

Fast and Robust Trilateration for Multi-Robot Tasks

Paul M. Maxim Suranga Hettiarachchi William M. Spears Diana Spears Jerry Hamann Thomas Kunkel

Abstract—The ability of robots to quickly and accurately localize their neighbors is extremely important for robotic teams. Prior approaches typically rely either on global information provided by GPS, beacons, and landmarks, or on complex local information provided by vision systems. In this paper we describe our trilateration approach to multi-robot localization, which is fully distributed, inexpensive, scalable, and robust. Our prior research [14] focused on maintaining multi-robot formations indoors using trilateration. This paper pushes the limits of our trilateration technology by testing formations of robots in an uncontrolled outdoor setting with relatively large inter-robot distances and high speeds. Rigorous experimental results demonstrate surprising robustness, as well as the limits of performance.

I. INTRODUCTION

The main contributions of this paper are: (1) a presentation of our robust and simple trilateration approach to multi-robot localization (i.e., each robot locates its neighbors), and (2) a description of a set of experimental results obtained with our trilateration approach under varying conditions. These experimental results highlight the advantages of our approach and clarify its limitations. The experiments pose severe demands on the trilateration system – because they are conducted in an uncontrolled outdoor environment with variations in height, surface, and other conditions between members of the robot team. They also stress the robot formations by testing their accuracy at relatively high speeds and large inter-robot distances. To the best of our knowledge, our project is the first to perform rigorous experimental tests of trilateration for robot formations under such extreme conditions. Despite the posed challenges, the robots retain relatively high-quality geometric formations. Furthermore, degradation in the quality of trilateration signals is surprisingly small as the inter-robot distances and robot speeds are increased. Our trilateration approach works as expected in enabling multi-robot formations indoors [14], and it greatly exceeds our expectations when thrust into an uncontrolled outdoor setting with varying terrain (e.g., grass versus concrete), rocks, protruding tree roots, leaves, pine cones and other ground protrusions. Because of our highly robust trilateration scheme for localization, the robots are repeatedly able to maintain excellent formations despite the prevalence of ground disturbances. Furthermore, unlike typical trilateration and other localization techniques that require LEDs or cameras, our approach is demonstrated to

be robust in the presence of considerable amounts of dust and wind (over 9 meters per second or 20 miles per hour) and other normal outdoor conditions, and we fully expect the trilateration to be able to handle rain, snow, nighttime, and other conditions. Note that here, as well as hereafter in this paper, we denote measurements using the metric system (and British).

The organization of this paper is as follows. Section II introduces our trilateration approach to robust localization, which is fully distributed and assumes that each robot has its own local coordinate frame (i.e., no global information is required). Each robot determines its neighbors’ range and bearing with respect to its own egocentric, local coordinate system. After such localization, sensor values and other data can be exchanged between robots in a straightforward manner. Next, Sections III and IV describe our trilateration implementation and current robot platforms, respectively. Sections V and VI present a summary of prior indoor experiments, followed by new outdoor experiments. The latter delineate the range of performance of our trilateration system. Section VII summarizes and concludes the paper.

II. LOCALIZATION VIA TRILATERATION

The purpose of our trilateration technology is to create a plug-in hardware module to accurately localize neighboring robots, without global information and/or the use of vision systems. Our localization technology does not preclude the use of other technologies. Beacons, landmarks, pheromones, vision systems, and GPS are not necessary, but they can be added if desired. The system described in this paper is intended for use in a 2D environment; however, extension to 3D is readily achievable. It is important to note that our trilateration approach is not restricted to one particular class of control algorithms – it is useful for behavior-based approaches [1], control-theoretic approaches [2], [3], motor schema algorithms [4], and physicomimetics [5].

Two methodologies for robot localization are *triangulation* and *trilateration* [6]. Both compute the location of a point (e.g., a robot) in 2D space. In *triangulation*, the locations of two “base points” are known, as well as the interior angles of a triangle whose vertices comprise the two base points and the object to be localized. The computations are performed using the Law of Sines. In 2D *trilateration*, the locations of three base points are known as well as the distances from each of these three base points to the object to be localized. Looked at visually, 2D trilateration involves finding the location where three circles intersect.

