iLOC: a localisation system for visitor tracking & guidance

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We report on an RF- and ultrasound based indoor localisation system which is used for visitor tracking in the iHomeLab laboratory: Visitors get an electronic name badge. This badge can be localised with an average accuracy of less than 10 cm deviation of its spatial position, by means of reference nodes distributed in the lab rooms. The localisation technology is based on ultrasound ranging.

I. Introduction

Ultrasound localisation systems have been known for a while, for example the "CRICKET", "CALMARI" or "BAT" systems [1]. They provide high and reliable accuracy, achieved with moderate effort when compared to newer approaches like ultra wideband systems. An overview of localisation techniques and solutions is given in [2]. The capabilities of embedded systems have evolved considerably since the development of the above-mentioned ultrasound systems. We present iLoc, a fully functional ultrasound/RF based system that employs a variety of new approaches such as amplitude analysis, the IPoK bus system, and a new data fusion algorithm for position estimation. Our system offers considerable advantages in hardware size, cost, deployment effort and accuracy.

The system comprises badges (name tags), detector nodes, and a position server. The *name tags* are equipped with a CC2430 System-on-Chip (Microcontroller and IEEE802.15.4 PHY Transceiver[2]) and an ultrasound transmitter. The tags emit ultrasound pulses at a rate of about 1 Hz, and are synchronized by radio messages. They operate with a duty cycle of 1:200 which allows several days of operation with a 25 mAh rechargeable lithium cell. Also, when the system is not active, the tags stepwise enter a 1:10000 duty cycle. The *badge* is equipped with a buzzer and with an accelerometer. The buzzer is used to inform the wearer for example that they should call the reception desk; and the accelerometer, besides delivering input for the power management software, translates user gestures to commands, for example to open a door by tilting the badge.

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The *reference nodes* are comprised of a HCS08 micro-controller, a cc2420 RF transceiver to send synchronization messages, and an ultrasound receiver. The nodes are connected to a server by a 2 wire bus, which serves as power supply and, by coupling the UART signals to the power lines, also as 500 kbps serial multipoint connection. Via this bus data packets for synchronization of the nodes, and ultrasound reception timestamps are transferred from- respectively to the server. With an update rate of 1 Hz, the system allows detection of 20 tags. The current setup uses 9..20 reference nodes, but the final deployment will include 50+ reference nodes.

In this paper, we will discuss the hardware, ultrasound detection, software aspects, and algorithms for position estimation. Furthermore we will report on the user interface and our experiences in deploying the system.

II. Principle of Operation

In Fig. 1 the principle of operation is shown. A dedicated reference node sends out a synchronisation signal to the other reference nodes at a rate of about 20 Hz such that their local

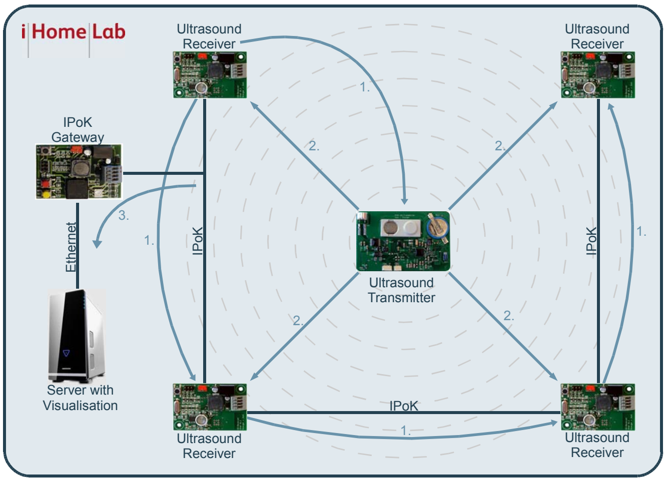

Fig. 1. Setup overview: 4 reference nodes are shown. The upper left receiver sends out a synchronisation signal (arrows labelled "1") by wire ("IPoK") to the other reference nodes and by radio to the mobile node (center). The mobile node emits an ultrasound pulse (arrows "2") and the reference nodes record the reception time. These observations are transferred via the "IPoK" wired bus and Ethernet to a positioning server, which calculates the position of the mobile node.

clocks are synchronised to about 1..2 µs. The signal is transferred via a serial multipoint connection, the "IPoK" (IP-over-Klingeldraht) 2 wire bus, which also supplies power to the reference nodes. By radio, the synchronisation signal is also sent to the mobile nodes (tags) which shall be localised. The signal contains a sequence number indicating which tag, upon reception of the RF packet, shall transmit an ultrasound pulse.

