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Docking Mobile Robots Using a Bat-like Sonar *

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Abstract—**The problem of docking two mobile robots using a wide-beam sonar system is considered. Because of the similarity to biological bats, the problem is discussed in terms of prey capture in two dimensions. The basics of the bat-like sonar system are described. Two measures of performance are considered: the capture probability and the mean capture time when capture occurs. These measures are computed in two ways: as the ratio of speeds of the prey to the pursuer is varied and as the strategies employing either qualitative information (prey is to the left or right) or quantitative information (range and azimuth to prey) are employed. The lower bound for the mean capture time is determined from game theory, which assumes complete information about the prey. The analysis is verified by performing experiments with a real mobile robot. Both capture probability and mean capture time are inversely related to the prey/pursuer speed ratio. It is also observed that, while qualitative information is sufficient for docking to occur, quantitative information allows successful docking over a larger range of speed ratios.**

I. INTRODUCTION

The problem of docking two robots is becoming important in multi-robot systems. This problem has been investigated by Fukuda and Nakagawa using infrared sensors [1]. Docking using a camera vision system was also recently discussed by Sharma and Aloimonos [2]. In this paper we demonstrate that sonar can also accomplish docking efficiently.

The docking problem using sonar in robotics is investigated in the context of prey-capture by bats. The basic limitations in docking can be found in the pursuer/evader problem in game theory [3]. By assuming perfect knowledge regarding the locations and trajectories of the two vehicles, the minimum time required to accomplish docking can be found, as shown below. Practical sensors not only prevent this bound from being met, but a[illegible] cases in which docking does not occur at all.

Conventional sonar systems employ sensors that have beam widths that are relatively narrow, e.g., the Polaroid sensor [4] has a beam width of 20^o. Such a narrow beam requires that the environment be scanned densely to determine the locations of obstacles [5]. In this paper we consider the use of a wide beam sensor system, one that has an effective beam width greater that 90^o. In nature, a bat has such a wide-beam sensor system to efficiently locate the position of prey in a large volume of space. Prey localization is performed by processing the arrival time of the echoes at the two ears, as described below.

A bat-like sonar system was implemented in our laboratory to mimic the behavior of biological sensing systems [6]. Below we refer to the mobile robot with sonar as $\mathcal{R}$, for ROBAT, and to the other as $\mathcal{M}$, for MOTH.

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 here.

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II. BAT-LIKE SONAR

BEAM PATTERN. In searching for prey, a bat transmits a ultrasound pulse from its mouth. Since the dimensions of the mouth are comparable with wavelength of the radiated pressure wave, the beam containing the pulse is very wide and propagates with a spherical wavefront. Then a reasonable approximation for the pressure amplitude pattern of the propagating pulse is given by[7]

$$p(r,\theta) \cong \frac{p_o r_o}{r}\, e^{-\frac{\theta^2}{2\sigma_T^2}} \quad \text{for} \quad r > r_o \qquad (1)$$

where r is the radial distance from the transducer (mouth), θ is the azimuth, σ_T is a measure of the beam width and p_o is the propagating pressure amplitude at range r_o along the line-of-sight ($\theta{=}0^o$). This amplitude pattern is similar to the beam of a flashlight: the cross-section forms a circular pattern that is strongest in the center and decreases with angular deviation $|\theta|$ from the center. Since the diameter of the beam cross-section increases with range, conservation of energy requires that the pressure amplitude varies inversely with range. If the ear has the same small dimensions as the mouth, Eq. (1) also describes the receiving sensitivity of the transducer by the reciprocity principle [8].

