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A Study on Intelligent Control of Mobile Robot with Ultrasonic Sensors

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Abstract: We present a new technique to autonomous navigation based on ultrasonic sensors for mobile robots traveling through the narrow aisle that leave only a few centimeters on each side between the guides and the robot. In our current implementation the ultrasonic sensor system fires at a rate of 100 ms, that is, each of the 8 sensors fires once during each 100 ms interval. This is a very fast firing rate, implemented here for optimal performance. This paper presents an extensively tested and verified solution to the problem. Our solution is based on the optimal placement of ultrasonic sensors at strategic locations around the robot. Both the sensor location and the associated navigation algorithm are defined in such a way that only the accurate radial sonar data is used for servoing.

Keywords: Ultrasonic sensors, Mobile robot, Obstacle avoidance.

1. INTRODUCTION

Our approach to narrow-aisle navigation is based on ultrasonic sensors. A comprehensive discussion of the characteristics and limitations of these sensors can be found in the literature and is omitted here. This paper describes an experimental obstacle avoidance system for mobile robots traveling through the narrow aisles of a warehouse.

Potential fields tend to blur individual range measurements by lumping them together into a single steering vector. By contrast, in narrow aisle navigation great accuracy is required for servoing in the immediate vicinity of guides and for the critical phase of entry into a narrow aisle.

The aisles are 55 cm wide while the robot has a width of 30 cm and a length of 48cm, but our method is generally applicable to a large class of narrow aisle navigation applications. Our robot, called HLOROBO, serves as a tested for the development of obstacle avoidance methods. Upon completion of this development, HLOROBO obstacle avoidance system will be implemented on HLOROBO, a much more sophisticated mobile robot currently under development at the Savannah River Technology Center. HLOROBO will be employed to traverse long aisles between stacks of 36-gallon steel drums, which are stored on forklift pallets as shown in Fig. 1.

When traveling in narrow aisles that leave only a few centimeters on each side between the guides and the robot (about 12 cm in our application), a measuring accuracy on the order of 1-2 cm is necessary for smooth servoing along the center of the corridor. The reasons are that the ultrasonic sensors are not suitable for narrow aisle navigation because of their poor angular accuracy.

For example, the widely used Polaroid ultrasonic sensors have a 15 radial accuracy of about 0.5 cm for short distances, but, with a 30 emission cone, the angular accuracy is extremely poor.

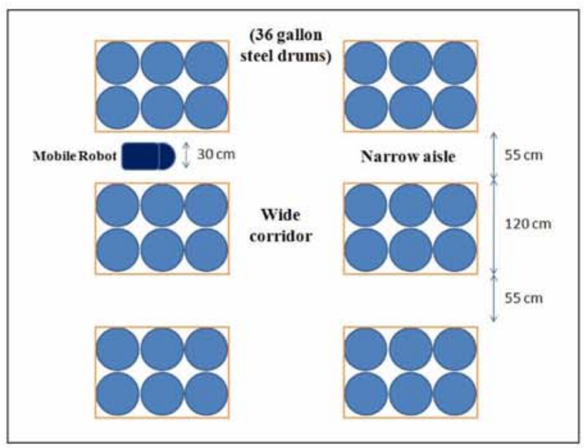

Figure 1: The drums are stacked up on wooden forklift pallets. The HLOROBO moves thought of 55 cm wide aisles among long rows of 36 gallon steel drums.

In general purpose obstacle avoidance methods there is no need for accurate measurements, because most systems are designed to respond to clusters of readings that indicate the existence of an object in a certain area of the world model. This is also evident in the great popularity of potential field-based obstacle avoidance systems. Conventional "general-purpose" obstacle avoidance systems usually surround the robot with a ring of ultrasonic sensors installed at 15° intervals. For

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omnidirectional robots of circular o shape, this design requires 360º/15º = 24 sensors mounted on a ring around the robot. Similar designs using 24 sensors in 15º intervals are described in the literature.

This paper presents an extensively tested and verified solution to the problem. Our solution is based on the optimal placement of ultrasonic sensors at strategic locations around the robot. Both the sensor location and the associated navigation algorithm are defined in such a way that only the accurate radial sonar data is used for servoing.

2. THE DESIGN OF SENSOR SYSTEM

The sensors are located on HLOROBO as shown in Fig. 2.

