball transfer) was placed under the dustpan to avoid excessive brush pressure.

C. Sensor Placement

The final robot performances will depend mostly on the on-board sensors. The proposed cleaning robot has the following sensors.

1) *Floor sensors:* using pairs of infrared sensors placed in the front of the bush to avoid falling downstairs. An infrared emitter is pointed at the floor and a receiver detects floor reflection. The main drawback of optical sensors is that they may need some maintenance to avoid dust accumulation. However, they are safe in case of failure because the normal breakdown signal is "floor not detected."
2) *Collision sensors:* using mechanical contact sensors placed for security reasons at the front of the brush and both sides of the robot to detect unexpected collisions.
3) *Distance sensors:* using ultrasonic sensors for distance measurements. Seven sensors are available (see Fig. 1). Three at the front of the robot and two on either side of the handle allow redundant measurements, of, for example, parallel alignment to a wall. The sensors are placed perpendicular to the ground without any inclination. In the near future, some of these sensors could be replaced by an embedded vision system build around a CMOS camera [11].
4) *People sensor:* using passive infrared sensors with the adequate Fresnel lens. There are two sensors: one at the front and the other at the back of the robot to cover the complete ground plane.

D. Battery Recharge

The use of batteries in a robot has the inconvenience that the recharge operation usually needs user manipulation. Most domestic machines recharge in the storage stage, but this could be a drawback because every robot operation could need two user operations: place to clean and storage for recharge. As a consequence, the recharge generates a delay between consecutive uses.

A way to reduce the number of nonsequential user operations is to include the recharge in the cleaning operation stage, that is, developing a complete cleaning station with the robot inside. Then, the station must be carried to the room, and when the cleaning ends (operation or batteries), the robot must return to the station and begin the recharge process without user operation. However, this solution also has two main drawbacks: the station weight and the return to the station operation, a very complex problem after running a long path.

The battery recharge sequence can be improved considering the robot owner's possible routine because the cleaning robot is meant to be useful for a man or woman, or couple, who leave home early in the morning and return in the afternoon or evening every working day. Then, the time available for cleaning a room can be at least 4 h. Therefore, if a battery can be fast charged in 2 or 3 h and the complete cleaning can be done in 15 to 30 min, there is enough time to first recharge the batteries and then to do the cleaning of the room.

This process can be done without a cleaning station; only small recharge equipment is needed (Fig. 2). The user must plug the recharge equipment into the robot through a flexible cable and the recharge equipment must be able to automatically unplug and collect the cable after complete recharge. The proposed recharge sequence has two main advantages: 1) the robot need not return to the exact starting point after cleaning and 2) the robot can be placed immediately in another room to start a new cleaning operation.

III. Safe Operation

The proposed robot utilization on working days without people in the room follows the recommendations of the International Standardization Organization (ISO) [12] that industrial robots should be strictly isolated from operators and workers. However, although it is obvious that domestic robots must be human-safe, the vagueness of the safety definition has limited research in this field [13], [14].

Safe operation can be defined from the point of view of the robot, the objects in the cleaning area, and the people around the robot. The safety of the robot and the objects is usually understood as the collision avoidance problem [8], [9]. In this case, the coverage algorithm uses the on-board sensors to explore the scenario and generate a path for collision avoidance. However, false measurements must be expected when using noncontact sensors and thus mechanical collision sensors are used to improve robot and object safety. Therefore, a cleaning robot is already designed to minimize the human collision risk. However, people can become dynamic obstacles and, although some methods are available to avoid collision by modifying the robot's trajectory [15]–[17], in our opinion, the best operation is to stop the robot and pass the responsibility for collision avoidance to the dynamic obstacle. This solution is also the best from the cleaning point of view because it avoids the unclean area being shadowed by the dynamic obstacle. Nevertheless, from the of human–robot compatibility point of view, the robot must be always clearly detected, perhaps by means of the generation of additional sounds or music or flashing positioning lights. However, false measurements of the scenario make dynamic object detection difficult. Accordingly, as a final precaution, soft material must be used in the robot cover, avoiding sharp edges in the final design, and the maximum speed of the robot must be limited to avoid physical injury in case of unexpected human collision [18].