For obstacle localization in two-dimensions, a long vertical pole-like obstacle is convenient since it is an omnidirectional reflector in the horizontal dimension. After being reflected, a plane incident wave is converted into a cylindrical echo. The amplitude of the echo from a pole than has the following form [9]

$$A(r_1, r_2, \theta_1, \theta_2) \cong \epsilon \, \frac{A_o r_o^{3/2}}{r_1 \sqrt{r_2}} \, e^{\frac{-(\theta_1^2+\theta_2^2)}{2\sigma_T^2}} \quad \text{for} \quad r_1, r_2 > r_o \tag{2}$$

where r_1 and r_2 are the distances, and θ_1 and θ_2 are the angular deviations of the reflector from the transmitter and the receiver respectively. A_o is the echo amplitude observed when T and R are coincident, for which $r_1 = r_2 = r_o$ and $\theta_1 = \theta_2 = 0^o$. The ϵ is the reflection coefficient of the reflector.

SONAR SYSTEM. For the bat-like sonar system implemented in our laboratory, we employed the Panasonic ultrasonic ceramic microphone (EFR-OSB40K2 [10]) that can be used both for transmitting and receiving signals. The radius of the sensor is 5.2 mm and it is resonant at 40 KHz. The beam-width parameter σ_T is equal to 30^o.

Three identical sensors were situated linearly with a center-to-center separation equal to 6 cm. The middle transducer T (the mouth of the bat) transmits an echolocation pulse, and the two side receivers R_L and R_R (left and right ears of the bat) capture the echoes reflected back by obstacles. The range r and azimuth θ of an obstacle are measured from the transmitter.

An obstacle is said to be *detectable* if it produces echoes that exceed the thresholds in both ears. If the threshold is denoted by τ, then we define the *receptive field* of the sonar system as the set of points in space for which $A_L > \tau$ and $A_R > \tau$, where A_L and A_R are the amplitudes in the left and right ears, given in (2).

LOCATION ESTIMATION. Analyzing the noisy echoes detected by the two receivers, the range r and azimuth θ of an obstacle in the receptive field are estimated from the value of TOF, denoted by t_F, at each receiver. These TOF values correspond to the round-trip distances from the transmitter to the receiver

$$z = \frac{ct_F}{2}$$

An estimate, denoted by the $\hat{z}$, occurs because of the presence of noise. Measurement $\hat{z}_1$ restricts the possible locations for the obstacle to lie on an ellipse whose foci are at T and R_L and similarly for $\hat{z}_2$. The two ellipses intersect at

$$\hat{r} = \frac{\hat{z}_1^2 + \hat{z}_2^2 - 2d^2}{2(\hat{z}_1 + \hat{z}_2)} \tag{3}$$

$$\hat{\theta} = \sin^{-1}\left[\frac{(\hat{z}_1\hat{z}_2 + d^2)(\hat{z}_1 - \hat{z}_2)}{d(\hat{z}_1^2 + \hat{z}_2^2 - 2d^2)}\right] \tag{4}$$

where d is the separation between T and each of the R's.

III. CONTROL STRATEGIES.

Two different control strategies are described that use different levels of information. Both are memoryless, assume no knowledge of $\mathcal{M}$'s motion and extract information sequentially from the environment. $\mathcal{R}$'s information about $\mathcal{M}$ is obtained at each scan instant and consists of noisy measurements of r and θ whenever $\mathcal{M}$ is within the receptive field.

QUANTITATIVE INFORMATION. Estimating $\hat{r}$ and $\hat{\theta}$ from the most recent echoes, $\mathcal{R}$ moves toward the estimated location of $\mathcal{M}$ within the receptive field. Due to the echo travel time, delayed estimates of $\mathcal{M}$'s position are observed. Given the range and azimuth estimates, $\mathcal{R}$ responds by making a rotation that centers the beam on $\mathcal{M}$'s current location and moves forward. In this way, the accuracy characteristics of the sonar system are exploited: the prey is positioned around the most sensitive part of the beam and the signal-to-noise ratio of the next echo is improved by decreasing the range (reduced $r^{-3/2}$ loss). This procedure is repeated several times, updating $\mathcal{M}$'s location after each iteration.