Thus, to locate a remote robot using 2D trilateration the sensing robot must know the locations of three points in

This work is supported in part by the Joint Ground Robotics Enterprise. The first four authors are with the Department of Computer Science, University of Wyoming, Laramie, WY, paulmax@uwyo.edu. The last two authors are with the Department of Electrical Engineering, University of Wyoming, Laramie, WY.

its own coordinate system and be able to measure distances from these three points to the remote robot.

A. Measuring Distance

Our distance measurement method exploits the fact that sound travels significantly more slowly than light, thereby enabling us to employ a Difference in Time of Arrival technique. The same method is used to determine the distance to a lightning strike by measuring the time between seeing the lightning and hearing the thunder.

To tie this to 2D trilateration, assume that each robot has one radio frequency (RF) transceiver and three ultrasonic acoustic transceivers. The ultrasonic transceivers are the “base points.” Suppose robot 2 simultaneously emits an RF pulse and an ultrasonic acoustic pulse. When robot 1 receives the RF pulse (almost instantaneously), a clock on robot 1 starts. When the acoustic pulse is received by each of the three ultrasonic transceivers on robot 1, the elapsed times are computed. These three times are converted to distances, according to the speed of sound. Because the locations of the acoustic transceivers are known, robot 1 is now able to use trilateration to compute the location of robot 2 (precisely, the location of the emitting acoustic transceiver on robot 2). Of the three acoustic transceivers, all three must be capable of receiving, but only one must be capable of transmitting.

Measuring the elapsed times is not difficult. Since the speed of sound is roughly 340.2 meters per second (at standard temperature and pressure), it takes approximately 2.9 ms for sound to travel 1 meter. Times of this magnitude are easily measured using inexpensive electronic hardware.

B. Channeling Acoustic Energy into a Plane

Ultrasonic acoustic transducers (also called “transceivers”) produce a cone of energy along a line perpendicular to the surface of the transducer. The width of this main lobe (for the inexpensive 40 kHz transducers used in our implementation) is roughly 30° . To produce acoustic energy in a 2D plane would require 12 acoustic transducers in a ring. To get three base points would hence require 36 transducers. This is expensive and is a large power drain. We adopted an alternative approach. Each base point is comprised of one acoustic transducer pointing downward. A parabolic cone is positioned under the transducer, with its tip pointing up toward the transducer (see Fig. 2 and Fig. 3 later in this paper). The parabolic cone acts like a lens. When the transducer is placed at the virtual “focal point” the cone “collects” acoustic energy in the horizontal plane, and focuses this energy to the receiving acoustic transceiver. Similarly, a cone also functions in the reverse, reflecting transmitted acoustic energy into the horizontal plane. This works extremely well – the acoustic energy is detectable to a distance of about 2.44 m (8'), which is quite impressive and more than adequate for our needs. Greater range can be obtained with more power (the scaling appears to be very manageable).

C. Related Work

Trilateration is a well-known technique for robot localization. Most approaches (including ours) are algebraic,

although recently a geometric method was proposed [7]. Many localization techniques, including those involving trilateration, use global coordinates [8]; however ours relies on local coordinates only.

MacArthur [9] presents two different trilateration systems. The first uses three acoustic transducers, but without RF. Localization is based on the differences between distances rather than the distances themselves. The three acoustic transducers are arranged in a line. The second uses two acoustic transducers and RF in a method similar to our own. Unfortunately, both systems can only localize points “in front” of the line, not behind it.

Cricket [10] is another system that makes use of RF and ultrasound for localization. It was developed to be used indoors. Compared to our system, which does not require fixed beacons, the Cricket requires beacons attached to fixed locations in order to function. This is not practical for mobile robot localization in outdoor environments.

