The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Robot Localization and Energy-Efficient Wireless Communications by Multiple Antennas

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Abstract – **Biologically-inspired swarm of robots with collaboration towards a common mission has a broad range of applications. However, the required dynamic localization among autonomous robots for such swarm collaboration, though usually implicitly assumed, has not been properly studied. In this paper, we address the roles of multiple antennas in localization and energy-efficient wireless communications for a swarm of robots. Following the gradient of signal powers along a trajectory, a robot can track the direction of a source robot. With three or more properly placed antennas that sense different phase shifts of carrier, a robot can localize a source. By lateration, three collaborative robots can localize a source with known distances to it. Via angulation technique, three robots can determine their geometric relationship with knowing two angles and one distance between them. The techniques can be extended from the 2-D to the 3-D space for application of wall-climbing robots. On the basis of knowledge of robot locations, beamforming techniques can be employed to receive and transmit signal towards the desired robot therefore improving energy efficiency and prolonging robot lifetime.**

Index terms – robotic, wireless communications, antennas

I. INTRODUCTION

Biologically-inspired swarm of robots with collaboration and effective networking towards a common mission has recently gained a great deal of attention by the research community [1]-[3]. These studies usually assume that robots are effectively networked and dynamically know locations of their neighbors, and focus on the motion dynamics and group behavior. However, such assumptions of available means for effective communication and dynamic localization between robots have not been properly addressed yet in the literature. One of the possible approaches for localization is the sonar technique by which a robot analyzes the echo of self-emitted ultrasound and determines the location of a neighbor. Another one is the imaging technique that localizes a neighbor robot by analyzing the real-time video at the scene. Ladar system can also be employed for detection and ranging. However, the equipment of these techniques is either heavy and power demanding or incapable of providing accurate localization, and thus preventing them from implementation on lightly-loaded power-contingent robots. Moreover, these techniques cannot provide high data rate communications among robots that are necessary for robot collaboration and group dynamics.

By using a single antenna, we have proposed a method [4] that dynamically estimates the power gradient of the received source signal along a trajectory and guides the robot move toward the source. However, a single antenna can only determine the direction of a source but not the distance and so is not suitable for real-time mutual localization among robots.

In this paper, we propose to use multiple antennas for robot localization and energy-efficient wireless communications. We demonstrate that with two properly placed antennas a robot can estimate the phase difference of the source carrier from the received signals and then instantly localize the source with ambiguity of sign of phase. However, three properly placed antennas are sufficient for a robot to localize the source. With collaboration of robots, lateration and angulation techniques [5] [6] can determine the geometric relations of three robots in the two-dimensional plane and four robots in the three-dimensional space. Beamforming techniques can allow a robot to optimally combine the signals received on multiple antennas to achieve maximum signal power. Conversely, the beamforming technique can also let a robot to optimally allocate power to transmitting antennas so that the target robot receives the maximum signal power.

The rest of the paper is organized as follows. In the next section we describe how multiple antennas techniques can be used to accomplish source localization and its application to multi-robot systems in the 2-D and 3-D spaces; in section III we discuss the role that beamforming and smart antennas can play in swarm robotics.

II. SOURCE LOCALIZATION

Localization is the process of obtaining the position of a source with respect to the receiver's own position. Depending on the application, this may involve not only the estimation of the direction to the source but also the distance to it. The required accuracy of those estimations is also a function of each specific application. In an assisted navigation scenario for instance, where a robot relies in a sensor network for moving around in an unknown environment, localization becomes a problem of accurately estimate the direction to the source, but the estimation of the distance uses a more relaxed criteria, where an approximate estimation is good enough. Details of different methods to obtain such measurements are discussed below.

A. With a single antenna

Consider that a source transmits a signal whose power attenuates with the distance *d* in accordance with the power decay law

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$$P(d) = \frac{\alpha P}{d^{\beta}} \quad (1)$$

where P is the transmission power, α is a constant, and the decay exponent $\beta \geq 2$ depends on the environment. When using a single antenna, only the signal power can be used in source localization; but with the measuring of the signal power at one position, a robot cannot localize the source completely. By measuring the signal power along a trajectory, the robot can estimate the gradient direction of the signal power that points at the source; but since the parameters α and β are usually unknown and are difficult to accurately be estimated due to the thermal noise, unknown radio propagation model in wireless communications, and motion errors, it is difficult to accurately obtain the distance to the source. Consider the navigation scenario where a robot searches for a fixed source. The robot only needs to know instantly the direction of the source so that it can move towards the source [4]. According to the power decay law (1), the gradient of signal powers directs the source, which can be instantly estimated from the signal strength measurements along a trajectory through which the robot has just passed. Simulation results demonstrate that the robot can successfully reach the source with probability close to one when the signal to noise ratio at the initial location is as low as 0 dB and the standard deviation of motion error is 10% step size.

