

# **Bat-Like Sonar for Guiding Mobile Robots**

**Roman Kuc and Billur Barshan**

The problem of docking mobile robots using a bat-like sonar system is considered in the context of prey capture in two dimensions. Two measures of performance are discussed: the capture probability and the mean capture time when capture occurs. These measures are evaluated as a function of the ratio of speeds of the prey to the pursuer and in terms of the control strategies employing either quantitative information (range and azimuth to prey) or qualitative information (prey is to the left or right). By constraining the prey motion to be linear, the lower bound for the capture time can be determined from game theory, which assumes complete information about the prey. The analysis is verified through simulations and by performing experiments with real mobile

robots. Both capture probability and mean capture time are observed to be inversely related to the prey/pursuer speed ratio. It is also observed that, while qualitative information is sufficient for capture, quantitative information allows capture to occur over a larger range of speed ratios. Some speculation on effective avoidance tactics by biological prey is presented. Overall, the results demonstrate that the bat-like sonar represents an efficient sensing system.

## **Prey-Capture Ability of Bats**

How do bats manage to catch insects? While the basic ideas have been known for some time [1], the availability of improved instrumentation has allowed this question to be reexamined by neuroscientists [2] and psychologists [3], [4], exploring the perception of the sonar signals and their mapping in the brain. From the engineering perspective, bat echolocation was analyzed by applying optimum correlation detection for binaural estimation of travel time and prey location [5]. Attempts are being made at applying some of these principles into hardware [6].

The same question is also relevant in the field of robotics. The prey-capture ability of bats impacts directly on the problem of docking two robots, which is becoming important in multi-robot systems. This problem has been

*The authors are with the Intelligent Sensors Laboratory in the Department of Electrical Engineering, Yale University, New Haven, CT 06520-2157. Billur Barshan is now with the Robotics Research Group, Dept. of Engineering Science, University of Oxford, OX1 3PJ, United Kingdom. Some of this material was presented at the 1991 IEEE International Conference on Systems, Man and Cybernetics, Charlottesville, VA, October 13-16, 1991 and at the 1991 SPIE Conference on Intelligent Robotic Systems, Boston, November 13-14, 1991. This work was supported by the National Science Foundation under Grant ECS-8802627.*

investigated by using infrared sensors [7] and by using camera vision [8]. We demonstrate that sonar can also accomplish docking. Acoustic ranging systems provide a convenient and inexpensive means for determining the proximity of objects and have been useful for implementing sonar systems for robot navigation [9]-[11], registration [12], obstacle avoidance [13], [14] and sonar map building [15], [16]. The main problem with current sonar systems, however, is that they do not work very reliably in unstructured environments. Problems arise in the straightforward, but naive, interpretation of the time-of-flight (TOF) reading: Objects that are present are not always detected and range readings produced by the TOF system do not always correspond to objects at that range [17], [18]. But in the robot docking problem, in which there is some control over the reflecting properties of the target and the environment, we show that sonar is a suitable sensing system.

A *bat-like* sonar system has been implemented by mimicking the sensor configuration of bats and applying some of their techniques for interpreting sonar signals [19]. We refer to our sonar-equipped pursuer mobile robot as  $R$ , for ROBAT, and to the prey mobile robot as  $M$ , for MOTH. In our simple model,  $M$  has no sensory feedback and is a passive prey unaware of the presence of  $R$ . Some insects do possess elementary sonar sensors and attempt to avoid capture by bats [20]. We will speculate on the general tactics of avoidance after we describe our system.

To gain insights about the effectiveness of sonar, we consider a simple model of prey capture in two dimensions (in a plane), in which  $M$  is the only obstacle present. Using this simple model, we can answer questions about the efficiency of sonar, what information is necessary for capture to occur and the types of control strategies that can be employed. Two measures of performance are employed: probability of capture and mean capture time after initial detection (if capture occurs). To allow analytic and experimental results to be compared, the capture of prey having *linear motion* is considered. Not only is this a reasonable model for some types of prey and for robot docking applications, but also the minimum capture time can be determined from the pursuer/evader problem in game theory [21], which assumes perfect knowledge regarding the location and trajectory of the evader.

For the controls community, the problem of prey capture may be reminiscent of target tracking and proportional navigation. However, there are some important differences. First, while in the tracking problem [22], an optimum estimate of the target location is desired, here the object is to *complete a task* and the feedback may compensate for location errors. Further, it is usually assumed that the measurements contain the true locations of the target, albeit in the presence of noise-induced errors. This is true here also, but only over a finite region, called the *receptive field*. Outside the receptive field, there is no perception of the prey. Since the prey can escape from the receptive field, either intentionally or by luck, we also include the *capture probability* as a performance criterion. In proportional navigation [23] the problem is usually treated in continuous-time or in discrete-time with uniform sampling, while the bat problem is inherently a discrete-time problem because of the discrete echoes. To improve its performance, the bat employs a very clever trick: it transmits the next interrogation pulse as soon as the echo from the previous pulse is received [1]. Since the range usually decreases during pursuit, an *asynchronous sampling* system results. This approach not only provides sufficient information for prey capture at every stage of pursuit, but allows the bat to follow the increasing perceived angular displacements of the prey as the range decreases.

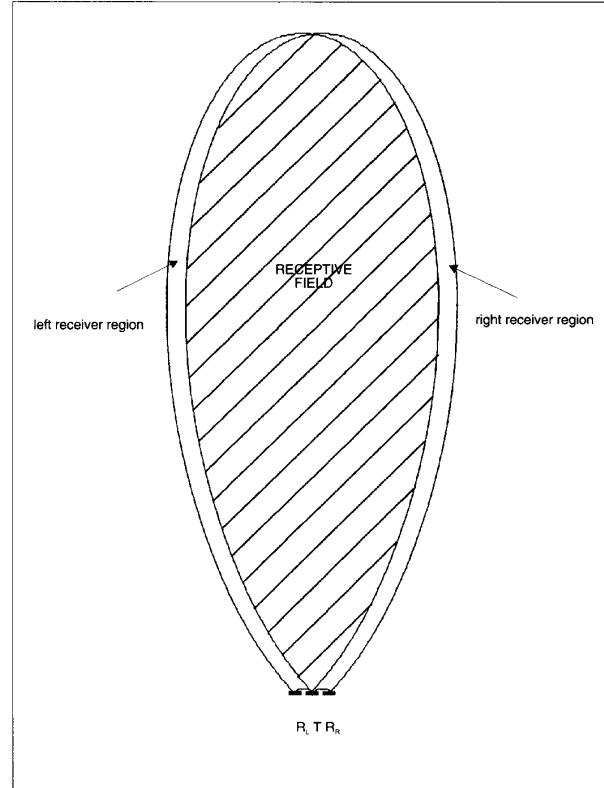


Fig. 1. Sonar receptive field for a cylindrical reflector.

