Experimental Localization with MICA2 Motes

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ABSTRACT

As research on Wireless Sensor Networks (WSNs) matures and the number of real life deployments increases, locationing (the problem of finding the physical placing of sensors without prior knowledge of their position) is attracting considerable interest. In almost any WSN application, localization knowledge within the network is a necessity: a sensor's data are only useful if put in context of where it came from – this is particularly the case in field sensing applications (i.e, the sensing of a phenomonen over an area or volume). The accuracy of localization therefore directly affects the accuracy of the information derived from the network. This paper describes the characterization of the accuracy achievable when localization is based on range data derived from acoustic time-of-flight measurements, and the consequent accuracy of the derived sensing surface.

Keywords: wireless sensor networks, motes, locationing.

1 INTRODUCTION – LOCATIONING METHODS IN WSN

Several algorithms currently exist to solve the localization problem statistically, by aggregating distances between pairs of sensors at a base station and reconstructing a map from the results. Multidimensional scaling [2] and least squares scaling [4] are two methods which work in this manner. Other algorithms use lateration to derive positional information [5,11,6].

The localization process usually comprises the following components – a ranging mechanism (by which range estimates between sensors are determined), a positioning computation (by which a position of a sensor is determined) and a localization algorithm (by which the locations of all of the sensors in a network are determined) [8]. The current state of the art in ranging and positioning is described below. Lateration is discussed in more detail in Section 3. Section 2 presents some of the commonly used methods for ranging.

2 RANGING FOR LATERATION

Ranging mechanisms provide a measure of the distance between two motes. There are currently several techniques to accomplish this, the most popular of which are:

Received signal strength (RSSI). The RSSI between two sensors can be used as an indicator of the distance they are separated by. In a perfect scenario, RSSI decays as an inverse square over distance, as described in [14]. At least at close ranges, the RSSI method may be expected to provide an accurate indication of range. Unfortunately, its accuracy in real applications could be less than hoped, for the following reasons:

1. In many situations, both indoors and outside, multipath reflections can greatly affect received signal strength because of constructive and destructive interference. This effect limits the use of the technique to open spaces.
2. Receivers generally have overload protection, in the form of doubled diodes at the antenna input. The transfer characteristic of these diodes can affect the RSSI at close ranges.
3. In commercial-off-the-shelf receivers, the RSSI will not necessarily be sufficiently consistent or noise free to be used as a good range indicator.

Hop counts provide another method to derive ranges from radio signals. This is attractive in simulated sensor networks, when connectivity is often assumed to be a disc of fixed radius around a sensor, certainly in earlier works [6,7,12,1]. However, in the real world, radio communication is not as reliable as this, and techniques which rely on a hop-count to estimate distances between sensors can produce radically incorrect results if a single hop in a chain fails [14].

Time-of-flight (ToF) gives a third method of ranging, based on the fact that ToF is directly proportional to the range, the constant of proportionality being cm/s^2 -- the speed of light. This however requires the measurement of the time of flight to nanosecond resolution to achieve accurate ranging at metre-scale distances. An alternative is acoustic ToF, in which the time of travel of an acoustic signal is measured. Since the speed of light is one million times greater than the speed of sound, a radio message is effectively instantaneous compared with an acoustic one. This makes the measurement of acoustic time of flight simple, the difference in arrival the between a radio and acoustic signal is taken as the time of flight for the acoustic signal. Acoustic time-of-flight ranging has been investigated by several different authors [4,14,10], to varying levels of accuracy.

The acoustic signal may be at audible frequencies, or it may use ultrasound. This requires the use of ultrasonic transmitters and receivers rather than loudspeakers and sounders ([5]and [15]). This method is capable of greater accuracy than when audible frequencies are used, since the wavelength (and therefore definition of measurement) is shorter. There are, however, limitations. The range may be more limited, as high frequency sounds are absorbed and dissipated more quickly than low frequency ones. Ultrasonic emission is also very directional, unless the transmitter is very small, so it is difficult to 'broadcast' ultrasonic ranging 'pings'. It also requires use of ultrasonic transducers, which may not be found within the standard sensor package within a mote.

