

The Sonar Ring: Obstacle Detection for a Mobile Robot

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Abstract

Ultrasonic pulse-echo devices have shown utility for obstacle detection in numerous mobile robot research efforts, as well as in commercial automatic guided vehicles (AGVs). A method for quickly obtaining multiple sonar range readings is presented. Thirty ultrasonic transducers are arranged in a ring and controlled by a computer. The system is predominantly composed of commercially available parts. Hardware specifications and operation details of this system are outlined.

1. Introduction

Whether a mobile robot should walk or roll, the ability to avoid obstacles in the path is a necessary and important one. In order to avoid objects, the robot must first detect them. This paper describes an acoustic ranging system for obstacle detection. The sonar ring serves as a navigation aid to the GMR autonomous vehicle AutoNav-2. A list of hardware specifications is given, the operating procedure is outlined, applications are delineated, and future work is mentioned.

For our purposes, an obstacle is any solid object which extends vertically more than an inch from the ground surface. Its existence is not necessarily known a priori. "Detection" is defined as a change in the robot state due to the acquisition of sensed data relating to a physical object (or objects). We say that the robot has detected an obstacle when a bit changes from 0 to 1, and there is an obstacle. If bit is set, and there is no obstacle, then a false detection has occurred. The latter is as much a problem to robot navigation as is the case of not detecting an obstacle. One method of overcoming this problem is to use multiple sensor types, and fuse the data stochastically. "Avoidance" of detected obstacles is distinct problem for mobile robots, taken to mean motion by the robot which allows it to reach a destination without contacting unexpected obstacles in its nominal path. Obstacle avoidance is an area yet to be addressed in our research.

2. Related Work

Many mobile robot research programs use acoustic sensing for obstacle detection, avoidance, and position estimation. Notable among these are Hilare [8], the CMU Imp [6], and Neptune [12], and the FMC RRV3 [14]. The sonar ring most resembles the ranging system in use at Carnegie-Mellon. Neptune has a 24-element circular ring of Polaroid sensors built by Denning Mobile Robotics [10]. The difference between the two systems lies in the number of sensors, and the control and processing method, which will be discussed. While many papers have been published on the use of sonar range data in mobile robot navigation, there are few that describe the requisite sonar ranging hardware, and that is the focus of this paper.

3. AutoNav-2, the Robot

As the *raison d'être* of the sonar ring is to aid a mobile robot, a short description of GMR's vehicle will follow. The GMR AutoNav-2 powertrain has two independent belt-driven wheels on a 57 cm wheelbase, with two spring-mounted casters fore and aft for stability. Two spring-mounted idler wheels with shaft encoders roll on the drive wheel axis, tracking the distance travelled. Power is obtained from two 12-volt, 75 amp-hour batteries. Wheels and a triplet of pan-tilt devices are controlled via motion servo cards. The pan-tilt controllers are linked via RS232 to the on-board MicroVAX-II, while the wheel servos are commanded by a 68000 microprocessor slaved to the MicroVAX-II. The 68000 implements a control law for the drive/steering system, and updates vehicle location in World coordinates from the idler wheel encoder inputs.

Sensors include a Sony CCD camera and a Polaroid sonar transducer mounted on each of two pan-tilt devices. Camera images are processed on-board with a custom multiresolution vision processor [11] linked to the MicroVAX-II. The third pan-tilt carries a short-range ($d < 1.0$ m) ultrasonic sensor, and a pneumatic parallel-jaw gripper on

