The iLoc+ Ultrasound Indoor Localization System for AAL Applications at EvAAL 2012

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Abstract. iLoc+ is an ultrasound ranging based indoor localization system based on the iLoc system of the iHomeLab Living Lab. For example, the system can be used for visitor tracking: Visitors get an electronic name badge comprising an ultrasound transmitter. This badge can be localized with an average accuracy of less than 30 cm deviation in its spatial position, by means of reference nodes distributed in the lab rooms. iLoc among others received a 3rd prize at the 2011 EvAAL localization competition performed at the CIAMI Living Lab, Valencia. iLoc+ is a further development of the iLoc system. It specifically addresses AAL scenarios, where besides a high accuracy also low installation effort and affordable cost is important. Therefore iLoc+ reference nodes operate wireless. Node positions are self-determined with respect to a few given reference locations.

1 Introduction

Ultrasound time-of-flight (TOF) measurement is a proven technology for indoor ranging and has already been successfully applied to indoor localization systems in the past. Prominent ultrasound based localization projects are for example the CRICKET, CALAMARI and BAT systems ([10,12,11]) and the recently developed iLoc system [4,5]. They provide high and reliable accuracy, achieved with moderate effort. The iLoc+ ultrasound ranging based indoor localization system (Fig. 1) comprises mobile nodes (badges, name tags), detector nodes and a position server, as well as a time synchronization transmitter. The name tags (Fig. 3) are equipped with a microcontroller, a radio transceiver and an ultrasound transmitter. They emit ultrasound pulses at a configurable rate, for example 2 Hz, with a duration of 1 ms. These pulses are received by some of the detectors.

The detector nodes, also called reference nodes, are located at fixed positions. Their coordinates are self-determined by the system using an autolocation scheme (see chapter 4). The nodes comprise a microcontroller and an ultrasound

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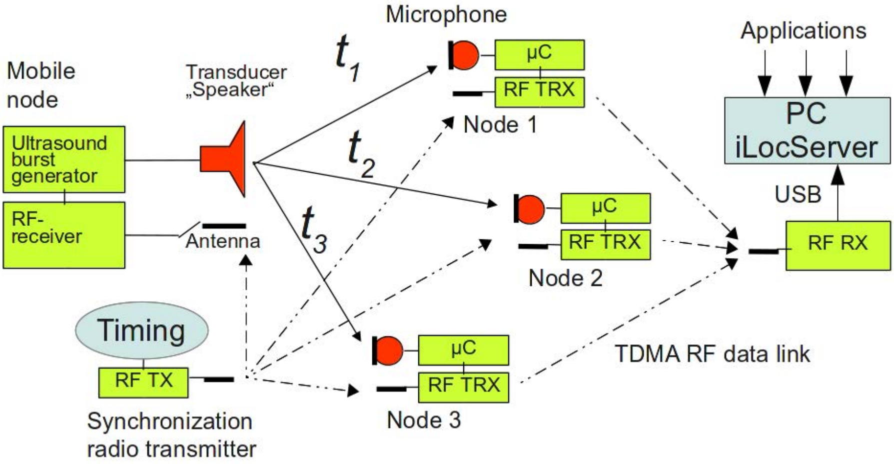

Fig. 1. Setup overview: A synchronization transmitter emits timing information via radio channel to the mobile node as well as to the receiver nodes (Node1 .. 3 shown in the image). The mobile node, for example a visitor badge, transmits a synchronized ultrasound burst. The receiver nodes detect the arrival time of this sound burst at their position and calculate the respective time of flights (TOF) t_1, t_2 and t_3. The TOF information is transmitted by radio to a receiver connected to the iLocServer. The server calculates the position and offers this information to interested applications.

receiver as well as a radio transceiver. The radio is used to receive time synchronization information and transmit data: The nodes record the reception times of ultrasound bursts transmitted by the badges, calculate the ultrasound time of flight (TOF) and transmit this information to the iLoc server. The server calculates position estimates from the received data by multilateration. The obtained position data may be used among others for visualization of visitor positions (see Fig. 2).