QUALITATIVE INFORMATION. In this case, only one bit of information is given to $\mathcal{R}$, whether $\mathcal{M}$ is to the right ($\theta < 0$) or to the left ($\theta \geq 0$). The *ad hoc* response by $\mathcal{R}$ is a rotation by a fixed angle β to the right or left. This *bang-bang* strategy represents the minimal information required to achieve prey capture. Previous results by others [2, 3] indicate that successful prey capture can be accomplished by employing only the direction θ of $\mathcal{M}$ relative to $\mathcal{R}$. Our results are less restrictive, indicating that only the binary information that $\mathcal{M}$ is either to the right or left of $\mathcal{R}$'s line-of-sight is sufficient for capture.

IV. BOUNDS ON PREY CAPTURE

In this section a lower bound on the time to capture

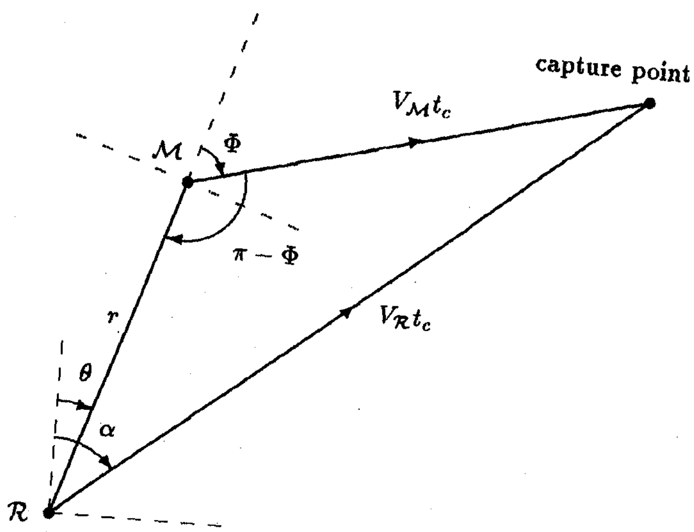

Fig. 1. Complete knowledge assumption for linearly moving prey.

linearly moving prey is derived by assuming that the pursuer $\mathcal{R}$ has complete knowledge about the evader $\mathcal{M}$ at all times and at all points in space. Let us consider $\mathcal{M}$ moving along a linear trajectory at speed $V_{\mathcal{M}}$. Suppose that $\mathcal{R}$ first detects $\mathcal{M}$ at range r and azimuth θ, as shown in Fig. 1. With complete information about $\mathcal{M}$'s linear path, i.e. r, θ, Φ and $V_{\mathcal{M}}$, $\mathcal{R}$ wants to intercept $\mathcal{M}$ as quickly as possible to minimize its energy expenditure, a reasonable biological cost function [11]. Then a unique linear trajectory with orientation α is defined, as shown in Fig. 1, with

$$\alpha = \theta + \sin^{-1}\left[\frac{V_{\mathcal{M}}}{V_{\mathcal{R}}}\sin\Phi\right] \quad (5)$$

The capture time is then equal to

$$t_c = \frac{r\left[\frac{V_{\mathcal{M}}}{V_{\mathcal{R}}}\cos\Phi + \sqrt{1-\left(\frac{V_{\mathcal{M}}}{V_{\mathcal{R}}}\right)^2\sin^2\Phi}\right]}{V_{\mathcal{R}}\left[1-\left(\frac{V_{\mathcal{M}}}{V_{\mathcal{R}}}\right)^2\right]} \quad (6)$$

Eq. (6) indicates that prey capture will occur in finite time only if $V_{\mathcal{M}} < V_{\mathcal{R}}$. Capture time is observed to be independent of θ and maximum when $\Phi = 0$. This means that moths that directly flee away from the bat in the direction of initial detection take the longest time to capture.

V. Simulation Studies

To test the significance of the available information, prey capture was simulated by a program that models the physical operation of the actual sonar system on a VAX 3100 work station.