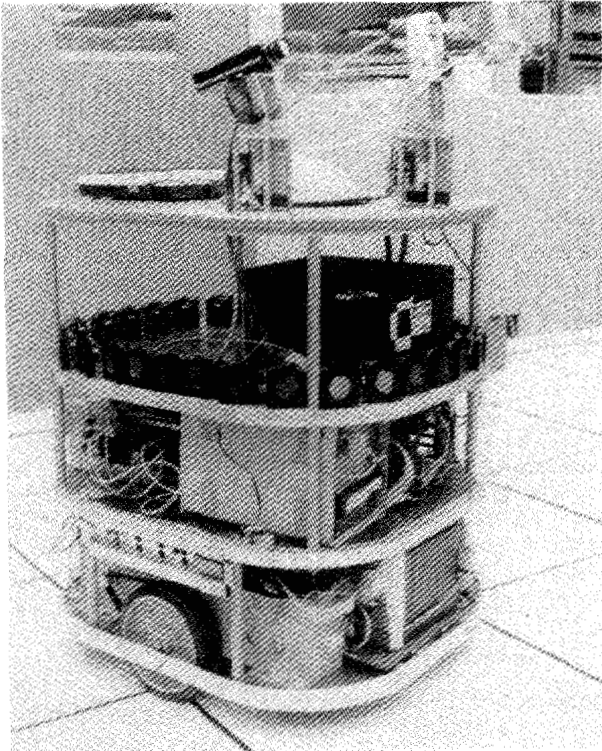


Figure 1. GMR AutoNav-2.

an air cylinder. This is used for small parts transfer. Finally, the sonar ring and an Odetics laser rangefinder are located between the cameras and computers, 57 cm from the ground. An off-board Lisp Machine* sends commands to and receives data from the MicroVAX-II over a radio link.

4. Ranging with Ultrasonic Sensors

The obstacle detection scheme to be described is based on acoustic wave propagation. The speed of sound in air depends on the ambient temperature, humidity, and pressure. Therefore, once this speed is measured or calculated, the distance travelled by an acoustic wave is determined by measuring elapsed time.

In a pulse-echo ranging system, a short ($t < 1$ millisecond) acoustic wave train is first emitted from a transducer. The range to an object is found by measuring the time between transmission of a pulse and the reception of its echo. It may happen that an acoustic pulse is transmitted, but no echo is detected. There are three probable explanations. First, the path may be free of any obstacle. Second, there may be an obstacle in the path, but its surface area and texture are such that the echo amplitude is too small to be detected by the receiver circuit. Third, the pulse is reflected away from the receiver by a surface which is not perpendicular to the transducer axis.

* Lisp Machine is a trademark of Symbolics Inc.

Considering the last case, there are certain obstacle configurations in which an acoustic sensor fails to detect an obstacle. For example, take an object with a specular surface which forms an angle of greater than 6° with the transducer axis. Six degrees is half of the beam width of a Polaroid transducer, corresponding to a 50% drop in pressure amplitude from on-axis response. A specular surface is one with roughness less than 5% of the acoustic wavelength [4], or 13 mils for a 50 kilohertz wave. In this case, the acoustic wave train is reflected away from the transducer, and no echo is received. It is possible that complementary sensing systems (based on principles other than acoustics) will find such objects in the environment.

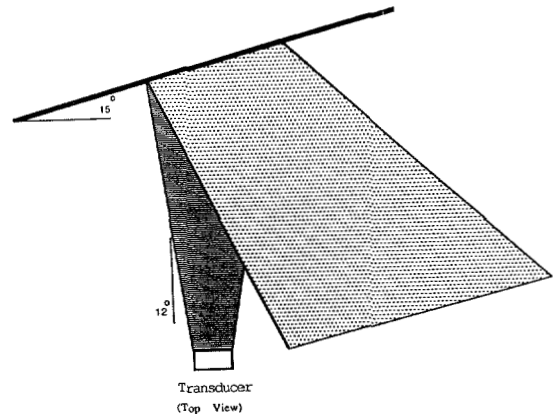


Figure 3. An undetected obstacle.

If no echo is detected by any sensor, the motion supervisor assumes that the robot can move safely along its path. The decision to move may be tempered by sensor models, and other a priori information about the world. Other issues related to obstacle detection using acoustic sensors are discussed in Hickling [9].

5. Sonar ring components

The sonar ring is comprised of four subsystems: a computer, dedicated timing circuitry, thirty transmit/receive circuits, and thirty ultrasonic transducers. System control is hierarchical, with the computer at the top level. This section will detail each component, beginning at the lowest level.