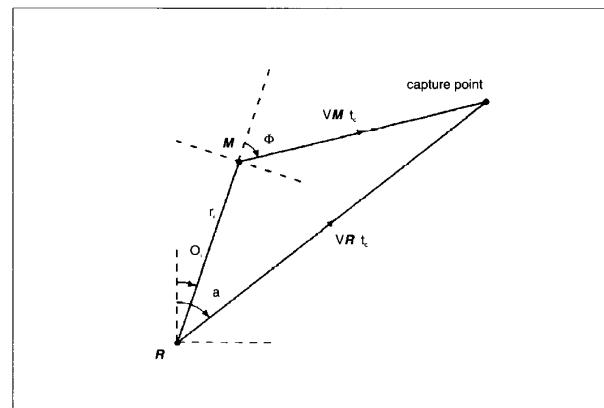


Fig. 2. Scenario for minimum capture time using complete knowledge of linearly moving prey.

In this article, the principles governing the bat-like sonar are described first. We then present two different control strategies that are based on the type of information available. The bounds on capture time are then derived from game theory. Our simulation studies are presented next, followed by the experimental verification using our laboratory mobile robots. The article ends with some speculation on the biological interpretation of these results for capture avoidance.

## Bat-Like Sonar

### Beam Pattern

In searching for prey, a bat transmits a ultrasound pulse from its mouth and/or nose. Since the dimensions of the mouth are comparable with the wavelength of the radiated pressure waves, the pulse is contained in a very wide beam and propagates with a spherical wave front. If  $r$  is the distance from the transmitter (mouth),  $\theta$  is the azimuth,  $\sigma_r$  is a measure of the beam width and  $p_o$  is the propagating pressure amplitude at range  $r_o$  along the line-of-sight ( $\theta=0^\circ$ ), then a reasonable approximation for the pressure amplitude pattern of the propagating pulse is given by [24]

$$p(r, \theta) \approx \frac{p_o r_o}{r} e^{-\frac{\theta^2}{2\sigma_r^2}} \quad \text{for } r > r_o. \quad (1)$$

For our bat-like sonar, we employ the Panasonic ultrasonic ceramic microphone (EFR-OSB40K2 [25]), that is used both for transmitting and receiving signals. This transducer has a radius of 5.2 mm and is resonant at 40 kHz. Using the sound speed value  $c = 343$  m/s [26], the wavelength ( $=f/c$ ) is equal to 8.6 mm. The beam-width parameter  $\sigma_r$  is equal to  $30^\circ$  and a reasonable value for  $r_o$  is 10 cm.

The amplitude pattern given by (1) is similar to that produced by a laser beam: the intensity forms a circular pattern that is strongest in the center and decreases with angular deviation  $|\theta|$ . Since the diameter of the beam increases with range, conservation of energy requires that the pressure amplitude varies inversely with range.

### Echo Amplitude

For two-dimensional prey capture in our laboratory, we employ a tall vertical pole-like object since it is an omni-directional reflector in the horizontal dimension. The incident wave is approximately plane over the dimensions of the pole. After being reflected, the plane incident wave is converted into a cylindrical echo, whose amplitude decreases as the inverse square root of the distance traveled. If the receiver has the same dimensions as the transmitter, the case in our sonar, the receiving sensitivity has the same angular dependence as given in (1). If  $r_1$  and  $r_2$  are the distances, and  $\theta_1$  and  $\theta_2$  are the angles of the object relative to the transmitter and the receiver, respectively, the amplitude of the echo from a pole is given by

$$A(r_1, r_2, \theta_1, \theta_2) \approx \frac{A_o r_o^{\frac{3}{2}}}{r_1 \sqrt{r_2}} e^{-\frac{-(\theta_1+\theta_2)}{2\sigma_r^2}} \quad \text{for } r_1, r_2 > r_o. \quad (2)$$

$A_o$  is the echo amplitude observed when the transmitter and receiver are coincident, for which  $r_1=r_2=r_o$ , and  $\theta_1=\theta_2=0^\circ$ . As an analogy in three dimensions, a small point-like target produces a spherical echo having a denominator term above equal to  $r_1 r_2$ , in which case (2) becomes equivalent to the well-known radar equation [27].

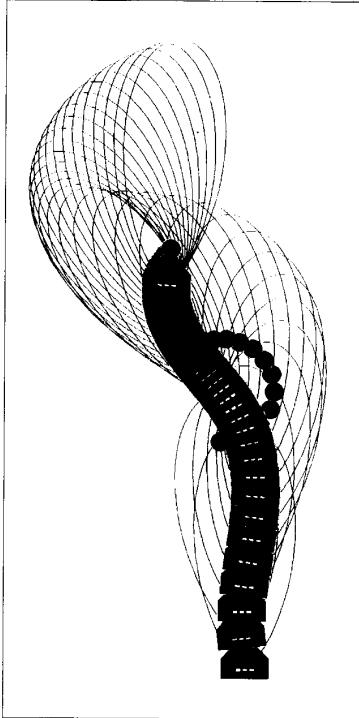


Fig. 3. Simulation showing capture of  $M$  moving away in a sinusoidal pattern. Locations are shown  $T_s$  s apart.

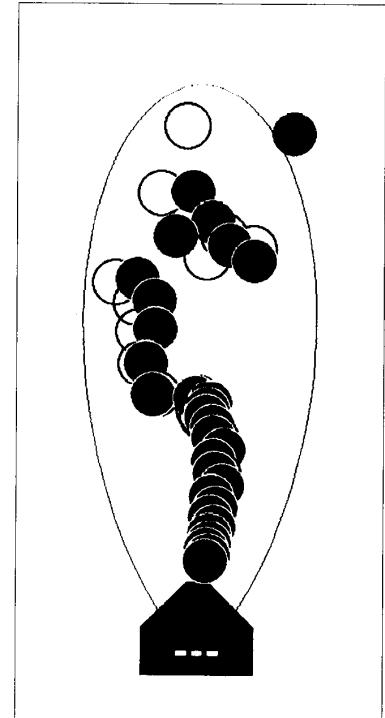


Fig. 4. Simulation showing the perceived and actual locations of  $M$  relative to  $R$  in the bat frame of reference. Open circles—perceived locations, closed circles—actual locations.