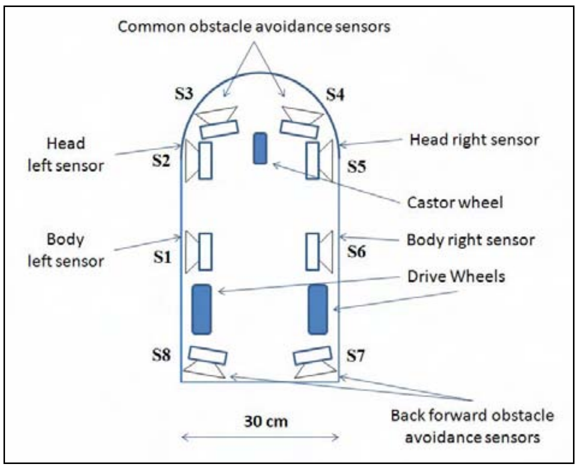


Figure 2: Location of the ultrasonic sensors

The purpose of sensors S1 and S6 is to show if there is an aisle or corridor opening at either side of the robot. Sensors S3 and S4 are used for simple obstacle detection. Sensors S7 and S8 are also used for simple obstacle detection on back forward moving.

However, the most important sensors in this robot are the sensors S2 and S5, because they offer several important benefits, especially for the purpose of servoing along the center line of the narrow aisles, it is of great benefit to be able to measure (and therefore know) the locus of the aisle's center line before the HLOROBO's body gets there.

The ultrasonic sensors are located on HLOROBO fire at a rate of 100 ms, that is, each of the 6 sensors fires once during each 100 ms interval. This is a very fast firing rate, implemented here for optimal performance. We believe that slower firing rates would also work, because all sensor-triggered critical decisions are made after the vehicle slowed down in anticipation of a critical decision.

Our ultrasonic sensor system is based on the widely used ultrasonic transducers from Polaroid, together with the standard Polaroid circuit boards. Since the minimum range of these sensors (41 cm) is not suitable for our application, we have added to each board a custom circuit that allows a minimum range of 7-10 cm (the exact range varies as a function of temperature and other external factors). The principle of operation for this modification circuit is described in the documentation that accompanies each Polaroid system.

All sensors are mounted at a height h = 10 cm, which assures that their center, is at the same height as the upper horizontal edge of the forklift pallets (see Fig. 3). Since the sensors measure the distance to the closest object, they will "see" the pallet most of the time (Fig. 3a). However, if a drum protrudes by a few inches (as is expected in our application), then the sonars will "see" the protruding part of the drum (Fig. 3b).

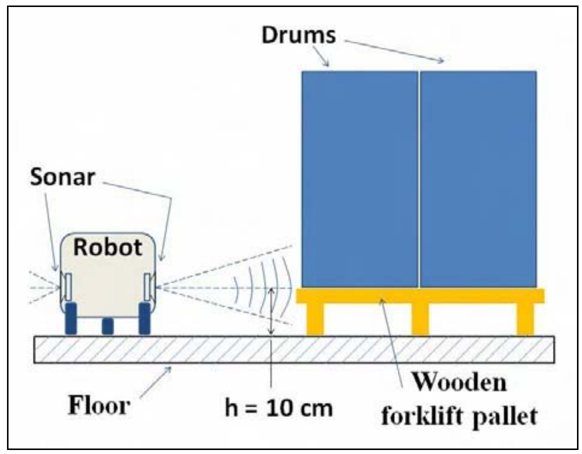


Figure 3: Ultrasonic sensors are mounted at the same height as the upper horizontal edge of the pallets.

3. MOTION CONTROL

In this paper we discuss four basic motion components were the focus of our research work, because in our application only these components needed to be automated. These basic components allow the robot to travel continuously and perform routine inspections. The other remaining components represent transient conditions that are out of this research and may be needed only rarely.

These characteristics are:

1. Travel along the centerline of a narrow aisle.
2. Turn out of an aisle and into a corridor (90°).
3. Driving in a main corridor, looking for the next aisle
4. Turn into an aisle after traveling in a main corridor.

