

Cooperative Control of Vehicle Swarms for Acoustic Target Recognition by Measurement of Energy Flows

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Abstract-- A control algorithm has been developed and experimentally validated for guiding swarms of robotic vehicles to reflected acoustic energy target locations. The algorithm uses pressure measurements from a sensor on each of the robots. The measurements are cooperatively processed to compute energy flows from which a direction of maximum reflected acoustic intensity is deduced. The swarm moves in this direction with constraints on spacing between individual members. This algorithm was validated using a collective of eight hand-emplaced microphones in an open-space area with a 50-meter separation between emitter and reflector locations. Source acquisition was accomplished using both an active and passive reflector. Signal-to-noise ratio was found to be a critical parameter to insure successful target acquisition.

I. INTRODUCTION

The use of sonar-equipped mobile robotics for detection and localization is a dynamic area of research. A significant amount has focused on single, relatively large, and expensive unmanned underwater vehicles (UUV's) using high frequency acoustic excitations [1], [2]. In contrast to present methods, we envision the use of inexpensive vehicles that individually have limited sensing capability, but by acting in concert can detect and re-locate to a target by tracking low-frequency sound waves.

Swarms of vehicles are both operationally robust and adaptive. They are robust in the sense that their numbers do not allow losses to compromise a mission, and adaptive in that they can be equipped with transmit and receive capabilities to enable changes to their collective character.

This study emulates a swarm detection scenario. An acoustic emitter ensonifies a field containing a swarm of vehicles and a target. The target reflects sound back towards

the swarm. From measured pressure data the swarm computes and iteratively follows the direction of maximum intensity to the reflector.

Figure 1 depicts a scenario for the use of swarms of robotic vehicles acting in cooperation to locate unknown acoustic sources. Each vehicle contains a single pressure sensor used to sample the local acoustic environment and a navigation aid (such as GPS) to determine its present location. All vehicles have the ability to communicate with each other.

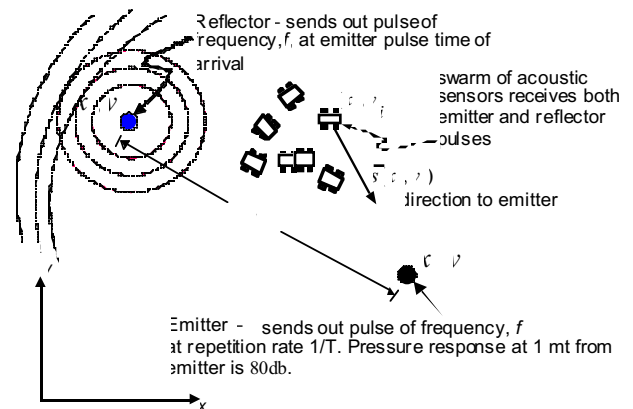


Fig. 1. Swarm targeting geometry

An acoustic source, the emitter, is located at (x_e, y_e) . This source sends an acoustic pulse of frequency, f , into the ambient environment. An acoustic target called the reflector is located at (x_r, y_r) . The reflector, ensonified by this pulse, immediately echoes it back at time of arrival. Robotic vehicles, positioned between these acoustic sources, sense both emitted and reflected pulse pressures.

Through cooperation, the swarm deduces the direction of propagation of waves passing through its local domain. From this information, the swarm is able to differentiate between wave pressure due to the emitter source and that due to the reflector source, and therefore, track reflector wave amplitude to the reflector location. It does this by deducing the direction of the spatially and temporally averaged intensity through its local domain.

Manuscript received February 1, 2002. This work was performed at Sandia National Laboratories and supported by the Office of Naval Research under MIPR N00167-01-MP-10106.

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II. THEORY

1) Hill function construction

As envisioned, robots are guided to acoustic sources by tracking the direction of acoustic energy flowing through the swarm. To do this they must be close enough to calculate a gradient of pressure, but not so close as to obtain erroneous measures of pressure due to multiple scattering off of each other.