Human safety operation could become a more serious problem with children as they could consider a robot to be a harmless toy. Therefore, the general recommendation with children in the room must be to stop robot operation. Robot

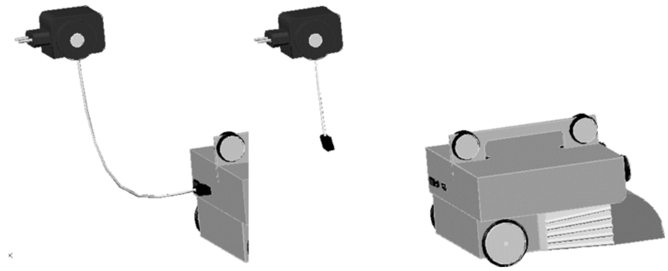

Fig. 2. Detail of battery charge and automatic unplug.

manipulation is then the worst situation because of the moving parts of the robot. In this case, the initial floor sensors can be used to detect robot manipulation although the use of extended floor sensors around the robot or tilt sensors or even accelerometers can be a way to improve safety.

Nevertheless, the easiest way to assure safety with children is by adding passive infrared sensors to the robot. These sensors can detect children as well as other people and pets in the room to be cleaned and then stop robot operation. Obviously, this human–robot compatibility option must be user-configurable to cover all possible situations: a pet in a cage, a man sitting on a sofa, etc. In our proposed design, one passive infrared sensor is located at the front and another at the back of the robot to cover the entire floor plane. A passive infrared sensor is the only sensor that covers the back of the robot because it has been designed to always move forward while operating. Backward movement is only allowed over very short distances and in certain situations with no risk of collision with static objects.

IV. Ultrasonic Sensors

Ultrasonic range measurements allow object detection, wall alignment, map building, path planning, and odometry error correction [19]. From our experience, the cleaning operation only requires detailed information of the environment involved in possible immediate movements by the robot. To cover these areas, seven sensors were placed on the upper part of the robot (Fig. 1): three pointing to the front, two to the right, and two to the left.

Polaroid 6500 Series electrostatic transducers with a $\pm 15^{\circ}$ beam were selected. These sensors are widely used in mobile robot applications because of their standard range: from 25 to 1300 cm. Ultrasonic distance measurement is based on the determination of the time of flight (TOF). This time can be measured accurately using correlation techniques [20], [21], but this approach was discarded because a dedicated digital signal processor is required. As an alternative, the standard ultrasonic driver based on the pulse-echo detection was modified to allow a range starting at 15 cm to avoid redundant short-range sensors around the robot. The used diver has a gain controlled amplifier synchronized with the firing pulse. A simple RC circuit is used to obtain an exponential decay to control the gain: after the firing pulse the amplifier has one-tenth of the full-gain and at a TOF equivalent to 30 cm in distance the amplifier reach full-gain. This configuration detects echoes normally hidden by the emitter pulse and avoids premature saturation in the echo

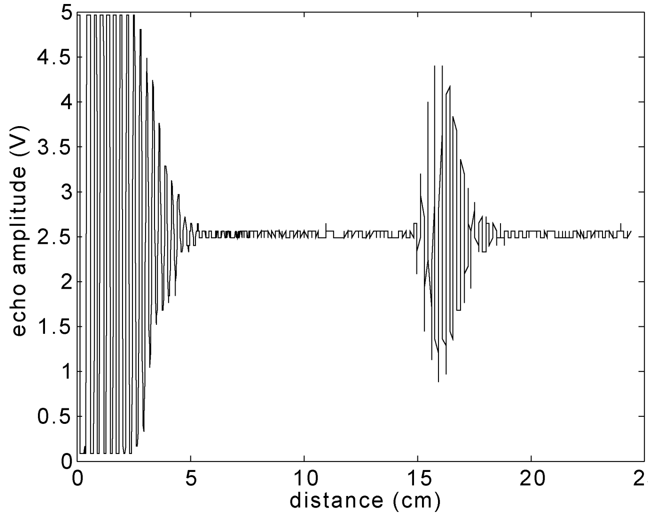

Fig. 3. Ultrasonic signal obtained with a wall at 15 cm.

