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Noise Rejection for Ultrasonic Sensors in Mobile Robot Applications

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ABSTRACT

This paper introduces error eliminating rapid ultrasonic firing (EERUF), a new method for firing multiple ultrasonic sensors in mobile robot applications. EERUF allows sonars to fire at rates that are five to ten times faster than those attained with conventional methods. At the same time, EERUF reduces the number of erroneous readings due to ultrasonic noise by one to two orders of magnitude.

While faster firing rates improve the reliability and robustness of mobile robot obstacle avoidance and are necessary for safe travel at higher speed (e.g., V > 0.3 m/sec), they introduce more ultrasonic noise and increase the occurrence rate of crosstalk. However, EERUF almost completely rejects crosstalk, making fast firing feasible. Furthermore, ERRUF's unique noise rejection capability allows multiple mobile robots to collaborate in the same environment, even if their ultrasonic sensors operate at the same frequencies.

This paper categorizes different types of ultrasonic noise, concerning mobile robot applications. For each category we present ways to identify and reject the resulting errors. We combine these individual rejection measures into one error rejection method that is then combined with a fast firing algorithm. The resulting combination is EERUF.

We have implemented and tested the EERUF method on a mobile robot and we present experimental results. With EERUF, a mobile robot was able to traverse an obstacle course of densely spaced, pencil-thin (3/8"-diameter) poles at up to 1 m/sec.

1. Introduction

Ultrasonic range sensors (URSs) are widely used in many mobile robot applications. Some limitations of URSs, such as poor angular resolution and specular reflections are well-documented in the literature [Flynn, 1988; Borenstein and Koren, 1988; Kuc and Barshan, 1989, Everett et al, 1990]. Another limitation, the sensor's susceptibility to *noise* is usually not mentioned at all or only in the context of *crosstalk* (a phenomenon where one sensor picks up the echo from another). Yet, crosstalk is only one particular form of noise. In this paper we categorize different types of noise and we discuss methods for rejecting each type of noise. We introduce a new method called *error eliminating rapid ultrasonic firing* (EERUF). EERUF combines different noise rejection techniques and optimizes them for rapid firing.

One URS frequently used in mobile robot applications is manufactured by POLAROID. This sensor produces a conical propagation profile with an opening angle of 15°-30°. A precise angle cannot be given since the strength of the echo depends (among others) on characteristics of the surface and the orientation of the reflecting object. However, since 15° is the more conservative assumption, many mobile robots have URSs installed on their periphery at 15° intervals, to guarantee complete coverage of the area around the robot in all directions. For omnidirectional robots of circular shape, this design requires 24 (=360°/15°) URSs mounted on a ring around the robot [Moravec, 1988; Crowley, 1989; Borenstein and Koren, 1989; Everett et al., 1990, Holenstein and Badreddin, 1991].

Even though other methods are possible, most implementations employ a firing method we call *scheduled firing*. In this method, each sensor fires according to a preset schedule. Usually, 4, 6, or 8 neighboring sensors are grouped and fire such that corresponding sensors (e.g., the first sensor in each group) fire simultaneously. We shall call sensors that fire simultaneously a "*squad.*"

One undesirable side-effect of using multiple sensors is the generation of crosstalk. Most researchers try to overcome this problem by firing one squad after the other at large intervals, so that the echo of the first squad has abated sufficiently before the next squad fires. The result of this cautious approach is a relatively slow firing rate, typically 300 to 600 ms (or more, in some applications), which permits only slow travel speeds for the mobile robot.

2. Ultrasonic noise and crosstalk

Ultrasonic noise and crosstalk can be classified according to certain characteristics, as listed below.

a. Environmental Ultrasonic Noise

Environmental ultrasonic noise may occur near certain machine tools or near discharging high-pressure air. This type of noise can be continuous and strong enough to disable ultrasonic sensors completely.

b. Environmental Noise From Other Ultrasonic Sensors

This type of noise is very likely to occur when more than one vehicle with URSs operates in the same environment. Typically, multiple vehicles would use the same kind of URSs, which would practically guarantee mutual interference. Note that ultrasonic noise generated by other URSs on other vehicles is discrete.

c. Noise From Onboard Ultrasonic Sensors — Crosstalk

Figure 1 shows a mobile robot equipped with multiple URSs in two typical indoor environments; both environments differ substantially in the way they promote crosstalk. For the following discussion, we define the term "*critical path*" as any path of ultrasound waves that are transmitted by one sensor and are received by another, thus creating crosstalk. The sensor that transmitted the ultrasound waves is labeled x, and the receiving sensors are labeled y.

