Optimisations for LocSens – an indoor location tracking system using wireless sensors

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Abstract: Ubiquitous and pervasive computing envisions context-aware systems that gather real-world information from many fixed and mobile microchips and sensors integrated in everyday objects. To provide valuable services, it is necessary to estimate the location of users or objects. Outdoor location tracking is achieved by Global Positioning System (GPS), but due to its poor indoor coverage, there is a need for alternative technologies in buildings. Since multiple wireless sensors may be situated in the environment, they can be used for location estimation and tracking. This paper presents LocSens, a cost-effective location tracking system based on sensor nodes with wireless connectivity. LocSens works with a minimum number of sensor nodes. It is established and tested in a real indoor scenario over multiple rooms. LocSens could be improved by optimising algorithms and using more precise sensor boards. Results confirm gained accuracy in location estimation and tracking of moving objects.

Keywords: ubiquitous computing; pervasive computing; wireless sensor network; indoor location estimation; indoor location tracking.


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1 Introduction

Recent developments in the area of ubiquitous and pervasive computing emphasise the interest in context-aware applications. Location is probably the most important context. Indoor location estimation and tracking remain challenging due to the lack of usable and cost-effective technologies. GPS has proved itself for outdoor usage. But it is not suitable for indoor applications due to poor coverage.

To gather real-world information from the environment, ubiquitous and pervasive systems build on sensors attached in everyday objects. Wireless connectivity of sensors opens a wide range of applications. The main focus of this paper is to use wireless sensor network for location estimation...
Since the cost for sensors is low, the location tracking system is assumed to be cost-effective. Using wireless connections, it is possible to calculate current location of a user or an object. For some applications it is even sufficient to estimate user’s location in a room. Providing more accuracy opens up an opportunity for more specific services. The Smart Doorplate project Trumler et al. (2003) establishes a ubiquitous environment with intelligent doorplates, which present information about the office and employees to the visitors outside. Electronic touch-screen displays provide location of the office owner and some status information, such as, person is on the phone, absent, or busy. This paper describes LocSens a location tracking system based on wireless sensors, that is used to get location information for Smart Doorplate services. LocSens works with fixed room sensors that communicate with mobile sensors carried by users.

Usually each sensor node in a wireless sensor network has its own processor, memory and application specific sensors. LocSens is implemented using two different kinds of sensor boards. The first sensor board is the ESB430 that is developed at the Freie University of Berlin (The Embedded Sensor Board ESB430, 2007). This board works with a TI MSP430, an ultra low power 16 bit RISC-based microcontroller with 60 KB flash ROM and 2 KB RAM. ESB430 has multiple sensors on-board. Figure 1 shows a picture of the ESB430 with its sensors and actuators. In a second phase of LocSens we replaced the sensor boards by the more up-to-date model MSB430. The MSB430 board has a modular structure, where specific sensor modules can be easily attached. In the basic form, there exist two modules: a basis module (MSB-430T) and a kernel module (MSB-430). The kernel module uses a TI MSP430F1612 microcontroller and a Chipcon CC1020 radio transceiver, both enhancing the performance in comparison to the older board ESB430 (The Modular Sensor Board MSB430, 2007). Also three sensors are attached on the kernel module: an acceleration sensor, a temperature sensor and a humidity sensor (see Figure 2).

It is a characteristic of sensor nodes that all resources are extremely limited:

- **Energy:** The energy supply is usually provided by a battery. LocSens uses cable operated sensor nodes for fixed positions in rooms as well as battery operated sensor boards carried by users.
- **Memory:** For current prototypes only a limited memory capacity is available. On the average, sensor boards have less than 20 kilobytes of RAM and about 100 kilobytes of flash memory.
- **Performance:** In order to reduce the energy consumption, low performance processors are used on sensor boards. In most cases, it is an 8-bit micro controller. Therefore, the performance and processing speed is very limited.
- **Communication:** Wireless communication has naturally a low data throughput. Additionally, problems with packet failures, packet loss and collisions lead to increased time delays.

The next section describes related location estimation and tracking approaches. Section 3 introduces the LocSens system and the testing environment. LocSens is evaluated on the ESB430 sensor boards using different estimation algorithms and optimisations. Section 4 describes the evaluation results. The paper ends with the conclusion.

**Figure 1** The ESB430 sensor board (see online version for colours)
2 Related work

The Active Badge system (Want et al., 1992) was an inspiration for several following projects. The goal of the Active Badge project was to easily locate persons in public buildings like hospitals. An application is to forward incoming phone calls to the current room phone near to the person’s location. The active badges are devices worn and used to identify the person by sending out an infrared signal every 100 milliseconds. The use of common IR technology holds the production costs low. Active badges have a range of 6 m and can run on battery almost for one year. Additional energy saving approaches can achieve a fourfold increase in service time. A network of sensors attached in each room receives the signals sent by these badges. Each sensor network is able to contain as many as 128 sensors which are connected to a workstation over a serial port. The workstations themselves are connected to a master that gathers and controls all sensor data. The Active Badge system can locate persons or objects in a room-wide range, but the resolution is very low and not sufficient. Another weak point is the high installation cost since all of the controlled area needs to be wired up, and extensions are hardly possible.