Our particular approach was inspired by the CMU *Millibot* project. They also use RF and acoustic transducers for trilateration. However, due to the very small size of their robots, each *Millibot* can only carry one acoustic transducer (coupled with a right-angle cone, rather than the parabolic cone we use). Hence trilateration is a collaborative endeavor that involves several robots. To perform trilateration, a minimum of three *Millibots* must be stationary and serve as beacons at any moment in time. The set of three stationary robots changes as the robot team moves. The minimum team size is four robots (and is preferably five). Initialization generally involves having some robots make L-shaped maneuvers, in order to disambiguate the localization [11]. Our approach operates with as few as two robots, due to the presence of three acoustic transducers on each robot (see below).

In terms of functionality, an alternative localization method in robotics is to use line-of-sight IR transceivers. When IR is received, signal strength provides an estimate of distance. The IR signal can also be modulated to provide communication. Multiple IR sensors can be used to provide the bearing to the transmitting robot (e.g., see [12], [13]). We view this method as complementary to our own; however, our method is more appropriate for tasks where greater localization accuracy is required. This is especially important in outdoor situations where water vapor or dust could change the IR opacity of air. Similar issues arise with the use of cameras and omni-directional mirrors/lenses, which require far more computational power and a light source.

D. Our Trilateration Approach

Our trilateration approach to localization is illustrated in Fig. 1. Assume two robots, shown as circles. An RF transceiver is in the center of each robot. Each robot has three acoustic transducers (also called *base points*), labeled **A**, **B**, and **C**. Note that the robot’s local XY coordinate system is aligned with the L-shaped configuration of the three acoustic transceivers, as shown in the figure. This simplifies the math [14]. Y points to the front of the robot.

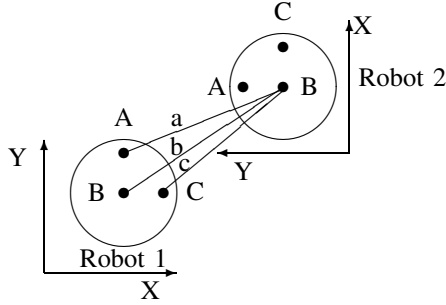


Fig. 1. Three base points in an XY coordinate system pattern.

In Fig. 1, robot 2 simultaneously emits an RF pulse and an acoustic pulse from its transducer **B**. Robot 1 then measures the distances **a**, **b**, and **c**. Without loss of generality, assume that transceiver **B** of robot 1 is located at $(x_{1B}, y_{1B}) = (0, 0)$ [15].¹ In other words, let **A** be at $(0, d)$, **B** be at $(0, 0)$, and **C** be at $(d, 0)$, where d is the distance between **A** and **B**, and between **B** and **C** (see Fig. 1). Assume that robot 2 emits from its transducer **B**.

For robot 1 to determine the position of **B** on robot 2 within its own coordinate system, it needs to find the simultaneous solution of three nonlinear equations, the intersecting circles with centers located at **A**, **B** and **C** on robot 1 and respective radii of **a**, **b**, and **c**:

$$(x_{2B} - x_{1A})^2 + (y_{2B} - y_{1A})^2 = a^2 \quad (1)$$

$$(x_{2B} - x_{1B})^2 + (y_{2B} - y_{1B})^2 = b^2 \quad (2)$$

$$(x_{2B} - x_{1C})^2 + (y_{2B} - y_{1C})^2 = c^2 \quad (3)$$

The form of these equations allows for cancellation of the nonlinearity, and simple algebraic manipulation yields the following simultaneous linear equations in the unknowns:

$$\begin{bmatrix} x_{1C} & y_{1C} \\ x_{1A} & y_{1A} \end{bmatrix} \begin{bmatrix} x_{2B} \\ y_{2B} \end{bmatrix} = \begin{bmatrix} (b^2 + x_{1C}^2 + y_{1C}^2 - c^2)/2 \\ (b^2 + x_{1A}^2 + y_{1A}^2 - a^2)/2 \end{bmatrix}$$

Given the L-shaped transducer configuration, we get [15]:

$$x_{2B} = \frac{b^2 - c^2 + d^2}{2d} \quad y_{2B} = \frac{b^2 - a^2 + d^2}{2d}$$

An interesting benefit of these equations is that they can be simplified even further, if one wants to trilaterate purely in hardware [14].