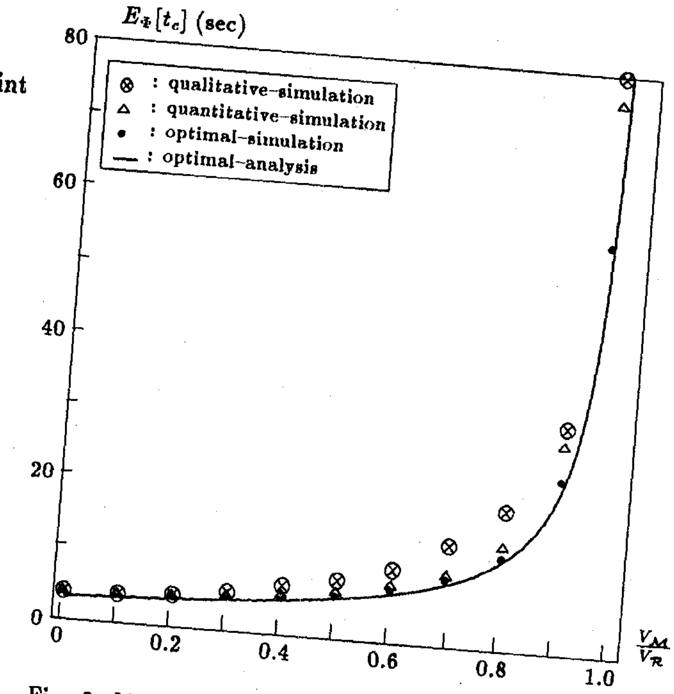

Fig. 2. Mean capture time vs. $\frac{V_{\mathcal{M}}}{V_{\mathcal{R}}}$ for $V_{\mathcal{R}}$=50 cm/s, T_s=1 s, r=200 cm, θ=0°, and β=10°.

First, a signal-to-noise ratio is specified, indicating the amount of noise that is present at the ears of ROBAT. The maximum observed signal amplitude with $\mathcal{M}$ located 10 cm from $\mathcal{R}$ to noise standard deviation is specified. A typical value is 60 dB. The threshold level τ is set equal to five times the noise standard deviation to prevent the occurrence of spurious detection. The value of τ defines the extend of the receptive field. In the simulations, the known location of $\mathcal{M}$ relative to the sensors indicates the amplitudes and delays of the echoes to the right and left ears. A typical echo waveform is assumed [6]. Random noise having the specified variance is generated and added to the echo waveform. The time that the echo plus noise exceeds the threshold defines t_F. Because of the noise, the time-of-flight values contain errors. The location of the prey *perceived by the bat* is determined from these observed measurements and the bat reacts to this information, usually by moving toward that location. The velocities $V_{\mathcal{R}}$ and $V_{\mathcal{M}}$ and the echo travel time determine the distances traveled by $\mathcal{R}$ and $\mathcal{M}$.

The simulation is started when $\mathcal{M}$ is located at the edge of $\mathcal{R}$'s receptive field along θ=0° and starts fleeing at random orientation Φ. For qualitative information, the bang-bang rotation angle β was chosen to be 10° (close to its optimal value as shown below). When $\mathcal{M}$ escapes out of the receptive field, for both systems, $\mathcal{R}$ responds by a saltatory search with ±45° rotations that cover the maximum possible area. If $\mathcal{M}$ escapes out of the receptive field and is not detected within 12 cycles of saltatory search, $\mathcal{M}$ is considered not captured, resulting in a decreased P_c.