As a result of the source distance being difficult to estimate instantly, the gradient approach with one antenna is unsuitable for instant mutual localization of a group of autonomous robots.

B. With multiple antennas

To overcome the difficulty of a single antenna, consider a number of antennas equipped on a robot. As it is shown in Fig. 1, the 0th antenna is located at the origin representing the robot location. The ith antenna is located in the polar coordinate at $\mathbf{a}_i = (r_i, \theta_i)$, $i = 1, \ldots, N$ where r_i and θ_i are distance and angle, respectively. A source located at the polar coordinate (d, θ) emits a signal of the form

$$v(t) = \sqrt{2P}\cos(2\pi ft + s(t)) \quad (2)$$

where f is the carrier frequency. $s(t)$ is the information symbol which is usually fixed in a symbol period. For the binary phase shift keying (BPSK), $s(t)$ takes on $\pm\pi$'s. Let d_i be the distance from the ith antenna to the source. After propagated through the space or the wireless channel, the signal received at the ith antenna is then

$$x_i(t) = \sqrt{\frac{\alpha P}{d_i^{\beta}}}\cos(2\pi ft - \varphi_i) + w_i(t) \quad (3)$$

where $w_i(t)$ is an additive Gaussian noise process.

We consider a scenario with a cyclical operation where the Doppler effect can be ignored: the robot stops to measure signals and then moves again. The result can be extended to the case when robots continuously move but with a relatively slow speed. The phase change due to the waveform propagation is

$$\varphi_i = \frac{2\pi}{\lambda} d_i - s + n_i(t) \quad (4)$$

where $\lambda = c/f$ is the wavelength, c is the speed of light, s is the information symbol in transmission and $n_i(t)$ is noise with uniform distribution over $[-\sigma, \sigma]$ and i.i.d. across antennas. The effect of noise can be suppressed by averaging multiple measurements taken in a symbol period. The phase change for the 0th antenna is obtained by replacing d_i in (4) with d. The objective is to obtain the distance d and the angle θ between the robot and the source from the phase shifts in the multiple antennas.

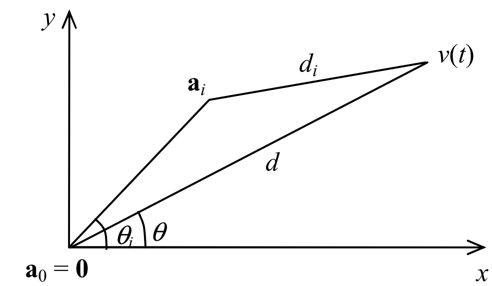

Fig. 1. Signal propagation to multiple antennas.

The distance difference between antennas can be obtained from (4) as

$$d_i - d = \beta_i \equiv \frac{\lambda(\varphi_i - \varphi_0)}{2\pi}. \quad (5)$$

Note that for any distance difference, the phase shift difference satisfies $-2\pi \leq \varphi_i - \varphi_0 \leq 2\pi$. To eliminate the ambiguity, we can impose $r_i \leq \lambda/2$. By simple geometry, the squared distance between the ith antenna and the source can be expressed as

$$d_i^2 = d^2 + r_i^2 - 2dr_i\cos(\theta - \theta_i). \quad (6)$$

Thus

$$\beta_i(d_i + d) = r_i^2 - 2dr_i\cos(\theta - \theta_i)$$

or

$$\beta_i(\beta_i + 2d) = r_i^2 - 2dr_i\cos(\theta - \theta_i). \quad (7)$$

If the antenna placement satisfies

$$\sum_{i=1}^{N} r_i\cos(\theta - \theta_i) = 0, \ \forall\theta, \quad (8)$$

then we can obtain the distance from the robot to the source

$$\hat{d} = \frac{\sum_{i=1}^{N} r_i^2 - \sum_{i=1}^{N}\beta_i^2}{2\sum_{i=1}^{N}\beta_i}. \quad (9)$$