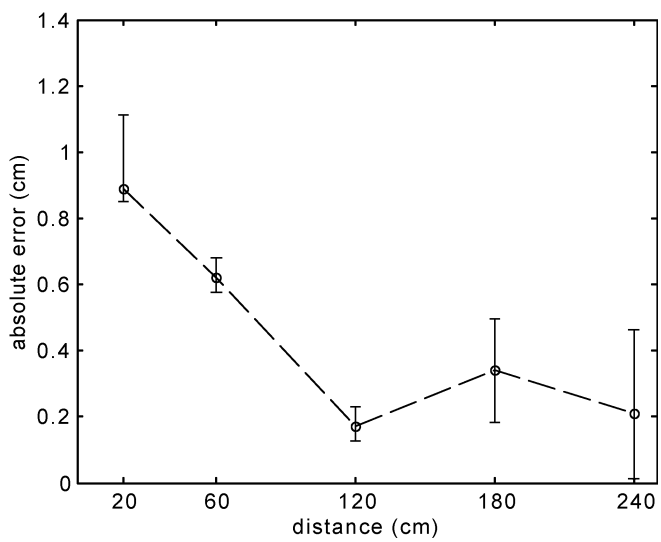

Fig. 4. Maximum, minimum, and mean absolute error after 100 measurements at selected points (laboratory temperature 24 °C).

signal (see Fig. 3). The absolute measurement error is less than 2 cm in a range from 15 to 250 cm with the modified gain-controlled driver. However, the new short-range is still too big for measurements with the robot close to a wall (or object). To solve this problem, lateral sensors were placed on the handle (12 cm inside the robot), allowing lateral measurements starting 3 cm from the robot. In addition, a temperature sensor is used to correct temperature dependence in TOF measurements [22].

In this robot, ultrasonic distance measurement is performed by time-based measurement between two edges using a microcontroller (μC). Most low-cost μC have from two to five hardware devices for time-lapse measurement, although at this stage, the time measurement for the seven sensors is implemented by software with good accuracy in the measurements (see Fig. 4). However, a dedicated hardware device will improve these results even more because our software time measurements are influenced by the hardware interruptions.

V. Motor Control

The robot has three motors. The brush motor fixes cleaning intensity and is initially controlled in an open loop by a pulse width modulation (PWM) signal. Robot mobility is obtained by two dc geared Maxon motors (12V, 73:1) placed at the back of the robot. Each motor has a Hewlett Packard digital encoder (1000 pulses per turn) for speed measurement. The driving motors are connected directly to two plastic wheels (6.8 cm diameter) with a soft central strip to avoid slippage. This configuration also reduces the mechanical twisting angle and the associated odometry errors.

Initially, a proportional integral and derivative control was planned and adjusted for motor control but, to simplify control implementation and to avoid slippage, only an integral controller is finally implemented. The control system was designed to be critically damped (Fig. 5) with a dynamic adaptation of the integral coefficients for both motors in the differential drive system. This dynamic adaptation is performed when the robot starts moving in the following manner. The initial motor speed transitions of both motors are analyzed and the maximum values are stored. These values are then compared and used for dynamic adaptation. For example, if the difference between these maximum values is bigger than two pulses (to filter some noise influence), one integral coefficient is also slightly modified in an integral manner.

The closed loop control is software based and was implemented in a μC that is less efficient than a dedicated hardware device. However, the implementation of adaptive algorithms is much simpler. Speed measurement is performed using hardware timers to count encoder pulses. The sampling period is obtained by using another internal timer, and the PWM signals are generated using dedicated internal hardware devices. The proposed integral control implemented with only shifted integer operations takes 11% of μC time (8 bits RISC/200 ns operation cycle). This time increases to 32% when a software-based floating point is used in the control loop.