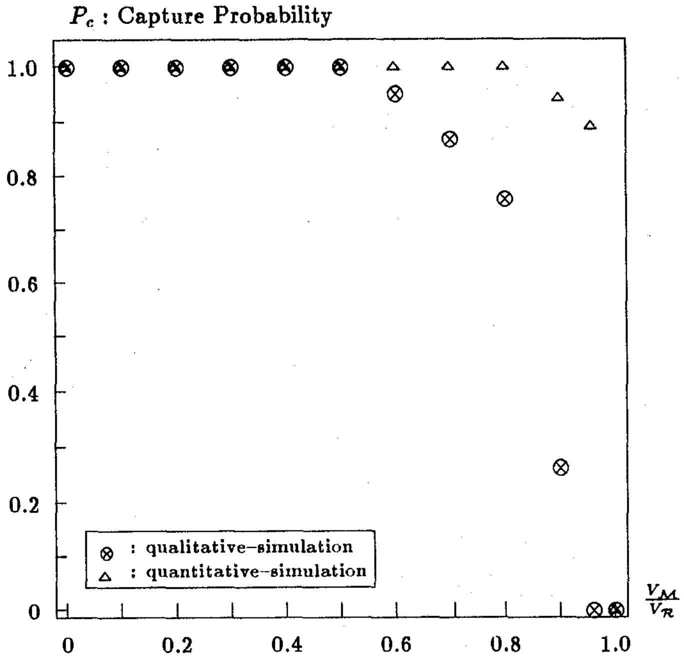

Fig. 3. Capture probability vs. $\frac{V_\mathcal{M}}{V_\mathcal{R}}$ for $V_\mathcal{R}$=50 cm/s, T_s=1 s, r=200 cm, θ=0° and β=10°.

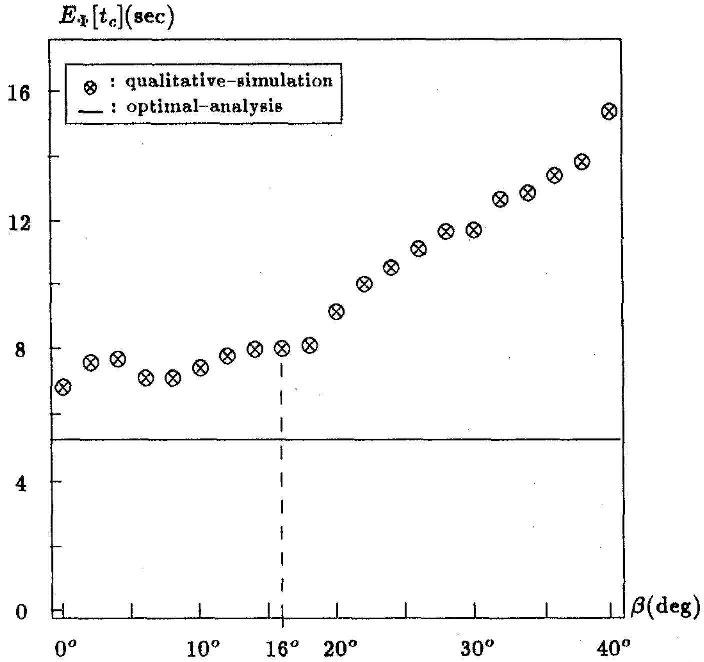

Fig. 4. Mean capture time vs. β for $V_\mathcal{R}$=50 cm/s and $V_\mathcal{M}$=25 cm/s.

VI. Performance Evaluation

The performance was analyzed by considering the expected value of the capture time by taking the expectation over the angle Φ. The analytically predicted performance was compared with a simulation of the perfect knowledge case (for verification) and simulations of the two receptive-field limited information cases. The signal-to-noise ratio was set at 60 dB. One hundred realizations are generated by randomizing the value of Φ to evaluate the penalty incurred on performance when the two levels of information extracted from the sensor system are employed.

A measure of the importance of information is provided by determining the corresponding cost in capture probability and mean capture time for each method. The simulation results are shown in Figs. 2–5. As apparent from the results, the technique based on complete information yields the highest capture probability and minimum capture time.