Figure 1a shows a *direct* critical path, where the robot is near a single wall. Because of the symmetry in Fig. 1a, two sensors are labeled 'y', since they are both on a critical path with sensor x. If sensors y fire shortly after sensor x, they would be awaiting the echo to their own signals by the time the echo from sensor x reaches them. Thus, the reading from sensors y would result in some arbitrary error, depending on the time difference T_{lag} between firing sensors x and y.

The situation is more complex for the *indirect* critical path in Fig. 1b. Here, at an instance t_0, sensor x fires and its soundwaves are reflected off *three* walls. Assuming the walls are fairly smooth (e.g., drywall), the reflected wavefront will reach sensor y after traveling through the distance $L=l1+l2+l3+l4$. If, at this time, sensor y is awaiting an echo of its own, then it will receive the signal from sensor x and interpret it as its own echo.

As is evident from Fig. 1b, crosstalk is not a phenomenon that occurs only under very extreme conditions. Once a critical path exists, crosstalk is a particularly damaging condition because it will *repeatedly* cause false readings in sensor y, until the robot moves out of the critical path situation. The following numeric example highlights this point.

For the symmetric case depicted in Fig. 1b it is clear that similar symmetric conditions prevail when the robot is a little closer or further from wall 2, as long as wall 2 lies between points *a* and *b* (located on the axes of symmetry, *S*). Therefore, the critical path of Fig. 1b exists while the robot travels through the distance $D_c = \overline{ab}$. For the geometric conditions in Fig. 1b, $D_c = 0.60$ m (approximately). Assuming a travel speed of $V = 1$ m/sec and a sampling rate of $T_p = 60$ ms for each sensor, sensors y will sample

$$n_c = \frac{D_c}{V\,T_p} = \frac{0.60}{1 \times 0.06} = 10$$

crosstalk readings. All of these readings will be near-identical but will be totally false, since they result from crosstalk. *Any algorithm that relies on multiple samples to gain confidence in the measured location of obstacles (e.g., [Moravec, 1988; Crowley, 1989]) will be misled to place very high confidence in the accuracy of these $n_c = 10$ recurring readings.*

3. Eliminating noise and crosstalk with the EERUF method

In this Section we introduce two methods for noise rejection. The first method, *comparison of consecutive readings*, is straight-forward. However, as we will show, this method cannot reject crosstalk. To reject crosstalk, we introduce a modification, called "*comparison with alternating delays.*"

a. Comparison of Consecutive Readings.

One simple method for eliminating occasional *random noise* is to compare two consecutive readings from the same sensor. The difference between any two consecutive readings, T_{delta}, is small if the readings result from "good" measurements (i.e., not caused by noise). One cannot assume $T_{delta} = 0$ because of the robot's motion and the discrete resolution of the sensors. In the following discussion we will call consecutive readings that differ only by less than a small amount T_{delta} *near-identical* readings. If a reading was caused by *random noise*, it is highly unlikely to be *near-identical* to the previous reading, whether the previous reading was "good" or caused by noise, too. Thus, *comparison of consecutive readings* can identify erroneous readings due to *random noise* and subsequently reject such readings.

b. Comparison With Alternating Delays.

While *comparison of consecutive readings* is an efficient way for rejecting erroneous readings caused by *random noise*, it is unsuitable for reducing crosstalk. This is so because crosstalk produces *systematic* (i.e., non-random), *near-identical* readings, as explained above. To overcome this problem, we introduce an *alternating* delay