2 Hardware

2.1 Interactive Badges

The interactive badge (Fig. 3) comprises the following hardware blocks: a CC2430 Texas Instruments microcontroller including IEEE 802.15.4 radio transceiver, antenna and HF matching network, a Bosch SMB380 triaxial acceleration sensor, a charge pump chip to generate a higher voltage (20 V) to drive the 40 kHz piezoelectric ultrasound transducer, the transducer itself, the LCD unit, and a rechargeable 25 mAh lithium battery. The power consumption of the badge hardware is in the range of 1..10 μW in standby mode and raises to about 50 mW in operational mode, with transition times < 1 ms. The microcontroller comprises a 32 kHz crystal-based wake up timer. The badges are equipped with an inductive battery charging

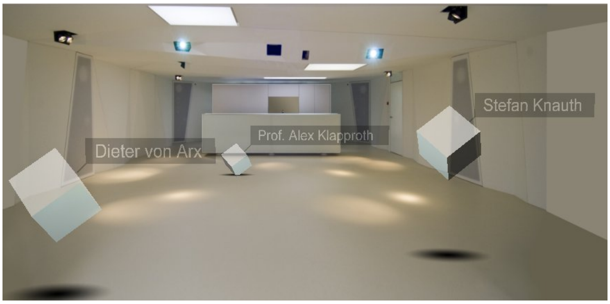

Fig. 2. 3D visualization of visitor positions in the iHome Living Lab. The positions are given as "hovering" cubes indicating the name of the badge bearer, embedded in a 3D visualization of the iHomeLab.

Fig. 3. Name badge with IEEE802.15.4 radio transceiver, ultrasound transmitter and LCD

circuity including a coil (part of the PCB layout), a rectifier and overvoltage protection. Charging of the badges takes place in their storage box equipped with two charging coils operating at a frequency of 125 kHz.

2.2 Reference Nodes

The reference nodes are Freescale HCS08GB60 Microcontroller based and equipped with a TI-CC2420 IEEE802.15.4 radio transceiver chip and an ultrasound preamplifier (see fig. 4). The ultrasound detection circuity generates two interrupts for two different sound levels. One level is just above the noise level, the second amplitude threshold is a bit higher. This allows to detect the reception time of the ultrasound pulse with a higher accuracy when compared to a single point detector: from the two thresholds the received amplitude of the signal can be estimated and used for correction of the time-of-flight. The transceiver is used to receive the timing information of the synchronization transmitter and to transmit the TOF information to the iLoc Server. As ultrasound reception is indicated by interrupts, the microcontroller can be at sleep mode while waiting for the ultrasound signal, waiting to perform time synchronization with the time transmitter, or waiting to transmit TOF data.

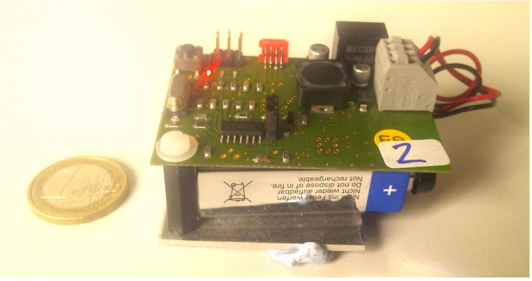

Fig. 4. Ultrasound receiver node assembly of battery, PCB and backplate for mounting. The PCB comprises microcontroller, ultrasound amplifier and 802.15.4 radio transceiver.

