Designing and Building a Multiple-Transducer Sonar System

Part 1 of 2: Design concepts, multiplexing, and crosstalk

by David J. Musliner and Rick Moll

Why Use Sonar?

Sonar is one of the most popular range-sensing methods used in mobile robots. Sonar systems providing accurate distance measurements can be built using low-cost, readily available components that are easily interfaced to microprocessor controllers. In this article, Part One of a two-part series, we provide a high-level view of the issues involved in designing a sonar sensing system, and discuss the design decisions made for two robot projects: David Musliner's SMart Autonomous Real-Time Vehicle (SMARTV) and Rick Moll's modular sonar system. Part Two of the series, "Construction and Interfacing", will appear in the next issue of TRP. Together, these articles describe the design and implementation of the two multiple-transducer sonar systems. Rick's sonar system is built around a Motorola 68332 microcontroller, while the SMARTV uses a Motorola 6811 microcontroller board, the MIT 6.270.

Sonar Sensing

Sonar sensors rely on one basic principle: sound bounces! Sound reflects off of surfaces in much the same way that a ball thrown against a wall will bounce back. Typically sonar sensors operate by sending out pulses of sound and then measuring the time between when the sound is sent out, and when the returning echo (the reflected sound pulse) is heard. This measurement technique is referred to as "Time Of Flight", or TOF. Since sound travels at a predictable speed (approximately 1100 ft/s), the echo's TOF will give a measurement of the distance traveled. Depending on the hardware used, the sonar echo may be listened for with the same transducer that generated the sound pulse, or separate transmit and receive transducers may be employed. For a more thorough introduction to sonar principles, see Bart Everett's article in this issue, "Understanding Ultrasonic Ranging Sensors".

Field of View. Various robot implementations have used a variety of ingenious approaches to achieve an increased field of view. These approaches have different hardware and software requirements, as well as differing cost and performance. For example, one of the most cost-effective solutions is the rotating sonar unit used in the now discontinued Heathkit HERO 2000 robot. HERO's sonar transducer points upwards toward an angled plastic reflector. The reflector is mounted on the shaft of a stepper motor, and can be rotated to give a 360 degree coverage in 24 steps of 15 degrees each. By rotating the inert reflector instead of the actual transducer, this organization avoids the need to transmit any electrical signals to the rotating parts. With the exception of the HERO, most sonar systems can be usefully characterized by the physical mounting of the transducers as:

- *Fixed* systems in which the transducers do not move relative to the robot. Fixed systems have their transducers spaced evenly around a ring or otherwise distributed in less-symmetric organizations. For an example of a non-symmetrical organization, see Illah Nourbakhsh's article "The Sonars of Dervish" in this issue.
- *Rotating* systems in which the transducers are mounted on a moving part of the robot, allowing controlled scanning of different regions. See Joe Jones article on RugNav in this issue.
- *Hybrid* fixed/rotating systems in which some transducers are fixed and some rotating. Kurt Konolige's mobile robot, ERRATIC, has a hybrid sonar system with a rotating front sonar unit covering about a 90 degree field of view [Konolige, 1995]. The transducer itself is mounted on the shaft of a servo motor. ERRATIC combines this sweeping front sonar with a set of fixed surrounding sonars placed in side and upward-pointing directions, akin to the strategic placement of sonars in Nourbakhsh's DERVISH.

Fixed-position sonar systems have a number of advantages over rotating systems, including:

- No need to wait for physical rotation, increasing the sensor polling rate.
- Capable of parallel sonar firing, increasing the sensor polling rate.
- No physical rotating parts to wear/break.

On the negative side, because they require more sonar hardware, fixed systems can be considerably more expensive, more power-hungry, heavier, and larger.

In this article we concentrate on methods that use multiple sonar transducers to achieve a broad field of view for a robot. In principle that could mean two rotating sonars each scanning 180 degrees, or it could be 24 fixed sonars spaced evenly around a ring, or even fixed-position sensors mounted in an asymmetric configuration. We will address many of the design decisions and implementation methods needed for any of these approaches.

Crosstalk. When multiple sonar sensors are used in close proximity, and especially when they are mounted on the same robot, crosstalk is virtually inevitable. Crosstalk occurs when one sonar "hears" the pulse from another sonar, thus getting an erroneous range reading. Crosstalk can arise from acoustic conditions that bounce the sound waves between two sonars, and also from electrical interference between sonars. We will describe the crosstalk problems encountered with our sonar systems, and the hardware and software solutions we have developed in response.

