2012-4

Asynchronous Ultrasonic Trilateration for Indoor Positioning of Mobile Phones

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2012-04-01

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Abstract. In this paper we discuss how the innate ability of mobile phone speakers to produce ultrasound can be used for accurate indoor positioning. The frequencies in question are in a range between 20 and 22 KHz, which is high enough to be inaudible by humans but still low enough to be generated by today's mobile phone sound hardware. Our tests indicate that it is possible to generate the given range of frequencies without significant distortions, provided the signal volume is not turned excessively high. In this paper we present and evaluate the accuracy of our asynchronous trilateration method (Lok8) for mobile positioning without requiring knowledge of the time the ultrasonic signal was sent. This approach shows that only the differences in time of arrival to multiple microphones (control points) placed throughout the indoor environment is sufficient. Consequently, any timing issues with client and server synchronization are avoided.

Keywords: Indoor Mobile Positioning, Ultrasonic Trilateration, LBS

1 Introduction

The role of mobile phones in society has changed dramatically in the past few years as for many people their SmartPhone is an omnipresent gateway to information. The mobile nature of the device is of key importance. Users have come to expect constant access to the phone's information facilities in many different circumstances and environments that take into account location and personal preference when providing useful and timely decision support services.

Currently outdoor Location Based Services (LBS) have the advantage of relatively reliable positioning via GPS (also Wi-Fi and GSM) and a defined business model for the delivery of content to the user. This has led to applications of outdoor LBS greatly expanding in recent years, leaving indoor locationing technologies and services on mobile devices to yet fully mature. The current state-of-the-art of merging accurate (i.e. sub-metre) indoor positioning and context-sensitive services for indoor LBS therefore is still an open problem.

The following factors make indoor positioning challenging:

1. Generally indoor environments require higher accuracy to be useful for practical LBS purposes. This is because when indoors we are dealing with objects and

distances on a smaller scale. While accuracy of +/- 10 meters may be good enough to direct someone to a cafe or a bus stop, indoors it could mean we are unsure in which room the user currently is located.

2. Locationing services that rely on satellite signals such as GPS for positioning do not work indoors at all because these signals require a direct line-of-sight to the receiver.

3. When used indoors, electromagnetic fields and sound signals can suffer from fading and multipath propagation when they encounter walls, windows, and other structures. This requires implementations of a robust solution that can effectively overcome the positioning difficulties typically found in cluttered, complex indoor environments.

Under these circumstances it is understandable that very specialized hardware may be required unless we are willing to sacrifice accuracy. However, given the role of commercial off-the-shelf (COTS) SmartPhones in today's society, they have by default become the platform of choice for implementations of indoor positioning and therefore the standard hw platform we have developed our Lok8 (locate) indoor positioning solution to work on.

While many mobile positioning approaches are erroneously described in the press as *triangulation*, where angles between mobile devices to various receivers (control points) would be required, what is in fact being described is *trilateration*, where distances to known control points or beacons are instead used in the positioning calculation. Significantly, what is often common among these solutions is some sort of timing synchronisation requirement between transmitter and receiver to provide a full measure of distance as inputs to the trilateration process.

The main contribution of our Lok8 approach is that we remove this often delicate synchronisation problem between transmitter and receiver by instead requiring that receivers (i.e. 3 or more microphones) be connected to a central server that starts a timer once an ultrasonic signal is detected by any of the mics. By making the time the original signal was sent irrelevant, only the differences in time between when the signal reaches each of the remaining microphones is needed in our solution. The result is a more robust mobile trilateration method.

As comprehensive explanation of mobile trilateration procedure is all too rare in indoor LBS literature, another worthwhile contribution of this paper is to describe in detail our subtle but significant modification to standard least squares trilateration in Section 3. Where standard trilateration assumes that distances from an unknown position to all control points are known a-priori, instead we only know the differences between these distances - not the distances themselves. So while our asynchronous trilateration derivation is similar to the standard case, the initial conditions are different and therefore the standard trilateration solution requires modification. Before this we first discuss some background work in Section 2, and follow this with a summary of our principal contributions to the field of indoor mobile positioning and plans for future work in Section 4.