In our system, three identical sensors are situated linearly with a center-to-center separation denoted by  $d$ , equal to 6 cm. The middle transducer  $T$  (mouth) transmits an acoustic pulse, and the two side receivers  $R_L$  and  $R_R$  (left and right ears) detect the echoes. An obstacle can be located, if it produces an echo that exceeds the detection thresholds in both ears. If the threshold is denoted by  $\tau$ , then we define the *receiver region* of a transmitter/receiver pair as the set of points in space for which  $A(r_1, r_2, \theta_1, \theta_2) > \tau$ . The *receptive field* of the sonar system is then the intersection of the receiver regions corresponding to the left and right ears, shown in Fig. 1, and represents the region over which the pole location can be determined. For the transducer pairs  $T-R_L$  and  $T-R_R$ , the equal amplitude contours of  $A(r_1, r_2, \theta_1, \theta_2)$  corresponding to  $\tau=40$  dB relative to the maximum amplitude are drawn to scale. The sensor spacing is 6 cm.

### Location Estimation

The echoes are always detected in the presence of noise. Analyzing the noisy echoes detected by the two receivers, the range  $r$  and azimuth  $\theta$  of an obstacle in the receptive field are estimated from the value of TOF at each receiver and are measured from the transmitter. The TOF, denoted  $t_{\text{TOF}}$ , is defined as the time after transmission that the noisy echo amplitude first exceeds the threshold  $\tau$ . The distance estimate from the left ear, denoted by the  $\hat{t}_L$ , is then equal to

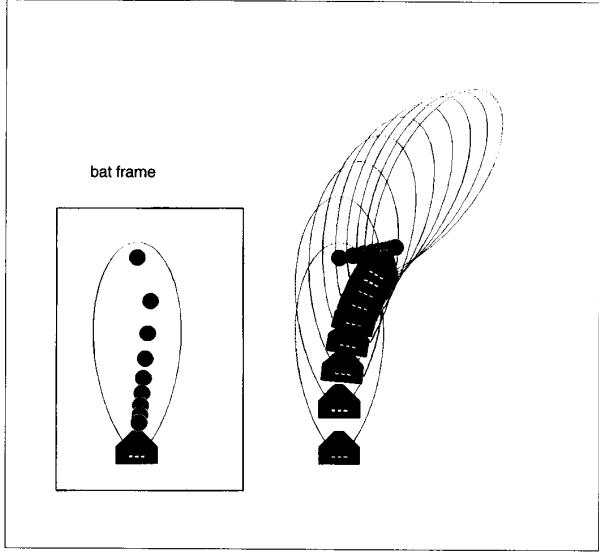


Fig. 5. Simulation showing trajectories using quantitative information.  $\mathbf{R}$  points in the direction of  $\hat{\theta}$  and moves forward each  $T_s$  s.

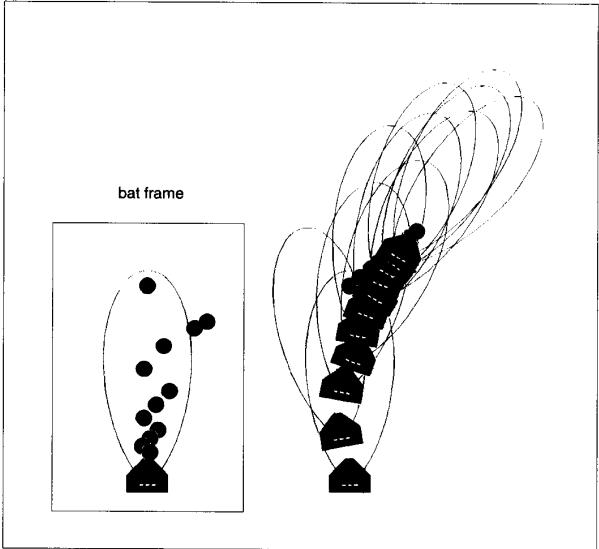


Fig. 6. A simulation showing trajectories resulting from the bang-bang method and the qualitative information. The bang-bang angle is  $10^\circ$ .

$$t_L = ct_{TOF,L} \quad (3)$$

This distance restricts the possible locations of the obstacle to lie on an ellipse whose foci are at  $T$  and  $R_L$ . A similar result holds for  $\hat{t}_R$  from the right ear. The two ellipses intersect at the *perceived location* of the obstacle  $\mathbf{M}$ , at range

$$r = \frac{\hat{t}_L^2 + \hat{t}_R^2 - 2d^2}{2(\hat{t}_L + \hat{t}_R)} \quad (4)$$

in front of  $\mathbf{R}$  and azimuth

$$\hat{\theta} = \sin^{-1} \left[ \frac{(\hat{t}_L \hat{t}_R + d^2)(\hat{t}_L - \hat{t}_R)}{d(\hat{t}_L^2 + \hat{t}_R^2 - 2d^2)} \right]. \quad (5)$$

### Control Strategies

Two control strategies are described that use different levels of information to direct  $\mathbf{R}$  to  $\mathbf{M}$ . Both are memory-less, assume no knowledge of  $\mathbf{M}$ 's motion and extract information sequentially from the echoes.  $\mathbf{R}$ 's information about  $\mathbf{M}$  is obtained from each scan and consists of estimates of  $r$  and  $\theta$  whenever  $\mathbf{M}$  is within the receptive field.

#### Quantitative Information

The estimates  $\hat{r}$  and  $\hat{\theta}$  from the most recent echoes represent the perceived location of  $\mathbf{M}$ . Due to the echo travel time, delayed estimates of  $\mathbf{M}$ 's position are observed. Of the two estimates,  $\hat{\theta}$  is more important for prey capture to occur, although the range estimate is useful for planning purposes, e.g., when  $\hat{r}$  is small the mouth should open. Given  $\hat{\theta}$ ,  $\mathbf{R}$  responds by making a rotation that centers the beam on  $\mathbf{M}$ 's current perceived location, transmitting a new interrogation pulse and then moving forward. This maneuver positions  $\mathbf{M}$  around the most sensitive part of the beam for the next echo. The signal-to-noise ratio (SNR) of the next echo is also improved by decreasing the range, by reducing the losses due to absorption [26] and diffraction, or  $r-3/2$  in (2). This procedure is repeated as  $\mathbf{R}$  approaches  $\mathbf{M}$ . Our system also includes a technique that is used by bats: a new interrogation pulse is transmitted soon after the echo is detected and processed. Because of the relatively slow speed of sound, this results in a type of asynchronous sampling in which distant prey are sampled less frequently than close prey. As pursuit ensues and the separation is reduced, this decrease in sampling period allows the increasing perceived angular motion of the prey to be followed more accurately.