Drivers and Interfacing. Sonar transducers typically must be driven with high voltages, on the order of several hundred volts. Consequently some kind of driver must be used when interfacing to a controller. This driver may also assist the controller with the TOF measurement.

A variety of sonar drivers and chip sets are available. However the Polaroid 6500 Series Sonar Ranging Module is by far the most common, especially within the robotics community. The driver is readily-available, being purchasable directly from Polaroid, and gives good off-the-shelf performance. Polaroid sells an "OEM" kit, which consists of two drivers and two transducers for about $100 US. Interfacing the driver to a controller is quite simple. A sonar pulse is generated by applying a rising edge to its INIT line. When the driver detects an echo it generates a rising edge on its ECHO line. By measuring the time between these two events, the controller can determine the TOF.

Sonar System Design

Building a sonar system with multiple transducers poses a number of significant challenges, including:

- Cost: more transducers and driver electronics are required.
- Power: sonar electronics require significant electrical power.
- Interfacing: triggering and measuring the TOF for multiple sonar transducers can require a large set of I/O channels, complex software, and even significant computational power.
- Size: the multiple transducers and driver electronics can consume a lot of space.
- Crosstalk: sonar systems employing multiple drivers can have significant crosstalk problems.

Consequently, designing a multiple-transducer sonar system involves making a number of decisions. Each of these decisions will have impact on the various costs and requirements of the system, as well as its performance.

Number and Placement of Transducers. Given a 15 degree field of view for each individual transducer, 24 transducers are required for full, gap-free 360 degree coverage. The use of this large number of transducers can result in a very expensive system. For example, the Polaroid transducers sell for approximately $16 US each–the $384 required for the 24 transducers, let

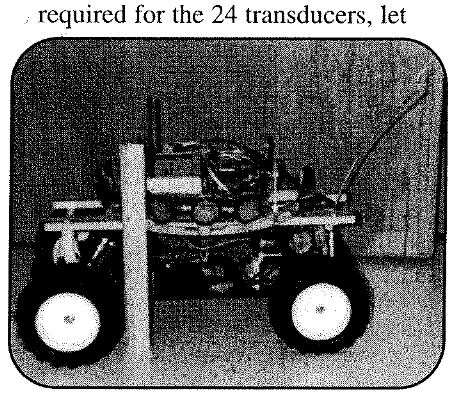

Figure 1: *The SMARTV robot with ruler showing its size.*

alone any drivers, may be outside of many budgets. The power and interface requirements for such a large ring may also be prohibitive.

The SMARTV (see Figure 1) was built to use 16 evenly-spaced transducers, giving a good compromise of cost and coverage. The SMARTV ring leaves close-range gaps in sonar coverage that can then be covered by lower-cost short-range sensors such as infrared or capacitance-based units. Often this tradeoff is acceptable because very-short-range measurements are less important to mobile robots, and the lower-cost sensors provide a reasonable stopgap measure.

Multiplexing–The Ratio of Transducers to Drivers. Another important design decision is whether to use separate drivers for each transducer, or to multiplex several transducers to each driver. While the highest performance can only be achieved when each transducer has its own independent driver, for many applications it makes sense to multiplex. Multiplexing can dramatically reduce the cost, power consumption, volume, weight, and interface demands of a multiple-transducer system. If, for example, a 24 transducer system uses three 8-to-1 multiplexers to connect 24 sonar transducers to just three sonar drivers, the cost, power, space, and I/O lines needed is significantly reduced. The primary disadvantage to multiplexing is the loss of the ability to fire all of the sonars simultaneously; with three driver boards, only three transducers can be fired at the same time. Of course, crosstalk problems generally prohibit simultaneous firing of 24 sonars anyway, so this disadvantage is less extreme than it might seem. In addition, the relatively simple controller hardware used by many small robots may simply not be able to interface to that many drivers, so again multiplexing may be the only viable option.