In the proposed control, the sampling period T_S is 6.5 ms and the initial integral constant value for both motors K_I is 0.25. Fig. 5 shows a typical encoder transient response where the maximum encoder values are zoomed and marked with a circle.

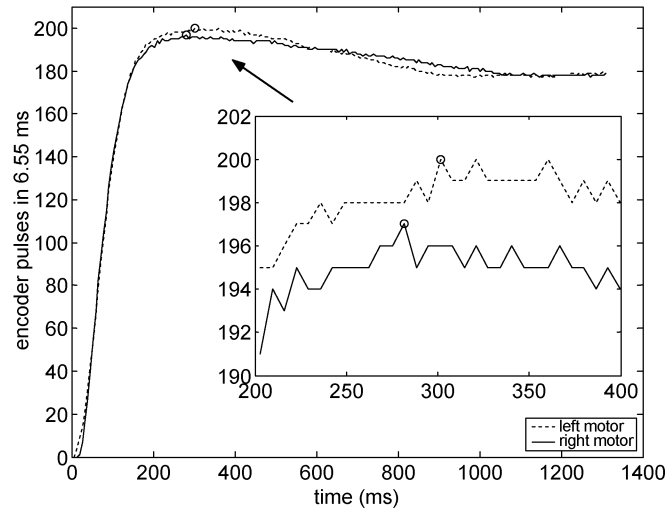

Fig. 5. Typical motors start transient. The position with the maximum encoder pulses data is zoomed.

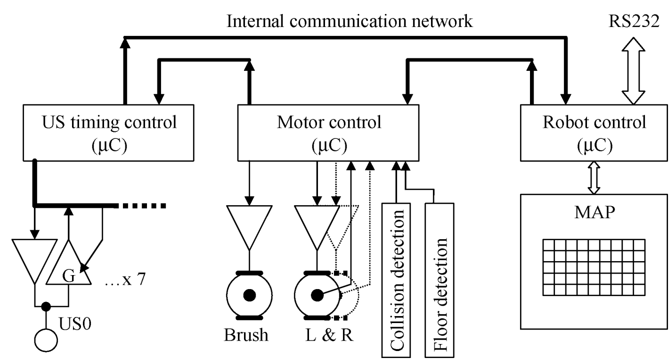

Fig. 6. Robot control diagram.

VI. Robot Control

Fig. 6 shows the proposed robot control diagram. At this stage, three standard low-cost μCs are used in the robot. It is expected that this initial design will converge to a more simplified one through the estimation of the computational requirements of the most important tasks: ultrasonic firing, path generation, robot control, and motor control. The use of several μCs in a network manner has the drawback that these low-cost devices do not usually have a big communications buffer to store the messages, so the message rate must be carefully controlled to avoid communication buffer overflow and message loss.

The robot control architecture (Fig. 6) was designed in a communications loop to minimize the message rate. The main μC (robot control in Fig. 6) generates the robot path and then sends relative movement orders to the μC that controls the motors. This second μC executes the planned movements taking care of the odometry measurements and, when the robot runs a small fixed relative distance, generates a set of messages for the μC that has to perform environment detection. Finally, ultrasonic distance measurement is then synchronized depending on the relative robot movements, and a set of messages with the relative distance run and the distances measured by the ultrasonic sensors around the robot are sent to the main μC for map generation and path planning.

The main μC is focused on the high-level coverage [23], [24] robot control. This μC has a memory bank with 256 KB available to store a map of the environment. At this stage, the memory is built using cheap I2C EEPROM devices for map reutilization, but this device has the drawback that every byte-store operation needs a 5-ms delay.

Fig. 7 shows possible robot representations in the map depending on the grid size: the brush area and the robot center of rotation are marked. The robot and scenario representation in the map could be improved by reducing grid size, but the odometry error and positioning uncertainty set a practical limitation. Two constraints must be imposed.