Analysis of our trilateration framework indicates that, as expected, error is reduced by increasing the “base-line” distance d . Our robots have d equal to 15.24 cm (6”). Error can also be reduced by increasing the clock speed of our trilateration module (although range will decrease correspondingly, due to counter size) [15].

By allowing robots to share coordinate systems, robots can communicate their information arbitrarily far throughout a robotic network. For example, suppose robot 2 can localize

¹Subscripts denote the robot number and the acoustic transducer. The transducer **A** on robot 1 is located at (x_{1A}, y_{1A}) .



Fig. 2. Acoustic transducers and parabolic cones.

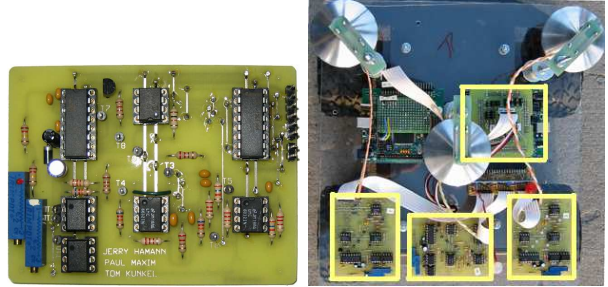


Fig. 3. The XSRF acoustic sensor printed circuit board (left), and the completed trilateration module (top-down view, right).

robot 3. Robot 1 can localize only robot 2. If robot 2 can also localize robot 1 (a fair assumption), then by passing this information to robot 1, robot 1 can now determine the position of robot 3. Furthermore, robot orientations can also be determined. Naturally, localization errors can compound as the path through the network increases in length, but multiple paths can be used to alleviate this problem to some degree. Heil [15] provides details on these issues.

In addition to localization, our trilateration system can also be used for data exchange. Instead of emitting an RF pulse that contains no information but only performs synchronization, we can also append data to the RF pulse. Simple coordinate transformations allow robot 1 to convert the data from robot 2 (which is in the coordinate frame of robot 2) to its own coordinate frame.

III. TRILATERATION IMPLEMENTATION

A. Trilateration Hardware

Fig. 2 and Fig. 3 illustrate how our trilateration framework is currently implemented in hardware. Fig. 2 shows three acoustic transducers pointing down, with reflective parabolic cones. The acoustic transducers are specially tuned to transmit and receive 40 kHz acoustic signals.

Fig. 3 (left) shows our in-house acoustic sensor boards (denoted as “XSRF” boards, for *Experimental Sonic Range Finder*). There is one XSRF board for each acoustic transducer. The XSRF board calculates the time difference between receiving the RF signal and the acoustic pulse. Each XSRF contains 7 integrated circuit chips. A MAX362 chip controls whether the board is in transmit or receive mode. When transmitting, a Microchip PIC microprocessor generates a 40 kHz signal. This signal is sent to an amplifier, which

then interfaces with the acoustic transducer. This generates the acoustic signal.

In receive mode, a trigger indicates that an RF signal has been heard and that an acoustic signal is arriving. When the RF is received, the PIC starts counting. To enhance the sensitivity of the XSRF board, three stages of amplification occur. Each of the three stages is accomplished with a LMC6032 operational amplifier, providing a gain of roughly 15 at each stage. Between the second and third stage is a 40 kHz bandpass filter to eliminate out-of-bound noise that can lead to saturation. The signal is passed to two comparators, set at thresholds of ± 2 VDC. When the acoustic energy exceeds either threshold, the PIC finishes counting, indicating the arrival of the acoustic signal.