2 Indoor Positioning Background

There are many different methods and reported accuracies for locating a mobile device indoors (see Table 1). Methods that use propagation of Radio Frequency (RF) signals are prevalent in this field, with the exception of computer vision, where simultaneous localization and mapping (SLAM) appears to be the most promising but considered by many an operational technology still in its infancy [1]. Computer vision techniques, while potentially very accurate, is characterized by high computational load, complicated procedures of recovery from tracking failures and susceptibility to camera shake and motion blur. These problems are addressed in the studies done by Williams et al. [2] and Wagner et al. [3]. Another difficulty associated with computer vision is that the user is supposed to be looking through the display screen when using the device.

Table 1: Comparison of Indoor Positioning Implementations

	Best Accuracy	**Underlying Technology**	**Available on SmartPhones**
Wide Signal Strength Fingerprinting	2.48m	GSM	no
Skyhook(GSM)	200m	GSM	yes
Navizon(GSM)	50m	GSM	yes
Skyhook(Wi-Fi)	10m	Wi-Fi	yes
Navizon(Wi-Fi)	20m	Wi-Fi	yes
RADAR	2m	WaveLan	no
GP for Signal Strength-Based Location Estimation	2m	Wi-Fi	yes
Ekahau	1m	Wi-Fi	no
The Bat	3cm	Ultrasound	no
The Cricket	3cm	Ultrasound	no
Lok8	**Sub-metre**	**Ultrasound**	**yes**

RF-based transceivers such as GSM, Wi-Fi and Bluetooth can be found on every modern SmartPhone. Five meter accuracy, one of the best results for indoor GSM positioning, was displayed by Otsason et al. with the help of wide signal-strength fingerprinting [4]. Unfortunately wide signal-strength fingerprinting is impossible on many modern phones due to OS restrictions. Other GSM positioning methods are generally impractical for indoor use due to poor accuracy. Wi-Fi positioning is on average better than twice as accurate as GSM. A method proposed by Ferris et al. where Gaussian processes are used to mathematically predict signal strength in areas outside the exact spots where fingerprints were taken seems to promising [5]. The best accuracy among commercial solutions using this approach was shown by Ekahau: 1-3 meters [6].

Bluetooth has the shortest range among the three wireless technologies but there are two major problems that make Bluetooth positioning particularly difficult. First of all it is designed to adjust signal strength when signals become too strong or too weak making any subsequent distance measurements based on signal strength unreliable. Disabling this feedback loop is discussed by Zhou et al. [7]. Another problem is that it takes a lot of time for a new device to be fully discovered. Very often it means that the user has already left the area [8]. This makes Bluetooth trilateration impractical; however coarser room-level positioning can be done relatively quickly as device pairing is not required.

Notably, it is not reported possible to achieve accuracy below one meter [9] using RF-based technologies present in mobile phones [4, 5, 10]. However, sound travels at significantly slower speeds than radio waves and can therefore be easily localised to a few centimetres due to this much longer time of flight. Other useful features of sound show that it is possible to emit a 21 KHz (just above the human hearing range) signal from a mobile phone speaker and successfully receive it with a conventional microphone [11]. In a separate study, Peng et al. [12] showed that it is possible to utilize sound in order to measure the distance between two mobile phones using synchronized time-of-arrival techniques.

In previous work [16], we tested the useable range of SmartPhone ultrasound to find that these signals can indeed be successfully detected up to distances of 20m or more (Figure 1). In this experiment, two values below 10 dB were registered but this is still well above the 21.5 KHz component of background noise, which is around 1 dB. However there is no guarantee that the maximum value belongs to a signal that arrived by direct path and not via a longer deflected path. In any case, it can be seen from the shape of the graph that even with speaker and microphone pointing directly at each other, signal strength can't be relied on alone to accurately measure distance.