#### Qualitative Information

In this case, only one bit of information is given to  $\mathbf{R}$ : whether  $\mathbf{M}$  is to the right ( $\theta < 0$ ) or to the left ( $\theta \geq 0$ ) of center. This information is available to the biological bat by simply comparing the arrival times of the echoes at the two ears. The response by  $\mathbf{R}$  that we consider is a rotation by a fixed angle  $\beta$  to the right or to the left, a transmission of a new pulse and a move forward. This *bang-bang* strategy employs the minimal information required to achieve prey capture. Previous results [8], [21] indicate that successful prey capture can be accomplished by employing the direction  $\theta$  of  $\mathbf{M}$  relative to  $\mathbf{R}$ . Our condition is less restrictive, indicating that only this binary information is sufficient for capture, as shown below.

### Bounds on Prey Capture

A simple lower bound for the capture time can be determined if we constrain the prey to move along a linear trajectory at speed  $V_M$ . Suppose that  $\mathbf{R}$  can move with speed  $V_R$  and detects  $\mathbf{M}$  initially at  $r_i$  and  $\theta_i$ , as shown in Fig. 2. With complete information about  $\mathbf{M}$ 's linear path (i.e.,  $r_i$ ,  $\theta_i$ ,  $\Phi$  and  $V_M$ ),  $\mathbf{R}$  wants to intercept  $\mathbf{M}$  as quickly as possible to minimize its energy expenditure, a reasonable biological cost function

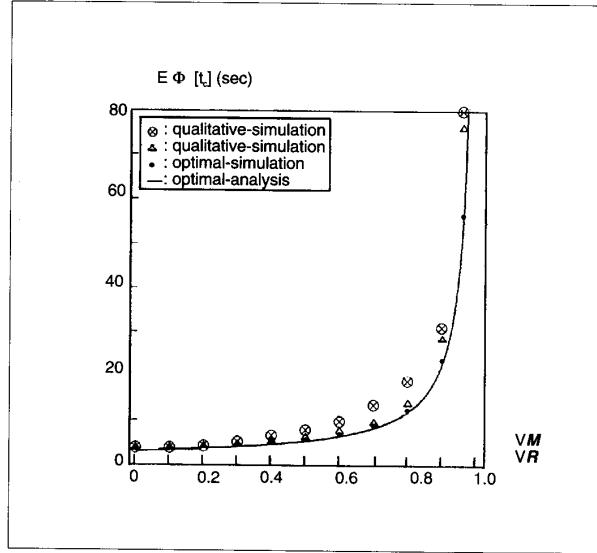


Fig. 7. Mean capture time versus  $V_M/V_R$  for  $V_R=50$  cm/s,  $r_i=2$  m ( $T_s=1$  s),  $\theta_i=0^\circ$ .  $\beta=10^\circ$  for qualitative system.

[28]. Then a unique linear trajectory with orientation  $\alpha$  is determined from game theory [21] with

$$\alpha = \theta_i + \sin^{-1} [(V_M/V_R) \sin \Phi]. \quad (6)$$

The capture time is then equal to

$$t_c = \frac{r_i \left[ (V_M/V_R) \cos \Phi + (1 - (V_M/V_R)^2 \sin^2 \Phi)^{1/2} \right]}{V_R \left[ 1 - (V_M/V_R)^2 \right]} \quad (7)$$

Capture time is observed to be finite only if  $V_M < V_R$ , independent of  $\theta$ , and a maximum when  $\Phi=0$ . This means that moths that flee directly away from the bat maximize the time to capture.

### Simulation Studies

To provide flexibility in varying the values of the various parameters discussed above, prey capture was simulated by a program that models the physical principles of the actual sonar system, described by (1)-(4), on a VAX 3100 work station.

#### Bat/Moth Model

In the simulations, the known locations of  $\mathbf{M}$  relative to the sensors indicate the amplitudes, by (2), and delays of the echoes to the right and left ears by (3). A narrow band echo waveform typical of the Panasonic sensor is assumed [19] and white Gaussian noise having a specified variance is added to the echo waveform to generate the observed signal at each ear. In our model, the SNR value is specified by the ratio of the echo amplitude from  $\mathbf{M}$  located 2 m from  $\mathbf{R}$  at  $\theta=0$  to the noise standard deviation. A typical SNR value is 20 dB. Note that the SNR increases as  $\mathbf{R}$  approaches  $\mathbf{M}$  because of the range-dependent echo amplitude. The detection threshold level  $\tau$  is set equal to five times the noise standard

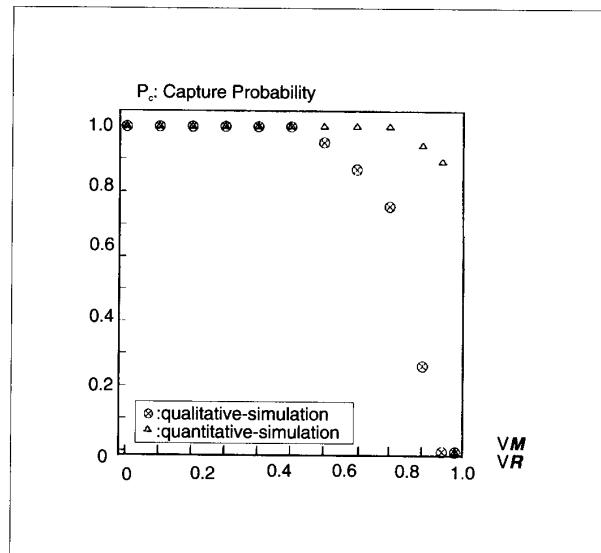


Fig. 8. Capture probability versus  $V_M/V_R$  for  $V_R=50$  cm/s,  $r_i=2$  m ( $T_s=1$  s),  $\theta_i=0^\circ$ .  $\beta=10^\circ$  for qualitative system.

deviation to prevent the occurrence of spurious detection, thus defining the receptive field. The time that the echo plus noise exceeds the threshold determines  $t_{TOF}$  from which  $\hat{r}$  and  $\hat{\theta}$  are computed by using (3), (4) and (5).  $\mathbf{R}$  reacts to this perceived location of  $\mathbf{M}$  by rotating toward that direction, transmitting a new pulse and moving a distance determined by its speed  $V_R$  and the scan interval between successive echoes, denoted by  $T_s$ . The value for  $V_R$  was chosen to be 50 cm/s, corresponding to the maximum speed of ROBAT. The value of  $T_s$  is determined from the TOF plus any processing time. To agree with our physical robots,  $T_s$  was set proportional to range and equal to 1 s at  $r=2$  m.

In both the simulations and experiments,  $\mathbf{M}$  was programmed to produce a variety of trajectories: linear, circular, sinusoidal with drift and random. The random motion was generated by applying independent white Gaussian random variables to two (x- and y-position) second-order digital filters that then produced a correlated sequence of (x, y) coordinates that  $\mathbf{M}$  followed. The values of  $V_M$  and  $T_s$ , determine the distance traveled by  $\mathbf{M}$  before the next echo is detected. In the simulations,  $\mathbf{R}$  was not dynamically limited, in that it was able to accomplish the required rotation and translation indicated by the sensor data.