This timing count provided by each PIC (one for each XSRF) is sent to a MiniDRAGON board² powered by a Freescale 68HCS12 microprocessor. The MiniDRAGON performs the trilateration calculations. Fig. 3 (right) shows the completed trilateration module from above. The MiniDRAGON is outlined near the center and the three XSRF acoustic sensors are outlined at the bottom.

B. Synchronization Protocol

Trilateration involves at least two robots. One transmits the acoustic-RF pulse combination, while the others use these pulses to compute (trilaterate) the coordinates of the transmitting robot. Hence, trilateration is a one-to-many protocol, allowing multiple robots to simultaneously trilaterate and determine the position of the transmitting robot.

The purpose of trilateration is to allow all robots to determine the position of all of their neighbors. For this to be possible, the robots must take turns transmitting. For our current implementation we use a protocol that is similar to a token passing protocol. Each robot has a unique hardware encoded ID. When a robot is transmitting it sends its own ID. As soon as the neighboring robots receive this ID they increment the ID by one and compare it with their own ID. The robot that matches the two IDs is considered to have the token and will transmit next. The other robots will continue to trilaterate. Each robot maintains a data structure with the coordinate information, as well as any additional sensor information, of every neighboring robot.

Although this current protocol is distributed, there are a few problems with it. First, it assumes that all robots know how many robots are in the collective. Second, the removal or failure of a robot can cause all robots to pause, as they wait for the transmission of that robot. We are currently working on new protocols to rectify these issues.

IV. THE MAXELBOT ROBOT PLATFORMS

Our University of Wyoming “Maxelbot” (named after the two graduate students who designed and built the robot) is modular. The platform is an MMP5, made by The Machine Lab³. A primary MiniDRAGON is used for control. It communicates via an I²C bus to all other peripherals,

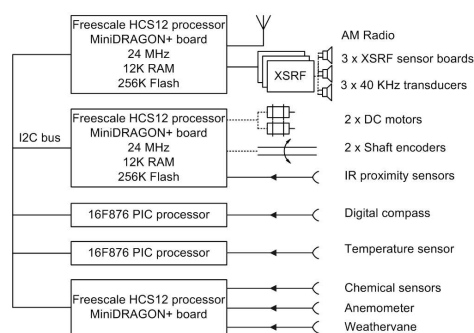


Fig. 4. The architecture of the Version 1.0 Maxelbot.

allowing us to plug in new peripherals as needed. Fig. 4 shows the architecture. The primary MiniDRAGON is the board that drives the motors. It also monitors proximity sensors and shaft encoders. The trilateration module is shown at the top of the diagram. This module controls the RF and acoustic components of trilateration. Additional modules have been built for digital compasses, thermometers, and chemical plume tracing. The PICs provide communication with the I²C bus.

V. PRIOR INDOOR EXPERIMENTS AND DEMONSTRATIONS

Numerous task-driven formations have been successfully performed with the Maxelbots indoors using trilateration. For details, see [14]. Here, we briefly summarize those results.

One of our research objectives is linear (also called “chain”) formations. This type of formation is especially useful for traversing corridor-like environments, such as sewers, underground pipes, or ducts. Our demonstrations show that three Maxelbots, roughly 30.5 cm (12”) apart, will stay in formation as the leader follows a curved trajectory.

A second demonstration is motivated by search and rescue. In particular, a group of three Maxelbots have to pull a box, which contains a doll simulating an infant victim. The desired behavior is as follows. There is one leader and two followers. The followers are 61 cm (24”) behind the leader and are separated by 122 cm (48”) from each other. The lead Maxelbot is not in physical contact with the box, but the box is tethered to the two followers. The Maxelbots succeed in pulling the box in a straight line, despite the unevenness of the load-carrying. The success is due to our trilateration.

