A Fuzzy Approach to Bluetooth Positioning

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Abstract: - In this work we present a positioning system which is based on low cost commercial ready to use Bluetooth devices. After reviewing available positioning technologies, we describe our system's principle of operation and architecture, and we present a fuzzy approach for raw data processing in order to estimate mobile devices position. Finally experimental tests on the arranged fuzzy algorithm are presented.

Key-Words: - Location, Bluetooth, positioning, ubiquitous computing, augmented reality, fuzzy systems.

1 Introduction

Position based services are becoming a relevant topic in context-aware applications. Location awareness is a basic requirement for new applications on mobile devices, as in the case of advertisement systems in large stores and guidance systems in museums with handheld devices which are only feasible with an accurate position estimation of the mobile terminal. There are many existing indoor and outdoor positioning systems which use different technologies and algorithms to accomplish the positioning task. Among them, the most famous is GPS system [1], which is based on radio time-of-flight lateration, and allows accuracy of 15 meters only in outdoor areas. ActiveBats [2] is an ultrasound time-of-flight lateration based system for indoor positioning, and allows sharp measurements (10 cm or less). In the MotionStar system [3], [4], scene analysis is used to obtain accuracy of 1 mm but the needed hardware is very expensive. The MSR RADAR [5] positioning system is based on the 802.11 RF lateration and allows accuracy of 3-4 meters. As the above listed systems, most of the existing positioning systems use expensive hardware to arrange location frameworks for ad hoc mobile terminals. This paper presents a Bluetooth based positioning system. Bluetooth [5], [7] is a low power technology which is suitable for applications in small areas. Bluetooth is integrated on a large variety of popular lowcost mobile devices, like cellular phones, PDAs or earphones. The proposed system is based on a fuzzy algorithm which uses distance estimation between some Bluetooth mobile devices to be located and some Bluetooth base stations, which are used as reference nodes. A possible use of the proposed system within an augmented reality environment is described in [11].

2 Related Work

Bluetooth and other RF devices allow position estimation by means of several existing methods. From now on, the term mobile device refers to a device to be positioned, reference device is a device whose location is known.

Angle Of Arrival (AOA) positioning is based on the direction of received signal. A reference device measures the signal angle of arrival, which is sent by a mobile device. Location can be estimated by triangulation if two reference devices at least perform measurements [8]. Angles measurements require a special antenna array.

Time Of Arrival (TOA) positioning method is based on delay measurement. A mobile device sends a signal to a reference device, which in turn sends it back to the mobile device. Finally the mobile device measures the roundtrip time (RTT) of the signal. This leads to a circle, whose radius corresponds to half of RTT and whose center is on the reference device. Therefore a position estimation of the mobile device can be obtained by measuring three circles at least and by calculating their intersection. However TOA positioning requires accurate clocks, because a 1.0 µs error in timing leads to a 300 m error in distance estimation [8]. With Bluetooth systems, the instantaneous timing of master packet transmission may deviate up to 1 µs from the average [7], so the accuracy is too low for TOA positioning.

With *Cell Identity* (CI) method, the network is divided into cells. Each cell corresponds to the radio coverage of a single reference device. A mobile device connected to a given reference device is inside its equivalent cell. Therefore, use of smaller cells improves the accuracy. Bluetooth nominal radio coverage is from 10 m (class 3 devices) to 100 m (class 1 devices). Therefore, pure CI positioning with Bluetooth devices is quite inaccurate. Cells overlapping and connectivity-induced geometric constraints improve accuracy [8]. For instance, a number of reference devices can be placed at known positions in a regular mesh. Application of this method only requires to know whether a mobile device is in range of a given reference node or not (Fig. 1). This method has the advantage of an easy and scalable implementation, but is coarse grained and needs a complex infrastructure.

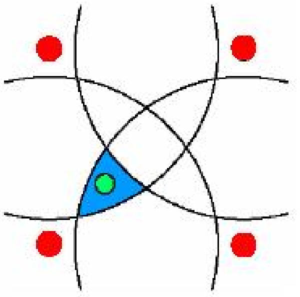

Fig. 1. CI enhanced positioning methods

RX power level positioning method is quite similar to the TOA positioning. Both methods locate mobile devices on intersection of three (or more) circles. In the case of RX power level positioning, the circles radius is evaluated based on the measured strength of received signals, thus requiring a relationship between signal strength and distance. RX power levels are usually measured in wireless networks for transmit power controlling and roaming.