Figure 2 The MSB430 sensor board (see online version for colours)

The RADAR project is a location tracking system based on wireless LAN (Bahl and Padmanabhan, 2000). RADAR is established in an area of 980 m² with more than 50 rooms. Three base stations are used to cover the whole building, where the coverage of stations partially overlap. A laptop with a WLAN adaptor works as a mobile device for locating and tracking. The laptop sends multiple UDP packets to the base stations that calculate signal strength and signal-to-noise ratio for each packet. It first builds a reference model with measurements consisting of 70 points in the building with data for each direction (north, west, south and east). RADAR stores at least 20 values of signal strength for each combination of location and direction. Additionally, it calculates the means, standard deviation and median for each position. The accuracy of RADAR is similar to the Active Badge system. It is only possible to locate people in rooms. But the installation cost is lower, since most buildings provide WLAN access infrastructures. The calculation of reference data is the main disadvantage of RADAR. Each change in the room structure requires an update of the reference model.

Another project that uses WLAN for location tracking is described in Ladd et al. (2002). This approach is similar to RADAR but uses a Bayesian interference algorithm for statical evaluation based on a specific model of state and observation spaces. The mean deviation could be improved compared to RADAR. Nevertheless, this approach is also highly dependant on the room structure. Even small changes lead to large number of re-calculations of the reference model.

Harter et al. (2002) present another approach for location and identification of objects based on ultrasound. Each person or object carries a device called bat that sends periodically an ultrasonic signal. Receivers of this signal are ultrasonic receiver units which are attached to fixed positions on the ceiling. These units are interconnected to a daisy-chained network. Using base stations, the ID of a corresponding bat, which needs to be localised, can be sent over a wireless connection. The bat responds with the ultrasonic signal. Using different arriving times at different receiver units, the location of the bat can be calculated. This project shows that ultrasound provides high precision for location. On the other hand, ultrasound is interference-prone. Other signals can easily jam the ultrasonic signal. Since also in this project the installation cost is very high, it is difficult to extend the system infrastructure.

Cricket (Smith et al., 2004) is another ultrasonic-based location system. In this approach the device carried by the person determines itself the location. This ensures the privacy of the person. Beacons attached to the ceiling periodically send a radio and ultrasonic signal. Using multiple signals from different beacons the personal device calculates the current position. In further work, cricket was extended to provide a tracking of moving objects. An outlier rejection component is used to eliminate measurement failures by deleting extremal values. Another component is the least square solver which has the task of minimising squared mean failures. Current states are stored by an extended Kalman-filter that can even predict future states. The installation cost of cricket is lower than other projects, but the interference problem of ultrasonic remains.

The technology of active RFID (Radio Frequency Identifier) tags is used in Ni et al. (2004). The aim of the LANDMARC project is to build a cheap location system that does not need sight contact and is insensitive to environment changes. LANDMARC uses RFID readers with a range of 150 feet. The range could be extended with specific antennas to 1000 feet. Additionally, the readers have an interface for wireless ethernet that allows flexible positioning. Each reader has eight reading ranges which can be changed incrementally. The reader can read out up to 500 tags in 7.5 seconds within each range. In a test scenario, four readers are attached in a
large room. Since there is no possibility to get the signal strength, the readers have to scan all eight ranges sequentially. LANDMARC sends detected tags over wireless connection to a central computer. Using reference measurements, it calculates the location of the tags. The results show that LANDMARC is insensitive for changes in the environment, like persons in the area. The main disadvantage of LANDMARC is the sequential scan of all reading ranges that takes nearly one minute for each turn. Also the readers are relatively expensive, which affects the installation cost.

3 LocSens – indoor location tracking

LocSens is based on an active environment, where room sensors, attached at fixed positions, communicate with mobile sensors carried by users. In order to determine an exact location, it is necessary to perform distance measurements to multiple points. LocSens is evaluated in a real test environment with three rooms. Figure 3 shows a ground plan of the test environment, as well as room sensors and points of measurements.

The transceiver of the sensor board ESB430 provides a value for the receiving level. This value indicates the distance between the current sensor node and the packet sender. A precise location tracking requires a nearly constant receiving level. Therefore, it is necessary to first test the stability of level values. One of the room sensors is attached to a PC, where measurement values can be read out from all sensors. As the first stability test, we sent sequentially radio packets to all room sensor boards and measured the receiving level. These tests ran over several nights to minimise the signal level deviation caused by interferences, e.g. through persons in the rooms. Figure 4 shows the level values of a sensor board measured over a full day.

