ANS 6th Topical Meeting on Robotics and Remote Systems," Monterey, California, February 5-10, 1995.

MOBILE ROBOT NAVIGATION IN NARROW AISLES WITH ULTRASONIC SENSORS

Johann Borenstein
The University of Michigan
Advanced Technology Lab
Ann Arbor, MI 48109
313-763-1560;fax 944-1113
johannb@umich.edu

David Wehe
The University of Michigan
Cooley Lab
Ann Arbor, MI 48109
313-764-5225;fax 763-4540
david_wehe@um.cc.umich.edu

Liqiang Feng
The University of Michigan
Advanced Technology Lab
Ann Arbor, MI 48109
313-936-9362;fax 763-1260
Feng@engin.umich.edu

Yoram Koren
The University of Michigan
G. G. Brown Bldg.
Ann Arbor, MI 48109
313-936-3596;fax 747-3170
yoram_koren@um.cc.umich.edu

ABSTRACT

This paper describes an experimental obstacle avoidance system for mobile robots traveling through the narrow aisles of a warehouse. In our application the aisles are 91 cm (36") wide and the robot has a width of 64 cm (25"), but the method described here is generally applicable to a large class of narrow-aisle navigation applications.

Our approach is based on the carefully designed placement of ultrasonic sensors at strategic locations around the robot. Both the sensor location and the associated navigation algorithms are designed in such a way that whenever accurate range data is needed (e.g., for servoing) a sensor is located so that its accurate radial measurements provide the required data.

I. INTRODUCTION

This paper describes an experimental obstacle avoidance system for mobile robots traveling through the narrow aisles of a warehouse. In the particular application discussed here the aisles are 91 cm (36") wide while the robot has a width of 64 cm (25"), but our method is generally applicable to a large class of narrow-aisle navigation applications. Our robot, called SWAMI Jr., is based on the TRC *LabMate* platform [16] and serves as a testbed for the development of obstacle avoidance methods. Upon completion of this development, SWAMI Jr.'s obstacle avoidance system will be implemented on SWAMI, a much more sophisticated mobile robot currently under development at the Savannah River Technology Center. SWAMI will be employed to traverse long aisles between stacks of 55-gallon steel drums, which are stored on forklift pallets as shown in Fig. 1.

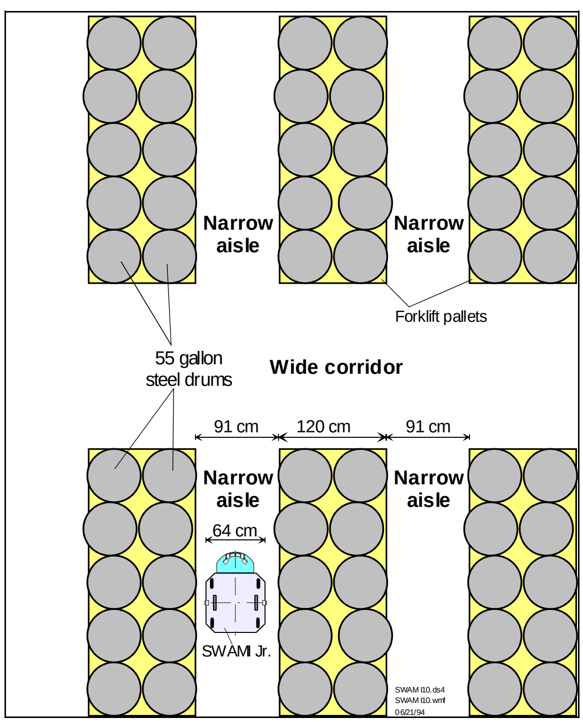

Figure 1: The work environment for SWAMI comprises of 91 cm wide aisles among long rows of 55 gallon steel drums. The drums are stacked up on wooden forklift pallets.

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 [1,5,9,11,12].

Conventional "general-purpose" obstacle avoidance systems usually surround the robot with a ring of ultrasonic sensors installed at 15^o intervals. For omnidirectional robots of circular shape, this design requires 24 (=$360^o/15^o$) sensors mounted on a ring around the robot. Similar designs using 24 sensors in 15^o intervals are described in the literature [2,6,7,8,1013,14]. 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. 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 walls and for the critical phase of entry into a narrow aisle.

At first glance one might suspect that ultrasonic sensors are not suitable for narrow aisle navigation because of their poor angular accuracy. For example, the widely used POLAROID ultrasonic sensors[15] have a radial accuracy of about 0.5 cm for short distances, but, with a 30^o emission cone, the angular accuracy is extremely poor. Yet, when traveling in narrow aisles that leave only a few centimeters on each side between the walls and the robot (about 14 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 problem is further exacerbated by the fact that the POLAROID sensors have a nominal minimum range of 41 cm

(16"): any object closer than 41 cm will be shown at a range of 41 cm or sometimes at unpredictable ranges above 41 cm (for example, if the echo is reflected back and forth twice). Although this minimum range can be reduced to about 20 cm (8")[a] with custom designed circuitry, it is clear that even the modified sensors, if mounted on the sides of the robot, cannot be used for servoing in a narrow aisle because the sensors will show the minimum range of 20 cm most of the time.

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.

This paper is structured as follows: Section II describes the sensor system in greater detail. Then, in Section III we discuss our algorithm. This algorithm comprises of four basic *motion components* for narrow aisle navigation: (1) driving inside an aisle, (2) turning out of an aisle, (3) driving inside a corridor, and (4) turning into an aisle. Section IV presents experimental results and Section V summarizes our conclusions.