Before discussing in detail, some frequently used terms should be defined:

"*Guide*" — Any physical obstruction alongside the desired direction of travel. In the HLOROBO application, Guides usually consist of 36 gallon drums standing on wood pallets. The drums are expected to be flush with the horizontal edge of the pallet, or they may protrude or be recessed by up to 10 cm. Since the snares are mounted at the same height as the horizontal edge of the pallets, they will "see" the horizontal edge of the pallet in-between drums, if a drum is missing (but the pallet is there), or if a drum is recessed. Alternatively, if as drum protrudes beyond the horizontal edge of the pallet, the sonars will "see" the protruding part of the drum (subject to limitations of specula reflections).

"*No-Guide*" — A name for ultrasonic range readings that are larger than a certain threshold.

Readings larger than this threshold are interpreted as "there is no *guide*;" readings smaller than (or equal to) this threshold are interpreted as "there is a *guide*." The *no-guide* (NG) value is computed such that they represent the largest range possible within the aisle. For the body sensors:

$$NG_C = L_{\max} - \frac{1}{2}W_{TRC} - D_C = 65 - \frac{30}{2} - 15 = 35cm$$

For the head sensors:

$$NG_H = L_{\max} - \frac{1}{2}W_{TRC} - D_H = 65 - \frac{30}{2} - 13 = 37cm$$

where:

$L_{\max} = 65$ cm	~	Maximal aisle width
$W_{TRC} =$ 30 cm	~	Width of HLOROBO base
$D_C =$ 15 cm	~	Distance between Body sonar and longitudinal center of HLOROBO base
$D_H =$ 13 cm	~	Distance between Head sonar and longitudinal center of HLOROBO base

3.1 Travel along the center line of a narrow aisle.

The velocity variation:

a. Acceleration for L_0 = 24 cm (i.e., the first 24 cm in the beginning of motion)

b. The end of strategy is verified by three consecutive readings of both the head and the body sonars. All six readings must exceed the no-guide threshold before the robot begins the "Turn out of an aisle and into a corridor (90°)" motion component. This prudent strategy is feasible because of the deceleration phase described in (c) as follows.

c. Deceleration is invoked when the head sonar (of the side around which the next rotation is pending) "sees" no-guide as shown in Fig. 4. Deceleration for the longitudinal distance between the head and body sonars: L_{FC} = 24 cm. The main benefit of this deceleration phase (other than smooth motion) is that the robot speed is very low when the body sonar reaches the edge of the aisle. Therefore, the body sonar's reading that is tested for the exit condition can be verified by taking multiple readings. Taking multiple readings at the vehicle's normal operating speed might take relatively long and allow the robot to exit too far out of the aisle before the exit condition is confirmed.

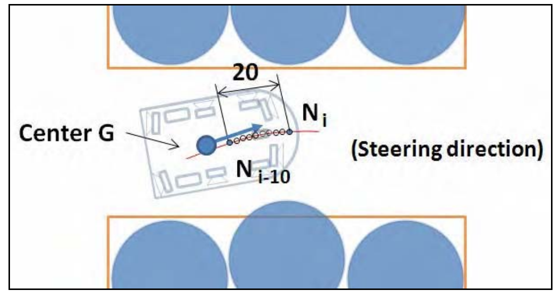


Figure 4: The robot measures the width of the aisle every one centimeter and computes the locus of the center point N_i. N_i is temporarily stored and, 10 intervals (= 10 cm) later, used as the momentary target point for steering.

Control Methods:

Range measurements from the head sensors are used to determine the absolute coordinates of the center of the aisle *N*. At a speed of 10 cm/sec and a firing rate of 100 ms, a new center point N_i can be computed at intervals of 100 msec × 10 cm/sec = 1 cm of travel. N_i is then stored in a ring buffer that holds 10 elements. This way, the newest element in the buffer is the present $N_{i=1}$ and the oldest element is N_{i-10} (i.e., 10×1 cm = 10 cm behind N_i). The control algorithm distinguishes among different states:

a. During steady-state, the motor controller controls the speed of the motors such that HLOROBO's center point G aims at N_{i-10} (i.e., at a point that is 10 cm behind N_i).

b. During the first 10 cm of travel, N_{i-10} has not been computed yet. During this transient distance the speed of the motors is controlled such that HLOROBO's center point G aims at the oldest existing *N* (i.e., N_1). Steady-state is reached when $i > 11$, and Control Methods (a) goes into effect.