Acoustic power per unit area is given by the acoustic intensity, $\vec{I} = P\vec{v}$, where \vec{I} points in the direction of wave propagation, P is acoustic pressure and \vec{v} is particle velocity [3]. Assuming an initial value of $\vec{v} = \vec{0}$, and emitter pulse period, T , particle velocity is proportional to $\int_0^T P dt$ and the instantaneous direction of energy flow is that of

$$\vec{D} = -\frac{\int_0^T P \vec{v} dt}{\int_0^T P dt} \quad (1)$$

Notice that \vec{D} is only a function of pressure and therefore can be deduced from swarm measurements.

Let $\vec{s}(x, y)$ (shown in Fig. 1) be a unit vector that points from the $(x, y)_i$ vehicle location toward the (x_e, y_e) emitter location. The inner product, $\vec{D} \cdot \vec{s}$, is positive only when significant wave energy is moving back toward the emitter. This energy is primarily energy from the reflector source. Since reflected waves have their highest intensity near sources, it is logical to consider a hill function of the form:

$$J(x, y) \dots \max(0, \vec{D} \cdot \vec{s}) \quad (2)$$

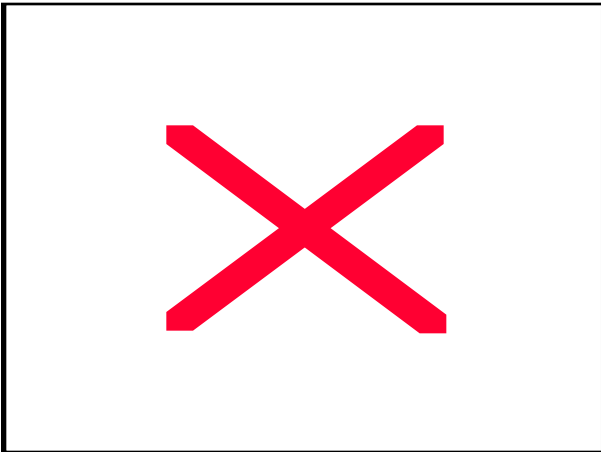


Fig. 2. Hill function and gradient orientation

To calculate $J(x, y)$ (and subsequently $\vec{D}(x, y)$), planar approximations employing nearest vehicle neighbors are used to first fit $P(x, y)$, then compute $\vec{D}(x, y)$, followed by

$\vec{D}(x, y)$. A planar approximation is also used to fit $J(x, y)$.

2) Swarm Spacing

Vehicles must be close enough to calculate $P_{i,fit}$ (for the i th vehicle) and prevent spatial aliasing, but not so close as to obtain erroneous measures of pressure due to scattering off of each other. Moreover, the swarm must be sufficiently large to be able to calculate a smoothed value of J_{fit} for use by the control law.

To make sure that the magnitude of reflections from neighboring robots is small, Rayleigh scattering theory is used [4]. According to Rayleigh theory, for a far field, spherical wave of length, λ , incident upon a scatter of volume, V , the ratio, η , of the magnitude of the scattered pressure, $P_{scattered}$, at a distance R from the center of the volume to the magnitude of the incident pressure, $P_{incident}$, at the center of the volume is given by:

$$\eta = \frac{|P_{scattered}|}{|P_{incident}|} = \frac{5\pi V}{2\lambda^2 R} \quad (3)$$

This solution is only valid when

$$\frac{8\pi^3 V}{\lambda^3} \ll 1, \quad (4)$$

which infers a low-frequency solution. From these equations, a heuristic analysis follows to derive an inter-vehicle spacing range and a suitable pulse waveform with which to ensoundify the field. To assure small reflections, we arbitrarily choose $\eta \leq 1/10$. Therefore, from (9)

$$\frac{5\pi V}{2\lambda^2 R} \leq 1/10. \quad (5)$$

Moreover, from (10) we choose

$$\frac{8\pi^3 V}{\lambda^3} < 0.01. \quad (6)$$

To calculate $P_{i,fit}$, the spacing between robots must be a fraction of a wavelength, (i.e., $\frac{1}{6}\lambda$) to provide a good fit and prevent aliasing. From this guideline, we specify an additional condition on robot spacing such that $R \leq \lambda/6$.