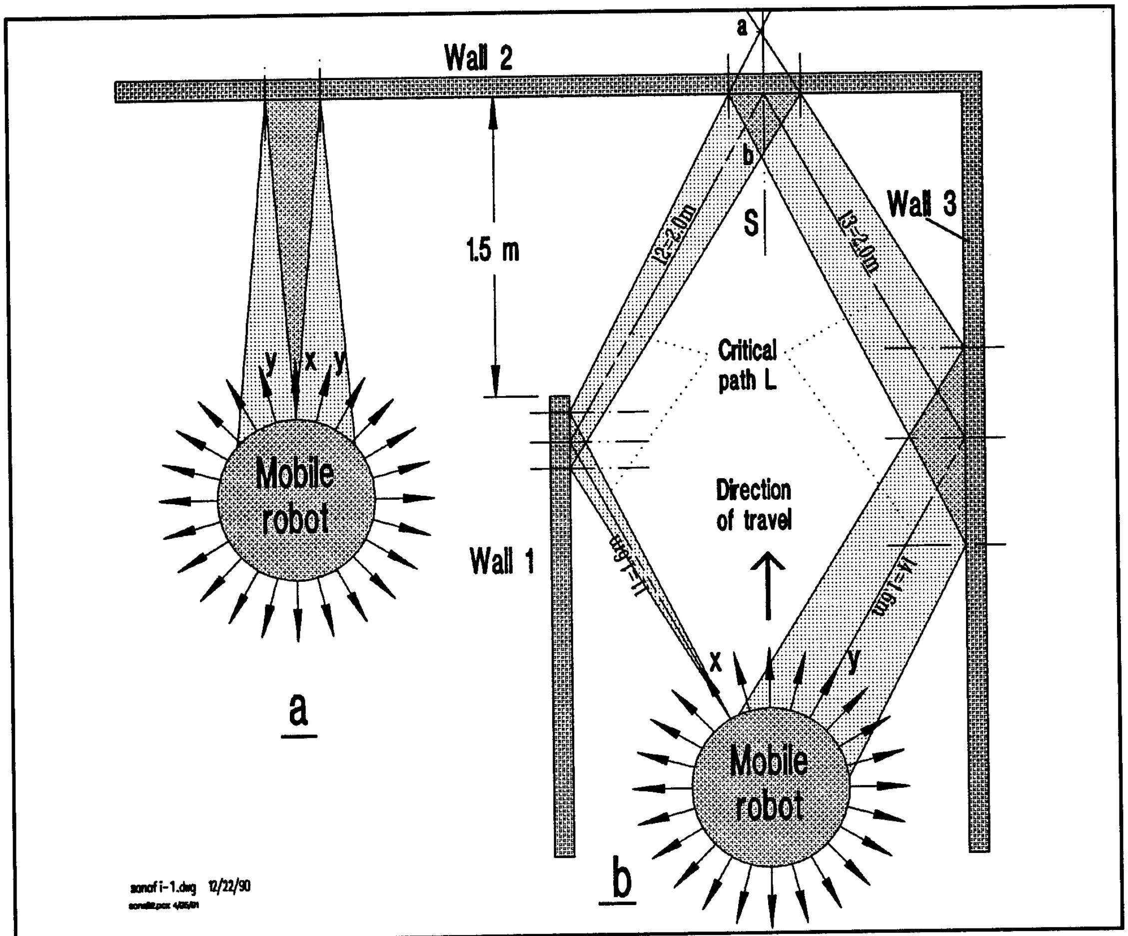

Figure 1: How *crosstalk* from onboard sensors is generated:
a. Direct *critical path.*; b. Indirect *critical path.*

T_{wait}, before each sensor fires. For each sensor i, T_{wait} alternates between two values, a_i and b_i, i.e., after each firing, $T_{i,wait}$ is toggled between $T_{i,wait,a}$ and $T_{i,wait,b}$. Note that a_i and b_i can be very small, on the order of a few milliseconds.

The basic set-up for our implementation of *scheduled firing* comprises k URSs spaced at 15° intervals and labeled 1, 2, ... k. We have experimentally determined that for a near-by wall (worst case), *direct path crosstalk* can affect 3 neighboring sensors (for example, when sensor #1 fires, sensors #2, #3, and #4 can receive the *direct path echo*). In order to avoid crosstalk in the first place — rather than having to reject an erroneous echo — each sensor in a group of 4 neighboring sensors fires at a scheduled interval. Intervals should be large enough to allow the echo of, say, sensor #1 to return from a near-by wall before any other of the 4 sensors in the group fires. Experimentally we found that intervals should be at least 15 ms, corresponding to a distance of 2.5 m between the wall and the sensors. Thus, firing sensors #1 to #4 at *scheduled times* T_{lag} = 0, 15, 30, and 45 ms (respectively), eliminates most *direct path crosstalk* resulting from objects up to 2.5 m away.