The third demonstration/experiment requires maintenance of formations while performing a “chemical plume tracing” (CPT) task [16]. The CPT objective is to locate the source of a hazardous airborne chemical plume by measuring flow properties, such as toxin concentration. This is best performed as a collaborative task. Using ethanol vapors and a Figaro TGS2620 metal oxide chemical sensor mounted on each platform, three Maxelbots succeed in maintaining a triangular formation in a roughly 7.6 m \times 7.6 m (25' \times 25') indoor laboratory environment. Out of 10 trials, the Maxelbot team achieves a 60% success rate with an average search time

²Produced by Wytec (<http://www.evbplus.com/>)

³See <http://www.themachinelab.com/MMP-5.html>



Fig. 5. Maxelbots outdoors in UW’s Prexy’s Pasture.

of just seven minutes. This is competitive with the best CPT results published, despite the fact that the experiments are conducted in a far more unstructured indoor environment than usual, as well as more stringent success criteria than usual. The trilateration not only helps the Maxelbots to stay in their triangular formation, but it also assists in data sharing for the computation of chemical gradients.

The indoor experiments just described are so encouraging that we have decided to push the limits of our technology and venture into highly unstructured outdoor environments. We are unaware of any other rigorous trilateration experiments in such challenging outdoor environments, speeds, and distances as what we describe next.

VI. NEW OUTDOOR EXPERIMENTS

This section presents three experiments that aid in identifying the strengths and limitations of the trilateration system in an uncontrolled outdoor setting. In particular, the Maxelbots are run outside in a region in the center of the University of Wyoming campus called “Prexy’s Pasture” (see Fig. 5)⁴. Prexy’s consists mostly of grass, of average height 5 cm (2”), interspersed with concrete sidewalks, trees, rocks, leaves, and other debris. The grass hits the bottom of the Maxelbot. Although generally flat, the ground slope can change rapidly (within 61 cm or 2’), by up to 20°, at boundaries. Results presented below are averaged over five independent runs, taken over a 20 minute interval.

The control algorithm used during these experiments simply maintains the proper distance by compensating with speed-ups, slow-downs, and turns. It is not designed to be particularly intelligent. The purpose of these experiments is to validate and test the hardware; the focus is not on the control software.

A. Trilateration Accuracy as a Function of Speed

The first experiment tests trilateration accuracy as speed increases. There is a leader and a follower Maxelbot. The follower tries to stay 102 cm (40”) behind the leader. The relative speed difference between leader and follower is 20%, with the follower having greater speed. The leader always runs at its designated power (speed). The follower may choose to run at a slower speed than its maximum. Three pairs of speeds are tested: 20%-40%, 40%-60%, and 60%-80%. Table I shows the mean and standard deviation of the results, averaged over five runs at each pair of speeds.

⁴<http://www.laramie.willshireltd.com/PrexysPasture.html>

TABLE I
ACCURACY OF THE FOLLOWER’S X AND Y POSITION WHEN THE DESIRED Y IS 102 CM (40”), AT DIFFERENT SPEEDS.

Speed (% power)		Follower-X cm (inches)		Follower-Y cm (inches)	
Leader	Follower	mean	Std. dev.	mean	Std. dev.
20	40	6.0 (2.4)	1.6 (0.6)	78.5 (30.9)	6.5 (2.5)
40	60	2.6 (1.0)	2.3 (0.9)	88.3 (34.8)	4.1 (1.6)
60	80	1.4 (0.5)	2.5 (1.0)	98.2 (38.7)	2.7 (1.1)

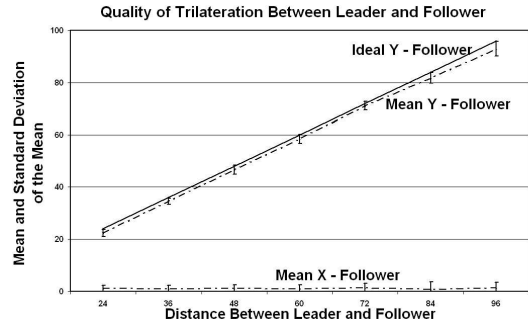


Fig. 6. Trilateration quality as a function of distance (in inches).