3 Operation, Timing and Synchronization

The maximum detection range of the iLoc ultrasound signal is about 15 meters. The pulse duration itself is about one msec, and this pulse propagates through air with the speed of sound (about 345 m/s at 22.5 °C). This corresponds to a maximum ultrasound pulse "livetime" of about 45 msec. This live time is given by the transmitter ultrasound amplitude, the sound path loss, and the receiver sensitivity, and is a consequence of the specific iLoc device parameters and the used sound frequency of 40 kHz. In order to avoid interference, a second ultrasound pulse should only be generated after this lifetime. For iLoc we chose 50 ms as the system time slot i. e. the pulse repetition rate.

There exist several design approaches for ultrasound localization systems with multiple mobile nodes. It is important to avoid ultrasound interference between the nodes (see for example [10]). One commonly used approach is to let the fixed infrastructure emit the pulses and send radio packets identifying the sending node. This has some advantages, for example privacy. The mobile node can detect its position without the system knowing that the mobile node exists. Also the number of mobile nodes is not limited in this case as they are passive. A disadvantage of this approach is that the mobile node has to listen for a certain time to radio and sound messages before being able to detect its position.

A main design goal of the original iLoc system was that the mobile nodes (currently the name badges) should consume as little energy as possible. Therefore we chose the opposite approach, using active mobile nodes and a passive detection infrastructure. The mobile nodes themselves emit the ultrasound pulse. For each node a 50 ms time slot is allocated, corresponding to the maximum lifetime of the propagating ultrasound pulse. The time needed for the position determination of n nodes is therefore $T = n \times 50\text{ms}$. A typical number of nodes in our lab is $n = 20$, so the position update rate for the nodes is 1 Hz. Other update rates are configurable, for example 10 Nodes with an update rate of 2 Hz each.

For correct TDMA operation and correct time-of-flight measurement, the whole system operates synchronized. A time synchronization accuracy of about

50 μs is achieved by the central synchronization radio transmitter. To establish this accuracy. the mobile nodes and the fixed nodes need to synchronize every 2-5 seconds. Actually the operation is as follows: The synchronization signal is sent with the slot rate, i.e. every 50 ms, containing also the number of the badge that shall send a pulse in the current slot. The mobile nodes therefore wake up just prior to the moment when they expect their next synchronization signal. They listen for the synchronization packet, readjust their clock, emit their ultrasound pulse and go to sleep again.

The whole sequence takes about 5 ms. Using a transmission rate of 1 Hz, this leads to a duty cycle of 1/200. The electric current in active mode is about 20 mA, leading to an average current of about 100 μA, at a voltage of 2.5 .. 3 V, enabling operation times of 10 days with a small lithium coin cell, and one update per second. Note that for the EvAAL competition, the update rate was 5 Hz, thus reducing lifetime by a factor of 5. The following table lists some operational times for the mobile node at 1 Hz update rate:

Battery type	Duty cycle	operational time
Lithium coin 25 mAh	1 sec	10 days
	10 sec	3 month
Lithium 500 mAh	1 sec	1/2 Year
	10 sec	> 2 Years
AA 2000 mAh	1 sec	2 Years

In the fixed nodes the ultrasound receiver is active at all times, and consumes a considerable current of about 1 mA, which restricts the lifetime to about 2 month, with AA cells. This is because the receiver nodes originally were designed for the older line-powered iLoc system. The remaining parts of the node, namely transceiver and microcontroller, are currently active four times per second, 5 ms each, leading to a duty cycle of 1/50. The four active times per second are used for TOF transmission to the iLoc server and for synchronization. During this active phases the node consumes about 20 mA. The nodes also wake up for a very short time after each time slot, i. e. 20 times per second, to check for- and evaluate TOF data of received ultrasound pulses.

A planned future version of the node hardware will comprise a much less “hungry“ ultrasound circuity. Combined with an intelligent duty cycle algorithm, which adopts the update rate to the activity of the localized person, a battery lifetime of several years also for the receiver nodes seems possible.