1) The distance from the wheel axis (center of rotation) to the brush axis must be an exact number of cells.
2) The brush length must be an odd number of cells

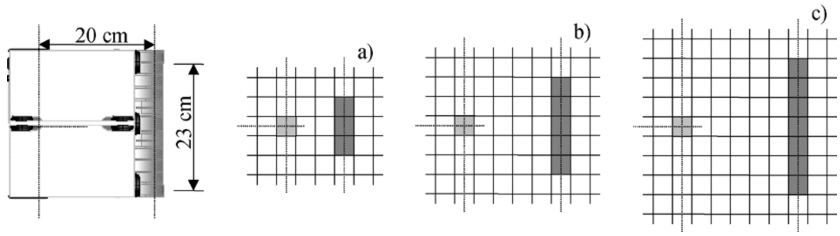

Fig. 7. Robot representations on the map depending on grid square size: a) 6.6 cm, b) 4 cm, and c) 3.3 cm.

These constraints allow robot positioning uncertainty of ± 0.5 cells in the map in both axis directions.

VII. Tests

Odometry errors are the most important problem in a robot that has to follow a long path. In this first test, the robot had to follow a straight-line path for 8 m using only the encoders of the motors in the feedback control loop. In a current even floor, the robot shows a slightly swinging trajectory along the displacement axis. In ten repetitions, the maximum lateral deflection was only -0.2 cm at 4 m and 0.5 cm at 8 m, and the maximum absolute error in the total distance was 0.3 cm. Repeating the test with the robot starting parallel to a wall and using the lateral ultrasonic sensors as a feedback trajectory control, the maximum lateral deflection error was reduced to 0.1 cm and the maximum error in the total distance was reduced to 1 cm.

Fig. 8 shows the results of a UMB test in a 4×4 m circuit using only the motor encoders for the odometry correction. When the robot runs the circuit anticlockwise; the ending position is 1 cm from the starting point. However, when the robot runs the circuit clockwise; the robot stops 7 cm from the starting point. In general, the UMB test permits reductions of odometry errors but, in this particular case, the swinging robot trajectory makes this error correction distance dependent. On repeating the UMB test on a 2, 4, 8, and 10 m square circuit, the correction for a certain distance worsens the results over other distances.

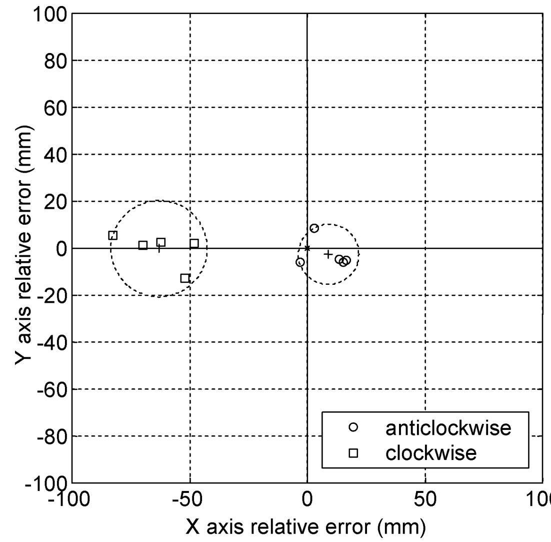

Fig. 8. UMB test results in a 4×4 m circuit.

Finally, for a small mobile robot, it is very important to have good detection skills for collision avoidance. In this test, several objects were placed at different locations in a plane in front of the robot. For this experiment, it is more important to know if the objects are detected rather than the measurement accuracy. Because of their physical location, frontal sensors can be used individually or collectively: emitting and receiving with the same sensor or using one sensor as the emitter and receiving with the three sensors. Fig. 9 shows the detection skills for the case of a cylindrical stick (2.4 cm diameter) placed at different locations in front of the robot; when the stick is detected using one sensor, its real location is marked with a circle in the figure. A cross is marked when the cylindrical stick is detected when using the three sensors as receivers. Alternatively, Fig. 10 shows the detection skills for the case of a rectangular stick (2×2 cm) with faces 45° from the sensor plane. When the stick is detected, its real position is marked with a diamond when using only one sensor and with a cross when using the three sensors as receivers. This stick orientation is the worst because of the smaller reflected sound energy. These two experiments show slight differences when receiving with one or three sensors, but the principal conclusion is that these small stick objects are always detected at least 20 cm before collision, enough distance to stop or maneuver the robot.