The results indicate that the best speed pair is 60%-80%. Analysis indicated that this was not due to the trilateration, but due to the controller and the speed (power) ratio between the follower and the leader. At slower speeds, the ratio was too high, resulting in the controller allowing the follower to get too close. We are currently modifying the software to allow the follower to determine the optimal power setting, based on the trilateration feedback. Further analysis indicated that a constant bias error is introduced if the acoustic transducers are not aligned perfectly with respect to the parabolic cones. Hence we introduced a self-calibration procedure at the beginning of every run. In the experiment below, we used the 60%-80% speed ratio and self-calibration. 80% power corresponds to slightly greater than 0.55 m (1.8’) per second.

B. Trilateration Accuracy as a Function of Distance

The second experiment tests the accuracy of trilateration as the distance between the leader and follower increases. The desired distance Y varies from 61 cm (2’) to 244 cm (8’) in increments of 30.5 cm (1’). Five runs are performed at each of these desired distances. The average and standard deviation (shown as vertical bars) of the trilateration readings are shown in Fig. 6.

The results are very accurate. The mean is extremely close to the desired following distance, and the standard deviation is quite small. The standard deviation gets slightly higher as the following distance increases, perhaps due to the small degradation in acoustic signal quality at greater distances. Above 244 cm (8’) the acoustic signal is lost.

TABLE II
ACCURACY OF THE THREE FOLLOWERS' X AND Y POSITIONS IN A
DIAMOND FORMATION.

	Ideal cm (inches)	Mean (inches)	Std. dev.
Maxelbot1-X	61 (24)	62.1 (24.5)	1.7 (0.7)
Maxelbot1-Y	61 (24)	54.8 (21.6)	2.7 (1.1)
Maxelbot2-X	-61 (-24)	-64.3 (-25.3)	4.2 (1.7)
Maxelbot2-Y	61 (24)	54.5 (21.5)	3.5 (1.4)
Maxelbot3-X	0 (0)	1.0 (0.4)	5.1 (2.0)
Maxelbot3-Y	122 (48)	111.8 (44.0)	4.6 (1.8)

C. Accuracy of Diamond Formation Preservation

In this experiment, three Maxelbots are required to maintain a diamond formation. There is a leader and three followers. The leader goes on a curved path, and the followers have to maintain certain XY-coordinates with respect to the leader (see the "Ideal" column in Table II). The leader is running at 60% power, and the followers are at 80% power with a variable turning speed. The wind speed near the ground ranges from 4 to 9 meters per second (10 to 21 mph).

Table II shows the XY-coordinates derived from the trilateration readings, for the three followers. From this table, it can be seen that the mean is very close to the ideal, and the standard deviations are small. Y is within 10% of the desired value, while X is within 5%. In other words, a very good, robust diamond formation is maintained by the trilateration system despite ground disturbances, wind, dust, and relatively high speed. The results are averaged over five independent runs.

D. Further Robustness Results

A more detailed data analysis has been performed for the cases when two Maxelbots are between 61 cm (2') and 244 cm (8') apart, and are running at the maximum pair of speeds. In all of these cases, the RF failure rate is 0.2%. Furthermore, the rate at which the RF pulse is received but acoustic pings are not received (at all three receivers) is only 1%. Almost every acoustic failure was isolated, and not consecutive. Consider the interpretation of these results. Given that acoustic pings are sent at a rate of approximately four per second (4.17 Hz), this implies that 1% of the time, the Maxelbots ran for only 0.25 seconds on old data. Only once were two consecutive pings in a row not received, yielding one 0.5 second gap in readings. This far exceeds our original design specifications.

Of all of our tests, the factor most important to success was the temperature. Below roughly 6°C (43°F) the electronics failed. Given that our components are not ruggedized, this is not surprising.