The simulation is started with  $\mathbf{M}$  located within  $\mathbf{R}$ 's receptive field, with  $r_i=2$  m and  $\theta_i=0^\circ$ , and fleeing at a random orientation  $\Phi$ .  $\mathbf{R}$  pursues  $\mathbf{M}$  using the information derived from the echoes and the time to capture is observed, if capture occurs. If  $\mathbf{M}$  escapes out of the receptive field,  $\mathbf{R}$  responds by a saltatory search with  $\pm 45^\circ$  rotations that explores the maximum possible area. If  $\mathbf{M}$  is not detected within 12 cycles of saltatory search,  $\mathbf{M}$  is considered to have escaped, resulting in a decreased probability of capture.

A typical example of  $\mathbf{R}$  pursuing  $\mathbf{M}$  is shown in Fig. 3. In this *global frame of reference*, time progresses from the bottom of the figure to the top.  $\mathbf{R}$  is represented by its triangular base with the sonar system, illustrated by a set of three small rectangles, located at the center of rotation. The receptive field is shown in outline. In this example,  $V_M=25$  cm/s ( $V_M/V_R=0.5$ ). The sequence of  $\mathbf{M}$ 's locations is shown as solid

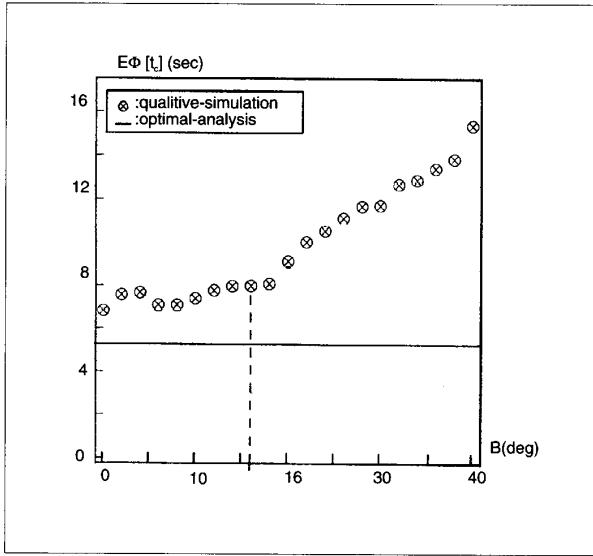


Fig. 9. Mean capture time versus  $\beta$  for  $V_R=50$  cm/s and  $V_M=25$  cm/s,  $r_i=2$  m and  $\theta_i=0$ .

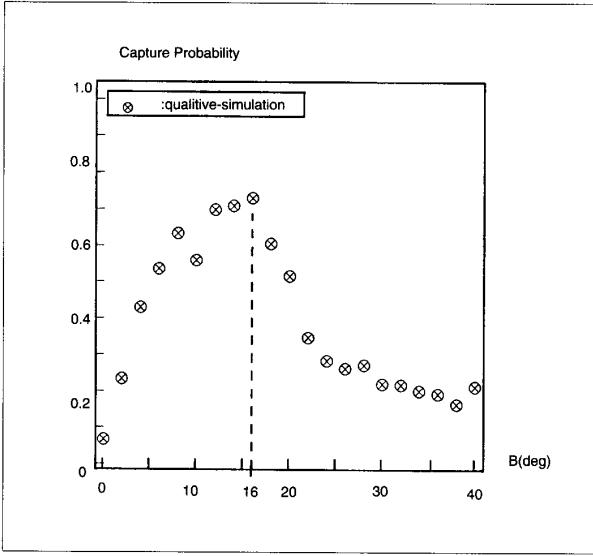


Fig. 10. Capture probability versus  $\beta$  for  $V_R=50$  cm/s and  $V_M=25$  cm/s,  $r_i=2$  m and  $\theta_i=0$ .

dots, added with each measurement spaced  $T_s$  apart. As  $R$  approaches  $M$ ,  $T_s$  decreases and the dots become closer together.

A better view of the process is obtained by shifting the origin of the coordinate system to the location of  $R$ , as shown in Fig. 4. In this *bat frame of reference*, the relative positions of  $M$  are shown as  $R$  closes in for capture. The solid circles show the actual locations of  $M$ , while the open circles show the perceived locations. The errors tend to be greater at larger ranges because of the lower SNR of the echoes. As the bat approaches its prey, there is an increase in echo amplitude, due to decreased  $r^{-3/2}$  loss, that reduces the location estimator variance. The

increasing sampling rate causes the successive locations to be increasingly correlated, helping  $R$  track  $M$  more accurately.

In the case of *linearly moving prey*, both displays are useful for observing the performance. In the global frame, game theory indicates that with perfect knowledge the bat trajectory to the capture point should be linear. In the bat frame, perfect knowledge also produces a linear trajectory. Any deviations from these linear trajectories indicate the effects of noise, the finite receptive field and the control strategy employed.

A typical trajectory using quantitative information ( $\hat{\theta}$ ) is shown in Fig. 5 using the same parameter values as above. We note that there is only a slight deviation from a linear path, indicating that the information provided by the sonar is not much worse than the complete information regarding  $M$ 's trajectory. If  $R$  is able to keep  $M$  close to the center of the receptive field, where the location errors are the smallest, then there is only a small penalty associated with using sonar. Of course, if we know  $M$ 's motion to be linear, we can do better by predicting the next location and moving toward it [29]. But in this paper we consider capture process to be memory-less, or based only on the most recent echoes.

The trajectory using the qualitative information and bang-bang control with  $\beta = 10^\circ$  is shown in Fig. 6. Note that  $R$ 's motion is not as smooth as with the quantitative method.  $M$ 's initial location in the center of the receptive field caused  $R$  to turn to the left, while  $M$ 's motion was to the right.  $M$  then appeared at the extreme right side of the receptive field at the next sensing time. The limited response of  $R$  and the motion of  $M$  caused the next location to be outside the receptive field. At this point, the only advantage of the qualitative system was exploited: to obtain the correct binary location information, it is sufficient to have the threshold exceeded in *only one ear*. If an echo is detected in the right ear but not in the left ear, then the prey must be to the right. Hence, for qualitative information, the receptive field is the union of the two receiver regions, rather than the intersection, as shown in Fig. 1.

#### Performance Evaluation

The capture probability and mean capture time were evaluated for the two receptive-field limited information cases. The capture time results were compared to the bound predicted from game theory. The mean capture time was computed by evaluating the expectation analytically over the angle  $\Phi$  in the range  $[-\pi/2, \pi/2]$  [30]. In the simulations, one hundred realizations of pursuit were generated by randomizing the value of  $\Phi$ . The simulation results are shown in Figs. 7-10. The following parameters are observed to be important for prey capture.