It is important to put into context the suitability of each of these methods, based on the size and density of the sensor network, and the sensors available to perform the ranging. In a very dense network in which accuracy is required to a few centimetres, and where the extra cost of the additional transducers is not an obstacle, ultrasound allows for fine grained distance. For instance, the standard 40kHz 'remote control' transducer allows a theoretical accuracy of 7.5mm.

The ability to implement audible acoustic ranging using regular mote hardware is very attractive for the experimenter. The experiments described in this paper were designed to determine, firstly, what level of practical accuracy can be obtained using audible acoustic ranging and, secondly, the scale of error that this will causes in lateration based locationing, which is discussed in the following section.

3 2-D AND 3-D LOCATIONING

When distances between motes can be measured and estimated their positions can be computed. A common way of calculating position is to use trilateration (with three motes) to provide 2d coordinates or multilateration (with four motes) to provide 3d coordinates. Any form of lateration requires that several sensors are already aware of their positions. These sensors are known as 'beacon' or 'anchor' nodes [4,8,11,7]. Some techniques involve a mobile beacon travelling through a sensor network, allowing the sensors to calculate their position with respect to a range of positions as the beacon moves [3,13].

Calculating position in two dimensions is a case of finding the intercept of several distance measurements from sensors with known coordinates. Each distance measurement from a sensor represents a radius around that sensor. With three measurements, the position can be determined in two dimensions, a process known as trilateration. In the case where exactly three sensor positions are known the equations are exactly determined, where more are known they are said to be overdetermined. Trilateration can then be performed by solving the following linear equations (see Equation 1) using Gaussian elimination, or otherwise.

$$2\begin{bmatrix}(x_3-x_1) & (y_3-y_1)\\(x_3-x_2) & (y_3-y_2)\end{bmatrix}\begin{bmatrix}x\\y\end{bmatrix}=\begin{bmatrix}r_1^2-r_3^2-x_1^2+x_3^2-y_1^2+y_3^2\\r_2^2-r_3^2-x_2^2+x_3^2-y_2^2+y_3^2\end{bmatrix}$$

Equation 1.

Calculating position in 3d space is a continuation of the idea of trilateration, but requiring a minimum of four distances, which become the intercept of four spheres. This is the case of solving three linear equations for three unknowns (x, y and z), which are shown in Equation 2.

$$2\begin{bmatrix}(x_4-x_1) & (y_4-y_1) & (z_4-z_1)\\(x_4-x_2) & (y_4-y_2) & (z_4-z_2)\\(x_4-x_3) & (y_4-y_3) & (z_4-z_3)\end{bmatrix}\begin{bmatrix}x\\y\\z\end{bmatrix}=\begin{bmatrix}r_1^2-r_4^2-x_1^2+x_4^2-y_1^2+y_4^2-z_1^2+z_4^2\\r_2^2-r_4^2-x_2^2+x_4^2-y_2^2+y_4^2-z_2^2+z_4^2\\r_3^2-r_4^2-x_3^2+x_4^2-y_3^2+y_4^2-z_3^2+z_4^2\end{bmatrix}$$

Equation 2.

When the distances are accurate, the position computation performs well, but given amounts of error in the measurements, the position can be wildly inaccurate, as documented below.

Simulated errors, consistent with those found in the practical experiments described in Section 4, were introduced into the measured ranges between the motes,. These ranges were then used to produce a location estimate for the motes, as detailed below

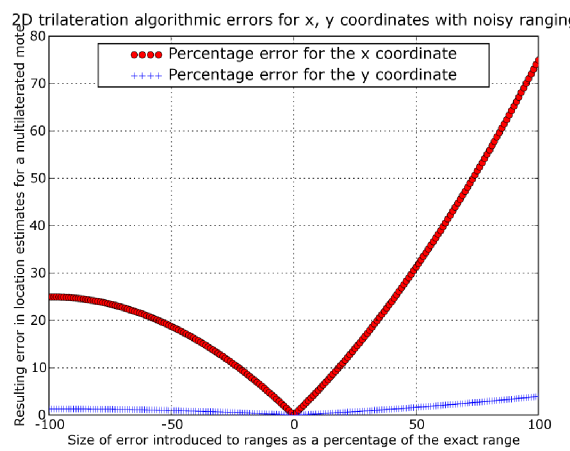

Figure 1. 2d multilateration errors for x and y coordinates with noisy ranging. See Table 1 for position data of the simulated motes.