4 Deployment Considerations and Real iLoc Installations

Basically, 3 range measurements from 3 different reference positions allow the determination of the tag position. Given the above mentioned 15 meter iLoc maximum ultrasound range, these conditions would be fulfilled for example by deploying the reference nodes in a lattice with a spacing of about 10 meters. Practically, depending on the desired accuracy, the density of reference nodes

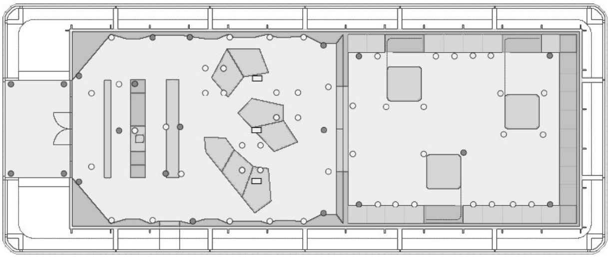

Fig. 5. Positions of the 70+ wired ultrasound receivers in the iHomeLab. The inner gray rectangle indicates the covered area (about 10m × 30m). The iHomeLab is located at Lucerne University of Applied Sciences at Campus Horw.

should be much higher. The typical node density used is one node per about 5 square meters. Then every point in the room is in the ultrasound range of more than 5 reference nodes, increasing the stability of the system against ultrasound interference for example by noise emitted from machinery or people. The ultrasound signal needs a line-of-sight for propagation, which can get lost by a shading caused by the body of the wearer of the tag or by other visitors in the same room. Also reflections have to be taken into account.

The iHome Living Lab setup is based on the older iLoc system, where the receiver nodes are wired by using the 2 wire ("IPoK") bus system [6] providing power supply and communication to the nodes. In the lab currently more than 70 nodes are arranged in 6 IPoK harnesses (fig. 5). Typically an emitted pulse is detected by about 5–15 receivers. Inconsistent range reports are rejected by the multilateration algorithm with a simple but computing intensive procedure: From the reported ranges for all permutations of 3 readings a position value is calculated. By stepwise removing of calculated positions lying outside of the mean value, the most probable readings are selected for the final trilateration [3].

In order to achieve a high accuracy of the system, the positions of the ultrasound receivers need to be accurately determined. Actually only a fraction of the positions have been manually measured. For the remaining positions only estimations have been entered to the database. Then the estimations have been adjusted by reference measurements: A mobile tag (name badge) was placed at a grid of known reference positions and time-of-flight results were recorded by the receivers. The position data of the reference receivers was then adjusted until the measured range values for a particular reference node matched best with the calculated distances. This fitting process was performed by minimizing the sum of the squared differences between measured range and calculated range.

For the EvAAL 2011 competition [2] the wired iLoc system was deployed at CIAMI Living Lab [1]. By using 3 pre-wired harnesses of about 10 nodes each, and placing the nodes more or less exactly on predefined positions, a 28 node system has been set up in about 1 hour, by 2 persons (fig. 6). In the competition, a localization accuracy of 80 cm (75th percentile) has been obtained by the system, during the tracking part of the competition.

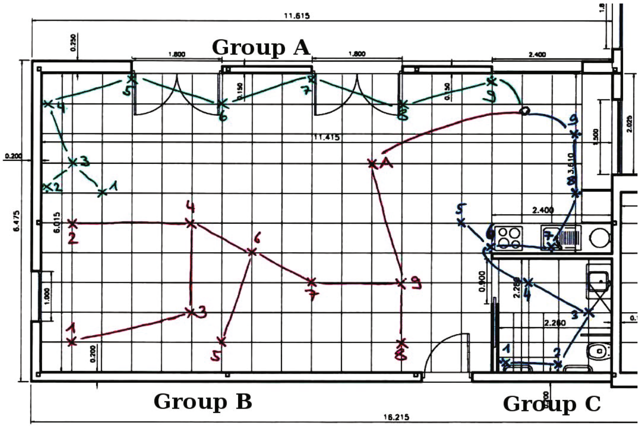

Fig. 6. Positions of the 28 iLoc receivers at CIAMI Living Lab (EvAAL 2011). The nodes were arranged in 3 wiring groups, as indicated in the image. The lab area covers 6 m × 11.2 m.