However, the result of measurements can be used for positioning aims as well. Bluetooth devices measure RX power level by using *Received Signal Strength Indication* (RSSI) and LinkQuality, which are implemented in the Bluetooth module and can be read through HCI commands [7]. Consequently, RX power level positioning seems to be the most applicable for Bluetooth devices. To this end, we found that Link Quality is a quite reliable parameter for distance estimation, while RSSI only allows to know whether the device is in a given base station power range or not [10]. Implementation of Link Quality parameter is recommended by Bluetooth standard specifications, so it is available on most of the commercial devices, and any Bluetooth terminal or access point can be used in a position estimation framework.

3 Positioning System Structure

The proposed system is composed by a federation of networked reference nodes and a location server (Fig. 2). A reference node (hereafter *Base Station*, BS) is arranged with a consumer Bluetooth device connected to a PC, whose fixed location is known. Each base station runs an application to discovery mobile devices through the local Bluetooth dongle. For each discovered mobile device, the application reads the Bluetooth unique address and sends it to the location server over a UDP socket. The location server parses the incoming data from all discovered mobile devices within the system covered area, and stores them in a database. The first time a mobile device is detected by a base station, the location server receives its address and notifies the other base stations of device detection. This way mobile devices become known devices for other base stations. Each base station holds a list of discovered and known devices and loops two sequential phases. In the first phase, the base station performs inquiries in order to discover new mobile devices. In the second phase it performs queries to all listed devices and reads the LQ value from each of them, and then it sends all data to the location server database. For each mobile device in the database, location server stores the Link Quality values read from all base stations, along with their last timestamp information. In order to accomplish the positioning task, a console application periodically performs data access from location server database.

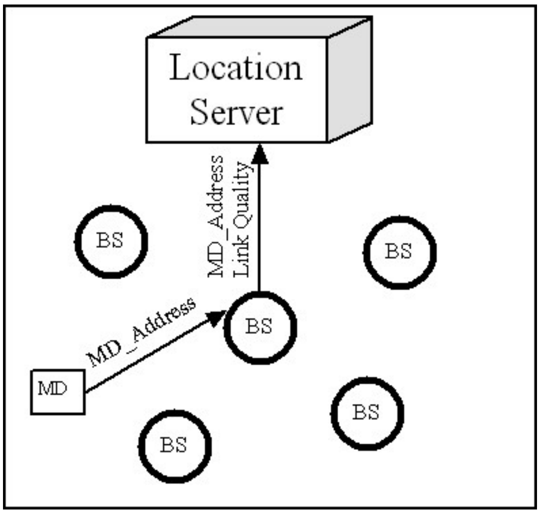

Fig. 2. Positioning system architecture

Mobile devices position estimation can be performed by converting acquired LQ data to distances with regression techniques and applying a triangulation algorithm [10]. However LQ values (and consequently distance values too) are affected by a high degree of uncertainty, so fuzzy techniques can be usefully applied for raw data processing.

4 A Fuzzy Approach

We chose to use a Mamdani-type fuzzy [9] system with M inputs and two outputs, where M is the number of base stations placed in the environment. Inputs are the normalized LQ values of each base station links with the mobile device to be tracked. Normalization is performed according to the following equation:

$$LQ_N = \frac{LQ - LQ_{cutoff}}{LQ_{\max} - LQ_{cutoff}}$$

where LQ_N is the normalized value, and LQ_{cutoff} , LQ_{max} are respectively the minimum meaningful measured value and the maximum measured value of the LQ parameter. Outputs are estimations of the mobile device rectangular coordinates with respect to a given reference system. The fuzzy system is defined by the following M rule:

> *if the LQ value of the mobile device link with the j^{th} base station is high, then the mobile device is near the j^{th} base station ($j = 1, 2, \ldots, M$).*

The fuzzy concepts in this rule are *high* and *near*. We bind the *high* concept with the simple triangular membership function shown in Fig. 3.