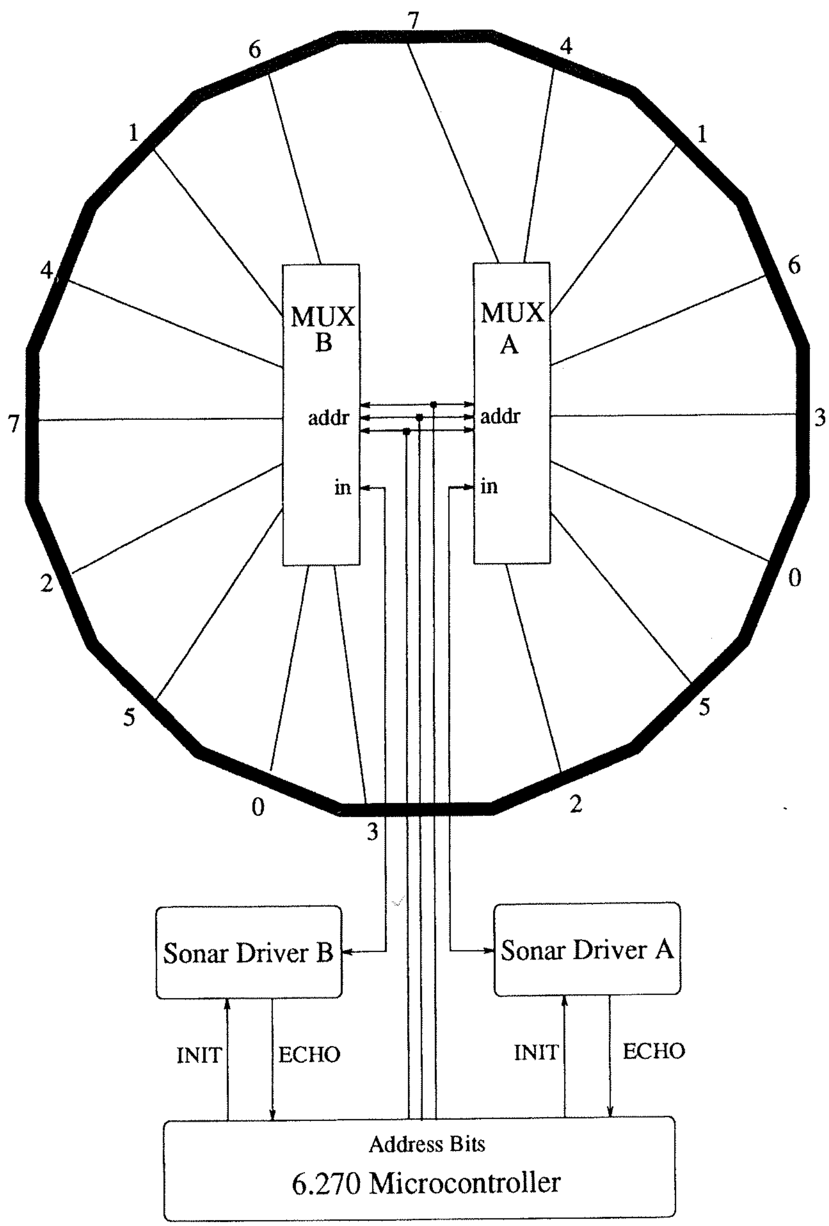

Figure 2: *Block diagram of SMARTV's multiplexed sonar system.*

Interfacing–The Number of Address Lines. Given decisions about multiplexing and the total number of transducers, there are still options on how to interface the multiplexers to the controller, depending on what level of transducer addressing is desired. At one extreme, each multiplexer can be individually addressed by the controller. Thus if M K-to-1 multiplexers with M drivers are used to control M*K transducers, M*log2(K) address lines would be required. This is the approach taken with Rick's 68332 microcontroller based modular sonar system.

At the opposite extreme, a minimalist system could use a single driver and a counter circuit with an increment line to cycle through the transducer addresses, giving an addressing interface with only one line. This approach is less desirable because it does not allow any parallel firing at all, and does not support random addressing in a straightforward manner.

There are an almost infinite variety of intermediate solutions as well. For example, the SMARTV sonar system (see Figure 2), because of its limited 6811 microcontroller board, uses two 8-to-1 multiplexers, sharing three address lines. Both multiplexers are always active. With this approach they will always track the three address lines together, but it does allow for random access to any pair of transducers. Note that the two sonar drivers (Polaroid 6500 Series) are independently controlled, thus allowing for simultaneous TOF measurements.

When making a decision about addressing, it is important to remember that the multiplexers must not be switched during the TOF measurement. The sonar driver must remain connected to the same transducer, through the multiplexer, for the entire pulse-to-echo period.