**Effect of Speed Ratio  $V_M/V_R$ .** The speed of  $M$  compared to  $R$  is the most important factor for accomplishing prey capture. Mean capture time and capture probability are shown as functions of  $V_M/V_R$  in Figs. 7 and 8. As expected, quantitative information yields better performance than qualitative information, but there is a range of  $V_M/V_R$  values over which they are almost equivalent. The results indicate that when  $V_M \leq 0.5V_R$ ,  $M$  is always captured with both systems. Using quantitative information, as long as  $V_M \leq 0.8V_R$ ,  $M$  is always captured. For  $V_M > 0.8V_R$ ,  $M$  manages to escape from the receptive field more often. In this case, the noisy measurements prevent  $R$  from placing  $M$  reliably in the center of the beam. For the qualitative system, when  $V_M > 0.5V_R$ , the  $\beta$ -limited rotation allows  $M$  to escape more often from the receptive field. It is interesting to note that the penalty of the qualitative system is not in a significant increase in capture time, but rather in a reduced capture probability.

*Scan Interval  $T_s$ .* Bats transmit a new pulse as soon as the echo from the previous pulse is detected and processed. To investigate the effect of varying  $T_s$ , a hypothetical processing delay was added to the TOF. Both quantitative and qualitative systems exhibit an increase in capture time and decrease in the capture probability as  $T_s$  increases. But as  $T_s$  approaches zero, the capture times exhibited by both the quantitative and qualitative systems approach the game theory bound [31].

This effect can be readily explained in control terms: the time delay  $T_s$  introduces a linear phase lag into the control loop, which, in turn, limits the open loop gain (bat maneuverability) for which the system is stable. As  $T_s$  is reduced, the slope of this phase diminishes, increasing the phase margin, thus allowing more gain and enhanced maneuverability for  $R$ .

*Effect of  $\beta$ .* The performance of the bang-bang control for different values of  $\beta$  is shown in Figs. 9 and 10. For these simulations, the saltatory search rotation angle was set equal to  $\beta$ , instead of the constant value of  $45^\circ$  used in the earlier simulations. If  $\beta$  is too small (or too large), the system is over-damped (or under-damped), and the capture probability is small. An over-damped system does not allow  $R$  to follow  $M$ , while an under-damped system causes  $R$  to overshoot  $M$ . An intermediate value of  $\beta=16^\circ$  yields the highest capture probability and yet reasonably small capture time. The small values of capture time around  $\beta=0^\circ$  indicate that only the "easy" prey are captured.

### Experimental Verification

Although the simulations are more flexible and efficient, real robots and sensor systems are essential for verification. A schematic diagram of the robots is shown in Fig. 11. Experiments with the robots in our laboratory in a  $4 \text{ m} \times 4 \text{ m}$  area free of obstacles other than  $M$  exhibited trajectories and results similar to those observed in the simulations.

*Description of ROBAT.* The mobile robot  $R$  is a position-controlled vehicle equipped with sonar. It consists of a triangular platform driven by two stepper motor wheels at the rear spaced 30 cm apart, and stabilized by a passive front caster. Its maximum speed is 50 cm/s. The transducers are located 40 cm above the platform (55 cm above the floor) to eliminate the reflections from the platform and to reduce the effect of multiple reflections from the floor. On-board electronics provide excitation for pulse transmission and amplifier/filters for signal detection. A cable carries the analog signal envelopes from the left and right receivers to a two channel A/D converter. The signal is processed with an IBM PC/286 that extracts the TOF values from the sensor data, computes  $\hat{r}$  and  $\hat{\theta}$ , determines the action to be taken and sends commands to the PDP-11/23 for motor control.

*Description of MOTH.* The second mobile robot  $M$  is a circular platform driven by two stepper motors with wheels 15 cm apart.  $M$  carries a vertically-mounted cylindrical reflector having diameter 16 cm and height 1 m. It is independently controlled through a cable by its own PDP-11/23 to move with maximum speed of 50 cm/s. Having no sensory feedback,  $M$  models a passive prey unaware of the presence of  $R$ .

*Experimental Procedure.* Experiments to observe capture in real-time were performed with  $R$  and  $M$ . The value of  $T_s$  was determined by the processing time of the data acquisition system. It increased linearly with range and, at  $r=2 \text{ m}$ ,  $T_s=1 \text{ s}$ .  $M$  was programmed to produce a variety of trajectories using the methods employed for the simulations. This task was simplified, since both  $M$  and  $R$  are operated as positional devices. The TOF's were determined from the detectable echoes and the range and azimuth estimates were computed using (4) and (5). For the quantitative system, the value of  $\hat{\theta}$  was used, while for the qualitative system only the sign of  $\hat{\theta}$  was employed. When the value of  $\hat{r}$  became

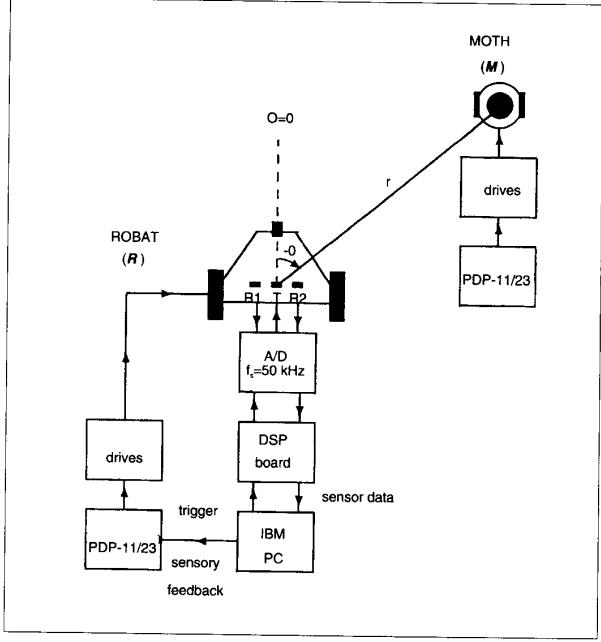


Fig. 11. Block diagrams of the robots.