II. THE ULTRASONIC SENSOR SYSTEM

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 15-20 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. The sensors are located on SWAMI Jr. as shown in Fig. 2.

All sensors are mounted at a height h = 12.5 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).

The interesting feature of the design in Fig. 2 is the forward-mounted sensor tray with sideways "looking" sensors #3 and #6. These two sensors are the most important ones of the system, because they are the only sensors that provide radial (and therefore accurate) measurements for servoing the robot during straight-line motion. The sensor tray and the forward location of sensors #3 and #6 offers several important benefits:

1. The sensors are recessed from the largest width of the robot by about 20 cm. Thus, even if the vehicle is as close to a wall as physically possible, theses sensors will still provide valid readings (in spite of the minimum distance constraint of the POLAROID sensors). By contrast, sensors #1 and #8 cannot be used for servoing, because most of the time they would be closer to walls than their minimum measuring distance allows.

2. Since the sensor tray is narrower than the robot body, SWAMI Jr. can "stick its nose" into an aisle ahead of the wider vehicle body, thereby greatly reducing the risk of collision. Our algorithm makes extensive use of this feature in the "enter into an aisle" motion component.

3. 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 wider vehicle body gets there. In the SWAMI Jr. design this preview distance is 20 cm. This ahead-of-time knowledge of

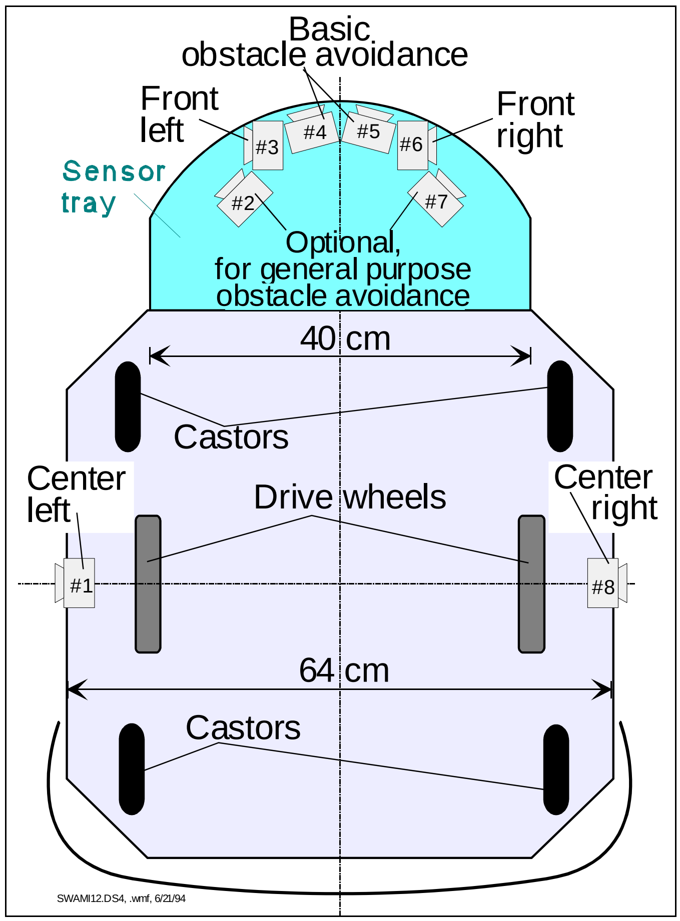

Figure 2: Most of SWAMI Jr's ultrasonic sensors are located on a forward-mounted sensor tray. Only sensors #1, #3, #6, and #8 are needed for narrow aisle navigation.

[a] A modified ultrasonic sensor system is commercially available from TRC. This system is said to have a minimum range of 7.5 cm (3").

the desired locus allows for very smooth control, especially if objects protrude into the vehicle's path.

The purpose of sensors #1 and #8 is to show if there is an aisle or corridor opening at either side of the robot (see detailed explanation in Section III). Sensors #4 and #5 are used for simple obstacle detection, and sensors #2 and #7 can be used for general-purpose obstacle avoidance outside of narrow aisle. During regular narrow aisle navigation as described below, sensors #2 and #7 are not needed.

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.[3,4] We believe that slower firing rates would also work, because all sensor-triggered critical decision (see discussion in Section 3) are made after the vehicle slowed down in anticipation of a critical decision.

III. THE MOTION COMPONENTS

In a preliminary analysis of narrow aisle navigation we found that seven distinct motion components can be distinguished. These components are:

1*. Driving inside an aisle
2*. Turning out of an aisle
3*. Driving in a main corridor, looking for the next aisle
4*. Turning into an aisle
5. Driving in main corridor, passing and skipping aisles
6. Driving in narrow aisle, passing and skipping a narrow corridor
7. Bringing the robot into a suitable position to start narrow aisle navigation

In the present paper we discuss only the first four components (marked with an asterisk). These 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 remaining components represent transient conditions that are needed only rarely.

Before we begin the discussion in detail, some frequently used terms should be defined.

<u>Definitions</u>

"*Wall*" — Any physical obstruction *alongside* the desired direction of travel.

In the SWAMI application, *walls* usually consist of 55 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 sonars 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 specular reflections).