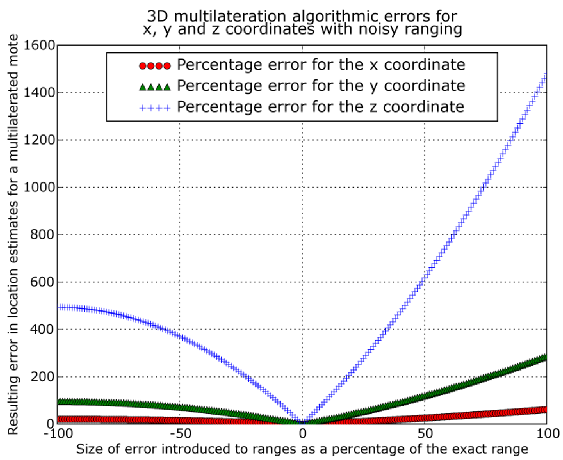

Figure 2. 3d multilateration errors for x, y and z coordinates with noisy ranging. See Table 1 for position data of the simulated motes.

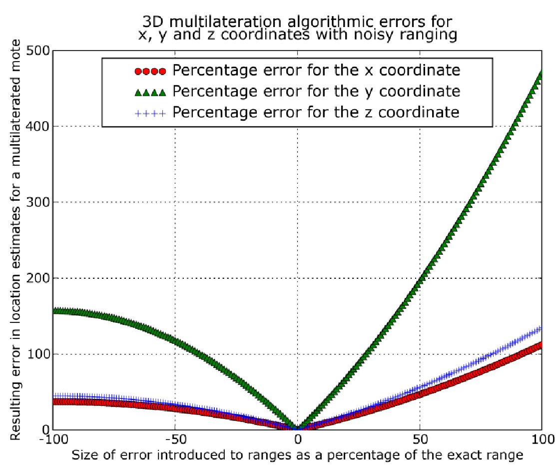

Figure 3. 3d multilateration errors for x, y and z coordinates with noisy ranging. See Table 1 for position data of the simulated motes.

The graphs shown in Figures 1-3 show the error behaviour of multilateration given noisy ranging estimates. This data was generated by giving known anchor points and the exact location of the sensor whose location is to be determined by lateration techniques. Exact ranges between each anchor and the unknown are then determined by Pythagoras' theorem. Noisy estimates for the ranges are generated by adding an error, Δ, to the exact values of each range. Values of Δ are percentages of the exact ranges, varying between $\pm 100\%$, incremented by 1% steps. Next, multilateration is performed on the anchor points and each set of ranging estimates with the various values of Δ. The set of multilaterated estimates is then used to calculate the lateration errors introduced by Δ, for each coordinate of the unknown point. These errors are given in Equation 3, where x_{est} is the estimated value of the x-coordinate of the unknown and x is the exact x-coordinate (and similarly for the other coordinates). These error values have been plotted for each value of Δ, for three sets of anchor points and unknowns.

$$\frac{|x_{est} - x|}{x}.100$$

Equation 3.

The three plots shown in Figures 1,2 and 3 show the error behaviour of 2d and 3d lateration for the following sets of anchor points and unknowns, which have been taken from the terrain modeling case study which is described in Section 5:

	Figure 1	**Figure 2**	**Figure 3**
Anchor 1	(25, 50)	(60, 31, 35)	(95, 90, 100)
Anchor 2	(50, 0)	(50, 23, 41)	(100, 105, 110)
Anchor 3	(0, 0)	(55, 46, 44)	(85, 80, 90)
Anchor 4	N/A	(49, 36, 42)	(110, 115, 105)
Unknown	(20, 19)	(83, 15, 10)	(50, 50, 50)

Table 1. Position data for simulated motes in study of the error behaviour of multilateration.