We now combine the *scheduled firing* scheme with the method of *comparison of consecutive readings* and the method of *alternating delays* as follows:

1. Sensors #1 - #4 are *scheduled* for firing at intervals T_{lag} = 0, 15, 30, and 45 ms.
2. Subsequent groups of four sensors (e.g., #5 - #8) use the same intervals (0, 15, 30, and 45 ms).
3. Sensors *don't actually fire* at their *scheduled* times, but rather commence a waiting period T_{wait}.

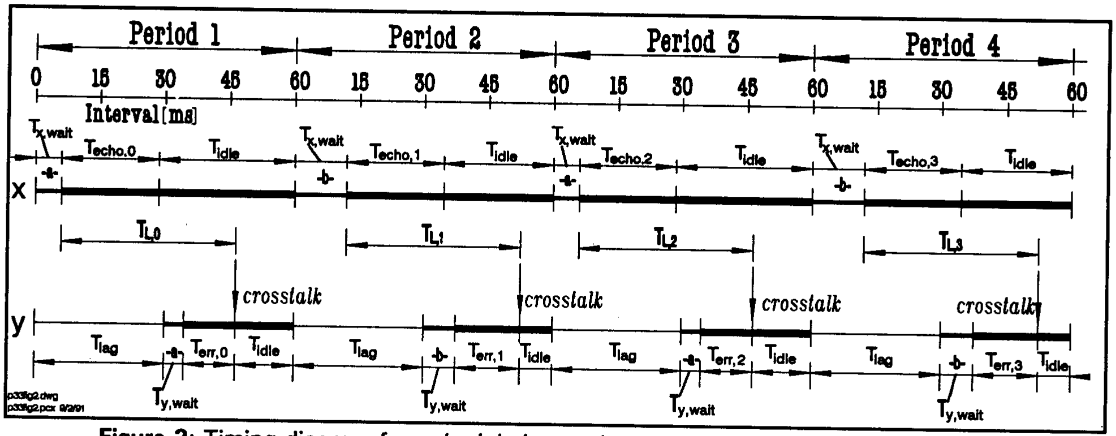

Figure 2: Timing diagram for *scheduled asynchronous firing* with *alternating delays*.

4. Delays T_{wait} *alternate* between two different values, a and b. Each sensor i has its own distinct set of $T_{wait,a}$ and $T_{wait,b}$.
5. Thus, a sensor actually fires at time $T_{lag} + T_{wait}$ (relative to the beginning of each period).
6. Every sensor fires exactly once within each period of 4×15 = 60 ms.

This implementation is shown in form of a timing diagram, in Fig. 2. Based on this diagram, we can show that crosstalk can be rejected by comparing consecutive readings, provided *alternating delays* are used:

The top row in Fig. 2 shows several *periods*, each divided into 4 intervals of 15 ms. The middle row shows the timing of a given sensor x which, in this example here, happens to be *scheduled* at $T_{lag} = 0$. At $t = T_{lag}$, sensor x begins a short waiting period, $T_{x,wait} = a$. Then, sensor x fires and awaits its echo. After the first echo is received ($T_{echo,0}$) sensor x does nothing (T_{idle}) until the end of the first period. This sequence repeats itself during the second period, with the exception that now sensor x waits for $T_{x,wait} = b$ before firing.

The bottom row shows the events for sensor y (the sensor affected by crosstalk from sensor x). In the example here, sensor y is *scheduled* for firing at $T_{lag} = 30$ ms. After waiting for $T_{y,wait} = a$ (recall that each sensor has its own distinct pair of delays a and b), sensor y fires and awaits its echo. However, assuming a critical path of length L (e. g., like the one in Fig. 1b) exists between sensors x and y, a crosstalk echo is received by sensor y a duration $T_{L,0}$ after sensor x fired, causing an erroneous reading of $T_{err,0}$ in sensor y. After receiving the (erroneous) echo, sensor y idles until the end of the period. This sequence repeats itself during the second period, with the exception that now y waits for $T_{y,wait} = b$ before firing. As can be readily seen from this timing diagram, the erroneous readings $T_{err,n}$ differ from $T_{err,n-1}$ and can thus be identified and rejected by the method of comparison of consecutive readings.