This pulse may be received by the reference nodes which are equipped with an ultrasound receiver. The reception time is recorded by the reference nodes and is transferred via the IPoK bus to a gateway and finally to a PC which collects the reception times and calculates time-of-flight data and finally evaluates the 3D spatial position of the tags.

The given ultrasound transmitters, receivers and electronics allow a detection of pulses over a distance of about 16 meters, under optimal conditions. This corresponds to a maximum time-of-flight of about 50 ms, thus allowing a repetition rate of about 20 Hz. Using 20 mobile nodes, each node may send one pulse per second and thus be localised with this rate.

III. "TAG" OR MOBILE NODE HARDWARE

The main components of the system are the mobile nodes (designed as visitor badges) and the reference nodes. The badges (Fig. 2) are made of a PCB which holds on one side the electronics and on the other side the visitors name label. The heart of the circuit is a TI CC2430 system on chip comprising an 8051 based microcontroller and an IEEE802.15.4 transceiver. The device has been chosen for its very low standby current in the range of 1 µA and for it's small form factor as well as for already available expertise, available development tools and reasonable development documentation. Of course this may not necessarily be the only reasonable choice [4].

A 40 kHz Ultrasound transducer is connected to two RS232 line drivers, which output about 10 Vpp on each

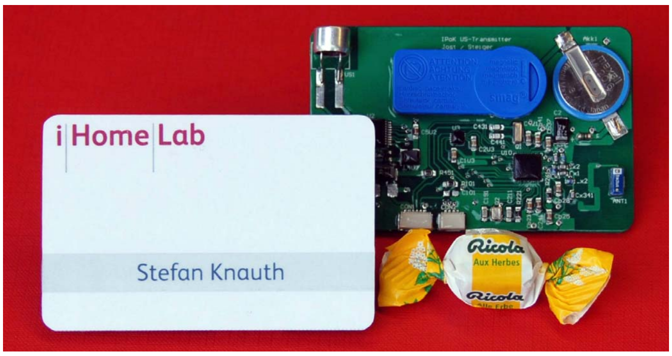

Fig. 2. Mobile Node: a visitor badge. The badge comprises a PCB equipped with a TI-CC2430 System-on-Chip including an IEEE802.15.4 transceiver, a chip antenna, a rechargeable lithium coin cell, an accelerometer, the ultrasound transducer and a driver for the latter.

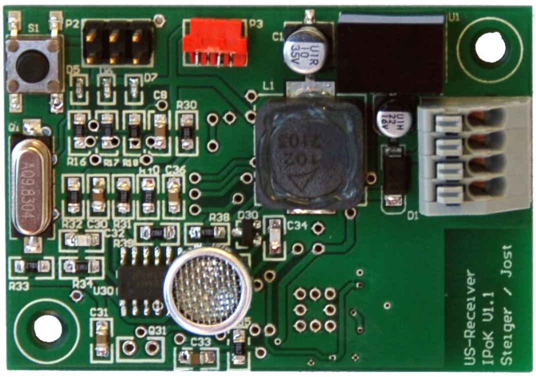

Fig. 3. Reference node: On the visible PCB side, connectors, a decoupling inductor, a DC-DC converter and the ultrasound transceiver plus driver can be seen. The back side holds a HCS08GB60 Microcontroller and a TI-CC2420 IEEE802.15.4 transceiver

terminal, leading to an electrical amplitude of 20 Vpp at the transducer. The driver chip contains a charge pump and a low power mode to reduce energy consumption. Furthermore a Bosch SMB380 accelerometer is attached to the microcontroller. This device serves multiple purposes: It may be used to read gestures of the user, like tilting the badge and send corresponding information to the system. Also, this device offers low current standby modes while still being able to detect movements of the badge, for example to wake up the main controller if the device is moved. In these modes the power consumption is below 15 µA. The synchronized badge sends out an ultrasound pulse each second - a process that takes about 5 ms, at a current consumption of about 20 mA. The tag is powered with a 25 mAh rechargeable Lithium coin cell. With the given duty cycle of 1/200, an overall average current consumption of 100 µA leads to an operational time of 250 h or 10 days. Since deep discharge of the coin cell degrades the latter already after some recharge cycles, the system goes to deep sleep when not moved, and resynchronizes only after some minutes for a "location update".