The graphs show plots for errors in each coordinate separately. The error behaviour for coordinates differs, depending on the placement of the anchor points. Where the average values for a particular coordinate in the anchor points is small (relative to the other coordinates) the error behaviour for that coordinate in the location estimate is relatively larger. Moreover, introducing negative errors to the ranging estimates seems to produce smaller errors in the resulting location estimates. The simulation results for the 2d case (Figure 1) have been confirmed experimentally. Figure 4 shows locationing errors for the same anchor points and unknown as seen in Figure 1, and confirm a wide variation in the x-coordinate and a narrow variation in the y-coordinate.

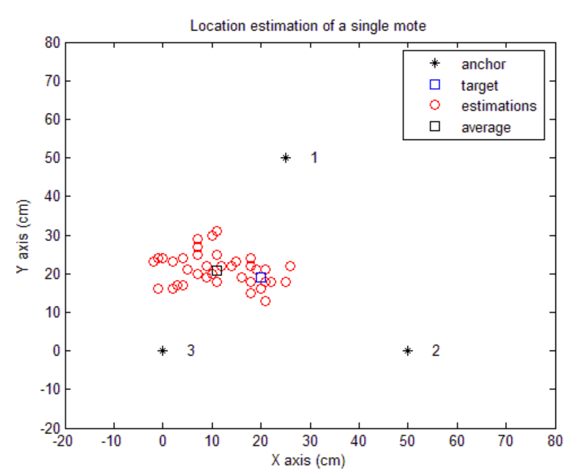

Figure 4. Experimental estimation of a mote's location in 2d

In 3d, the degree of inaccuracy caused by a particular range error depends on the relative position of the four motes involved in the lateration. If the error is imagined as a 'shell' around each range sphere, then the volume of the locationing error is given by the intersection between the four shells. This is at a minimum if the shells cross normal to each other, and at a maximum if the crossing approaches being tangential. The minimum error is when the mote being located is at the centroid of an equilateral tetrahedron, and larger when the arrangement differs markedly from this. Unfortunately, in the situations in which locationing will be used, the optimum geometry needed to minimize errors cannot be guaranteed. If the nodes in sensor networks are carefully positioned when installed, their location is known, and automatic locationing is not required. On the other hand, it is needed for ad-hoc, 'scattered' networks, which are just the ones in which the arrangement of nodes is will be random. Locationing must therefore depend on a good enough quality of ranging.

4 RANGING ERRORS

The first practical work described here has been aimed at determining the degree of accuracy that might be expected from acoustic ranging. Initial experiments into positioning used the Vanderbilt acoustic ranging libraries [10], which determine the range as follows:

A radio packet and an acoustic 'chirp' are sent simultaneously from one mote to another.

The receiving mote, on reception of the radio packet, starts a timer, which measures the time until the audible chirp is heard on the mote's microphone. The mote detects the amplitude envelope of the chirp, having first passed the incoming signal through a digital FIR band-pass filter which selects only for the frequency of the chirp.

Consideration of the physics of this ranging mechanism suggests that inaccuracies may occur from several different sources.

1. Effectively, the envelope is sampled at the frequency of the chirp. According to Nyquist's sampling theorem, the maximum accuracy of a measurement made of the envelope is half the chirp frequency, or twice its wavelength. In the case of the motes used, the chirp frequency is ~4.5 KHz, the maximum resolution, therefore is ~444µs, and the range error ~0.133m This error would be manifested as a Gaussian error distribution around the correct range.
2. The chirp envelope is timed by a constant frequency clock, the frequency in this case being 32.712 kHz (watch crystal). The time of flight cannot be determined more accurately than one tick of this clock, in which time sound travels around 1cm.
3. It is not clear that the envelope detection is always consistent, in any case. There can be noise errors associated with this part of the process.
4. There are some time delays in the system, such as the time taken to process the FIR filter. These add a consistent offset to the calculated range.

Experimental results have broadly confirmed the level of accuracy possible, although the error distribution does not always follow a neat Gaussian curve.

5 ERRORS AND LATERATION

Errors may be reduced by making many range estimates and averaging them. However, this requires the use of many ranging chirps, which in turn consumes power. Since preservation of battery power is of prime concern in wireless sensor networks, it would be advantageous to use as few ranging operations as possible, so long as acceptable accuracy can be achieved. Of course, what is 'acceptable' in terms of accuracy, depends on the application. In this paper, the area of interest is location finding, and it is in that context that the effect of range errors needs to be known. Once again, the level of accuracy that is deemed 'acceptable' depends on the application, so rather than determine the level of range error which produces a given level of location error, the work here characterizes the location error produced by a spread of range errors.