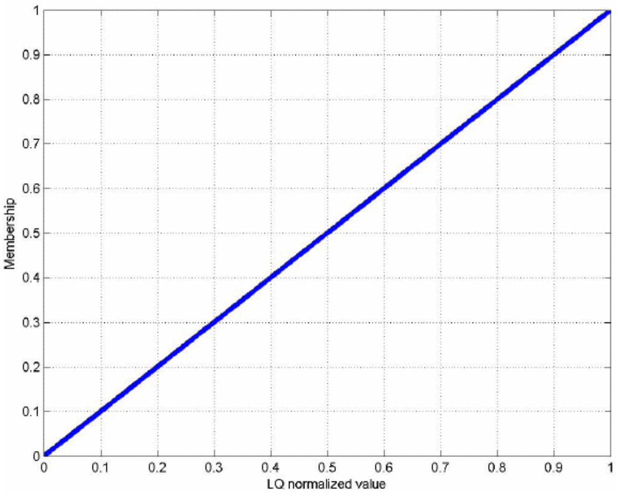

Fig. 3. Input membership function

We also bind the *near* concept with the following membership function:

$$\mu_j(x,y) = \begin{cases} 1 - \sqrt{\left(\frac{x - x_j}{\delta_j}\right)^2 + \left(\frac{y - y_j}{\delta_j}\right)^2} & \text{if} \quad 1 - \sqrt{\left(\frac{x - x_j}{\delta_j}\right)^2 + \left(\frac{y - y_j}{\delta_j}\right)^2} \le 1 \\ 0 & \text{else} \end{cases}$$

where x and y are rectangular coordinates of the mobile device, x_j and y_j are rectangular coordinates of the j^{th} base station, and δ_j is a suitable scaling factor. In order to ensure that non-zero portions of surfaces $z = \mu_j(x, y)$ (hereafter *membership surfaces*) correctly overlap, we take

$$\delta_j = \max\left\{\delta_j^x, \delta_j^y\right\}$$

with

$$\delta_j^x = \min_{i: x_i \neq x_j} \left| x_i - x_j \right|$$

and

$$\delta_j^y = \min_{i: y_i \neq y_j} \left| y_i - y_j \right|$$

In other words, δ_j^x is the smallest non-zero difference between the j^{th} base station x-coordinate and the other base stations x-coordinates, and δ_j^y is the smallest non-zero difference between the j^{th} base station y-coordinate and the other base stations y-coordinates. Then membership surfaces are scaled according to the input LQ normalized values. Namely, if $z = \mu_j(x, y)$ is the j^{th} membership surface, the scaled membership surface is $z = \mu_j^*(x, y)$, with:

$$\mu_j^*(x, y) = LQ_N^j \times \mu_j(x, y)$$

where LQ_N^j is the LQ normalized value associated to the LQ value read by the j^{th} base station. In order to obtain our fuzzy system output, we merge the scaled membership surfaces $z = \mu_j^*(x, y)$ in an unique surface $z = \mu^*(x, y)$ according to:

$$\mu^*(x, y) = \max_j \mu_j^*(x, y)$$

and then we defuzzify by taking the centroid x and y coordinates of the volume under $z = \mu^*(x, y)$ surface, according to:

$$x_C = \frac{\int x\mu^*(x, y)dxdy}{\int \mu^*(x, y)dxdy}$$

and

$$y_C = \frac{\int y\mu^*(x, y)dxdy}{\int \mu^*(x, y)dxdy}$$

where x_C and y_C are estimations of the mobile device position.

5 Experimental Results

We carried out our experiments within our department (Fig. 4), where ten base stations were placed in the points marked with red circles (M = 10).