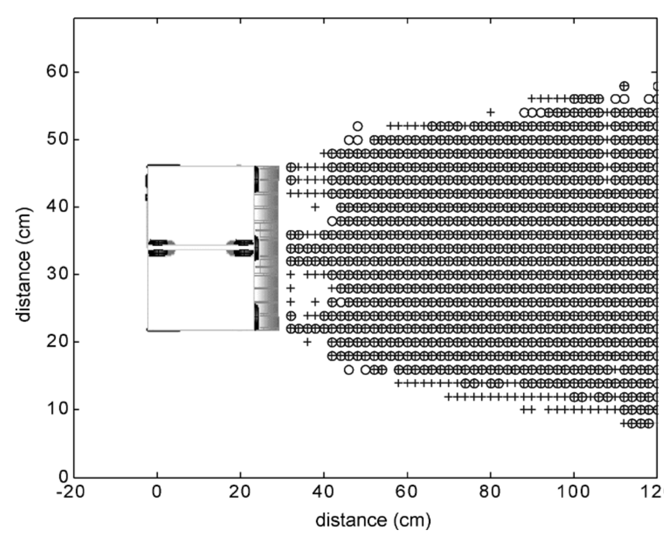

Fig. 9. Cylindrical stick detection shape. Emitting and receiving with the same sensor (circle) and receiving with three (cross).

VIII. Remarks and Conclusions

This paper describes the integrated use of different fields oriented toward the design of a complete floor-cleaning mobile robot. The design of the robot is discussed, and the compatibility between human being and cleaning robots is analyzed with the

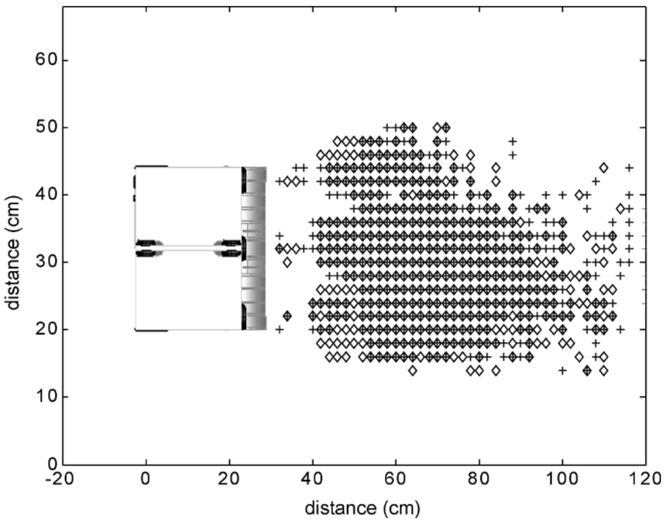

Fig. 10. Square stick detection shape. Emitting and receiving with the same sensor (diamond) and receiving with three (cross).

conclusion that robot operation can be and probably must be isolated from human beings. Alternatively, the use of passive infrared sensors in cleaning robots is proposed for safety considerations.

In this design a new procedure for battery recharge operation is proposed to reduce user interaction with the robot.

A new gain-controlled ultrasonic driver is proposed to allow distance measurements starting at 15 cm. Tests show a high degree of accuracy, while the detection of small sticks near the robot is also guaranteed.

The odometry results presented in this paper were obtained using one demonstration robot, and thus no generalization can be directly assumed for hypothetical industrial production. Nevertheless, the results for this particular action show low odometry errors using only the motor encoders in the feedback loop, but the twisting robot trajectory hides possible systematic odometry errors. However, these errors can be minimized when an external reference can be used as a trajectory feedback, thus making this robot an ideal platform for the implementation of sensor-based coverage algorithms for cleaning applications.

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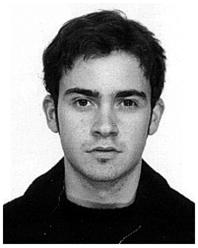

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