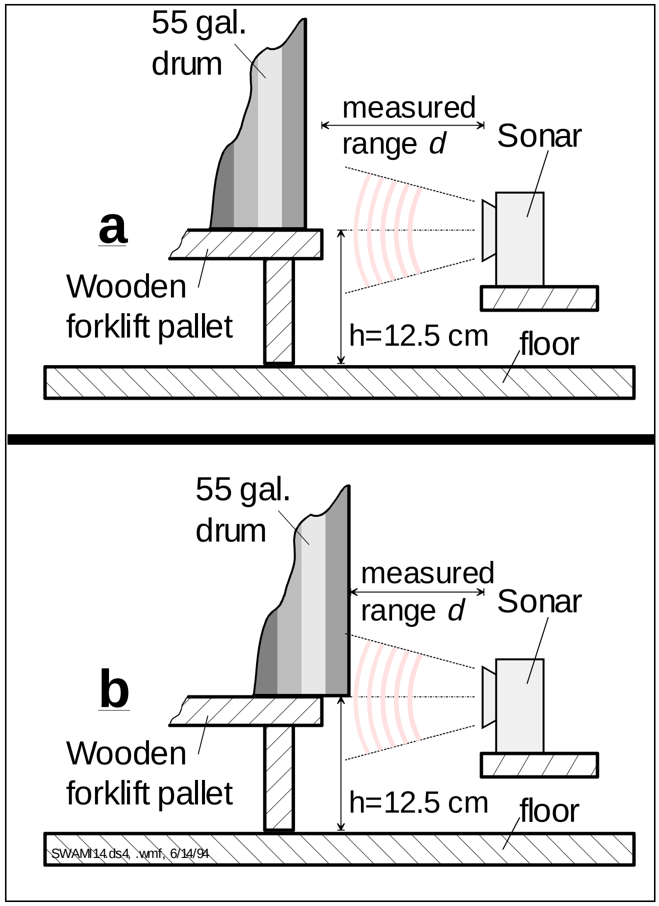

Figure 3: All ultrasonic sensors are mounted at the same height as the upper horizontal edge of the pallets.

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

Readings larger than this threshold are interpreted as "there is no *wall*;" readings smaller than (or equal to) this threshold are interpreted as "there is a *wall*." The *no-wall* (NW) threshold differs for front and center sonars, but the two threshold values (NW_F and NW_C, respectively) can be determined easily from the geometric conditions in the aisle. Both *NW* values are computed such that they represent the largest range possible within the aisle.

The threshold for NW_F is derived for the front sensors as:

$$NW_F = L_{max} - ½W_{TRC} - D_F = 100 -64/2 - 11 = 57 \text{ cm} \qquad (1)$$

and for the center sensors as

$$NW_C = L_{max} - ½W_{TRC} - D_R = 100 -64/2 - 32 = 36 \text{ cm} \qquad (2)$$

where

L_{max} = 100 cm - Maximal aisle width

W_{TRC}	=	64 cm	-	Width of SWAMI Jr. base
D_F	=	11 cm	-	Distance between front sonar and longitudinal center of SWAMI Jr. base
D_C	=	11 cm	-	Distance between center sonars and longitudinal center of SWAMI Jr. base

A. Driving Inside an Aisle

Description:
Travel along the center line of a narrow aisle.

Control Strategy:
Range measurements from the front sensors are used to determine the absolute coordinates of the center of the aisle M. At a speed of 20 cm/sec and a firing rate of 100 ms, a new center point M_i can be computed at intervals of 100 msec × 20 cm/sec = 2 cm of travel. M_i is then stored in a ring buffer that holds 10 elements. This way, the newest element in the buffer is the present $M_{i=1}$ and the oldest element is M_{i-10} (i.e., 10×2 cm = 20 cm behind M_i). The control algorithm distinguishes among different states:

a. During steady-state, the motor controller controls the speed of the motors such that SWAMI Jr.'s center point C aims at M_{i-10} (i.e., at a point that is 20 cm behind M_i).

b. During the first 20 cm of travel, M_{i-10} has not been computed yet. During this transient distance the speed of the motors is controlled such that SWAMI Jr.'s center point C aims at the oldest existing M (i.e., M_1). Steady-state is reached when $i > 11$, and control strategy (a) goes into effect.

Exception handling:

a. *Stop if an obstacle is detected in the robot's path*
If either of the two obstacle detection sensors (#4 and #5 in Fig. 2) detects an obstacle ahead of the robot, SWAMI Jr. 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 an 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.

b. *Aisle is 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 #4 and #5 as an obstacle, or it will be treated as a legitimate protrusion of the *wall*. In the latter case, SWAMI Jr. measures and computes the exact width of the remaining opening and compares it with a threshold for the minimum allowable aisle width, which is 75 cm in our application. If the measured width is above the threshold, SWAMI Jr. will continue and plot its path along the center between the protrusion and the other *wall*. If the measured width is below the threshold, SWAMI Jr. stops and notifies the operator.

c. *Either one of the two front sonars sees* no-wall

This condition is most likely not an exception, but rather an indication that the robot has reached the end of the aisle. However, it is possible that this condition is caused by a temporary discontinuity in the aisle *walls*. For example, a piece of one of the wooden pallets may be broken off underneath a drum just where the drum's surface produces a specular reflection. Another likely cause for this exception is the situation where the left and right *walls* do not have exactly the same length (i.e., when the robot exits from an aisle). In either case, the algorithm reacts to this condition as follows:

1. The robot begins to decelerate (see Refinements, below) in anticipation of a pending exit from the aisle. If the exception turns out to be only temporary (i.e., it is not the end of the aisle), the robot will simply resume its nominal speed — the temporary deceleration caused no harm and is usually not noticeable at all.