To average out noise effect, we can use

$$\hat{d} = \frac{\frac{1}{N}\sum_{i=1}^{N} r_i^2 - \frac{1}{N}\sum_{i=1}^{N}\beta_i^2}{\frac{2}{N}\sum_{i=1}^{N}\beta_i}. \quad (10)$$

From (5), $\cos(\theta - \theta_i) = (r_i^2 - \beta_i(\beta_i + 2d))/(2dr_i)$. Let

$$\phi_i = \cos^{-1}\left(\frac{r_i^2 - \beta_i(\beta_i + 2d)}{2dr_i}\right).$$

For each antenna $i \neq 0$, one of the two antipodal solutions $\theta_i \pm \phi_i$ is correct. If the multiple antennas are properly placed, the ambiguity of sign can be eliminated. Let

$$(\hat{a}_1, \ldots, \hat{a}_N) = \arg \min_{(a_1,\ldots,a_N)\in\{-1,1\}^N} \sum_{i=1}^{N}\left(\frac{1}{N}\sum_{j=1}^{N}(\theta_j + a_j\phi_j) - (\theta_i + a_i\phi_i)\right)^2 \quad (11)$$

Then the angle can be obtained as

$$\hat{\theta} = \frac{1}{N}\sum_{j=1}^{N}(\theta_j + \hat{a}_j\phi_j). \quad (12)$$

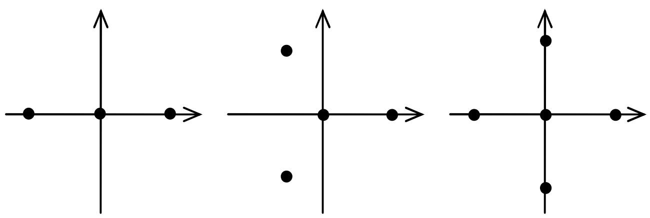

Fig. 2. Examples of antenna placement.

Examples of antenna placement that satisfies condition (8) are shown in Fig. 2. For three antennas placed at $\mathbf{a}_0 = (0,0)$, $\mathbf{a}_1 = (r,0)$, and $\mathbf{a}_2 = (r,\pi)$, the robot-source distance equals

$$d = (Nr^2 - \beta_1^2 - \beta_2^2)/(2(\beta_1 + \beta_2)).$$

The angle is

$$\theta = \cos^{-1}\left((\beta_2 - \beta_1)(\beta_2 + \beta_1 + 2d)/(4dr)\right).$$

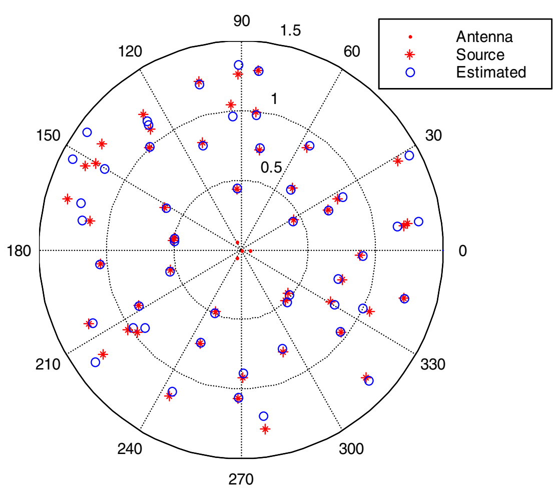

Fig. 3. Estimated source location via four antennas in Fig. 2.

Note that this antenna placement cannot distinguish the sign of angle. Moreover, if $\beta_1 + \beta_2 = 0$, which means $2d = d_1 + d_2$ or either $\theta = 0$ or $\theta = \pi$, then the distance d cannot be determined. To remove the ambiguity, we can consider four antennas placed at $\mathbf{a}_0 = (0,0)$, $\mathbf{a}_1 = (r,0)$, $\mathbf{a}_2 = (r, 2\pi/3)$, and $\mathbf{a}_3 = (r, -2\pi/3)$. The five antennas placed at $\mathbf{a}_0 = (0,0)$, $\mathbf{a}_1 = (r,0)$, $\mathbf{a}_2 = (r,\pi/2)$, $\mathbf{a}_3 = (r,\pi)$, and $\mathbf{a}_4 = (r, 3\pi/2)$ can also eliminate the phase ambiguity.