$V \cup 0.0654m^3$ (assuming a swarm of RATLER™ vehicles[5]). Therefore, from (11) and using the value of $R, \lambda \leq 2.14m$. From (12), $\lambda \leq 11.14m$. Since the larger value of λ is more restrictive, we require a pulse wavelength, $\lambda \leq 11.14m$, and

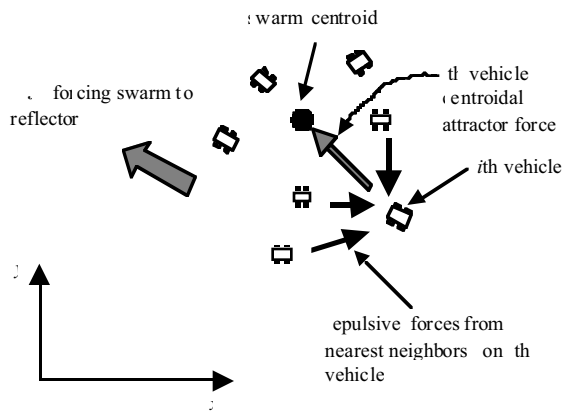
using the fact that $\lambda = c/f$ and that the speed of sound in air, $c = 313\text{m/s}$, the pulse frequency, $f \leq 26\text{Hz}$. For this waveform and from (11) and (13), the robot spacing can vary over the range, $0.04\text{m} \leq R \leq 1.96\text{m}$. $f \leq 127\text{Hz}$ to effect this same spacing in water ($c = 1490\text{m/s}$).

3) Collective Control Algorithm

It is assumed that individual vehicles of the swarm communicate to share their positions, pressure measurements, and gradient computations. With J_{fit} , and range, R , between robots, the displacement of each robot can be calculated using the following modified gradient control law

$$\Delta \vec{r}_i = \frac{\Delta_{\max}}{1+\alpha} (\Delta \vec{r}_{i,search} + \Delta \vec{r}_{i,swarm}) \quad (7)$$

where $\Delta \vec{r}_i$ is the displacement of the i^{th} robot, Δ_{\max} is the maximum allowable value of $|\Delta \vec{r}_i|$, $\alpha \in (0,1]$, $\frac{\Delta_{\max}}{1+\alpha} \Delta \vec{r}_{i,search}$ is the displacement of each robot in the J_{fit} direction, and $\frac{\Delta_{\max}}{1+\alpha} \Delta \vec{r}_{i,swarm}$ is a displacement used to maintain proper vehicle spacing as given in equation (16). The displacement $\frac{\Delta_{\max}}{1+\alpha} \Delta \vec{r}_{i,search}$ in (17) is the same for all robots (for a planar approximation to J); however, the displacement $\frac{\Delta_{\max}}{1+\alpha} \Delta \vec{r}_{i,swarm}$ varies from robot to robot.



$\Delta \vec{r}_{i,swarm}$ is computed via an inverse square repulsion law.

Fig. 3. Swarm control geometry

4) Simulation

A MATLAB simulation for a vehicle swarm was constructed. The set of simulation parameters pertinent to this

Signal to noise ratio	10 to 1
Emitter and reflector source strengths:	80dB@1m from the source
sensor positioning error	0.1 m of relative position error
sampling rate	1024Hz
repetition rate of emitter	1 Hz
number of robots	8
Number of $P(x,y,t)$ averages for creating J	12
Maximum move distance Δ_{\max}	10 m

study is contained in the following table¹:

Simulation results are shown for the above case in Fig. 4, where the reflector has been located and acquired by the swarm collective in 3 moves. The sample pressure data has been generated and averaged to simulate the minimization of additive background noise and corresponds to the #1 sensor at the initial swarm location, which was about midway between the acoustic sources.