2. The normal "drive inside an aisle" controller determines the center of the aisle from the distances to both *walls*. In order to provide this information, even if one of the front sensors sees *no-wall*, the missing information is interpolated from the average of earlier range readings that were gathered while driving through the same aisle.

Exit Condition:
Front sonar AND center sonar (of the side around which the next rotation is pending) see *no-wall*.

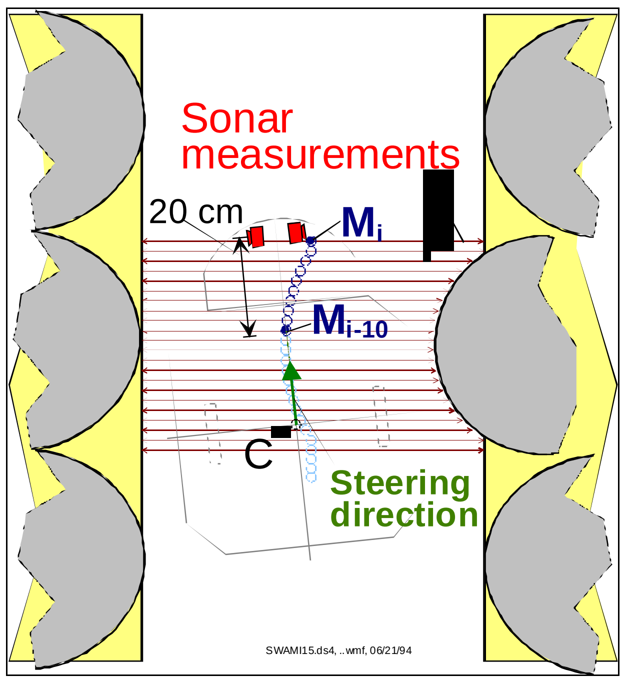

Figure 4: Every two centimeters the robot measures the width of the aisle and computes the locus of the center point M_i. M_i is temporarily stored and, 10 intervals (= 20 cm) later, used as the momentary target point for steering.

Refinements:

a. Acceleration for L_0 = 40 cm (i.e., the first 40 cm in the beginning of motion)

b. Deceleration for L_{FC} = 40 cm, where L_{FC} is the longitudinal distance between the front and center sonars. Note that deceleration is invoked when the front sonar (of the side around which the next rotation is pending) "sees" *no-wall* as shown in Fig. 5. The main benefit of this deceleration phase (other than smooth motion) is that the vehicle speed is very low when the center sonar reaches the edge of the aisle. Therefore, the center 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. By contrast, because of the deceleration phase the robot's speed is down to roughly 1/10th of its operating speed at the time the vehicle exits from the aisle, which allows the robot to take three verification readings within less than 1 cm of travel.

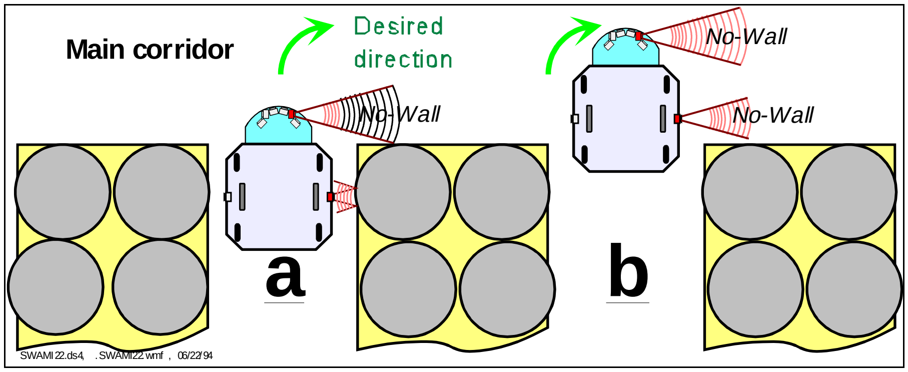

Figure 5:
a. When the front sensor of the side around which the next rotation will take place sees *no-wall*, the vehicle begins to decelerate in anticipation of the pending turn.
b. When the center sensor sees *no-wall*, SWAMI Jr. begins to turn.

c. The exit condition is verified by three consecutive readings of both the front and the center sonars. All six readings must exceed the *no-wall* threshold before the robot begins the "turning out of an aisle" motion component. This prudent strategy is feasible because of the deceleration phase described in (b) above.

B. Turning Out of an Aisle

Description:

Turn out of an aisle and into a corridor (the amount of rotation is usually 90°).

Control Strategy:

The controller computes and maintains motor velocities so that the robot turns around a pre-programmed center of rotation 'O' (see Fig. 6). In our application 'O' is located on the outer perimeter of the robot. Rotation about 'O' *guarantees* that SWAMI Jr. will not collide with either one of the walls of the aisle out of which the robot is exiting.