From the analysis and verification of our bat-like sonar system, we have observed that the following parameters are important for prey capture:

Effect of relative speed. The speed of $\mathcal{M}$ compared to $\mathcal{R}$ is the most important factor in accomplishing prey capture. Mean capture time and capture probability are shown as a function of $\frac{V_\mathcal{M}}{V_\mathcal{R}}$ in Figs. 2 and 3. As expected, quantitative information yields better performance than qualitative information, but there is a wide range of $\frac{V_\mathcal{M}}{V_\mathcal{R}}$ values over which they are comparable. The results indicate that moths with velocities below $0.5V_\mathcal{R}$ are always captured with both methods. With quantitative information, moths moving as fast as $0.8V_\mathcal{R}$ are successfully captured. For $V_\mathcal{M} > 0.8V_\mathcal{R}$, $\mathcal{M}$ escapes from the receptive field more often. For the qualitative system, when $V_\mathcal{M} > 0.5V_\mathcal{R}$, the rotation limited by β allows more moths to escape from the receptive field. It is interesting to note that the penalty of qualitative systems is not in a significant increase in capture time but rather in a reduced capture probability.

Effect of β. The performance of the bang-bang algorithm for different values of β is shown in Figs. 4 and 5. For these simulations, the saltatory search rotation angle was set equal to β, instead of the constant value of 45° used in the earlier simulation results. If β is too small (or too large), the system is overdamped (or underdamped). An overdamped system does not allow $\mathcal{R}$ to follow $\mathcal{M}$, while an underdamped system causes $\mathcal{R}$ to overshoot $\mathcal{M}$. An intermediate value of β=16° yields the highest capture probability and yet reasonably small capture time. The small values of capture time around β=0° indicate that only the "easy" prey are captured.

VII. Experimental Verification

Although the simulations are more flexible and efficient, real robots and sensor systems are essential for verification. Experiments with the robots in our laboratory in a 4 m×4 m area free of obstacles other than $\mathcal{M}$ have indi-

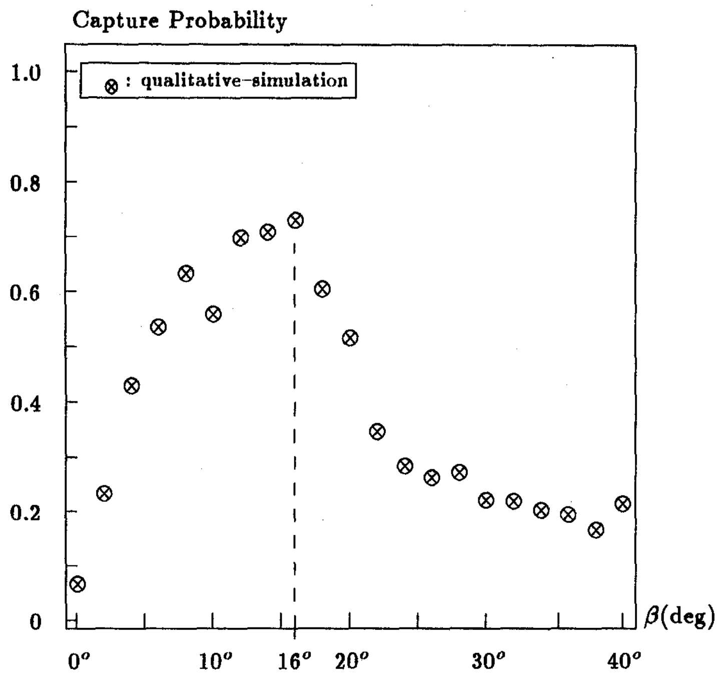

Fig. 5. Capture probability vs. β for $V_{\mathcal{R}}$=50 cm/s and $V_{\mathcal{M}}$=25 cm/s.

cated results similar to those of the simulations.