VII. SUMMARY AND FUTURE WORK

This paper describes a robust 2D trilateration framework for the fast, accurate localization of neighboring robots. The framework uses three acoustic transceivers and one RF transceiver. Our framework is designed to be modular, so that it can be used on different robotic platforms, and is not restricted to any particular class of control algorithms.

Although we do not rely on GPS, stationary beacons, or environmental landmarks, their use is not precluded. In addition to being robust, our framework is fully distributed, inexpensive, and scalable.

To illustrate the general utility of our framework, we demonstrated the application of our robots in a wide variety of situations. The results from these experiments highlight the surprising accuracy and robustness of our trilateration framework under challenging conditions, as well as its limitations (range and environmental temperature).

In the future, we plan to replace our heuristic control algorithm with our physicomimetics framework (already accomplished with our indoor experiments). We will investigate hardware that will allow us to increase the rate of acoustic pings as well as range. Currently our electronics are fully exposed to the elements. Some form of ruggedization will be implemented.

Open Source Project URLs

Schematic details and videos of the Maxelbots may be found at <http://www.cs.uwyo.edu/~wspears/maxelbot>.

REFERENCES

- [1] Balch, T., Hybinette, M.: Social potentials for scalable multirobot formations. In: IEEE Transactions on Robotics and Automation. Volume 1. (2000) 73–80
- [2] Fax, J., Murray, R.: Information flow and cooperative control of vehicle formations. IEEE Transactions on Automatic Control **49** (2004) 1465–1476
- [3] Fierro, R., Song, P., Das, A., Kumar, V.: Cooperative control of robot formations. In Murphey, R., Pardalos, P., eds.: Cooperative Control and Optimization. Volume 66., Hingham, MA, Kluwer Academic Press (2002) 73–93
- [4] Brogan, D., Hodgins, J.: Group behaviors for systems with significant dynamics. Autonomous Robots **4** (1997) 137–153
- [5] Spears, W., Spears, D., Hamann, J., Heil, R.: Distributed, physics-based control of swarms of vehicles. Autonomous Robots **17(2-3)** (2004)
- [6] Borenstein, J., Everett, H., Feng, L.: Where am I? Sensors and Methods for Mobile Robot Positioning. University of Michigan (1996)
- [7] Thomas, F., Ros, L.: Revisiting trilateration for robot localization. IEEE Transactions on Robotics **21(1)** (2005) 93–101
- [8] Peasgood, M., Clark, C., McPhee, J. Localization of multiple robots with simple sensors. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'05). (2005) 671–676
- [9] MacArthur, D.: Design and implementation of an ultrasonic position system for multiple vehicle control. Master's thesis, University of Florida (2003)
- [10] Nissanka, B., P.: The cricket indoor location system. Doctoral thesis, Massachusetts Institute of Technology, Cambridge, MA (2005)
- [11] Navarro-Serment, L., Paredis, C., Khosla, P.: A beacon system for the localization of distributed robotic teams. In: International Conference on Field and Service Robots, Pittsburgh, PA (1999) 232–237
- [12] Rothermich, J., Ecemis, I., Gaudio, P.: Distributed localization and mapping with a robotic swarm. In Şahin, E., Spears, W., eds.: Swarm Robotics, Springer-Verlag (2004) 59–71
- [13] Payton, D., Estkowski, R., Howard, M.: Pheromone robotics and the logic of virtual pheromones. In Şahin, E., Spears, W., eds.: Swarm Robotics, Springer-Verlag (2004) 46–58
- [14] Spears, W., Hamann, J., Maxim, P., Kunkel, T., Heil, R., Zarzhitsky, D., Spears, D., Karlsson, C. Where are you? In Şahin, E., Spears, W., eds.: Swarm Robotics, Springer-Verlag (2006)
- [15] Heil, R.: A trilaterative localization system for small mobile robots in swarms. Master's thesis, University of Wyoming, Laramie, WY (2004)
- [16] Zarzhitsky, D., Spears, D., Spears, W.: Distributed robotics approach to chemical plume tracing. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'05). (2005) 4034–4039