Exception handling

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

Exit condition:

a. Front-side sensor (either right or left, according to direction of rotation) measures a range of

$$R_F \leq ½\, W_{TRC} - D_F + D_{ss} = 32 - 11 + 20 = 41 \text{ cm} \qquad (3)$$

where

D_{ss} = 20 cm - Arbitrarily chosen reference steady-state distance between the vehicle side and the corridor side of the *wall*.

b. Pre-programmed amount of rotation (here: 100°) is completed. The amount of rotation (100°) has been chosen arbitrarily; any amount that is ≥ 90° (90° is the nominal amount of rotation required for turning out of the aisle and into the corridor) is reasonable. The reason for this exit condition is to serve as a safeguard if the primary exit condition (a) fails.

C. Driving in the main corridor, looking for the next aisle

Description:

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

Control Strategy:

This motion component has two distinct control strategies. Strategy (**a**) governs the motion while both the front and the

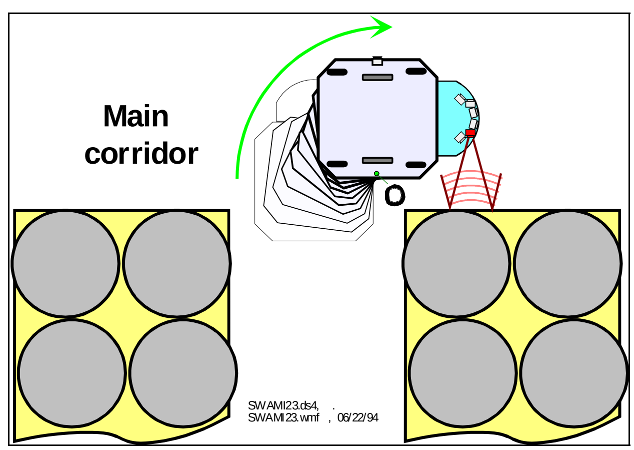

Figure 6: SWAMI Jr. rotates around point O until the exit condition is met.

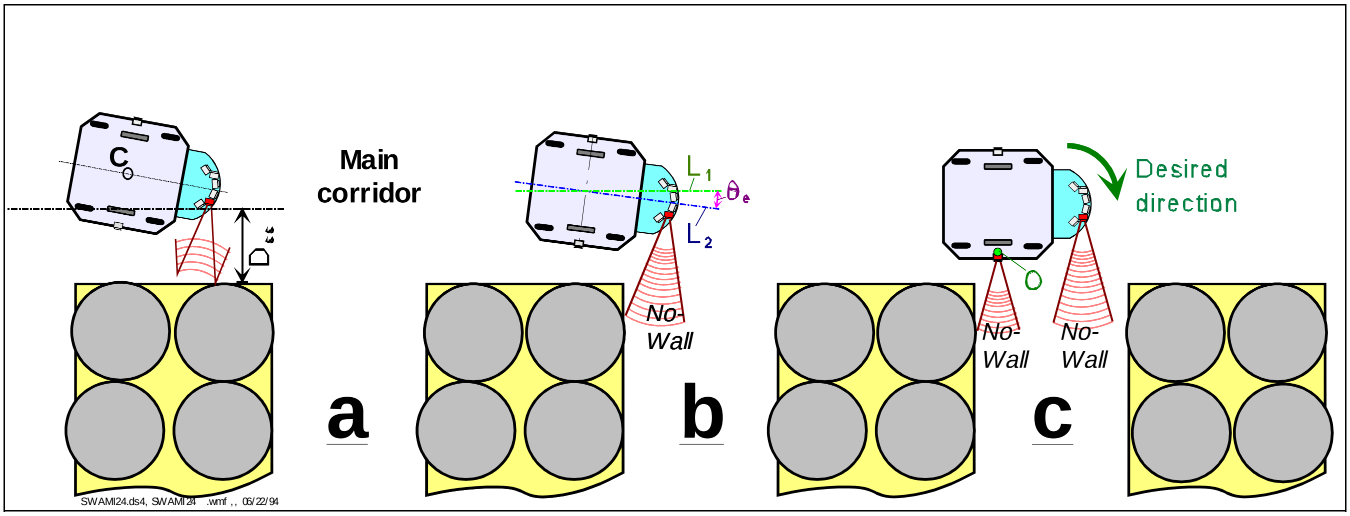

Figure 7:

When traveling along the short side of a drum/pallet *wall*, SWAMI Jr. employs two basically different control strategies.

a. As long as the front sensor "sees" the *wall*, the robot tries to reach a steady state distance D_{ss} from the *wall*.

b. After a short distance the front sensor no longer "sees" the *wall*. At this time the robot tries to reach a heading perpendicular to the next aisle; the robot also decelerates in anticipation of the following turn.

c. When both front and center sensor "see" *no-wall* the vehicle is ready to turn into the next aisle.

center sonar of the side of the robot that is facing the *wall* "see" the *wall*. This condition is shown in Fig. 7a. Strategy (**b**) governs the motion while the front sensor "sees" *no-wall*, as shown in Fig. 7b. This is the case once the front of the robot has reached the next aisle and the front sensors now "looks" into the next aisle. Both strategies are described in more detail below.

a. The short side of the rectangular pallet/drum *wall* has the width of two rows of drums, that is 2×60 cm = 120 cm. During the first part of the motion, both the front and the center sonar can "see" this *wall*, but only the front sonar can reliably and accurately measure the distance to this *wall*. The center sonar cannot reliably measure the distance to the *wall* because of the minimum distance constraint of the POLAROID sensors (nominally 41 cm, and 20 cm after our custom modification). For this reason we use only the front sonar for servoing the robot along the *wall* at a distance of 20 cm. It is desirable to keep this distance small, in order to facilitate re-entry into the next aisle, as will be discussed below. This typical wall-following controller is implemented as a *proportional-integral* (PI) controller.