Thirty Polaroid instrument grade electrostatic transducers individually convert acoustic waves into voltage signals, and vice versa. Technical specifications, frequency range, and beam pattern for this transducer may be found in Biber et al.[3], and in Polaroid [15]. A theoretical description of its beam pattern is reprinted below. It indicates that the transducer has an acoustic beam width of 12° between the -6 dB points, at 50 kilohertz. This agrees well with the results we obtained for two transducers. The beam angle should be used only as a rough measure of the probability of reception of an echo from a smooth surface. The differences in the surface area, texture, orientation, and size of an object will affect the echo signal strength.

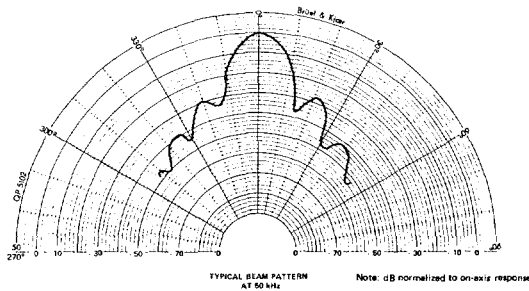


Figure 3. Beam pattern of the Polaroid transducer.

The 30 sensors are arranged in a ring in order to obtain 360° horizontal range data. The transmit/receive axis of each transducer lies in the same horizontal plane at 12° azimuthal intervals.

Attached to each transducer is a Texas Instruments SN28827 Sonar Ranging Module. This device generates a 16-cycle, 49.4 kilohertz pulse whenever an input line is raised to a TTL high-logic-level. During transmission, a two amp drain on the power supply drives a 300 volt (peak to peak) transmit wave train. To avoid spikes on the power line, an RC pair is added to each module. With a 99% charge time of 50 ms, the RC pair allows rapid cycling. The entire ring may be cycled at 16.7 hertz, for a maximum of 500 range readings per second.

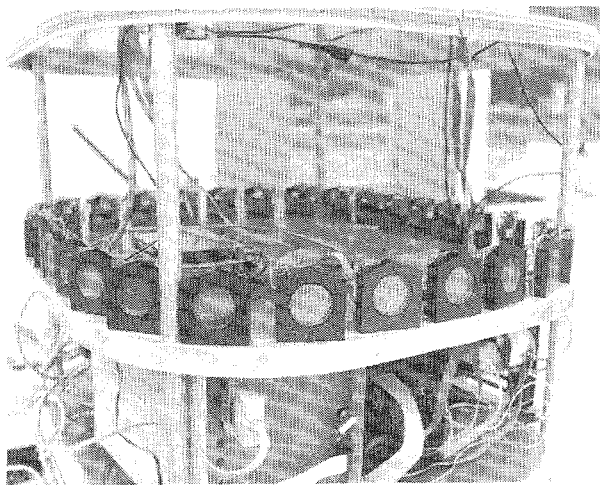


Figure 4. The sonar ring.

After transmitting the pulse, the SN28827 puts a 150 volt dc bias across the transducer, so an echo may be detected. To avoid the possibility of confusing the ringing of the transducer with an acoustic echo, the module blanks echoes prior to 2.38 ms from the beginning of pulse transmission. This creates a lower bound of .42 meter on the range of the system with factory settings. An increased or decreased blanking period may be achieved with additional control signals to the module.

The pressure amplitude of an acoustic pulse is attenuated in air from wave spreading and absorption. There is further attenuation upon collision with obstacles. To overcome the problem of detecting a rapidly diminishing signal, the receiver control chip increases the gain in sixteen discrete steps, as the time from transmission increases from 0 to 38 ms. Relative gain may be varied up to four times by changing the value of resistor R1. If an echo is detected by the receiver chip, the ECHO output line on the module rises to a TTL high-logic-level. More information on the operation of the sonar ranging modules may be found in the TI literature [16].