Robot will not continue moving if either first or second condition appears:

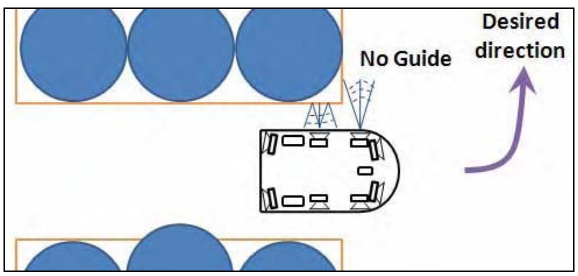
a. Aisles are too narrow

If an object is close to a side of the aisle but small enough to allow passage, then either it will be detected by sensors S3 and S4 as an obstacle, or it will be treated as a legitimate protrusion of the *guide*. In the latter case, HLOROBO measures and computes the exact width of the remaining opening and compares it with a threshold for the minimum allowable aisle width, which is 45 cm in our application. If the measured width is above the threshold, HLOROBO will continue and plot its path along the center between the protrusion and the other *guide*. If the measured width is below the threshold, HLOROBO stops and notifies the operator.

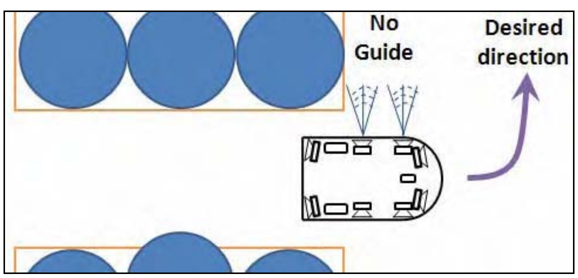
b. An obstacle is detected in the robot's path

If either of the two obstacle detection sensors (S3 and S4 in Fig. 2) detects an obstacle ahead of the robot, HLOROBO stops. Unlike in most common obstacle avoidance systems, in our application there is no point in trying to circumnavigate an obstacle: if an obstacle is present in a narrow aisle, then the aisle blocked. At this time the system may alert the operator or maneuver backward out of the aisle, depending on the application.

3.2 Turn out of an aisle and into a corridor (90°).



(a)



(b)

Figure 5: HLOROBO begins to decelerate and to turn when the head side sensor "sees" no-guide (a), and when both of the head & body sensors "see" no-guide (b).

Control Methods:

The controller computes and maintains motor velocities so that the robot turns around a center of rotation 'C' about 90° (see Fig. 6). In our application 'C' is located on the outer perimeter of the robot. Rotation about 'C' guarantees that HLOROBO will not collide with either one of the guides of the aisle out of which the robot is exiting.

Robot stops if an obstacle in the robot's path is detected.

This strategy will complete if:

a. According to direction of rotation, either head right sensor or head left sensor measure a range of

$$R_F \leq \frac{1}{2}W_{TRC} - D_F + C_W = 65 - \frac{30}{2} - 12 = 38cm$$

where

C_W: Arbitrarily chosen reference steady-state distance between the HLOROBO side and the corridor side of the guide.

b. The rotation of 95^0 is completed. This exit condition is to serve as a safeguard if the primary exit condition (above) fails.

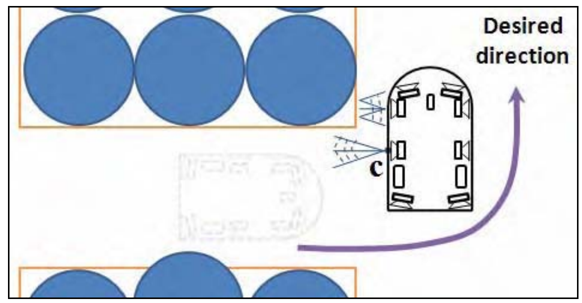


Figure 6: HLOROBO rotates around point C until the end of strategy is met.

3.3 Driving in the main corridor, looking for the next aisle

The velocity variation

This motion component comprises of driving through a short distance of roughly straight-line motion along the short side of a rectangular pallet/drum *guide*, until the next aisle is encountered.