b. When the front sonar reaches beyond the edge of the next aisle, its readings can no longer be used for servoing. The center sonar cannot be used for servoing either because its readings are below the minimum distance. Therefore a second control strategy is invoked: "Travel in (and hold) a direction perpendicular to the direction of the last aisle." The rationale behind this approach is simple: In the pallet/drum application (and really in most warehouse environments) aisles and corridors are perpendicular to each other, and, more importantly, aisles are parallel to each other. Thus, maintaining a direction perpendicular to the last aisle will guarantee a direction of travel that is perpendicular to the next aisle. The direction of the previous aisle can be determined by averaging orientation measurements that were obtained through dead-reckoning. If aisles are very long then the vehicle will accumulate orientation errors (due to dead-reckoning) that will cause large inaccuracies in the averaged direction. Thus, in long aisles only the orientation data from the last 3-5 meters should be used to compute the average direction.

The controller for strategy (b) is implemented as a PI-controller

Exception handling:

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

Exit Condition:

Same as described in Section III.A

Refinements:

Same three refinements as described in Section III.A

D Turning Into an Aisle

Description:

Turn into an aisle after traveling in a main corridor.

Control Strategy:

Same as in III.B (Turning out of an aisle). "Turning into an aisle" 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 B and computing a path between these two points. The technical difficulty with such an approach lies in the difficulty of locating point B 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 B and it requires only vague measurements of point A. To understand how our method works we have to recall some characteristics of the previous motion component (Section III.C):

During the "travel in a corridor looking for a new aisle" motion the robot tried to maintain a certain distance D_{ss}= 20 cm from the narrow side of the wall (Strategy **a** shown in Fig. 7a) and, using strategy **b** in the second part of that motion, the robot is aligned in parallel with the narrow side of the *wall* when exiting that motion (as shown in Fig. 7b). Upon exiting, the robot's drive axis must necessarily be beyond A, because the center sensor, located exactly along the drive axis, is already "looking" into the aisle (Fig. 7c). Therefore, a 90° rotation around point 'O' (which coincides with the location of the center sensor) is guaranteed not to collide with corner A. This approach does not consider point B 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.

Let us assume the ideal condition, in which the robot is aligned in parallel to the short side of the *wall* and travels at the desired distance D_{ss} = 20 cm from the *wall*. 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. 9. under these ideal conditions the center sensor located at point 'O' in Fig. 9 will see *no-wall* at the moment when the axis of the robot has advanced a distance x beyond the corner of the *wall* A. In the subsequent rotation around 'O' no part of the robot will protrude outside a circle of radius R, as shown in Fig. 9. Note that R is only a function of the geometric properties of the robot; for SWAMI Jr. we measured R = 69 cm. From the geometry of Fig. 9 we can now derive that the condition $L > x + y$ will guarantee collision-free turning into the aisle. It is easy to see from Fig. 9 that $x = D_{ss}\mathrm{tg}(\alpha/2)$ and that $y = (R^2 - D_{ss}^2)^{½}$ so that the condition for collision free turning becomes

$$L > D_{ss}\mathrm{tg}(\alpha/2) + (R^2 - D_{ss}^2)^{½} \qquad (4)$$

Substituting the numeric values of our application into Eq. (5) yields

$$L > 20\mathrm{tg}(15^o) + (69^2 - 20^2)^{½} = 71 \text{ cm} \qquad (5)$$

The result of Eq. (5) shows that *theoretically* the robot could safely enter any aisle of width L > 71 cm. In practice, of course, there are significant delays to consider. For example, it is not guaranteed that the center sensor is sampled at exactly the position shown in Fig. 9. Furthermore, for reliable operation it is necessary not to act immediately on the first *no-wall* reading from the center 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 from Section III.C that the robot decelerates as soon as the front sensor sees *no-wall*, 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 exit condition) equate to only 1-2 centimeters of travel. At a slower firing rate, for example at 200 ms (which is feasible with the off-the-shelf sonar system from TRC) proportionally longer delays can be expected.

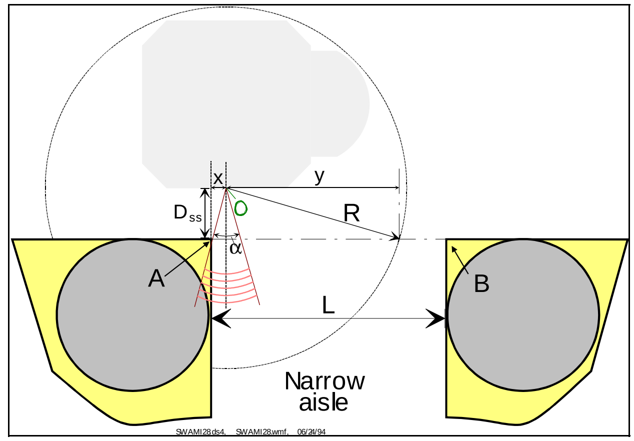

Figure 9: Geometry just prior to turning into an aisle

Exception handling

Our system monitors the optional sensors #2 and #7. If range readings from these sensors drop below a certain thresholds during the turning motion, the vehicle stops because a collision with the corner B (see Fig. 9) is imminent. During the development of our software we ran SWAMI Jr. for weeks through a drum/pallet setup without collision and without triggering sensors #2 or #7 even once (except for collisions caused by clearly identifiable bugs in the ongoing software development or hardware problems).