The chart shows that values are mostly located in a thin band, which indicates a good stability. But there exist also some irregular deviations.

Besides the room sensor nodes, there is also a mobile user sensor board. Furthermore, signal strength of the user board was measured by room sensor nodes. As shown in Figure 3, points of measurement form a raster with a distance of one meter between each point. Figure 5 shows the user carrying mobile sensor node and measurement equipment. The aim was to build up a reference model that is used for location estimation. For each point the coordinates, user’s line of sight (N, E, S, W), and receiving level of all three room nodes were stored in a database. In order to have a reliable basis, 120 data points for each line of sight were gathered, achieving 33,600 data points altogether.
The location estimation algorithm compares current receiving levels with the data records in the database. In order to optimise the estimation, we implemented several algorithms. The first approach is the randomised evaluation, which is actually not practical, but often used as comparison to other approaches. Randomised evaluation chooses randomly \( k \) neighbouring points \( r_1, \ldots, r_k \) from the reference database. The position \( P \) is calculated by interpolating between these points with fixed weights of \( \frac{1}{k} \):

\[
P = \sum_{i=1}^{k} \frac{1}{k} r_i
\]  

As further approach for location estimation, we chose Nearest Neighbour in Signal Strength Space (NNSS). This algorithm differs from the previous one, because it considers \( k \) points \( n_1, \ldots, n_k \) from the reference database, which have the lowest Euclidian distance to the current measured receiving level. Position \( P \) can be calculated in the same way by interpolation with weights of \( \frac{1}{k} \).

The disadvantage of both previous algorithms is that fixed weights are used. In order to optimise the search for appropriate neighbouring points, we implemented a Statistical Approach (STAT) that uses the density of a multidimensional normal distribution as an auxiliary function:

\[
f(\tilde{x}) = \left( \frac{1}{\sqrt{2\pi}} \right)^n \frac{1}{\sqrt{\det(\Sigma)}} e^{-\frac{1}{2} (\tilde{x} - \mu)^T \Sigma^{-1} (\tilde{x} - \mu)}
\]  

where:

- \( n \in \mathbb{N} \)
- \( \tilde{x} \in \mathbb{R}^n \)
- \( \mu \) expectation vector, \( \mu_i = E(X_i) \)
- \( \Sigma \) variance-covariance matrix, \( \sigma_{ij} = \text{Var}(X_i) \), \( \sigma_{ij} = \text{Cov}(X_i, Y_j) \)
- \( i \neq j \)

In the present case with three room nodes, there is a three-dimensional random variable \( X(n = 3) \), which describes the receiving level at the three room sensor boards. For each reference point \( p_i \), the values of \( \mu_i \) and \( \Sigma_p \) are calculated. Moreover, the density \( f_p \) can be determined at each reference point \( p_i \). The \( k \) reference points \( s_1, \ldots, s_k \) with the highest density \( d_1, \ldots, d_k \) are chosen for the estimation of the current position, in the way that weights \( w_1, \ldots, w_k \) are calculated as follows:

\[
w_i = \frac{d_i}{\sum_{j=1}^{k} d_j} \forall j = 1, k
\]  

Finally the position \( P \) can be calculated as:

\[
P = \sum_{i=1}^{k} w_i s_i
\]
4 Evaluation

LocSens was evaluated in a test environment with several sensor boards. We implemented above described algorithms to calculate the position of a user in an office environment with three rooms. The location estimation was performed using two different kinds of sensor boards: ESB430 and MSB430. We also performed a location tracking by calculating the location continuously.

4.1 Results using ESB430

Based on the algorithms described in the previous section, we performed several tests, where the location was calculated at different points in the rooms using sensor boards ESB430. Standing at a specific position, three neighbouring points were chosen for interpolation. Figure 6 visualises the percentiles for all three algorithms (NNSS, STAT, rand), i.e. the percentage of points where the difference between calculated and real position is $x$ m (e.g. 25% of the calculated positions have a deviation of 0–1.5 m from the real position). The results show that NNSS and STAT achieve considerably better results than the randomised algorithm, whereas NNSS provides best values.

For the first enhancement, we examined the impact of neighbours by increasing the number of considered neighbouring points. Figure 7 describes NNSS performed from 1 to 7 neighbours. Using two neighbours instead of only one provides a clear improvement. In the 90th percentile the deviation decreases by 1.10 m. This value is enhanced by 0.36 m when three neighbours are considered. With more than three neighbours the improvement is not much better. STAT presents similar results. Therefore, it makes only sense to consider at most four neighbours.

In order to examine the impact of the reference data on the precision of location, we performed further tests, changing the number of considered reference points. Decreasing the number of reference points leads to better performance, because the lookup for neighbours takes less time. The results in Figure 8 show that even with nearly half of the reference points, STAT provides acceptable values, and NNSS behaves similarly. Also the number of data sets at each reference point can be decreased without losing much location precision.