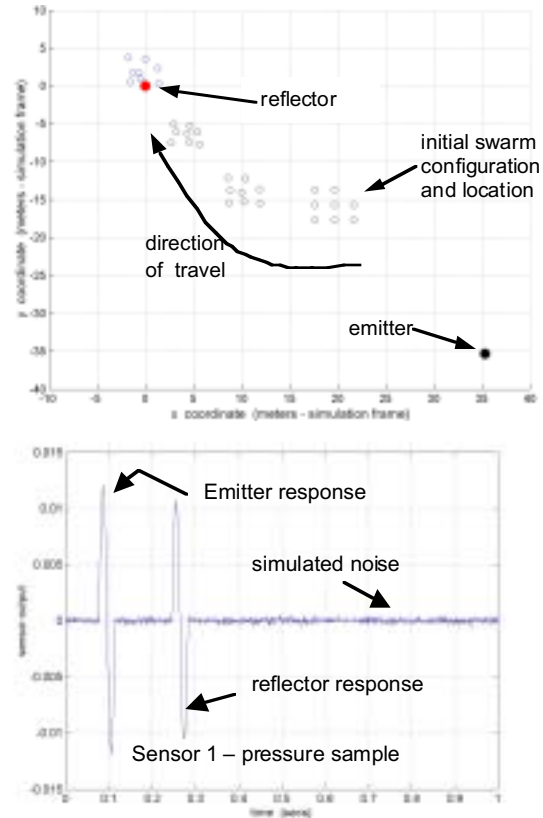


Fig. 4. Simulation results: Vehicle moves and sample sensor data

III. EXPERIMENTAL VALIDATION

The experiment was conducted in air in the open-space area by Sandia's Robotic Vehicle Range to minimize reflections from structures and attenuate background noise.

The acoustic sources were built using commercial acoustic

¹ Signal/noise ratio is defined as the ratio of the amplitude of measured pressure 60m away from an 80dB@1m acoustic source to the amplitude of measured noise.

components [6]. Acoustic bandwidth for the range 17.5 – 70Hz at 112dB was selected. Two of these (emitter and reflector) were assembled for the system testing. Eight PCB Acoustic piezoelectric microphone sensors [7] were used. Microphone size was approximately that of a U.S. quarter coin.

It was decided to use hand-emplaced sensors with a tape measure positioning system, versus using GPS receivers. The tape measurement variance (given winds and terrain variation) was approximately 0.1 meter. The measurement coordinate system differed from that of the simulation and a law of cosines transformation was used to “traverse” between the two.

Active reflector output was tuned to a level with that measured at a 50m range from the emitter. Once benign atmospheric conditions were achieved, 100 s of 26Hz pulse pressure data (P) from the eight sensors were averaged in 1s blocks. The average 1 s block was then processed to compute the Δr_i 's for the next move. New positions were computed and the sensors were subsequently moved. Changes from simulation were a signal/noise = 30 and 100 averages were used to formulate a suitable pressure history for processing to get updated vehicle positions.

Results were obtained for both active and passive reflector cases, the latter of which is presented here. A Nissan pickup (5 m x 1.5 m profile area) was used as the reflector. It was found

that this target proved even better than an active reflector at being acquired by the swarm. The algorithm directed the swarm in a straight line to the target and data analysis was done for only two moves. This run was compared with simulation, which is shown on the lower of Figure 5. The empty circles indicate the simulated data, which was also generated for a signal/noise ratio of 30 and ± 0.1 m position range errors.

IV. CONCLUSIONS

A swarm collective control algorithm for application to target detection has been derived and validated. The algorithm updates the positions of the swarm elements by combining two effects. The first is the gradient of the swarm-computed acoustic power flow field generated by emitter ensonification and reflector scattering, which moves the swarm towards the reflector target. The second combines inverse-square repulsive and attractive forces to maintain individual member spacing and allow continuous, accurate power flow estimations. Test results show that the method can acquire multiple reflectors in the field, but will gravitate towards the region of highest sensed acoustic intensity.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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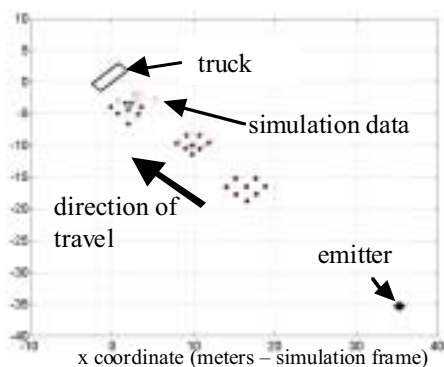


Fig. 5. Equipment and Results