4. Implementation and experimental results

We implemented and tested the EERUF method on the commercially available *LabMate* robot [TRC]. The *LabMate* is 75 cm long, 75 cm wide (including bumpers), and has a maximum speed of 1 m/sec. In our experimental system we used eight POLAROID sensors that were symmetrically spaced at 15° intervals (see Fig. 3).

A '386-20 MHz computer ran the EERUF algorithm as an *interrupt-driven background task*, which communicated range readings to the main task via a *first-in first-out (FIFO)* queue in shared memory. The main task was the *vector field histogram* (VFH) obstacle avoidance method [Borenstein and Koren, 1990a and 1991a] combined with the *histogrammic in motion mapping* (HIMM) method [Borenstein and Koren, 1990b and 1991b].

We set up an obstacle course comprising of *pencil-thin (8 mm diameter)* vertical poles spaced approximately 1.6 m from each other (see Fig. 4). With the EERUF method, the robot was able to traverse this course at its maximum speed of 1 m/sec and an average speed of 0.8 m/sec (the maximum speed was reduced before and during tight turns, for dynamic reasons).

In another experiment we found that EERUF allowed equally fast obstacle avoidance even in the presence of *intense ultrasonic noise* from another mobile robot with 24 URSs. Also, as can be seen in Fig. 4, the far corner of the lab has highly reflective smooth walls that strongly promote crosstalk and so do the *reflective poster boards* (with surfaces similar to plexiglass) shown in Fig. 4. With EERUF, the robot was able to avoid all obstacles while traveling at up to 1 m/sec.

Besides the in-motion experiments described here, we tested EERUF extensively in a reproducible, stationary test-environment. Typical results show successful rejection of over 97% of *direct* and *indirect path* crosstalk (from onboard sensors), or errors caused by external sources. The EERUF method consistently produced one to two orders of magnitude fewer errors than a "conventional" firing scheme (i.e., without error rejection) operating at the same firing rate.

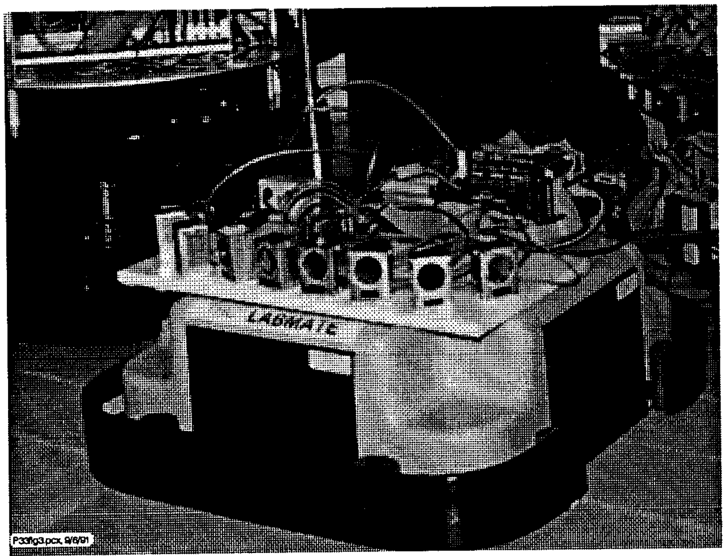

Figure 3: One of the University of Michigan's 4 *Labmate* robots, equipped with an array of eight URS (spaced at 15° intervals).