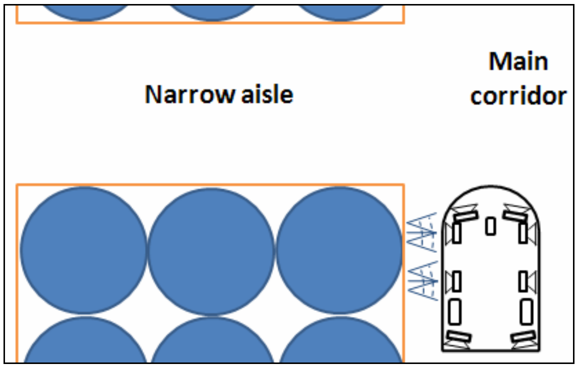
Control Methods:

This motion component has two distinct control strategies. Strategy (a) governs the motion while the body sonar of the robot that is facing the guide "sees" the guide. This condition is shown in Fig. 7a. Strategy (b) governs the motion while the head sensor "sees" no-guide, as shown in Fig. 7b. Both strategies are described in more detail below.

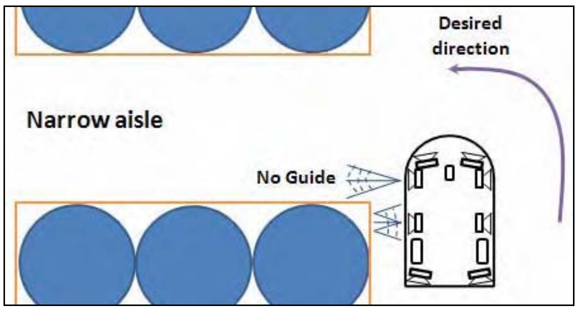
a. The short side of the rectangular pallet/drum guide has the width of two rows of drums that is 2 × 60 cm = 120 cm.

b. When both the head and body sonar's reaches beyond the edge of the next aisle, the robot stops and prepares to turn in an aisle.

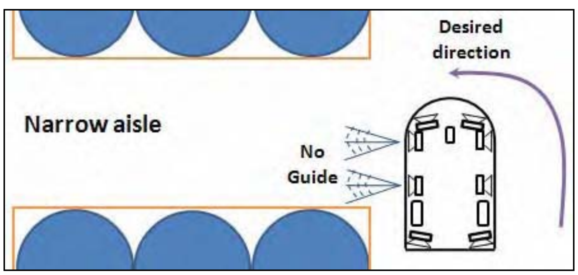
Robot will stop if an obstacle in the robot's path is detected. If both of head sonar and body sonar sees no-guide, that's reason for the end of strategy.



(a)



(b)



(c)

Figure 7: HLOROBO traveling along the short side of a drum/pallet guide: When body sensor "sees" no-guide the robot is stop and then turn into the next aisle.

3.4 Turn into an aisle after traveling in a main corridor.

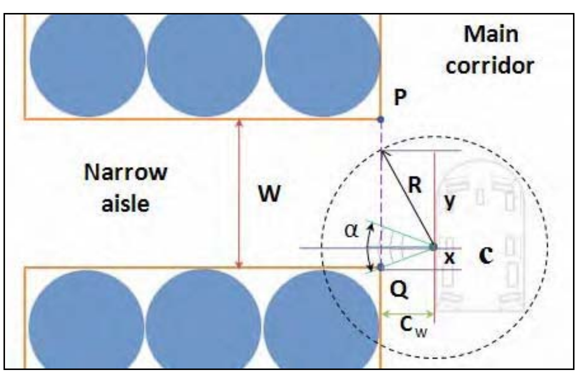


Figure 8: The geometry progressive just prior to turn into an aisle after traveling in a main corridor.

Control Methods

"Turn into an aisle after traveling in a main corridor" is the most critical motion component, because it is the motion during which a collision is most likely. Conventional solutions aim at measuring the location of corner points A and Q and computing a path between these two points. The technical difficulty with such an approach lies in the difficulty of locating point Q precisely, especially when the robot approaches from the direction shown in Fig. 7. Our method differs from conventional ones in that it does not require any sensor-derived measurements of point Q and it requires only vague measurements of point P. To understand how our method works we have to recall some characteristics of the previous motion component are as follows.

During the "travel in a corridor looking for a new aisle" motion the robot tried to maintain a certain distance C_w = 10 cm from the narrow side of the guide, the robot is aligned in parallel with the narrow side of the *guide* when exiting that motion. Upon exiting, the robot's drive axis must necessarily be beyond P, because the body sensor, located exactly along the drive axis, is already "looking" into the aisle. Therefore, a 90º rotation around point 'C' is guaranteed not to collide with corner P. This approach does not consider point Q at all, but it will work as long as the narrow aisle is "sufficiently" wide. Just how much is "sufficient" depends on the geometry and dynamics of the robot, as well as on the ultrasonic properties of the sensors and the environment.