IV. REFERENCE NODE HARDWARE AND THE IPOK BUS SYSTEM

The reference nodes are line-powered and therefore low power consumption is not as crucial as for the badge. On the other hand, a large number of these devices have to be deployed and therefore installation (wiring) shall be as easy as possible. Therefore the design is considerably different from that of the badges, notably is for example the use of a different microcontroller. The reference nodes comprise a Freescale HCS08GB60 Microcontroller.

For communication between the nodes we chose "IPoK" (IP over Klingeldraht), a protocol recently developed by us for easy networking of small (in size and cost) embedded devices. The idea behind IPoK is to use a 2-wire multipoint connection (e.g. a RS485) and also to supply power via the same two lines.

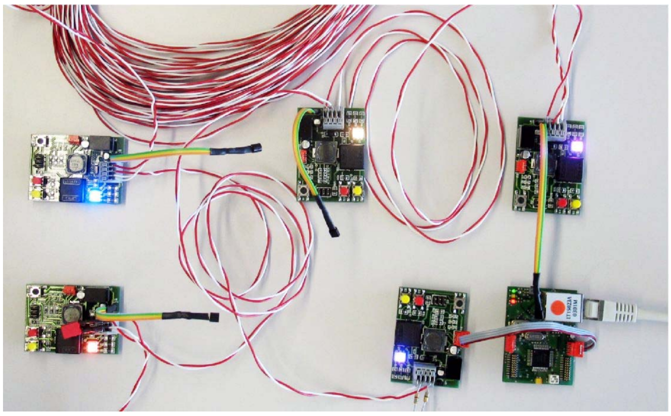

Fig. 4. Example of an "IPoK" (IP over Klingeldraht) deployment: 5 Nodes and a Gateway are connected together with a 2 wire bus carrying power as well as IP data packets. On the lower right side the Ethernet gateway is visible.

The IPoK bus carries a 7..30 Volt supply, which is decoupled from the lines by inductors and then converted to 3.3 Volts with a DC-DC converter. The data TX signal is directly coupled in from the Microcontroller. The HCS08 series of controllers offer a 20 mA line driver for the included UART such that the controller can directly drive the line via a capacitor. When not sending, the UART line can be switched to high impedance and no external driver is necessary. For RX, the signal is AC coupled to a comparator or even easier, to a pair of standard HC14 Schmitt-Triggers. This leads to a minimum hardware effort for the bus system. For the HCS08 series of controllers, we have ported the UIP internet protocol stack which is widely used for embedded systems.

Finally, the synchronisation master node needs also an IEEE802.15.4 transceiver, to broadcast synchronisation packets. In fact, all reference nodes are equipped with a TI-CC2420 RF chip. Actually, the badges do not need to receive each synchronisation pulse but may also run for some seconds before losing synchronisation. This allows the role of the master to be rotated between the reference nodes and increase the radio coverage. The radio chip on the reference nodes is also used to synchronise different IPoK segments between each other.

The ultrasound receiver of the reference nodes comprises a 2-stage op-amp amplifier and two comparators for two different signal levels. This allows detecting not only the time-of-arrival of the ultrasound signal, but also the strength of the ultrasound signal.

V. Deployment

As mentioned, the maximum range of the ultrasound signal is about 16 meters. Principally, three range measurements at different positions allow the determination of the tag position. Practically, the density of reference nodes should be much higher, such that the distance to the farthest node does not exceed about 5 meters, and that each point is covered by more than 3 nodes. This is due to the fact that the ultrasound signal needs a line-of-sight for propagation and gets shaded for example by the body of the wearer of the tag or of other visitors in the same room. Fig. 5 and 6 gives an impression of the iHomeLab, and Fig. 7 shows the positions of the reference nodes. Twenty (20) nodes were initially placed in the two rooms and the entrance, as shown in Fig. 3. Recently, the density has been increased to about 50 nodes to further increase the accuracy and coverage of the system.