Fig. 3 demonstrates fifty estimated locations and the source locations randomly generated with the distance to robot in the range of 0.4 to 1.4 meters. The carrier frequency is f = 2.4 GHz (λ = 0.125 m), $r = \lambda/2$, and $\sigma = 2\pi\times10^{-3}$. The error between the estimated and the source locations increases as the distance increases. The average error is 0.036 meters and the standard deviation is 0.034 meters.

C. Through robot collaboration

A group behavior can be realized by each robot communicating with its neighbors. Equipped with multiple antennas, the robots estimate the locations of other robots and then exchange the location information via wireless communications. To this end, each robot maintains and periodically updates a table that stores the estimated locations of its neighbors. Then the robots in a neighborhood mutually validate their locations by the lateration and angulation techniques and therefore improve the accuracy of estimated locations.

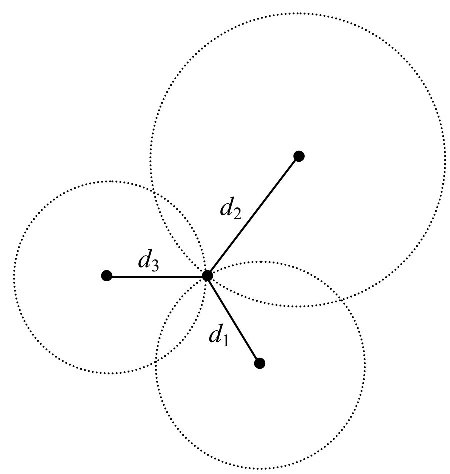

Fig. 4. Lateration: the distances from three non-collinearly located robots can localize the source in the 2-D plane.

Lateration determines the location of a source based on the distances from a number of robots. As shown in Fig. 4, knowing the distance to a source, one robot cannot determine the source location due to the angle ambiguity, that is, the source may be possibly located at any point on the circle with a radius equal to the known distance. Two collaborative robots knowing the distances to the source can reduce the ambiguity of location to the two possible points. Furthermore, three non-collinearly located robots knowing the distances to the source can completely determine the source location. Hence, by lateration the robots can mutually validate their estimated locations through collaboration with wireless communications.

Angulation computes the location of a source by the fact that the angles of two robots relative to the source and the distance between the two robots can determine the source location as shown in Fig. 5. Consequently, two collaborative robots by exchanging the location information can crossly validate the estimated source location and therefore improve the accuracy of estimated robot localizations. This technique can be applied to a group of robots to mutually improve the accuracies of their measured locations.

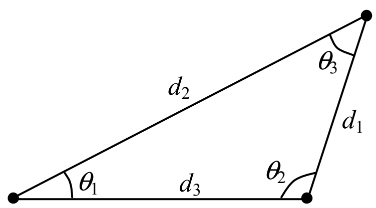

Fig. 5. Given any two angles and the distance between them, the 2-D geometric relation of three robots is determined.

The multi-antenna technique and wireless communications provide the means for application of the lateration and angulation techniques. The protocols for robot collaboration and dynamic network management for lateration and angulation need to be further studied.

D. Extension to 3-D space

A swarm of wall-climbing robots [7] might be particularly useful for monitoring complex environments. Due to the increased space dimension, the mutual localization of swam wall-climbing robots is more complicated but the principle of the multi-antenna as well as the lateration and angulation technique is the same as in the 2-D space. The techniques discussed above can be extended from the 2-D to the 3-D space. To eliminate the azimuth angular ambiguity, two more antennas along the z-axis are necessary. The second configuration in Fig. 2 where three antennas are placed at the vertices of a 2-simplex (i.e. an equilateral triangle) and one at the center is the simplest placement of fewest antennas to determine a source in the 2-D space. Similarly, the configuration of four antennas placed at the vertices of a 3-simplex (i.e. a regular tetrahedron) and one at the center is the simplest placement of fewest antennas to localize a source in the 3-D space. Complex configurations with more antennas can also be considered to provide more reliable estimation of source location. An example of such a configuration can be six antennas placed at the vertices of two 2-simplexes perpendicular to the z-axis and symmetric to the origin and one placed at the origin.