Exit condition:

Same as in III.B (Turning out of an aisle).

Refinements:

One important refinement of the above algorithm is a change in the location of the point of rotation, 'O' (see Fig. 9). In the above explanation we assumed that 'O' was located on the periphery of the robot, that is 64/2 = 32 cm from SWAMI Jr.'s center point 'C'. Relocating 'O' along the drive axis affects the robot's turning path proportionally. For example, moving the

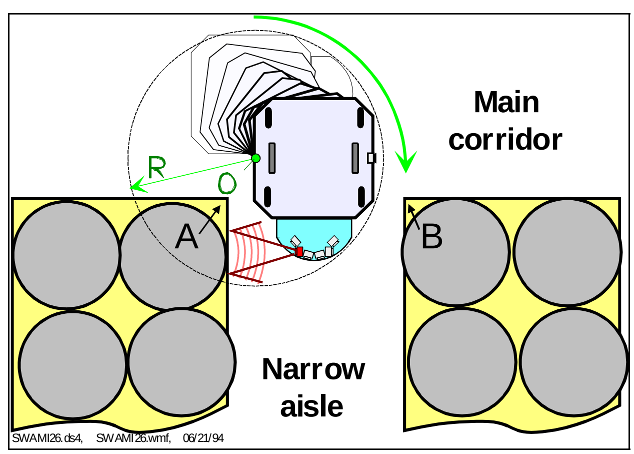

Figure 8: Turning into a narrow aisle is the most critical motion component.

center of rotation 'O' closer to the center point 'C' will cause the robot to be closer to point 'A' upon completion of the turning move. Similarly, moving 'O' further away from 'C' will cause the robot to be closer to point 'B' upon completion. With this simple adjustment experimenters can compensate for sensor delays or other recurring disturbances.

IV. EXPERIMENTAL RESULTS

SWAMI Jr. is based on a TRC *LabMate* platform. Our experimental vehicle, shown in Fig. 10, is equipped with eight POLAROID ultrasonic sensors, which we customized for short range measurements ($R_{min} \leq 20$ cm). SWAMI Jr. is controlled by a Compaq 486/66 MHz computer, although the CPU speed of a 386/20 MHz computer would be sufficient. The computer controls the *LabMate* through our custom made HCTL 1100 motion control interface, which completely bypasses the *LabMate's* original on-board computer and HCTL 1100 motion control chips. SWAMI Jr. can be controlled remotely by means of a 6 channel FM proportional-digital radio control joystick; the kind that is used by model airplane enthusiasts. The pulse width modulated receiver output is sampled by the onboard computer through a 5-channel AMD timer chip. The two sizeable loud speakers seen in Fig. 10 output computer-generated speech from the on-board *SoundBlaster* 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.

During the last four weeks of our experimental work we ran the robot many times through an aisle-and-corridor setup similar to the one in Fig. 1. In these runs the robot did not collide even once, except for cases caused by software bugs or hardware problems. In most of our experiments we ran the robot at a speed of 30 cm/sec and in aisles that were only 80 cm wide. Occasionally we ran the robot at 40 cm/sec. These runs were also successful, although the robot came near to colliding with entry point 'B' (in Fig. 8) because of the changed dynamics. Nonetheless, we feel confident that the algorithm could easily be adjusted to accommodate even higher speeds than 40 cm/sec, if the relevant deceleration parameters were adjusted correctly.

V. CONCLUSIONS

We have introduced a new approach to narrow aisle navigation based on ultrasonic sensors. This approach emphasizes the importance of the optimal location of the sonars to achieve extremely reliable and robust performance. During many weeks of testing in repeatedly modified environments the robot did not collide even once, except for those collisions that were caused by software bugs or hardware problems.