5 Autolocation of Reference Nodes

The manual position determination of the reference nodes can be a time consuming and error prone process. For AAL deployments, low installation costs are important to gain acceptance for a system. A possible automatic reference position determination solution is “leap-frogging” [9], especially feasible for temporary deployments: Here the position of some reference nodes for example at a corner of the deployment area is determined manually. Then a subsequent node is localized by the system using the already localized nodes, and so on. This mode requires the ability to use a given ultrasound transducer of a node not only as receiver, but also as transmitter. Unfortunately this simple approach accumulates positioning errors leading to quite inaccurate positions for distant nodes. More sophisticated algorithms use complex parallel evaluation of all measured node distances (see for example [8] for RF based ranging).

The iLoc+ system uses receivers mounted under the ceiling. The directional propagation characteristics of the used ultrasound transducers favors the indirect transmission path from transmitter to the floor and back to the receiver under the ceiling. Therefore direct observation of the inter-node distance by the nodes themselves is not feasible. The node autolocation procedure for iLoc+ is performed with the help of mobile nodes distributed temporary on the floor. Some of them are placed at known locations, others only help to link together the net of the distance measurements. For the Cricket ultrasound system [8] working autolocation with development of sophisticated algorithms and high obtained accuracy has been described by Mautz and Ochieng [7]. Our system currently uses the much simpler multilateration approach of selecting the most “believable” ranges by evaluating all possible permutations of three range readings, as described in this paper (Section 4) and more detailed in [3].

Fig. 7. Hardware used for the test run: Visible are 25 receiver nodes (table left side), 15 calibration nodes (table right side), 5 of them equipped with ultrasound booster amplifiers, and a notebook acting as iLoc server.

6 Setup and Test Run at Madrid University Living Lab

In a first step 19 positions were marked on the floor of the living lab by tape measure (see fig. 8 left). The coordinates of the positions were defined in advance. They were altered where necessary for example if a predefined coordinate was not usable due to furniture. A pre-engineered file containing these coordinates was manually adjusted to reflect the actual 19 calibration positions. Calibration transmitters were placed on the positions. Then 25 battery powered wireless ultrasound receiver nodes (fig 7) where blue-tacked under the ceiling or at the walls at a height of about 2 meters. This manual placement was performed using a sketch indicating desired positions, but the actual positions were not measured, as to save installation time. The actual installation time was about one man hour. The node positions have been documented by photos and have been determined by analysis after the competition.

Then the automatic position determination procedure was triggered. This worked by ultrasound determination of the distance matrix between the calibration nodes and the receiver nodes. Of course a particular node did receive signals only from a fraction of the calibration nodes. The determination procedure did consider the 9 nearest calibration nodes for calculation of the receiver position, or less if there were less reported distances.

In the right part of fig. 8 the receiver node positions are shown. Diamonds indicate “true“ positions which have been roughly determined by evaluation of photos. Asterisks indicate positions obtained by the autolocation procedure. The following 11 node positions could be determined with an estimated error below