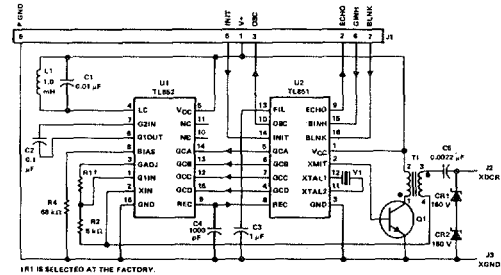


Figure 5. Schematic of the TI Sonar Ranging Module.

The third component of the system is the timing circuitry. On AutoNav-2 this task is performed by two commercial timer boards. Codar Technology M-Timers* share a backplane with the MicroVAX II** computer. Similar timers are available for other popular bus types. These timers communicate with the computer over the Q-bus, and with the TI SN28827 modules via wire cabling. Each M-Timer has 15 independently programmable 16-bit counters, addressed in three groups of five counters. Up to 16 vectored interrupts may be produced by each board. There are 36 buffered I/O lines per board available, of which a total of 60 are used by the sonar ring. More information on these boards may be found in [1], [2], [5].

Each sonar transducer has a dedicated counter. When the count corresponding to the pulse time of flight is obtained, it is stored in the counter. The MicroVAX II may then read the count value at leisure.

The signal to transmit a pulse is generated by the M-Timers, on command from the MicroVAX II. Each counter has a programmable output and input line. The output line controls when a pulse is transmitted, while the input line stops the count sequence if and when an echo is detected.

* M-Timer is a trademark of Codar Technology, Inc.

** MicroVAX and Vaxeln are trademarks of Digital Equipment Corporation.

Finally, the MicroVAX II controls the operation of the sonar ring at the highest level of hardware. A driver for the M-Timers is written in Vaxeln Pascal. Application programs may use the driver to obtain range values as needed.

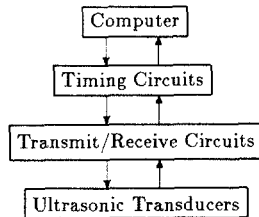


Figure 6. Sonar ring components.

6. Operation details

The control and time of flight counting tasks are decentralized. This enables both higher data acquisition rates, and greater flexibility in sensor selection. Any combination of sensors may be fired at almost any frequency. The limitation is that no sensor may be cycled faster than once every 60 ms. The usual result of ignoring this limitation is a blown transistor on the ranging module. Simultaneous firing of all 30 transducers is possible, although acoustic interference may occur; that is, a wave produced by one transducer may be detected by a different transducer.

If multiple sensors transmit every 60 ms, then the acoustic beam reflections from objects in the environment can cause range readings that are not easily analysed. A simple mapping of range data to sensor axis orientation is insufficient and possibly misleading in this case. To be able to make a direct correlation between range value and sensor angle, a wave propagation delay must be introduced into the sensor firing control system. Sensors offset by 60° or more may be fired simultaneously, as acoustic communication between sensors is unlikely if their beam axes form a large angle. With a 40 ms propagation delay, 150 range readings that are correlated to sensor angle can be obtained every second.

To explain how the sonar ring obtains range values, it helps to look at a Pascal procedure named `check.any`. Its use is in obtaining a single range reading from a selected transducer.

```

PROCEDURE check.any(loc: INTEGER);
VAR
  i: INTEGER;
BEGIN
  cnt.write(loc,disarmer);      {disarm counter}
  cnt.write(loc,ldphold);      {point to hold reg}
  cnt.write(loc+1,hold.const); {reload hold reg}
  cnt.write(loc,load);        {load the counter}
  cnt.write(loc,clrtoq);      {adjust o/p level}
  fire_it(loc);               {transmit pulse}
  WAIT_ANY(TIME:= ms_40);     {wait for echo}
  cnt.write(loc,save);        {save the count}
  cnt.write(loc,ldphold);     {point to hold reg}
  range_map[loc]:= cnt.read(loc+1);
  {read register, update array with contents}
END;
  
```

Assuming that the M-Timers have been initialized, the first step in getting a new range value is to disarm the counter. In `check.any`, a 16-bit code stored in the array `disarmer` is written to the appropriate register on one of the two boards. This register location is indicated by the variable `loc`, the input parameter for the procedure.