Figure 5. Case study terrain (100cm x 50cm x 70cm)

The case study chosen for demonstrating locationing was that of terrain reconstruction. Four anchors were deployed on the terrain surface in figure 5. Sensors were added one at a time, and at random positions. They were iteratively localized using 3-d multilateration, based on distance estimates between the anchor points and the target sensors, wherever possible. When estimates could not be obtained from anchor points, previously localized sensors were used instead.

A total of 10 sensors were localized to give a set of 14 data points over a 100 x 50 x 70cm area. The network was of a single-hop type, along with a centralized controller which performed the multilateration for all motes.

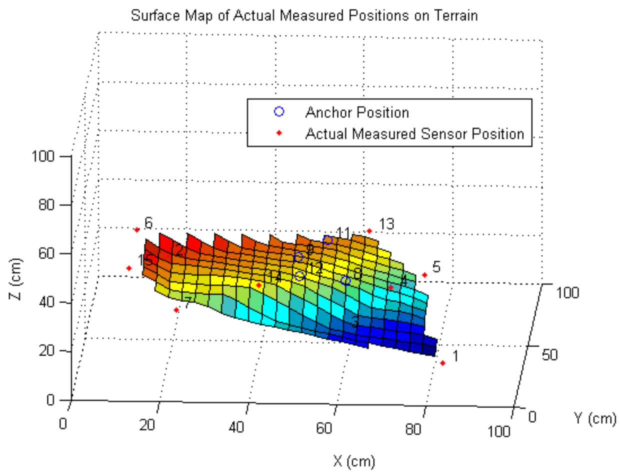

Figure 6. Actual positions of motes, hand measured

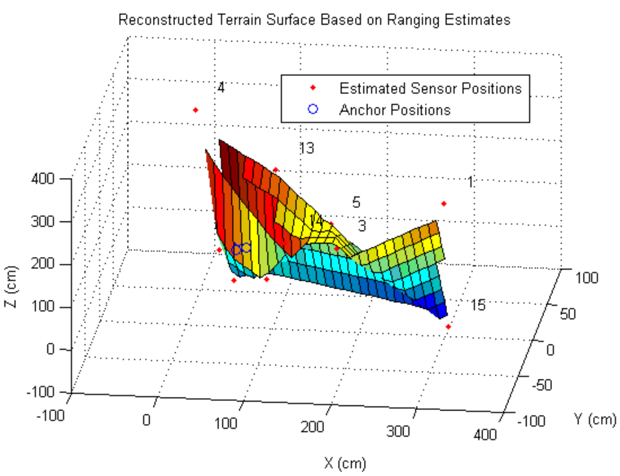

Figure 7. Reconstructed view of the terrain

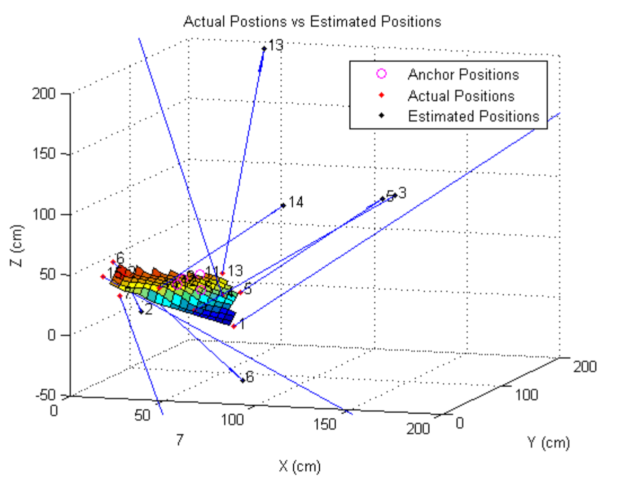

Figure 8. Actual terrain vs estimated positions

Figure 6 shows the points as determined by hand-measuring the surface. Figure 7 shows the attempted reconstruction of the surface with acoustic time of flight measurements and using the 3-d multilateration techniques described in this paper. Figure 8 shows the difference between the real terrain and the reconstructed one.