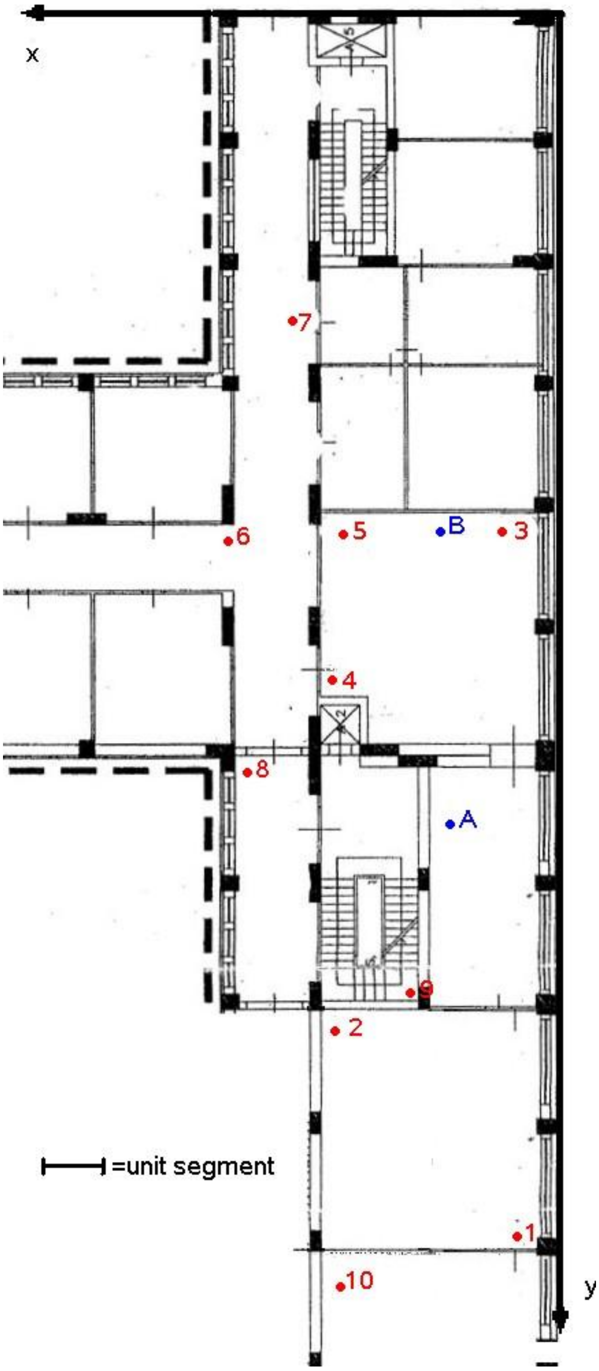

Fig. 4. Experimental setup

Their rectangular coordinates in the reference system in Fig. 4 are shown in Table 1.

Base Station #	*x*	*y*
1	0.0	21.5
2	4.3	18.2
3	0.0	8.7
4	3.0	13.0
5	4.3	8.7
6	6.3	9.5
7	5.3	5.8
8	6.3	13.5
9	3.0	17.8
10	4.3	23.5

Table 1. Base stations rectangular coordinates

Two devices to be positioned were placed in the two points marked with a blue circle in Fig. 4. The device at point A (whose rectangular coordinates are $x_A = 2.5$, $y_A = 15$) was a notebook with a Bluetooth dongle plugged in. *LQ* values measured from the base stations are shown in Table 2, along with the corresponding normalized values (here $LQ_{max} = 255$ and $LQ_{cutoff} = 180$).

Base Station #	*LQ*	LQ_N
1	214	0.4533
2	240	0.8000
3	210	0.4000
4	230	0.6667
5	213	0.4400
6	180	0
7	185	0.0667
8	255	1.0000
9	214	0.4533
10	200	0.2667

Table 2. LQ values read with a mobile device at the point A

The $z = \mu^*(x, y)$ surface is sketched in Fig. 5, and the estimated mobile device position is given by:

$$x_C = 1.83079$$

$$y_C = 15.4125$$

with an absolute error

$$E = \sqrt{(x_A - x_C)^2 + (y_A - y_C)^2} = 0.7861$$

and a relative error

$$\varepsilon = \frac{E}{\sqrt{x_A^2 + y_A^2}} = 0.0517 = 5.17\%.$$

The device placed at the point B (whose rectangular coordinates are $x_B = 2$, $y_B = 10$) was a cellular phone with Bluetooth connectivity capabilities. *LQ* values measured from the base stations are shown in Table 3, along with the corresponding normalized values (here $LQ_{max} = 213$ and $LQ_{cutoff} = 203$. Zero values just mean that the mobile device was not in the range of the corresponding base stations).