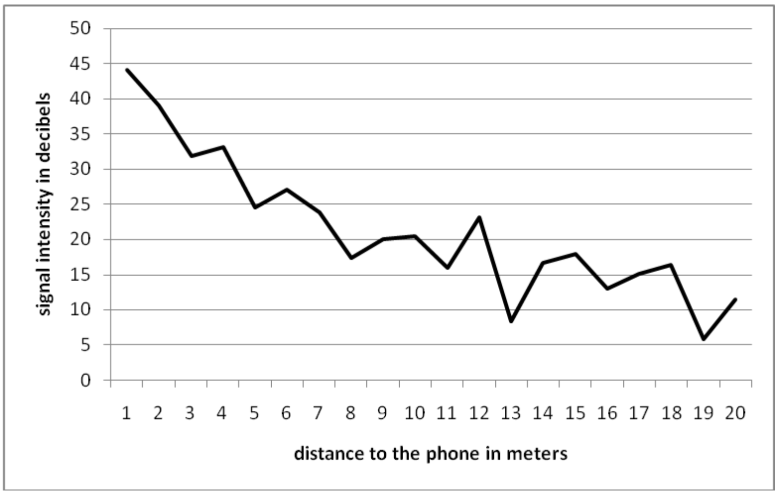

Fig. 1. Relationship between signal strength and distance for conditions where SmartPhone speaker and microphone point at each other.

Therefore, in our Lok8 trilateration method we endeavour to make use of the useful characteristics of inaudible mobile ultrasound by exploiting the *differences* in signal time-of-arrival at a static microphone array for accurate mobile positioning. An accuracy comparison of our method compared to other reported indoor positioning methods, together with their availability for implementation on today's SmartPhones, is also given in Table 1.

3 Time Difference of Arrival (TDOA) Trilateration

Sound is a mechanical wave which travels at speeds much slower than the speed of light. In dry air at a temperature of 25°C the speed of sound is only 346 m/s. At such propagation speeds, one sample of a standard 44.1 KHz stream (44100 cycles/second) accounts for 0.8cm of distance [4, 13]. In other words a signal will travel only 0.8 centimeters in the duration of the smallest time grain. Technically it is possible to work with sound even at 384 KHz, which can give much finer accuracy.

As discussed previously, by using trilateration it is possible to calculate one's position based on the distance to several other (control) points with known positions [14, 15]. To find one's position in 2 dimensions the number of required known points is 3; for position in 3 dimensions the number of known points is 4. Given that the speed of sound propagation is constant under the same temperature and humidity conditions, the time it takes a signal to travel between the phone to each known microphone control point can be directly converted into distance between the phone and microphones. This is the TOA (Time of Arrival) approach. In general, the main problem with this approach is that both the time the signal was sent and the time it was received are required in order to get the time of flight.

In our scenario of quickly and accurately locating a mobile phone indoors, TOA requires that times from two separate systems with two separate clocks will have to be synchronised - a major source of error. As such it is desirable to compare only the time of arrival at each of the microphones and ignore completely the time the signal was originally sent from the phone, making Lok8 a TDOA (Time Difference of Arrival) approach. The problem is illustrated in Figure 2 and the detailed solution follows.

Problem:

- Mobile phone (P) has unknown position (X_P, Y_P).
- 4 microphones (M1, M2, M3, M4) have known positions (X_{M1}, Y_{M1}), (X_{M2}, Y_{M2}), (X_{M3}, Y_{M3}), (X_{M4}, Y_{M4})
- 4 distances (d_1, d_2, d_3, d_4) from P to M1, M2, M3, M4 are unknown but the differences between them (m_2, m_3, m_4) are measured ultrasonically; these are the *observations*.
- Find coordinates of $P=(X_P, Y_P)$ by solving a system of equations (mathematical model) that relates the $m = 3$ *observations* (m_2, m_3, m_4) to the $n = 2$ *unknown parameters* (X_P, Y_P).