Description of ROBAT. A schematic illustration of the robotic system is shown in Fig. 6. The mobile robot $\mathcal{R}$ is a position-controlled vehicle that carries the sonar system on-board with a maximum speed of $V_{\mathcal{R}}$=50 cm/s. It consists of a triangular platform, placed on top of a passive front caster and two stepper motor wheels. The transducers are located high above the platform to eliminate the reflections off the platform and the floor. On-board electronics provide excitation for pulse transmission and amplifier/filters for signal detection and envelope extraction. A cable carries the analog signal envelopes to an A/D converter. The control and processing of the signals is accomplished with an IBM PC/286 that extracts information from the sensor data, determines the action to be taken and sends commands to a PDP-11/23 for motor control.

Description of MOTH. Although smaller than $\mathcal{R}$, the second mobile robot $\mathcal{M}$ in our system is similar in that it is a platform driven by two stepper motors. $\mathcal{M}$ carries a vertically-mounted cylindrical reflector having diameter 16 cm and height 1 m. Unlike $\mathcal{R}$, $\mathcal{M}$ has no sensory feedback, hence it models a *passive prey* unaware of the presence of $\mathcal{R}$. It is independently controlled through a cable by its own PDP-11/23 to move along a linear trajectory with maximum speed $V_{\mathcal{M}}$=50 cm/s.

Experimental setup. To verify the analytical results and to compare the qualitative and quantitative methods,

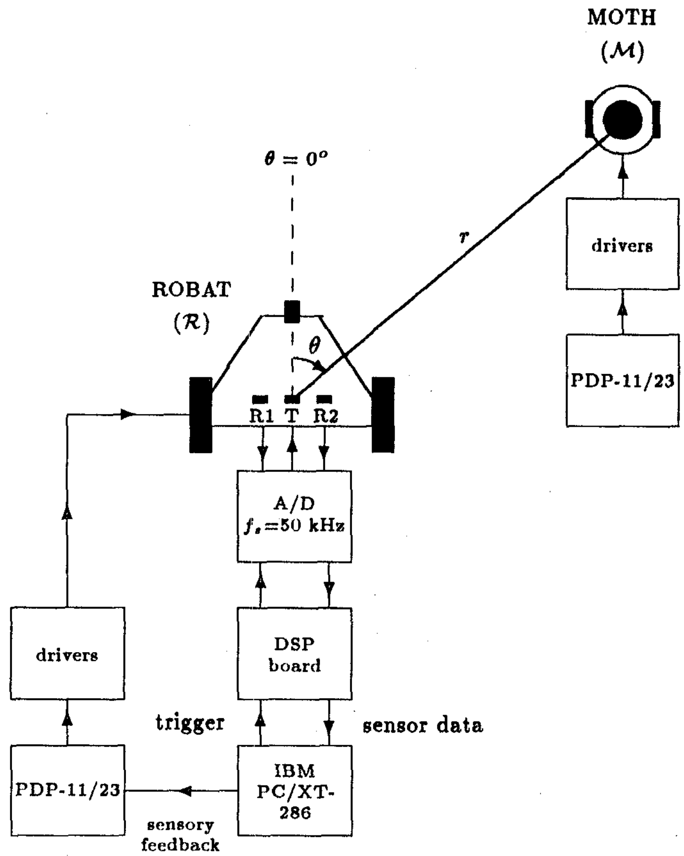

Fig. 6. Configuration of the robotic system.

experiments were performed in real-time with $\mathcal{R}$ and $\mathcal{M}$.

The experiments are started with $\mathcal{M}$ located at the center of $\mathcal{R}$'s receptive field along θ=0° with an initial r=80 cm and fleeing at random orientation Φ. For qualitative information, the bang-bang rotation angle β was chosen to be 20°. Five different trials were realized for each algorithm at angles Φ=0, ±30°, ±60°, ±90° for different speeds of $\mathcal{M}$. For a given $V_{\mathcal{M}}$ and Φ, the capture time was averaged over the five trials to compensate for the experimental errors. These errors are due to the low SNR that occurs at the initial large range, 80 cm.