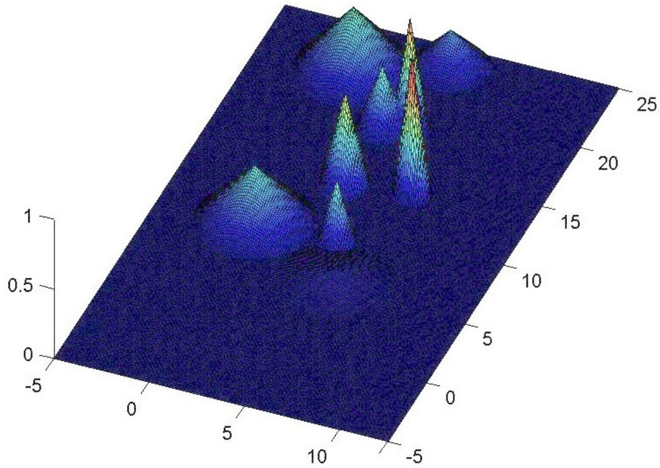

Fig. 5. The $z = \mu^*(x, y)$ surface with a mobile device at the point A

Base Station	*LQ*	*LQ_N*
1	0	0
2	0	0
3	0	0
4	213	1
5	213	1
6	206	0.9671
7	203	0.9531
8	0	0
9	0	0
10	0	0

Table 3. LQ values read with a mobile device at the point B

The $z = \mu^*(x, y)$ surface is sketched in Fig. 6, and the estimated mobile device position is given by:

$$x_C = 3.76572$$

$$y_C = 11.2111$$

with an absolute error

$$E = \sqrt{(x_B - x_C)^2 + (y_B - y_C)^2} = 4.9678$$

and a relative error

$$\varepsilon = \frac{E}{\sqrt{x_B^2 + y_B^2}} = 0.2100 = 21.00\%.$$

The raised value of the relative error is due to the large number of base stations from which the mobile device signal is not received.

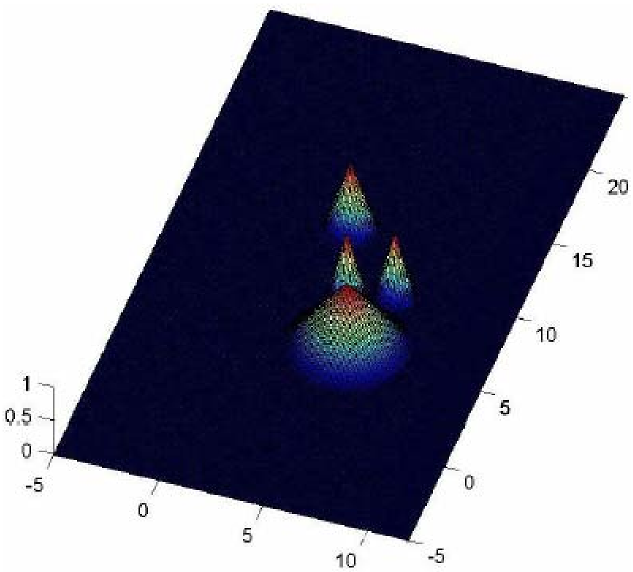

Fig. 6. The $z = \mu^*(x, y)$ surface with a mobile device at the point B

6 Conclusions and future work

In this paper we presented a fuzzy approach for raw Link Quality data processing in order to perform Bluetooth based positioning of a mobile device. Experimental data show that the relative positioning error is quite small if all of the base stations receive the mobile device signal, while it is larger otherwise, so the algorithm could be improved by correctly taking into account signal absence at some base stations.

The proposed fuzzy approach is not suitable for position tracking of fast moving devices, because it's quite complex from a computational point of view. However it could be integrated with a neural network [12] to correctly bind acquired Link Quality values with mobile device position with no need to run the fuzzy algorithm every time the mobile device changes its position.

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