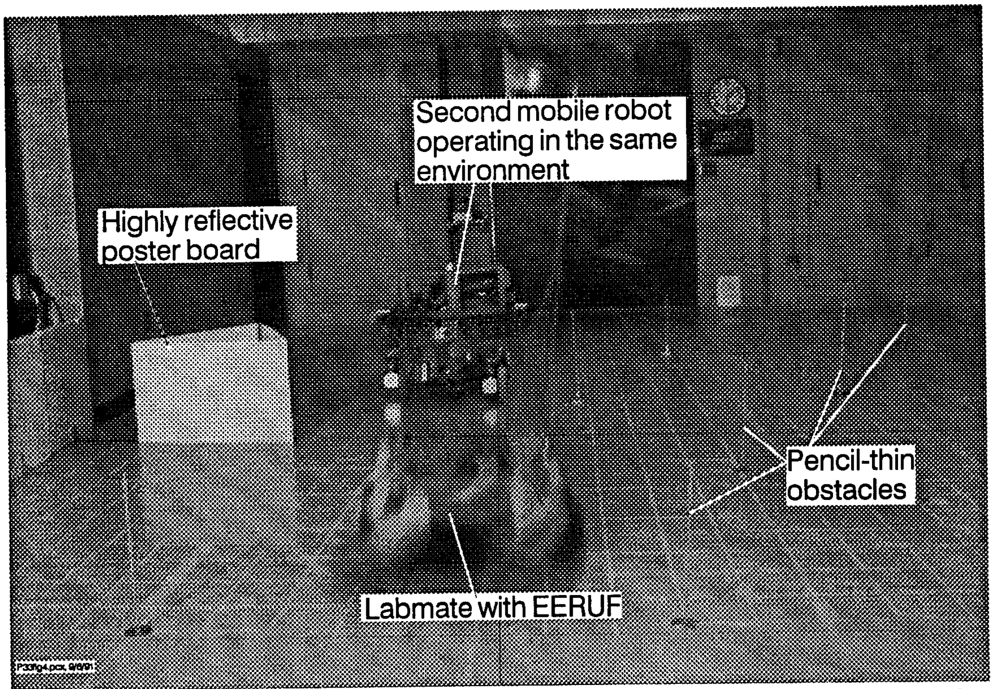

Figure 4: With EERUF, the *Labmate* zaps through an obstacle course at 1 m/sec. Another mobile robot nearby generates ultrasonic noise at a rate of 24 firings per 160 ms.

5. Conclusions

We have introduced *error eliminating rapid ultrasonic firing* (EERUF), a new method for firing multiple URS. EERUF is able to identify and reject erroneous readings due to crosstalk and discrete external noise. EERUF is based on the principle of comparison of consecutive readings, but, in addition, employs *alternating wait states* before firing each sensor. The latter measure artificially creates differences between consecutive crosstalk readings, while leaving "good" readings unaltered. In summary, these are the advantages of the EERUF method over conventional firing methods:

1. *Multiple* mobile robots can operate in the same environment, without interference among their URSs.
2. The *reliability and robustness* of single robot obstacle avoidance are significantly improved.
3. With EERUF, mobile robots are able to traverse obstacle-cluttered environments safely and much faster than with conventional methods. We have successfully demonstrated obstacle avoidance at 1 m/sec, which was limited only by the physical capability of the mobile platform. We expect that EERUF will allow safe obstacle avoidance at speeds of up to 2 m/sec.

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6. References

1. Borenstein, J. and Koren, Y., 1988, "Obstacle Avoidance With Ultrasonic Sensors." *IEEE Journal of Robotics and Automation*, Vol. RA-4, No. 2, 1988, 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., 1990a, "Real-time Obstacle Avoidance for Fast Mobile Robots in Cluttered Environments." *Proceedings of the* 1990 IEEE International Conference on Robotics and Automation, Cincinnati, Ohio, May 13-18, pp. 572-577.
4. Borenstein, J. and Koren, Y., 1990b, "Real-time Map-building for Fast Mobile Robot Obstacle Avoidance." *SPIE Symposium on Advances in Intelligent Systems, Mobile Robots V*, Boston, MA, Nov. 4-9, pp. 74-81.
5. Borenstein, J. and Koren, Y., 1991a, "The Vector Field Histogram — Fast Obstacle-Avoidance for Mobile Robots." *IEEE Journal of Robotics and Automation*, Vol. 7, No. 3., June, pp. 278-288.
6. Borenstein, J, and Koren, Y., 1991b, "Histogramic In-motion Mapping for Mobile Robot Obstacle Avoidance." *IEEE Journal of Robotics and Automation*, Vol. 7, No. 4, pp. 535-539.
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. Moravec, H. P., 1988, "Sensor Fusion in Certainty Grids for Mobile Robots." *AI Magazine*, Summer, pp. 61-74.
13. POLAROID Corporation, Ultrasonic Components Group, 119 Windsor Street, Cambridge, MA 02139.
14. TRC (Transition Research Corporation), 15 Great Pasture Road, Danbury, Connecticut, 06810.