Solution:

Although the coordinates of P could be found using readings from only 3 microphones (2 observations), 4 or more readings can be effectively used in the method of *Least Squares* to determine the *Most Probable Value* (MPV) for the coordinates of P, plus a *Standard Deviation* for the MPV.

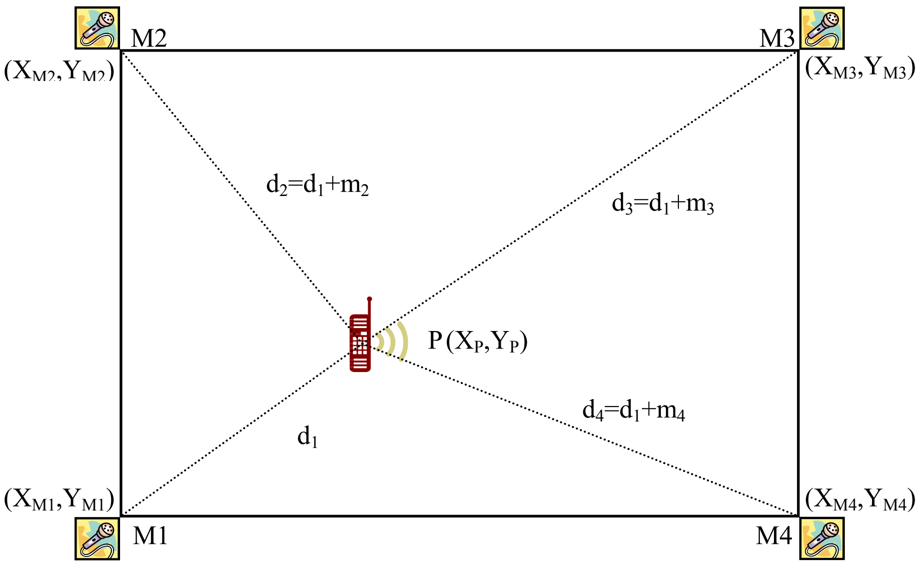

Fig. 2. Time Difference of Arrival. Control points M1, M2, M3 and M4 are known microphone positions. Point P is the unknown mobile phone's position, coordinates of which we are trying to find. Lines d1, d2, d3 and d4 are unknown distances between the phone and each microphone. However, what are known are the differences between the three measurements: m2, m3 and m4.

Least Squares Method for TDOA Trilateration:

From Pythagoras we derive the following *mathematical model* to describe the ultrasonic relationships between phone P and microphones M1, M2, M3, M4:

$$d_1^2 = (X_P - X_{M1})^2 + (Y_P - Y_{M1})^2 \quad \text{or} \quad d_1 = \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$

$$d_2^2 = (X_P - X_{M2})^2 + (Y_P - Y_{M2})^2 \quad \text{or} \quad d_2 = \sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2}$$

$$d_3^2 = (X_P - X_{M3})^2 + (Y_P - Y_{M3})^2 \quad \text{or} \quad d_3 = \sqrt{(X_P - X_{M3})^2 + (Y_P - Y_{M3})^2}$$

$$d_4^2 = (X_P - X_{M4})^2 + (Y_P - Y_{M4})^2 \quad \text{or} \quad d_4 = \sqrt{(X_P - X_{M4})^2 + (Y_P - Y_{M4})^2}$$

However, we can re-write d_2, d_3, d_4 in terms of d_1:

$$d_2 = d_1 + m_2$$
$$d_3 = d_1 + m_3$$
$$d_4 = d_1 + m_4$$

And then substitute above d_1 expressions back into the mathematical model:

$$d_1 + m_2 = \sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2} \text{ or } m_2 = \sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2} - d_1$$
$$d_1 + m_3 = \sqrt{(X_P - X_{M3})^2 + (Y_P - Y_{M3})^2} \text{ or } m_3 = \sqrt{(X_P - X_{M3})^2 + (Y_P - Y_{M3})^2} - d_1$$
$$d_1 + m_4 = \sqrt{(X_P - X_{M4})^2 + (Y_P - Y_{M4})^2} \text{ or } m_4 = \sqrt{(X_P - X_{M4})^2 + (Y_P - Y_{M4})^2} - d_1$$