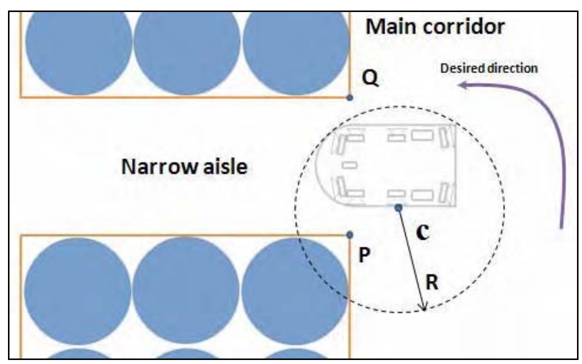


Figure 9: HLOROBO is turning into a narrow aisle

Let us assume the ideal condition, in which the robot is aligned in parallel to the short side of the *guide* and travels at the desired distance C_w = 12 cm from the *guide*. Let us further assume that there are no delays in the sonar measurements and that the sonar emission cone is exactly α =30 wide, as shown in Fig. 8. under these ideal conditions the body sensor located at point 'C' in Fig. 8 will see *no-guide* at the moment when the axis of the robot has advanced a distance x beyond the corner of the *guide* P. In the subsequent rotation around 'C' no part of the robot will protrude outside a circle of radius R, as shown in Fig. 8. Note that R is only a function of the geometric properties of the robot; for HLOROBO we measured R = 46 cm. From the geometry of Fig. 8 we can now derive that the condition $W > x + y$ will guarantee collision-free turning into the aisle. It is easy to see from Fig. 8 that $x = C_W tg(\alpha / 2)$ and that $y = \sqrt{R^2 - C_W{}^2}$ so that the condition for collision free turning becomes

$$W > \sqrt{R^2 - C_W{}^2} + C_W tg(\frac{\alpha}{2})$$

Substituting the numeric values of our application into the above equation, we assume:

$$W > \sqrt{46^2 - 12^2} + 12tg(\frac{30^0}{2}) = 48cm \quad (1)$$

The result of Eq. (1) shows that *theoretically* the robot could safely enter any aisle of width W > 48 cm. In practice, of course, there are significant delays to consider. For example, it is not guaranteed that the body sensor is sampled at exactly the position shown in Fig. 8. Furthermore, for reliable operation it is necessary not to act immediately on the first *no-guide* reading from the body sensor, but rather to take multiple readings (three, in our application) for verification. Multiple readings, of course, introduce further delays. On the other hand, we recall the robot decelerates as soon as the head sensor sees *no-guide*, and that therefore the robots speed is very slow when these delays are incurred. In our experiments we found that the delays (caused by the three readings taken for verification of the end of strategy) equate to only 1-2 centimeters of travel. At a slower firing rate, for example at 200 ms, proportionally longer delays can be expected.

4. EXPERIMENTAL RESULTS

Our experimental vehicle - HLOROBO, shows in Fig. 10, is equipped with 8 Polaroid ultrasonic sensors, which we customized for short range measurements (8-10 cm), the two sizeable loud speakers output computer-generated speech from the on-board audio board. Spoken text during demos and debugging sessions is useful to explain what the robot is doing at key decision points, without forcing the observer to direct his or her attention to a computer monitor and to wait for written explanations to show up on the screen.

This approach emphasizes the importance of the optimal location of the sonar to achieve extremely reliable and robust performance. Most successfully implemented conventional general purpose obstacle avoidance algorithms rely on a statistical interpretation of the often inaccurate sonar range data. Because of the statistical uncertainty inherent in these systems they cannot avoid occasional collisions, especially when navigating in narrow aisles or doorways. By contrast, the algorithm presented in this paper has been shown to cope reliably and repeatable with narrow aisles and narrow-aisle entry, even under changing conditions.

Figure 10: The image of the HLOROBO.

5. CONCLUSIONS

We have proposed a new technician based on ultrasonic sensors for narrow aisle passing. We have presented an extensively tested and verified solution to the problems. Our solution is based on the optimal placement of ultrasonic sensors at strategic locations around the robot. Both the sensor location and the associated navigation algorithm are defined in such a way that only the accurate radial sonar data is used for servoing.

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