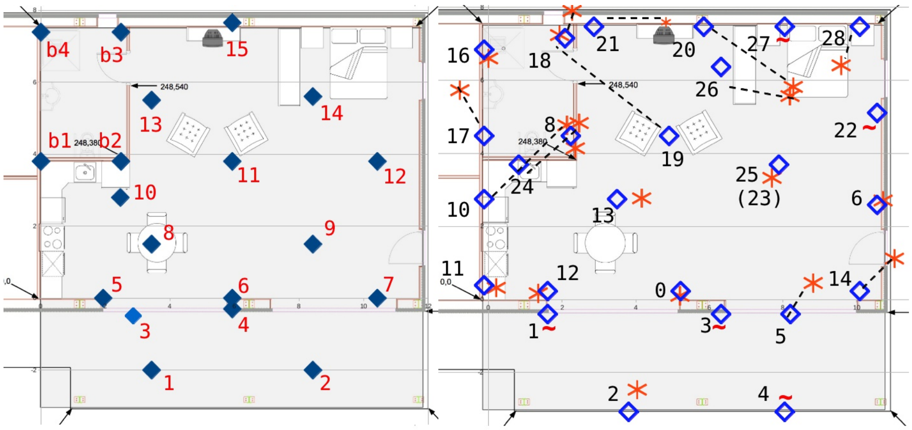

Fig. 8. Left: true positions of the calibration transmitters. They have been placed by tape measure. Right: Positions of ultrasound receiver nodes. Diamonds indicate true receiver node positions, asterisk indicate positions determined automatically by the autolocation procedure. Tilde signs indicate receiver opositions which were not determined by autolocation. For large displacements between true and calculated position the respective positions are connected with a dashed line.

1 meter: Nodes 0, 2, 5, 6, 8, 11, 12, 13, 16, 18, and 25. Medium accuracy (1m .. 2.5 m) has been obtained for the 6 nodes enumerated 14, 17, 21, 24, 26 and 28. The 3 Nodes numbered 10, 19 and 27 were beyond 2.5 m of error. The position of 5 nodes (1, 3, 4, 22 and 27) could not be determined by the autolocation procedure.

As it can be seen, only a minority of positions has been determined with displacements below one meter. Intentionally we expected more or less that all or at least the vast majority of the node positions would be determined with reasonable accuracy. During installation, auto-calibration and the test run a variety of sensor data has been logged. Among others this comprises the raw time-of-flight data, the node id's used for the lateration procedure and the measured distance matrix. From an analysis of this data, the following shortcomings could be identified:

- The outside area was equipped with four calibration transmitters. This turned out to be not enough: Only 2 out of 5 receivers placed outside have been located and therefore outside position determination was not possible during the test run.
- The bedroom area was also not well covered by calibration nodes, leading to failure in determination of the nodes 22 and 27.
- In the region of the two armchairs and the television, position determination was heavily distorted. Data analysis leads to the assumption that the signals of some more distant calibration nodes, namely Nodes 8, 9, 10, and 11 (with respect to the right side of fig 8) did not reach the nodes on the direct

way but "bounced" one time, e. g. they traveled from the calibration node on the floor to the ceiling, got reflected back to the floor and only then reflected to the detectors at the ceiling. This led to longer TOF values with the effect of "pushing" back the calculated positions from the calibration nodes. Especially sensor 19 with its central role has a large coverage, this influenced the test runs considerably.
- Also the kitchen area and the bathroom area suffered from displacements between true and detected positions. Here we assume that reflections at the walls in conjunction with long lasting ultrasound pulses (inter-slot interference) introduced the errors. This is under further investigation.

After auto-calibration, i.e. automatic determination of the 25 receiver node positions, the calibration transmitters had done their duty and were removed from the floor. The iLoc server was switched to normal position detection mode in order to track the position of the actor wearing the iLoc badge. As the time for the whole test run was limited, a manual determination of the node positions was not possible, and the tests had to be performed with the autocalibration generated position data. Obviously this limited the accuracy achievable during the test runs.

However, luckily, the effect of the deviation in node position determination is partly compensated as during the test run the error sources are the same. The transmitted signal of the node carried by the person to be tracked will undergo the same deviations as the signals from the calibration nodes. In that way, the system works like a fingerprinting system and accuracy is better than expected from the errors in node positions. Also, the multilateration algorithm comprises a "reasoning" mechanism which removes unlikely distance values which can arise for example from wrongly determined node positions.