Next, a new value is loaded into the correct counter, first by pointing to the counter, then by writing the value. `Hold.const` is equal to 14120, which corresponds to 35.3 ms at 0.4 megahertz, the counter's programmed clock rate. At a speed of 340 meters/second, a sound wave travels 12 meters in 35 ms. Ten meters is the maximum range of the transducer and ranging module pair, but for indoor use we find 6 meters to be a more useful maximum range setting.

The value in the load register is loaded into the counter by writing a code from the load array to a command register. This value will be decremented by clock pulses once the counter is armed. The last step before firing is to adjust the level of the output bit for the counter group in question.

After these preliminary steps have been taken, the counter is disarmed, but otherwise ready to begin counting. The procedure `fire_it` writes a command to a register that arms the appropriate counter, starting the count process. Clock pulses decrement the counter, until it has a value of zero. At this point, the output bit toggles to a TTL high-logic-level, which causes the TI sonar ranging module to transmit a pulse through the Polaroid transducer. Simultaneously, the value in the hold register is loaded into the counter, and decremented by clock pulses. The `hold.const` value diminishes until the ranging module receives an echo, stopping the clock pulses, and halting the count. If no echo is received by the time `hold.const` is reduced to zero (in 35 ms), then the counter disarms itself automatically, and toggles the output bit to a low-logic-level. This in turn disables the sonar module.

While sonar ranging is taking place, the Vaxeln process is put "asleep" by a WAIT_ANY command. Forty milliseconds after firing, it is awakened, and the next line of code is executed. A save command is written to a command register, transferring the contents of a counter into its hold register.

The next command causes a pointer to point at the hold register where the count resides. The data register is read accessing the hold register contents. These contents are converted to millimeters in the cnt_read procedure, then stored in the array range_map. The two most current sets of range data are kept in a blackboard area, for easy access from separate processes running on the MicroVAX-II.

7. Results

A sample range scan is shown in **Figure 7**. Sonar range data points are represented here by circular arcs, to account for beam width. The actual shape of the wavefront is not known precisely, but may be modelled by a first-order Bessel function [13]. Readings of 6000 mm indicate that no object exists within 6 meters, and not necessarily that an object has been detected at that distance.

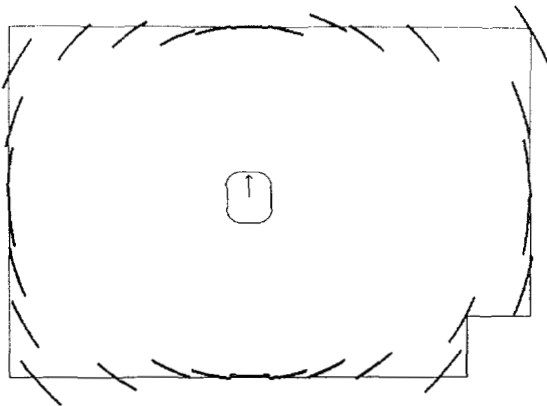


Figure 7. Sonar scan in an empty room, 16'x24'.

A couple of observations are made about this result. It is a typical range scan, not filtered or averaged. Wall surfaces lack uniform texture, complicating the analysis. However, the first detected echo (upon which the ranging is based) originates in most cases from the edge of the beam first contacting the wall.

In corners of the room, multiple reflections occur before the reception of an echo above the detection threshold. This explains the range datum for the upper-right corner of the figure. As the acoustic wave travels a greater distance, the time to echo reception is increased. The best way to treat this case is to expect it beforehand, and include surface orientation information in the a priori map. An example of this approach may be found in [7].