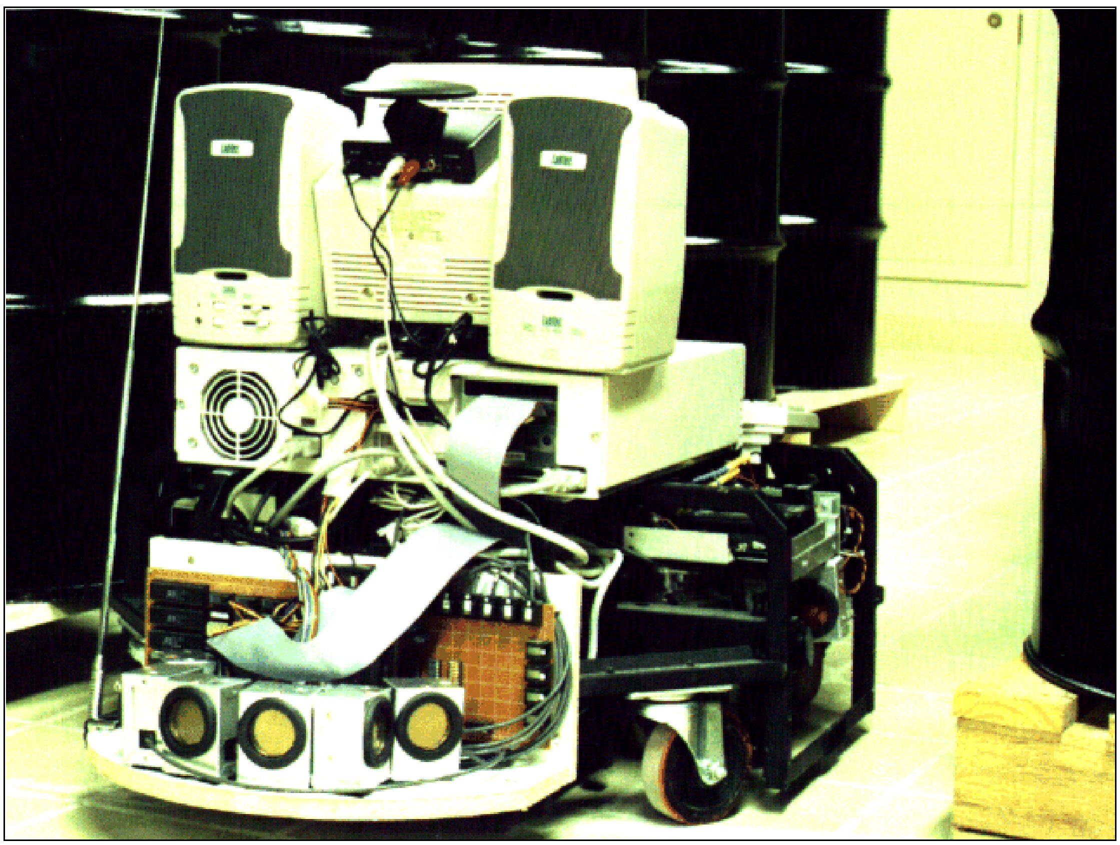

Figure 10: SWAMI Jr., the University of Michigan's mobile robot for narrow aisle navigation.

Most successfully implemented conventional general purpose obstacle avoidance algorithms (including our previously developed *Vector Field Histogram* (VFH) method [3,4]) 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 repeatably with narrow aisles and narrow-aisle entry, even under changing conditions. Our system can be implemented easily on existing mobile robots, simply by adding the two front-mounted sensors #3 and #6.

VI. ACKNOWLEDGEMENTS

This work was sponsored by the Department of Energy Grant DE-FG02-86NE37969. Special thanks to Dr. Clyde Ward from the Westinghouse Savannah River Technology Center for his many useful suggestions and guidance.

VI. REFERENCES

1. Borenstein, J. and Koren, Y., 1988, "Obstacle Avoidance With Ultrasonic Sensors." *IEEE Journal of Robotics and Automation*, Vol. RA-4, No. 2, pp. 213-218.

2. Borenstein, J. and Koren, Y., 1989, "Real-time Obstacle Avoidance for Fast Mobile Robots." *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 19, No. 5, Sept/Oct, pp. 1179-1187.

3. Borenstein, J. and Koren, Y., 1991, "The Vector Field Histogram – Fast Obstacle-Avoidance for Mobile Robots." *IEEE Journal of Robotics and Automation*, Vol. 7, No. 3., June, pp. 278-288.

4. Borenstein, J, and Koren, Y., 1991, "Histogramic In-motion Mapping for Mobile Robot Obstacle Avoidance." *IEEE Journal of Robotics and Automation*, Vol. 7, No. 4, pp. 535-539.

5. Bozma, Ö. and Kuc, R., 1991, "Characterizing Pulses Reflected From Rough Surfaces Using Ultrasound." *Journal of the Acoustical Society of America*, vol. 89, no. 6, pp. 2519 -2531.

6. Buchenberger, M., Jörg, W., and Von Puttkamer, E., 1993, Laserradar and Sonar-based World Modelling .." *1993 IEEE Conference on Robotics and Automation*, Atlanta Georgia, May 10-15, pp. 534-541.

7. Crowley, J. L., 1989, "World Modeling and Position Estimation for a Mobile Robot Using Ultrasonic Ranging." *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*, Scottsdale, Arizona, May 14-19, pp. 674-680.

8. Everett, H. R., Gilbreath, G. A., Tran, T. and Nieusma, J. M., 1990, "Modeling the Environment of a Mobile Security Robot." *Technical Document 1835, Advanced Systems Division, Naval Ocean Systems Center, San Diego, California 92152-5000*, June.

9. Flynn, A. M., 1988, "Combining Sonar and Infrared Sensors for Mobile Robot Navigation." *The International Journal of Robotics Research*, Vol. 7, No. 6, December pp. 5-14.

10. Holenstein, A. A. and Badreddin, E., 1991, "Collision Avoidance in a Behavior-based Mobile Robot Design." *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, Sacramento, California, April, pp. 898-903.

11. Kuc, R. and Barshan, B., 1989, "Navigating Vehicles Through an Unstructured Environment With Sonar." *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*. Scottsdale, Arizona, May 14-19, pp. 1422-1426.

12. Kuc, R., 1991, "Why Sonar Works (when it does)." Submitted to the *Journal of IEEE Trans. Robotics and Automation*.

13. Moravec, H. P., 1988, "Sensor Fusion in Certainty Grids for Mobile Robots." *AI Magazine*, Summer, pp. 61-74.

14. Pin, F. G. et al., 1989, "Autonomous Mobile Robot Research Using the Hermies-III Robot." *IROS International Conference on Intelligent Robot and Systems*, Tsukuba, Japan, Sept.

15. POLAROID Corp, Ultrasonic Components Group, 119 Windsor Street, Cambridge, MA.

16. TRC (Transition Research Corporation), 1994, Shelter Rock Lane, Danbury, CT.