Electrical Power. Another important aspect of sonar system design is providing electrical power for the sonar driver. A number of important issues need to be considered:

- peak power consumption
- steady state power consumption
- electrical noise generation
- electrical noise susceptibility

When a driver generates a sonar pulse significant peak power can be consumed. For example the Polaroid 6500 Series driver can consume up to 2A during the transmit period. Because of this large power peak, sonar drivers can also generate significant electrical noise. Often a "filter" and/or "energy storage bank" must be used to provide the driver's peak power requirements, while also reducing the electrical noise the driver generates back into the power bus.

Not only can sonar drivers generate a lot of electrical noise on the supplying power bus, they can also be very susceptible to noise on the bus from other sources (like other sonar drivers). After a sonar driver generates a pulse it must then listen for the returning echo. This returning echo can be very weak, especially at large distances, requiring a large amplification of the echo signal. This amplifier within the driver can be very susceptible to false echo triggering in the presence of noise on the power supply.

Besides requiring large amounts of peak electrical power, sonar drivers can also have large steady state power requirements. Again using the Polaroid 6500 Series sonar driver as an example, this driver can consume 100mA at 5V, or 500mW. While this may not seem like much, if a large sonar ring with 24 sensors is used, with a driver for each transducer, 12W of power will be consumed for the sonars alone! This can be a daunting amount of power for a small robot and explains the use of huge lead-acid batteries in some large research robots employing sonar rings.

Electrostatic Crosstalk. Very high voltages (often on the order of hundreds of volts) are used by drivers to pulse sonar transducers. Because of these high voltages large electrostatic pulses can be generated. On multi-sonar systems, these electrostatic pulses can cause crosstalk between drivers. Because of the small echo signals that drivers must detect (sometimes in the range of microvolts) they can be very sensitive to electrostatic interference unless proper precautions are taken. This can especially be a problem with multiplexed drivers where long cables are often employed to connect to the transducers. However, even if shielded cables are used, the transducers themselves, if in close proximity, can couple electrostatic crosstalk between them. Because of this, multi-driver sonar systems must often not only use shielded cables, but must also shield the transducers and the multiplexer.
It is important to understand that it is in the use of multiple drivers that one must be careful; because when multiple drivers are used, one driver may be listening, when another driver fires a pulse. A single driver system will not have this problem. However, long unshielded cables and the use of a multiplexer will increase the sonar system's susceptibility to electrostatic interference from other near-by robots using sonar, or from nearby LCD screens like those used in laptop computers!

"The other major source of interference between sonar sensors is acoustic crosstalk–in which one transducer actually "hears" the echo of another transducer's sonar pulse."

Acoustic Crosstalk. Besides electrostatic crosstalk the other major source of interference between sonar sensors is acoustic crosstalk–in which one transducer actually "hears" the echo of another transducer's sonar pulse. We have implemented software techniques that attempt to detect and eliminate acoustic crosstalk between sonars. These methods are based on the patented Error Eliminating Rapid Ultrasonic Firing (EERUF) method developed by Borenstein and Koren [1995]. The basic idea they developed was to fire a ring of sonars in sequence very rapidly, but essentially alternating between two different schedules of firings, so that any pair of sonars is first fired with a certain unique time delay between them, and then on the next cycle, with a different delay between them. If crosstalk is occurring between sonars, this variation in the timing relationships will appear as a variation in the sonar distance readings, which can easily be detected to ignore (eliminate) those crosstalk-affected readings. In other words, if one sonar is hearing another's pulse and the delay between the firing of those two sonars is varied, then the crosstalk-impaired sonar will return varying readings. Of course, legitimate changes in sonar readings are caused by motion of the robot or detected obstacles, and we would not want to ignore those accurate but varying readings. Because subsequent EERUF sonar readings are taken very close together (rapidly), legitimate variations due to motion are small compared to the variations induced by the alternating firing delays. In the next part of this article, EERUF, as well as modifications useful for low-cost multiplexed systems, will be examined in more detail.

Conclusion

In part 1 of this article we have discussed why sonar is a popular range-sensing method for mobile robots. We have shown various approaches used by roboticists to deal with sonar's limited field of view. We have shown the tradeoffs involved in the design of multi-transducer sonar systems.

In the next issue of TRP we will conclude this article by presenting the construction techniques needed to build multi-transducer sonar systems. We will present a detailed design using the Polaroid 6500 Series driver, a custom multiplexer, and software implementing acoustical crosstalk elimination techniques.

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