Then replace d_1 in m_2, m_3, m_4 equations above with equivalent d_1 expression from mathematical model to give:

$$m_2 = \sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$
$$m_3 = \sqrt{(X_P - X_{M3})^2 + (Y_P - Y_{M3})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$
$$m_4 = \sqrt{(X_P - X_{M4})^2 + (Y_P - Y_{M4})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$

Re-write above three mathematical model equations as *observation equations* by adding a residual v_m to each measurement:

$$\text{F:} \quad m_2 + v_{m2} = \sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$
$$\text{G:} \quad m_3 + v_{m3} = \sqrt{(X_P - X_{M3})^2 + (Y_P - Y_{M3})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$
$$\text{H:} \quad m_4 + v_{m4} = \sqrt{(X_P - X_{M4})^2 + (Y_P - Y_{M4})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$

Because number of measurements (m = 3) is greater than number of unknowns (n = 2), use Least Squares to determine the MPV of the unknowns (X_P,Y_P). Since the observation equations are non-linear in the unknowns (X_P,Y_P), a first-order *Taylor Series* is needed to approximate a set of linear observation equations before taking partial derivatives.

Considering function F above (describing ultrasonic relationship between M2 and P):

$$\text{F:} \quad m_2 + v_{m2} = \sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$

This non-linear function can be written as:

$$F(X_P, Y_P) = m_2 + v_{m2}$$

Where

$$F(X_P, Y_P) = \sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2} - \sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}$$

The above function is *linearized* using a first-order Taylor Series approximation:

$$F(X_P, Y_P) = F(X_{Po}, Y_{Po}) + \left(\frac{\partial F}{\partial X_P}\right)_o dX_P + \left(\frac{\partial F}{\partial Y_P}\right)_o dY_P$$

Where

- X_{Po} and Y_{Po} are initial estimates of SmartPhone position in the environment calculated by taking average of all known microphone positions.
- $F(X_{Po}, Y_{Po})$ is the non-linear function evaluated with these estimates.
- dX_p and dY_p are corrections to the initial estimates such that $X_p = X_{p_o} + dX_p$ and $Y_p = Y_{p_o} + dY_p$

The partial derivatives $\left(\frac{\partial F}{\partial X_P}\right)$ and $\left(\frac{\partial F}{\partial Y_P}\right)$ are found by first re-writing function F:

F: $$F(X_P, Y_P) = \left((X_P - X_{M2})^2 + (Y_P - Y_{M2})^2\right)^{\frac{1}{2}} - \left((X_P - X_{M1})^2 + (Y_P - Y_{M1})^2\right)^{\frac{1}{2}}$$

and then take partial derivative with respect to X_P:

$$\frac{\partial F}{\partial X_P} = \frac{1}{2}\left((X_P - X_{M2})^2 + (Y_P - Y_{M2})^2\right)^{-\frac{1}{2}} \bullet 2(X_P - X_{M2})$$

$$-\frac{1}{2}\left((X_P - X_{M1})^2 + (Y_P - Y_{M1})^2\right)^{-\frac{1}{2}} \bullet 2(X_P - X_{M1})$$

$$= \frac{(X_P - X_{M2})}{\sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2}} - \frac{(X_P - X_{M1})}{\sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}}$$

$$= \frac{(X_P - X_{M2})}{d_1 + m_2} - \frac{(X_P - X_{M1})}{d_1}$$

and then with respect to Y_P:

$$\frac{\partial F}{\partial Y_P} = \frac{1}{2}\left((X_P - X_{M2})^2 + (Y_P - Y_{M2})^2\right)^{-\frac{1}{2}} \bullet 2(Y_P - Y_{M2})$$