The 50 nodes are arranged in 6 IPoK bus lines, which are connected by Ethernet to the positioning server. For deployment reasons and easy firmware updates, the ultrasound transducers were mounted separate from the node electronics and wired with normal shielded audio cables.

The positions of the reference nodes have to be determined at least with the desired positioning accuracy of the system. This turned out to be a quite time consuming task, and therefore the positions were not directly determined by meter measurements. Instead, an ultrasound transmitter has been placed at positions of a well defined grid which has been marked on the floor. The reference node positions were determined by the system itself, by recording the measured distance values and then calculating the node positions from the measurement results.

Fig. 5. Render of iHomeLab at Lucerne University: View from outside.

Fig. 6. Inside the iHomeLab: View from the Lab towards the Lounge

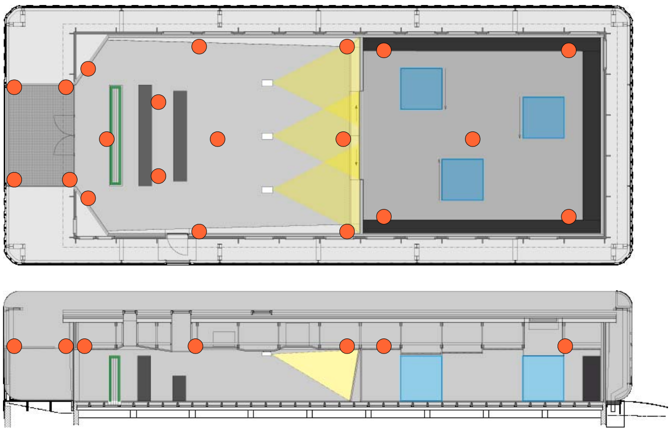

Fig. 7. Node deployment map. Red points mark receiver positions. The length of the environment is about 32 meters, width is 10 meters and mounting height of the receiver transducers is about 2 meters.

VI. Position Calculation

For a mobile node, time-of-flight data is converted to distances by using the appropriate sound velocity and a system-induced constant time offset. Typically for each node a set of about 10 values is obtained. One often-used possibility to calculate the position is to perform a least-square calculation or fit of the ten values. This method did not lead to the desired accuracy since it averages over all measurements and includes "bad" measurements with the same weight as "correct" range measurements.

We investigated the nature of errors which occur in the measurements. A linear averaging method performs well on gaussian error distributions in the measurement values. But the obtained range values showed a different behaviour: Repeated measurements for a given tag position showed that about 95% of the "correct" values fell into an interval of 2 cm. Errors did occur most likely from non-line-of-sight measurements and from reflections, and led to results being some 10 cm or even more away from the correct result Also acoustic noise led to wrong measurements, which manifested in reporting of arbitrary range values.

Therefore we chose a different approach to combine the range measurements to a result: We obtain n range measurements with distance values s(i), i = 1..n, each from a different reference node at position $p_{REF}(i)$. For a trilateration calculation, 3 ranges are needed. So we calculate positions p(s(i), s(j), s(k)), for all possible permutations (i,j,k) out of the n values. The number of such tuples is of the order n^3.

The first step to reduce the number of results is to select only those results which make sense i.e. only those positions which can be accessed by a visitor. This also removes the mirrored results which are given by the trilateration calculation.

For each position p, also a so-called stability factor is calculated. More simply, the stability factor expresses how strong a measurement error will influence the calculated position. The stability factor is the divergence of the position p when varying s(i), s(j), and s(k):

After calculating p(s(i),s(j),s(k)), also three positions each with a short range variation Δ of typically 1 cm are calculated:

$$p\_di=p(s(i)+\Delta,s(j), s(k))$$
$$p\_dj=p(s(i),s(j)+\Delta, s(k))$$
$$p\_dk=p(s(i),s(j), s(k)+\Delta)$$

The length L of the vector (p_di-p, p_dj-p, p_dk-p) / Δ is a measure for the stability of the obtained position p, for the three nodes i,j, and k. Here, smaller L's indicate a higher "stability" or quality of the measurement result.