While three non-collinearly located robots can localize a source by lateration, in the 3-D space one more robot is needed to eliminate the ambiguity in the third dimension. Hence, four non-coplanarily located robots knowing the distances to a source can determine its location. In the 2-D space, angulation computes the source location by two angles and one distance from two robots. In the 3-D space, one more robot is needed to remove the ambiguity of azimuth angle. To improve the location accuracy, a larger number of robots than necessary can collaborate with cross validation of their locations.

III. Beamforming and Smart Antenna

Beamforming is a signal processing technique that can be used to increase the transmit or receive gains on antenna arrays for directional transmission and reception of signals [8]. Beamforming can also be applied to focus transmitted signal on the desired receiver direction or to reject the interference in multiple received signals.

Consider that multiple receive antennas are implemented on a robot. The signals received at these antennas from a source differ in the carrier phase. With the knowledge of the source location, the receive robot can optimally combine the signals being received to achieve the maximum signal to noise ratio (SNR) in detection of information symbols. Consider the placement of multiple antennas in the proceeding section. The received signal at the ith antenna described by (3) has phase shift φ_i or time delay d_i/c. The signal powers on multiple antennas $\alpha P/d_i^{\beta}$ differ slightly because the distances between the antennas are small relatively to the distance to the source. To achieve the maximum SNR of combined signals, we add all the received signals $x_i(t+d_i/c)$ with the ith signal delayed by $-d_i/c$. To achieve the maximum SNR for symbol detection, we can consider the sufficient statistic

$$y=\sum_i\left(\frac{2\pi d_i}{\lambda}-\varphi_i\right). \qquad (13)$$

For the BPSK modulation with $s \in \{-1, 1\}$, the SNR for the bit detection $s=\text{sgn}(y)$ is equal to $3(N+1)/\sigma^2$, which increases approximately $10\log_{10}N$ dB with the number of receive antennas. The beamforming technique can also be similarly applied to transmission of complex symbols. The maximization of SNR in beamforming is obtained only if the source location is known via multiple antennas. The maximization of SNR increases the energy efficiency, which in turn prolongs robot lifetime, and therefore is particularly useful when the power is stringent such as in micro-autonomous robots applications. In addition to the source localization with multiple antennas, collaboration and management over the networked robots are required for application of the beamforming technique. Accordingly, protocols for cross physical and network layers need to be thoroughly studied and developed.

A beamformer can also be applied to the transmission of signals. Consider a robot equipped with multiple transmit antennas. By knowing the location of a receive robot, the strengths and phases of signals transmitted through the multiple antennas carrying the same data, can be smartly distributed so that the power of signal arriving at the receive robot is maximized. If the signal transmitted through the ith antenna is $v_i(t)=\sqrt{2P}\cos(2\pi ft-s(t)+2\pi d_i/\lambda)$ where the distance d_i from the ith antenna to the robot is known, then the signals transmitted through multiple antennas have the same phase shift. Since the distances between the antennas are much shorter than the distance from the transmit and the receive robots, the differences of power attenuation for the antennas is ignorable. Hence, the uniformity in phase shift of received signals makes the power of received signal maximized. It is clear that if multiple transmit antennas are implemented on the transmit robot and multiple receive antennas are implemented on the receive robot, the beamforming techniques can be simultaneously applied in both robots and therefore significantly improve the energy efficiency.

Smart antennas [9], which are also known as adaptive array antennas, use smart signal processing algorithms to identify the direction of arrival (DOA) of the signal, to calculate beamforming parameters, and to track a mobile source. The algorithms for smart antennas in literature are useful in networking swarm robotics, which is worth to further study.

IV. Conclusions

We have addressed the roles of multiple antennas in robot localization and energy-efficient wireless communications. A robot implemented with one receive antenna can search a source by following the gradient direction of received signal strength along a trajectory. Three and more properly placed antennas can localize a source by utilizing the carrier phase differences on multiple antennas. With the collaboration through wireless communications, a group of robots can crossly validate their locations by lateration and angulation. These techniques based on multiple antennas can be easily extended from the 2-D to the 3-D space for application for wall-climbing robots. Once the locations are known, the robots can employ the beamforming and smart antenna techniques therefore improving the energy efficiency and prolonging robot lifetime.

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