$$-\frac{1}{2}\left((X_P - X_{M1})^2 + (Y_P - Y_{M1})^2\right)^{-\frac{1}{2}} \bullet 2(Y_P - Y_{M1})$$

$$= \frac{(Y_P - Y_{M2})}{\sqrt{(X_P - X_{M2})^2 + (Y_P - Y_{M2})^2}} - \frac{(Y_P - Y_{M1})}{\sqrt{(X_P - X_{M1})^2 + (Y_P - Y_{M1})^2}}$$

$$= \frac{(Y_P - Y_{M2})}{d_1 + m_2} - \frac{(Y_P - Y_{M1})}{d_1}$$

Where d_1 is always (re)evaluated using Pythagoras at current estimates for (X_P, Y_P).

Therefore:

$$F(X_P, Y_P) = F(X_{Po}, Y_{Po}) + \left(\frac{(X_P - X_{M2})}{d_1 + m_2} - \frac{(X_P - X_{M1})}{d_1} \right)_o dX_P + \left(\frac{(Y_P - Y_{M2})}{d_1 + m_2} - \frac{(Y_P - Y_{M1})}{d_1} \right)_o dY_P$$

So the linearized observation equation for m_2, describing the ultrasonic relationship between microphone M2 and phone P becomes:

$$\left(\frac{(X_P - X_{M2})}{d_1 + m_2} - \frac{(X_P - X_{M1})}{d_1} \right)_o dX_P + \left(\frac{(Y_P - Y_{M2})}{d_1 + m_2} - \frac{(Y_P - Y_{M1})}{d_1} \right)_o dY_P = (m_2 - m_{2o}) + v_{m2}$$

Likewise for function G (between M3 and P):

$$\left(\frac{(X_P - X_{M3})}{d_1 + m_3} - \frac{(X_P - X_{M1})}{d_1} \right)_o dX_P + \left(\frac{(Y_P - Y_{M3})}{d_1 + m_3} - \frac{(Y_P - Y_{M1})}{d_1} \right)_o dY_P = (m_3 - m_{3o}) + v_{m3}$$

and function H (between M4 and P):

$$\left(\frac{(X_P - X_{M4})}{d_1 + m_4} - \frac{(X_P - X_{M1})}{d_1} \right)_o dX_P + \left(\frac{(Y_P - Y_{M4})}{d_1 + m_4} - \frac{(Y_P - Y_{M1})}{d_1} \right)_o dY_P = (m_4 - m_{4o}) + v_{m4}$$

When using Matrix Methods for Least Squares, the observation equations are represented in matrix form as:

$${}_mA_n \, {}_nX_1 = {}_mL_1 + {}_mV_1$$

Where in our case:

- $m = 3, n = 2$

- ${}_{m}A_{n}$ contains the coefficients of the unknowns (X_P, Y_P)
- ${}_{n}X_{1}$ contains the corrections to be applied to the initial estimates for the unknowns (dX_P, dY_P)
- ${}_{m}L_{1}$ contains the measurements (m_2, m_3, m_4)
- ${}_{m}V_{1}$ contains the residuals (one for each measurement)

Solving for X gives the solution:

$$X = \left(A^T A\right)^{-1} A^T L \quad \text{where:}$$

$$A = \begin{bmatrix} \frac{(X_P - X_{M2})}{d_1 + m_2} - \frac{(X_P - X_{M1})}{d_1} & \frac{(Y_P - Y_{M2})}{d_1 + m_2} - \frac{(Y_P - Y_{M1})}{d_1} \\ \frac{(X_P - X_{M3})}{d_1 + m_3} - \frac{(X_P - X_{M1})}{d_1} & \frac{(Y_P - Y_{M3})}{d_1 + m_3} - \frac{(Y_P - Y_{M1})}{d_1} \\ \frac{(X_P - X_{M4})}{d_1 + m_4} - \frac{(X_P - X_{M1})}{d_1} & \frac{(Y_P - Y_{M4})}{d_1 + m_4} - \frac{(Y_P - Y_{M1})}{d_1} \end{bmatrix}$$