Fig. 9 (left) displays a trace of the actor walking on path one from the entry to the bathroom. As it can be seen, the average accuracy is in the range of 1 meter. In fig. 9 (right) a trace of the third path is shown. Here it can clearly be seen that position determination at the outside area mostly failed. It worked a bit since the glass doors of the lab were opened and the ultrasound signal transmitted by the badge propagated also into the lab where it was detected by receivers 6, 13 and 25. In the entrance area the determination was also quite bad. The table and kitchen area performed reasonable. The two figures show that some areas were quite well covered, while others were not.

7 Results and Outlook

The iLoc+ indoor localization systems currently tracks for example 10 mobile nodes with a position update rate of two measurements per second per node, with an accuracy below about 30 cm, for single measurements with no temporal averaging applied. The system is designed for tracking of persons or assets in an AAL context. iLoc+ is a wireless system. Mobile nodes may operate several month without recharging of the battery. Fixed nodes battery lifetime is currently limited to about 2 months.

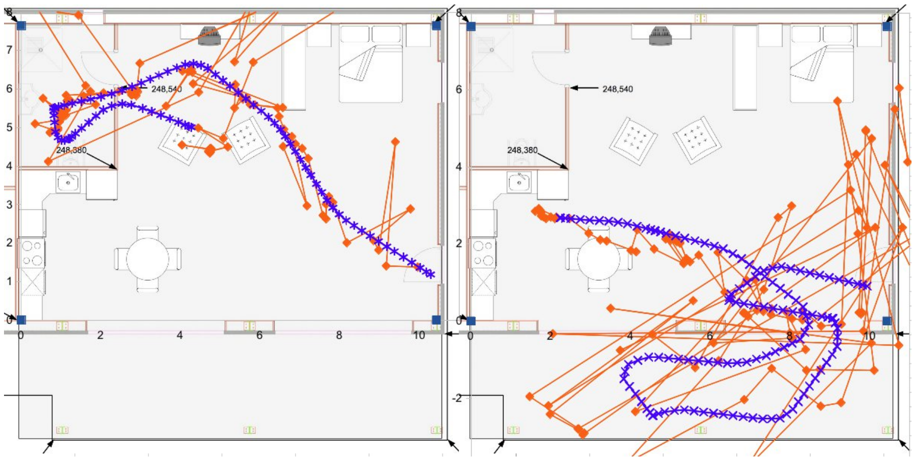

Fig. 9. Trace of the actor walking on path 3: Black squares indicate true positions, blue ones indicate iLoc+ determined positions.

The fixed infrastructure comprises at least 4 fixed nodes per room, for larger rooms a node should be placed for every 5 m^2 area. The iLoc+ system uses an autolocation procedure to determine the positions of the reference nodes after their placement. Therefore calibration nodes have to be placed at known positions for example on the floor.

The system is currently under development. The EvAAL 2012 competition run allowed us to test the system in a very different situation compared to our home lab. Even if the system was in a very early stage, we were able to install and run the system at the competition within the compact time frame. The observed performance of only 2 meters on average was well below our expectations with respect to the EvAAL 2011 result of 85 cm obtained with the older iLoc system. As a main reason we identified shortcomings of the autocalibration algorithm, and the yet time intensive procedure of calibration node placement as well as some software bugs attributed to the early development stage of the system. The test run has however shown that the principle idea to operate 25 or more wireless ultrasound receivers is quite possible and besides the autocalibration phase, the system is quite usable already.

The evaluation pointed out some shortcomings like the yet uncomfortable handling of the badge, suboptimal integrability and of course the yet to high duration of the installation phase. Nevertheless, in the accuracy score the iLoc+ system reached a third place.

The development includes the basic ranging electronic setup, firmware, system aspects, the timing- and multilateration algorithms, middleware and application software. Current applications of the system are visitor tracking and fall detection. Future planned developments include reducing the power consumption of the fixed nodes and test of further autolocation and multilateration algorithms. The ancestor of iLoc+, the iLoc ultrasound indoor localization system is deployed at the iHomeLab Living Lab at Lucerne University of Applied Science.

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