Nevertheless, it is important to choose the right reference points for the calculation. If the user stands near a wall, it is not reasonable to choose reference points from the other side of the wall. In order to ensure this, we optimised the reference database by storing the current room for each point of measurement. This was easy to realise using the infrared sender/receiver of the sensor board. Figure 9 shows that both approaches (NNSS and STAT) provide much better results when additional sensor information is considered.

Figure 6 Percentile for NNSS, STAT and random evaluation using 3 neighbours (see online version for colours)

![Figure 6](image)

Figure 7 Percentile for NNSS using 1–7 neighbours (see online version for colours)

![Figure 7](image)
4.2 Results of optimisations using MSB430

In a second phase we used the more up-to-date sensor boards MSB430 which have more performance and a better radio transceiver. We also modified the NNSS algorithm to achieve optimised accuracy. Instead of regarding 100 reference data sets in NNSS for each position and line of sight, we used an arithmetic mean of all relevant reference data points. This modified algorithm is called M-NNSS. Figure 10 shows the results of M-NNSS and NNSS using MSB430 sensor boards. The algorithms were performed regarding 1–7 neighbouring points.

The results show a clear enhancement compared to ESB430 (see Figure 7). M-NNSS achieves higher accuracy in upper percentiles. The average variance is in M-NNSS 2.34 m and in NNSS 2.58 m. Table 1 gives an overview of several location estimation techniques compared with LocSens. As seen in this table LocSens achieves very good accuracy values with very low installation costs.

<table>
<thead>
<tr>
<th>System</th>
<th>Technology</th>
<th>Range (indoors)</th>
<th>Accuracy</th>
<th>Size of test environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active badge</td>
<td>Infrared</td>
<td>&lt; 6 m</td>
<td>exact room</td>
<td>unknown</td>
</tr>
<tr>
<td>RADAR</td>
<td>WLAN</td>
<td>25 m–50 m</td>
<td>2.75 m</td>
<td>44 m × 23 m</td>
</tr>
<tr>
<td>LANDMARC</td>
<td>active RFID</td>
<td>50 m</td>
<td>1 m</td>
<td>9 m × 4 m</td>
</tr>
<tr>
<td>LocSens (ESB430)</td>
<td>RF</td>
<td>&lt; 20 m</td>
<td>2.90 m</td>
<td>10 m × 8 m</td>
</tr>
<tr>
<td>LocSens (MSB430)</td>
<td>RF</td>
<td>&lt; 20 m</td>
<td>2.34 m</td>
<td>10 m × 8 m</td>
</tr>
</tbody>
</table>
4.3 Results of location tracking

After examining possible optimisations of location estimation, we performed tests with LocSens where we tracked a moving user. Figure 11 shows the actual path of the user through the rooms. We chose the STAT algorithm for location tracking. In order to gain fast calculation of current positions, only four data sets for each reference point are considered. This ensures a real-time tracking of the user. Figure 12 visualises the calculated positions of the user moving along the path shown above.

In the first step we used again the ESB430 sensor boards. For some points, there are position changes of several meters. Even changes through walls are calculated incorrectly. For further optimisations, we could solve these problems. At first, we limited the considered reference points to only points in a specific distance to the last position. Using the vibration sensor of the user sensor board, it is possible to detect the motion intensity. This information can be used to dynamically adapt the distance variable. If the user walks faster, the range of considered points increases automatically. Furthermore, position changes through walls can be avoided by allowing room changes only near to doors.

Figure 13 shows the calculated path after optimisations. The tracking precision in the smaller rooms could be clearly enhanced. In the large room there are still position changes of several meters, but the actual path of the user can be approximated.

As next step, we performed the location tracking by using the enhanced sensor boards MSB430. Because of the better results in location estimation, we expected an optimisation of location tracking with MSB430 boards. As first modification, we used four room sensors instead of only three. The user walked the same route as shown in Figure 11. Actually, Figure 14 illustrates the enhancement of location tracking using MSB430 sensor boards.
Figure 12  Calculated path of user without optimisation (see online version for colours)

Figure 13  Calculated path of user with optimisation (see online version for colours)
5 Conclusion

This paper presented LocSens, an indoor location tracking system based on wireless sensors. Since sensor boards are produced with low costs, the usage of wireless sensors minimises installation cost of the overall system. LocSens was implemented with different location estimation algorithms. We evaluated the impact of several modifications on reference data, in order to enhance system performance. Also the usage of additional sensor information increased the precision of calculation. In order to with different hardware platforms, we performed LocSens using two different kinds of sensor boards. Results show that using enhanced sensor boards increases the accuracy. LocSens achieves acceptable results in location estimation and real-time location tracking.

References