$$X = \begin{bmatrix} dX_P \\ dY_P \end{bmatrix} \qquad L = \begin{bmatrix} m_2 - m_{2_0} \\ m_3 - m_{3_0} \\ m_4 - m_{4_0} \end{bmatrix} \qquad V = \begin{bmatrix} v_{m2} \\ v_{m3} \\ v_{m4} \end{bmatrix}$$

Matrix X contains the corrections to be applied to the original estimates for (X_P, Y_P). These new (X_P, Y_P) coordinates are then used to recalculate updated distances for $(d_1, m_{2_0}, m_{3_0}, m_{4_0})$. The process is repeated until coordinates of (X_P, Y_P) don't change significantly (e.g. in the 3rd decimal place for mm precision).

After a solution has been reached, the residuals V for each measurement and Standard Deviation of *unit weight* σ_o for the overall least squares adjustment can be calculated with:

$$V = AX - L \qquad \text{and} \qquad \sigma_o = \pm\sqrt{\frac{\left(V^T V\right)}{r}}$$

Where *degrees of freedom* r = m–n and the Standard Deviation of each adjusted unknown is then given by:

$$\sigma_{Xi} = \pm\sigma_o \sqrt{\left(Q_{XiXi}\right)}$$

In our case $\boldsymbol{\sigma_{X_1}}$ is the Standard Deviation for X_P, and $\boldsymbol{\sigma_{X_2}}$ is the Standard Deviation for Y_P. These standard deviations imply that there is a 68% probability that the adjusted values for X_P and Y_P are within $\pm\sigma$ of this amount.

$(A^T A)^{-1}$ is called the *variance-covariance* matrix or (Q_{XX}) matrix and (Q_{XiXi}) is the *variance* of unknown *i*, or the element in the i^{th} row and i^{th} column of the $(A^T A)^{-1}$ matrix.

Practical Example:

To test the accuracy of our TDOA Trilateration method, we used it to calculate the position of several random SmartPhone locations and compare the results to their actual positions in Figure 3. We used four control points (microphones) arranged in the corners of a rectangular room to locate the phone's position at 6 different locations within the room.

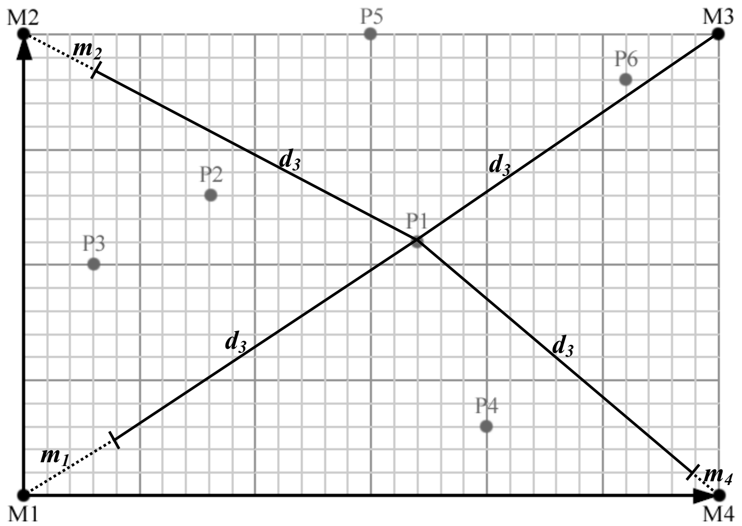

Fig. 3. TDOA Trilateration experiment with four microphones and six different smartphone positions. Control points M1, M2, M3 and M4 are microphones. Points P1, P2, P3, P4, P5 and P6 are actual SmartPhone locations. Each square of the grid represents 1 unit in length.