In the experiments the speed of sound was artificially reduced, by setting the echo delay at the maximum range equal to one second. This delay allows a more realistic relationship between the speed of sound and $V_{\mathcal{R}}$ and an agreement with the conditions used in the simulations.

Experimental results. The results for $V_{\mathcal{M}}$= 8,6,4 cm/s are shown in Fig. 7 as a function of Φ. As expected, the experimentally observed capture time decreases with increasing $|\Phi|$, indicating a similar form as the lower bound for capture time. Even though the quantitative method produces a smaller mean capture time, the difference between using qualitative vs. quantitative information is only marginal. However, with these sub-optimal methods, it may take 4–8 s. longer to capture the prey.

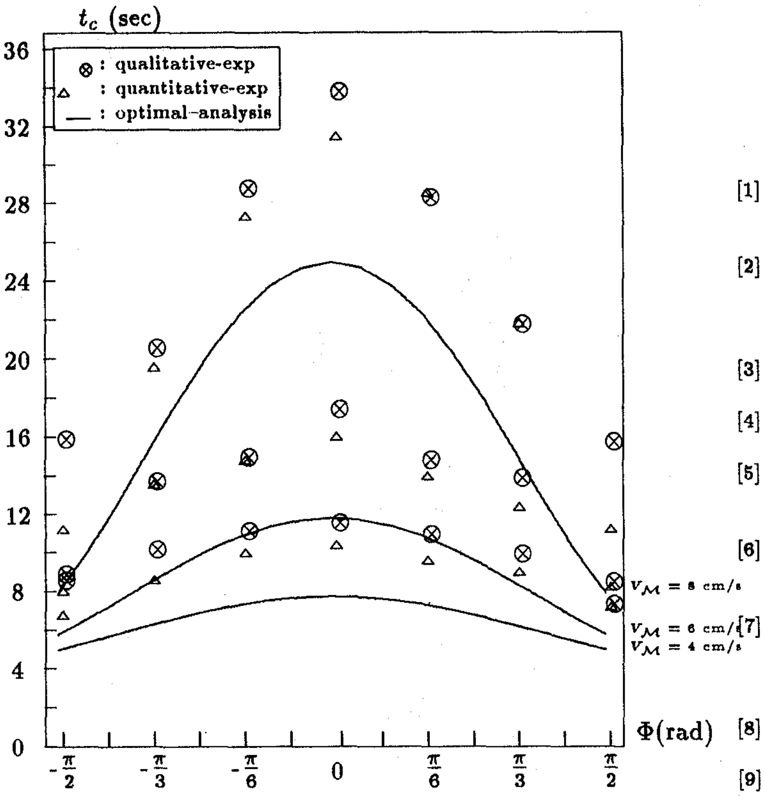

Fig. 7. Experimental results showing capture time t_c as a function of Φ for $V_{\mathcal{R}}$=9.8 cm/s and r=80 cm. The solid line corresponds to the optimal solution.

This difference between the experimental results and the minimum capture time increases for faster moths.

VIII. Summary

Two different prey capture strategies were compared for a robotic system, in which a mobile robot equipped with a wide-beam sonar system detects, pursues and captures a second mobile robot with no sensory feedback. Most important parameters for prey capture are the speed ratio of the prey to the predator. It was observed that although binary information about the prey direction was sufficient, quantitative information increased the capture probability and reduced the mean capture time. Both systems are comparable when $\frac{V_{\mathcal{M}}}{V_{\mathcal{R}}}$ <0.5. For faster moths, penalty for qualitative information is not a significant increase in capture time, but reduced capture probability. On the average, prey capture took 2–4 s longer than the minimum capture time predicted from the complete knowledge case, indicating that the bat-like sonar represents an efficient sensing system.

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