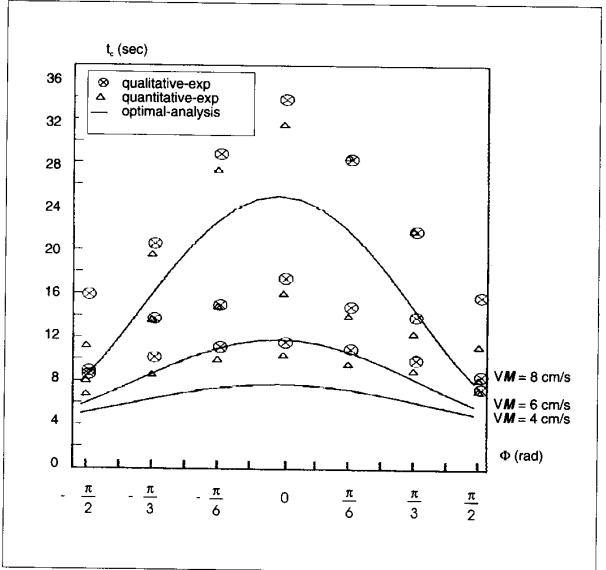


Fig. 12. Experimental results showing capture time  $t_c$  as a function of  $\Phi$  for  $V_R=9.8 \text{ cm/s}$ ,  $r_i=80 \text{ cm}$  and  $\theta_i=0$ . Capture occurs when  $\hat{r} \leq 35 \text{ cm}$ . The solid line indicates the bound predicted from game theory.

smaller than 35 cm, just beyond the front edge of  $R$ ,  $M$  was considered to be caught. In general, the trajectories produced by the robots were similar to those observed in the simulations.

To verify the results for linear motion, the experiments were conducted with  $M$  located initially at the center of  $R$ 's receptive field with  $\theta=0^\circ$  and  $r=80 \text{ cm}$  and fleeing at selected values of  $\Phi$ .  $V_R$  in the

experiments was 9.8 cm/s and the capture time was observed as  $V_M$  was varied with values 4, 6 and 8 cm/s. For the qualitative system, the bang-bang rotation angle  $\beta$  was set at 20°. For given values of  $V_M$  and  $\Phi$ , the capture time was averaged over five trials to compensate for the experimental errors due to the low SNR that occurs at the initial large range. Because of the difficulty of keeping the cables connected to  $R$  and  $M$  from tangling, the number of experiments was limited and did not allow accurate estimates of the capture probability to be obtained.

**Experimental Results.** The average capture times are shown in Fig. 12 as a function of  $\Phi$ . As predicted from the theory, the experimentally observed capture time decreases with increasing  $|\Phi|$ . Although the trends are clearly evident, the experimentally observed capture time values exceed the bounds predicted by game theory and the values observed in the simulations by about 30%. The main reason for the discrepancy is that the simulations did not include the dynamics of  $R$  and  $M$ . ROBAT's acceleration is limited by the torque of the stepper motors and both the rotations and translations are performed by the same wheels. Both effects reduce ROBAT's speed and increase the capture time.

### Speculation on Avoidance Tactics

Having described the sonar characteristics important for capture, we can speculate on how prey can attempt to avoid being caught. An insect equipped with modest sensing detects the incident pulse, while the bat must detect the much smaller echo. The insect's main goal should be to escape out of the bat's receptive field. Let us say that the bat first detects the insect at the most distant end of the receptive field and that the insect first becomes aware of the bat at that point. To escape, some insects perform a passive dive [20]. This is an effective tactic to escape out of the receptive field. Now, let us assume that the bat anticipates this maneuver, what should it do to increase its chances of capture? Some bats fly while directing its sonar slightly upward [20]; by diving, the insect falls into the receptive field and becomes easy prey. Now, what is an insect supposed to do if it knows that the bat is so clever? Since our bat tries to position the prey in the center of the receptive field during pursuit, escape from the receptive field is most easily accomplished when it is narrow, either at distant range, as above, or at close range. So, if an insect knows the direction of attack, it could wait until the bat is very close and then try a mad flight to the side. The general direction of the bat can be determined from the sound intensity, but how does the insect determine the closeness of the bat? Possibly, from the asynchronous sampling employed by the bat: just before capture, the clicks turn into a *buzz* [1] and it is time to flee. We are currently in the process of verifying these speculations with our robots.

### Summary

A bat-like sonar was described and applied to the problem of docking mobile robots. The docking problem was described in the context of prey capture in two dimensions, in which a mobile robot equipped with sonar detects, pursues and captures a second mobile robot. Two capture strategies, determined by whether the information was quantitative or qualitative, were compared. The performance was evaluated by monitoring the capture probability and the capture time, assuming that capture occurs. The most important parameter for successful prey capture is the speed ratio of the prey to the predator. It was observed that

although binary information about the prey direction was sufficient for capture to occur, quantitative information increases the capture probability and reduces the capture time. Both systems perform comparably when  $V_M/V_K \leq 0.5$ . For faster moths, the penalty for qualitative information is not a significant increase in capture time, but a reduced capture probability. Overall, the bat-like sonar represents an efficient sensing system for accomplishing prey capture. No wonder that it is used in nature.

### References

- [1] D.R. Griffin, *Listening in the Dark*. New Haven, CT: Yale Univ. Press, 1958.
- [2] N. Suga, "Biosonar and neural computation in bats," *Scientific Amer.*, vol. 262, pp. 60-68, June 1990.
- [3] J.A. Simmons, A.J.M. Moffat, and W.M. Masters, "Sonar gain control and echo detection thresholds in the echolocating bat, *Eptesicus fuscus*," *J. Acoust. Soc. Amer.*, vol. 91, pp. 1150-1163, Feb. 1992.
- [4] D.J. Hartley, "Stabilization of perceived echo amplitudes in echolocating bats," *J. Acoust. Soc. Amer.*, vol. 91, no. 2, pp. 1120-1149, Feb. 1992.
- [5] R.A. Altes, "Angle estimation and binaural processing in animal echolocation," *J. Acoust. Soc. Amer.*, vol. 63, pp. 155-173, Jan. 1978.
- [6] J.A. Simmons, P.A. Saillant, and S.P. Dear, "Through a bat's ear," *IEEE Spectrum*, pp. 46-48, Mar. 1992.
- [7] T. Fukuda and S. Nakagawa, "Dynamic reconfigurable robotic system," in *Proc. IEEE Conf. Robotics and Automation*, 1988, pp. 1581-1586.
- [8] R. Sharma and J. Aloimonos, "Target pursuit or prey catching using qualitative visual data," in *Proc. AAAI-90 Workshop on Qualitative Vision*, Boston, MA, July 29, 1990, pp. 195-198.
- [9] J.L. Crowley, "Navigation for an intelligent mobile robot," *IEEE Trans. Robot. Auto.*, vol. RA-1, pp. 31-41, Mar. 1985.
- [10] A.M. Flynn, "Combining sonar and infrared sensors for mobile robot navigation," *Int. J. Robot. Res.*, vol. 7, pp. 5-14, Dec. 1988.
- [11] R. Kuc and B.V. Viard, "A physically-based navigation strategy for sonar-guided vehicles," *Int. J. Robotics Res.*, vol. 10, pp. 75-87, Apr. 1991.
- [12] M. Drumheller, "Mobile robot localization using sonar," *IEEE Trans. Pattern Anal. Machine Intell.*, vol. 9, pp. 325-332, Mar. 1987.
- [13] R. Kuc, "A spatial sampling criterion for sonar obstacle detection," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 12, pp. 686-690, July 1990.
- [14] J. Borenstein and Y. Koren, "The vector field histogram: Fast obstacle avoidance for mobile robots," *IEEE Trans. Robot. Auto.*, vol. 7, pp. 278-288, June 1991.
- [15] A. Elfes, "Sonar based real-world mapping and navigation," *IEEE Trans. Robot. Auto.*, vol. 3, pp. 249-265, June 1987.
- [16] Ö. Bozma and R. Kuc, "Building a sonar map in a specular environment using a single mobile transducer," *IEEE Trans. Pattern Analysis and Machine Intelligence*, vol. 13, pp. 1260-1269, Dec. 1991.
- [17] R. Kuc and M. W. Siegel, "Physically-based simulation model for acoustic sensor robot navigation," *IEEE Trans. Pattern Anal. Machine Intell.*, vol. 9, pp. 766-778, Nov. 1987.
- [18] J. Borenstein and Y. Koren, "Obstacle avoidance with ultrasonic sensors," *IEEE Trans. Robot. Auto.*, vol. 4, pp. 213-218, Apr. 1988.
- [19] B. Barshan and R. Kuc, "A bat-like sonar system for obstacle localization," *IEEE Trans. Syst., Man Cybern.*, May 1992.