Regarding input data for testing the Lok8 trilateration algorithm, the locations of M1(0,0), M2(0,20), M3(30,20), M4(30,0) were used and the initial distances between the mics and the various phone positions were measured manually. Although we could have used Pythagoras in Figure 3 to calculate exactly the measurements representing the ultrasonic distances between the microphones and various phone positions, we wanted to introduce some error in the measurements so chose instead to simply use a ruler to measure these distances on paper to one decimal point precision. After that we subtracted the shortest measured distance for any given phone position from each of the remaining three mic distances. The resulting 3 distance differences were then used as "ultrasonic" input to the asynchronous trilateration procedure in addition to the known microphone locations.

For example, for phone position P1 the measured distance to M1 was 20.2, to M2 19.2, M3 15.8, and M4 17.0. The shortest distance is to M3, therefore it is subtracted from the other 3 distances to leave; m_1= 4.4, m_2= 3.4, m_4= 1.2. These values simulate time measurements translated to distance for the ultrasonic signal to reach these 3 mics after first triggering the server clock at M3. The input data is summarised in Table 2 and the trilateration results for the phone's position relative to the 4 microphones are compiled in Table 3. Notice that if we assumed metres for units in this example, the standard deviations for the phone positions are of sub-metre accuracy.

Table 2: Sample TDOA Trilateration input. Second and third columns contain coordinates of a microphone and fourth column contains differences between distance to mic and closest mic. In this example microphone M3 is closest to phone position P1 so its corresponding distance difference equals zero.

Mic	**X**	**Y**	**Distance Difference (m_i)**
M1	0	0	4.4
M2	0	20	3.4
M3	30	20	0
M4	30	0	1.2

Table 3: Comparison of TDOA output and expected results. Second column contains X and Y coordinates of a given phone position, third column contains coordinates of the phone as calculated by our TDOA trilateration procedure. Fourth and fifth columns contain the Standard Deviations (σ_X, σ_Y) for each trilaterated phone positon and number of iterations to get there.

Phone Point	**Actual Location**	**TDOA Trilateration**	**Standard Deviation**	**Number of Iterations**
P1	17 , 11	16.987, 10.986	0.0002, 0.0003	3
P2	8 , 13	7.978, 12.966	0.0158, 0.019	3
P3	3 , 10	2.96, 10.0	0 , 0	4
P4	20 , 3	20.002, 2.996	0.011, 0.0195	3
P5	15 , 20	15.0, 20.0	0 , 0	4
P6	26 , 18	25.999, 18.031	0.0144, 0.0214	4

4 Conclusions and Future Work

In this paper we demonstrated an asynchronous trilateration method that can be reliably used to accurately locate an ultrasonic signal source without knowing the time the signal was sent. This eliminates the need to synchronize clocks between signal source and receivers.

An advantage of using a Least Squares approach for trilateration is its ability to tolerate errors in measurements; with more measurements provided, less is the impact from a single erroneous measurement. Also, due to the iterative nature of this approach allowing for a large *pull-in range*, initial approximations for a phone's position in a room can be simply taken as the average of all microphone (control point) positions. While the algorithm can work with only three receivers (mics), at least four or more are recommended for scenarios where measurements are likely to be contaminated with signal noise caused by multipath propagation.

For future work we plan to implement our TDOA Trilateration method in a real-time indoor positioning system on COTS SmartPhones and interconnected mics. We will then evaluate how well Lok8 manages with unavoidable measurement errors due to background noise, obstructions, and uncertainty due to the presence of multiple ultrasonic source devices.

5 Acknowledgments

The authors wish to thank the Higher Education Authority (HEA) in Ireland and their Technological Sector Research Strand III for funding the ultrasound work in the Lok8 project. Preparation of this publication and the asynchronous trilateration work was funded by a Strategic Research Cluster Grant (07/SRC/I1168) by Science Foundation Ireland under the National Development Plan. The authors also gratefully acknowledge this support.

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