6 CONCLUSIONS

Location finding is an important function in ad-hoc wireless sensor networks. Locationing based on lateration appears to be one of the most direct and promising methods, but depends on the availability of good range information between the mote being located and those with known position, being used as beacons for the locationing operation. The acoustic method of ranging, which seems to offer the prospect of providing consistent and accurate ranging, has been tested practically, and found to fall short in this respect. This opens the prospect of spending energy, which in a mote is in short supply by averaging over several ranging operations to reduce the intrinsic error of the method. To conserve as much energy as possible, such repetition of ranging must be performed only so much as is necessary to produce the accuracy required for a particular application. The effect of range errors on location accuracy has been determined using simulation based on test data, to allow an informed choice of required range accuracy, and therefore the amount of averaging necessary if a given level of location accuracy is required.

REFERENCES

[1] He, T. et al, "Range Free Localization Schemes for Large Scale Sensor Networks", Proceedings of ACM Mobicom 2003, San Diego, CA, 2003, pp 1-10.

[2] Ji X., Zha H., "Sensor Positioning in Wireless Ad-hoc Sensor Networks Using Multidimensional Scaling", INFOCOM 2004

[3] Kushwaha M., Molnar, K., Sallai J., Volgyesi P., Maroti M., Ledeczi A. "Sensor Node Localization Using Mobile Acoustic Beacons", The 2nd IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS 2005), CD-Rom, Washington, DC, November 7, 2005.

[4] Kwon Y., Mechitov K., Sundresh S., Kim W. Agha G., "Resilient Localization for Sensor Networks in Outdoor Environments", 25th International Conference on Distributed Computing Systems (ICDCS), 2005

[5] Moore D., Leonard, Rus D., Teller S.. "Robust distributed network localization with noisy range measurements." In Proceedings of the Second ACM Conference on Embedded Networked Sensor Systems (SenSys '04). Baltimore, MD.

[6] Nagpal. R, Shrobe. H., Bachrach. J, "Organizing a Global Coordinate System from Local Information on an Ad Hoc Sensor Network", In the 2nd International Workshop on Information Processing in Sensor Networks (IPSN '03), Palo Alto, April, 2003.

[7] Niculescu. D, Nath, B. "Ad hoc positioning system (APS)", In IEEE Global Communications

Conference (GlobeCom '01), pages 2926-2931, San Antonio, TX, USA, November 2001.
[8] Oliveira. H, Nakamura. E, Loureiro. A, Boukerche. A, “Error Analysis of Localization Systems for Sensor Networks”, GIS '05, Bremen, Germany.
[9] Priyantha. N.B, “The Cricket Indoor Location System”, PhD Thesis, Massachusetts Institute of Technology, June 2005.
[10] Sallai J., Balogh G., Maroti M., Ledeczi A., “Acoustic Ranging in Resource Constrained Sensor Networks”, Technical Report, ISIS, Vanderbilt University, 2003
[11] Savarese, C., Rabaey, J., and Langendoen, K. “Robust positioning algorithms for distributed ad-hoc wireless sensor networks.” USENIX Annual Tech. Conf. 2002
[12] Shang. Y, Ruml. W, Zhang. Y, Fromherz. MPJ, “Localization from Mere Connectivity”, MobiHoc’03, June 1–3, 2003, Annapolis, Maryland, USA.
[13] Stoleru, R., He, T., Stankovic, J. A., and Luebke, D. 2005. “A high-accuracy, low-cost localization system for wireless sensor networks.” In Proceedings of the 3rd international Conference on Embedded Networked Sensor Systems (San Diego, California, USA, November 02 - 04, 2005). SenSys '05. ACM Press, New York, NY, 13-26.
[14] Whitehouse K., “The Design of Calamari: an Ad-hoc Localization System for Sensor Networks”, Master’s Thesis, UC Berkeley, 2002
[15] Whitehouse. K, Karlof. C, Woo. A, Jiang. F, Culler. D, “The Effects of Ranging Noise on Multihop Localization: An Empirical Study”, The Fourth International Conference on Information Processing in Sensor Networks (IPSN '05). Los Angeles, California. April 25-27, 2005.