[20] M. May, "Aerial defense tactics of flying insects," *Amer. Sci.*, vol. 79, pp. 316-328, July-Aug. 1991.

[21] R. Isaacs, *Differential Games*. New York: Wiley, 1965.

[22] C.-B. Chang and J.A. Tabaczynski, "Application of state estimation to target tracking," *IEEE Trans. Auto. Control*, vol. AC-29, pp. 98-109, Feb. 1984.

[23] A.E. Bryson and Y.C. Ho, *Applied Optimal Control*. Waltham, MA: Ginn and Co., 1969.

[24] B. Barshan and R. Kuc, "Differentiating sonar reflections from corners and planes by employing an intelligent sensor," *IEEE Trans. Pattern Anal. Machine Intell.*, vol. 12, pp. 560-569, June 1990.

[25] Panasonic Corporation, "Ultrasonic ceramic microphones," Burlington, MA 01803, 1989.

[26] R.C. Weast, *CRC Handbook of Chemistry and Physics*, 59th ed. Cleveland, OH: Chemical Rubber Company, 1979.

[27] A.L. Maffett, Ed., *Topics for a Statistical Description of Radar Cross Section*. New York: Wiley, 1989.

[28] J.M.V. Rayner, "The cost of being a bat," *Nature*, vol. 350, pp. 383-384, Apr. 1991.

[29] B. Barshan, "A sonar-based mobile robot for bat-like prey capture," Ph.D. diss., Yale Univ., University Microfilms, Ann Arbor, MI, 1991.

[30] B. Barshan and R. Kuc, "Bat-like sonar system strategies for mobile robots," in *Proc. IEEE Int. Conf. Syst., Man and Cybern.*, Charlottesville, VA, Oct. 13-16, 1991.

[31] B. Barshan and R. Kuc, "Bat-like mobile robot for tracking a moving obstacle," in *Proc. SPIE Intell. Robotic Syst. Conf.*, Boston, MA, Nov. 11-15, 1991.



**Roman Kuc** received the B.S.E.E. in 1968 from the Illinois Institute of Technology, Chicago, and the Ph.D. degree in electrical engineering in 1977 from Columbia University, New York, NY. From 1968 to 1975 he was a Member of Technical Staff at Bell Laboratories, engaged in the design of audio instrumentation and in the development of efficient speech coding techniques. From 1977 to 1979 he was a Postdoctoral Research Associate in the Department of Electrical Engineering, Columbia University, and the Radiology Department, St. Luke's Hospital, where he applied digital signal processing to extract information from diagnostic ultrasound signals. In 1979, he joined the Department of Electrical Engineering, Yale University, where as the Director of the Intelligent Sensors Laboratory he is pursuing research in the solution of inverse problems and in intelligent sensors for robotics and biomedical applications. He is the author of *Introduction to Digital Signal Processing* published by McGraw-Hill. He is a past chair of the Instrumentation Section of the New York Academy of Sciences and member of the Board of Advisers of the Medical College in Lviv, Ukraine. He is a member of Tau Beta Pi, Sigma Xi and the Acoustical Society of America.



**Billur Barshan** was born in Istanbul, Turkey. She received the B.S.E.E. degree and the B.S. degree in physics from Bogazici University, Istanbul, Turkey, in 1986. From 1987 to 1991 she was a Research Assistant at Yale University, New Haven, CT, where she received the M.S. and Ph.D. degrees in electrical engineering in 1988 and 1991. Recently, she joined the Robotics Research Group at University of Oxford, Oxford, U.K., as a postdoctoral researcher. Her current research interests include sensor-based robotics, inertial navigation systems and sensor data fusion.

## 1992 SMC Conference

The 1992 IEEE International Conference on Systems, Man, and Cybernetics will be held on October 18-21, 1992, at The Knickerbocker Hotel, Chicago, Illinois. Nick DeClaris and Dick Saeks are co-chairs.

SMC '92 will include a program of tutorials, contributed and invited sessions. Special sessions will be organized on Medical Systems and Informatics, Power Systems, and Telefony, in addition to topics in Man-Machine Systems, Robotics, Large-Scale Systems, Applications of Neural Networks, Socio-Economic Systems, Knowledge-Based Systems, Organizational

Structures, Manufacturing and Testing, and Command and Control Systems.

The Knickerbocker Hotel is located in Chicago's North Michigan Avenue Entertainment and Shopping Districts, a few blocks from Lake Michigan. Chicago's climate is at its best in October and the city has direct connections via O'Hare International Airport, throughout the nation and the world. For further information contact: Ms. Leal Smith, Conference Secretary, Room 218, E1 Building, Illinois Institute of Technology, Chicago, IL 60661, U.S.A. (312) 567-3406.

### 1993 SMC Conference

The venue for the 1993 SMC Conference will be Le Touquet (Paris Plage). Le Touquet is a resort town on the North East coast of France. With the planned opening of the Channel Tunnel in June 1993, Le Touquet is ideally placed for U.S. participants to visit London, Paris, and Brussels.

The Conference General Chairs Madan Singh and Pierre Borne are currently in the process of forming an international program committee and making the arrangements to ensure that the 1993 conference does indeed prove to be intellectually exciting as well as fun.