8. Applications

On the GMR mobile robot AutoNav-2, the sonar ring performs two roles. First, it provides a means for safe odometric-based robot movement. Range readings from the three forward sensors are subjected to thresholds so robot motion is sensitive only to obstacles located in the path. When a returned range reading falls below preset thresholds, a flag is set, and the robot brings itself to controlled stop. To reduce the frequency of false detections, sonar range data is filtered through a least median of squares estimator [17]. This filter rejects large erroneous range readings without biasing the rest of the data, as would result from an averaging method.

The second application of the sonar ring on AutoNav-2 is a wall-following sensor. Any flat, vertical surface is followed by servoing on the distance and orientation information provided by the sonar ring. An $R(\theta)$ map of sonar data is maintained using the LMS estimator, and a position and orientation error is supplied to the robot motion controller, which steers the robot according to the given control law.

9. Future

We hope to use the obstacle detection apparatus described to avoid unexpected objects in the nominal robot path, and to do this while in motion. A potential-field approach with repellent obstacles and attractive goal points appears to hold promise. Also to be explored is a phased array sonar transducer with a narrower beam width, higher data rate, axial resolution, and signal-to-noise ratio than comparable long-range pulse-echo sensors.

References

- [1] Advanced Micro Devices, Inc. *Am9519A Universal Interrupt Controller*. Sunnyvale, Cal., 1984.
- [2] Advanced Micro Devices, Inc. *Am9513A/Am9513 System Timing Controller*. Sunnyvale, Cal., 1984.
- [3] C. Biber et al., "The Polaroid Ultrasonic Ranging System," *Proc. 67th Conv. of the Audio Eng. Soc.*, New York, NY, Oct. 31–Nov. 3, 1980.
- [4] B. Carlin, *Ultrasonics*, New York, NY, McGraw-Hill, 1960.
- [5] Codar Technology, Inc. *M-Timer User's Manual*. Document No. 130-1401. Longmont, Colorado, March 1985.
- [6] J. L. Crowley, "Dynamic World Modeling for an Intelligent Mobile Robot using a Rotating Ultrasonic Ranging Device," *Proc. IEEE Int. Conf. on Robotics and Automation*, March 1985.
- [7] M. Drumheller, "Mobile Robot Localization Using Sonar," *A. I. Memo 826, MIT A. I. Lab*, January 1985.

- [8] G. Giralt, R. Chatila, and M. Vaisset, "An Integrated Navigation and Motion Control System for Autonomous Multisensory Mobile Robots," *Proc. First Int. Symp. on Robotics Research*, Bretton Woods, NH, Aug. 28-Sept. 2, 1983.
- [9] R. Hickling and S. P. Marin, "The Use of Ultrasonics for Gauging and Proximity Sensing in Air." *J. of the Acoustical Soc. of Am.*, 79, No. 4, Apr. 1986.
- [10] M. B. Kadonoff, "Navigation Techniques for the Denning Sentry," *Proc. SME Robotics Research Conf.*, Scottsdale, AZ, Aug. 18-21, 1986.
- [11] I. Masaki, "Modular Multi-resolution Vision Processor," *Proc. IEEE Int. Conf. on Robotics and Automation*, April 1986.
- [12] H. P. Moravec, A. Elfes. "High Resolution Maps from Wide Angle Sonar," *Proc. IEEE Int. Conf. on Robotics and Automation*, March, 1985.
- [13] P. M. Morse, *Vibration and Sound*. 1976; rpt. Am. Inst. of Physics, 1981.
- [14] A. M. Parodi, J. J. Nitao, L. S. McTameney, "An Intelligent System for an Autonomous Vehicle," *Proc. IEEE Int. Conf. on Robotics and Automation*, April 1986.
- [15] Polaroid Corp. *Ultrasonic Ranging System*. Cambridge, Mass., Ultrasonic Ranging Marketing Division, 1982.
- [16] Texas Instruments, Inc. *Linear Circuits Data Book*. Dallas: Information Publishing Center, 1984.
- [17] C. M. Wang, "A Robust Estimator For Wall Following," submitted to *Comm. in Statistics*.