The variation of the observed position for a given length modification Δ of one of the three ranges used for calculation will always be $L \geq \Delta$, as one can understand easily if thinking of 3 tubes connecting an object with the three reference nodes. If one of the tubes is made 1 cm longer, the position of the object must change at least by 1 cm. As, for L, this is performed with all three reference distances, the minimum resulting position variation will be $\sqrt{(3\Delta^2)}$, and the smallest obtainable value for L will be $\sqrt{(3)}$.

Only positions for which the stability factor does not exceed a defined threshold (typically 4..6) are taken into account for the further calculation.

Now the positions are averaged, and the position which is furthest away from this average position is removed from the set of calculated positions. This step is repeated as long as there are more than two positions in the set. Finally, the position with the lower stability factor is chosen as the real position of the tag.

This is a quite complicated and compute-intensive algorithm for finding out the 3 best range values out of a set of ranges, but it also operates quite stably under problematic conditions. A main difference to other approaches is that here no averaging or otherwise merging of the measurements is performed, but the most likely value triplet i,j,k is selected out of the measurements. The approach has been chosen because we observed that a reported ranges is either very accurate or is more or less random. The obtained positioning error obtained by the method is well below 10 cm (standard derivation and absolute position)

The described algorithm provides a position result for each transmitted ultrasound pulse, i.e. at an update rate of 1 Hz for each mobile tag. The position may of course be used as input for further processing with state estimators and propagator models, for example a Kalman filter. For the given applications, the accuracy and stability of the results was so convincing that we did not see the need to include such processing.

VII. Visualisation and other Applications and Services

An overview of the positioning software system is given in Fig 7. The obtained positions can be queried from the position server. One main application is the visualisation of the position of visitors carrying the iLoc visitor badge. Fig. 9 displays a screen shot of a 3D representation of a laboratory room. The position of the tags 3 and 7 are visible. Note that the visualisation component is attached via the software-interface (currently .NET) to the position server and is therefore decoupled from the core iLoc system.

Further applications are currently focused on the topic of assisted living, a core research objective of the iHomeLab. Detection of falls has already been performed using the position information and the accelerometer included in the badge. If a badge (and presumably also the bearer) is detected to lie on the floor for a certain time, an alert is generated and emergency personnel may be alarmed.

Another demanded application is currently in development: an even smaller tag that can be attached to objects like a box for medicine. An Inhabitant is then able to locate these belongings if he has forgotten the location where he has placed them. Since the position of such things will typically not vary much, a reduced duty cycle can be used, allowing battery lifetimes in the range of some months or years.

VIII. Results

An ultrasound and IEEE802.15.4 based localisation system has been developed and deployed within a site. The system operates reliably and allows position detection with an accuracy under 10 cm. Careful hardware and software design has led to a system which can be installed with moderate cost in typical indoor housing or laboratory environments. The development covers not only the basic ranging electronics, but also system aspects and application software. Current implemented tasks of the system are visitor tracking and fall detection.

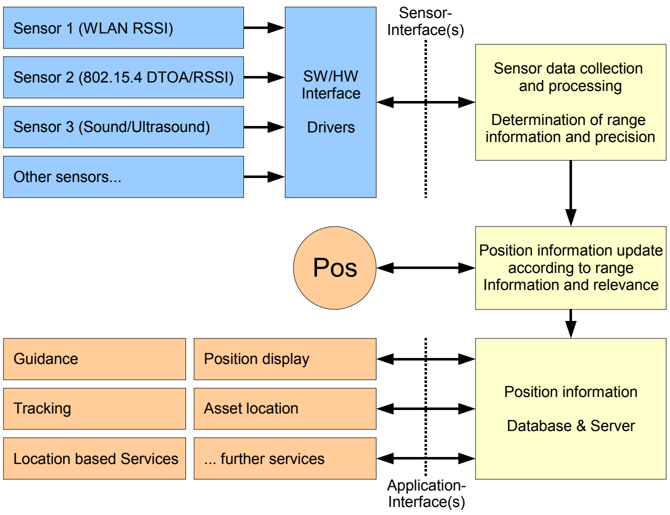

Fig. 8. High-Level overview of the iLoc localisation system: Sensor data is processed by the localisation engine which provides position information via an application interface to interested applications.

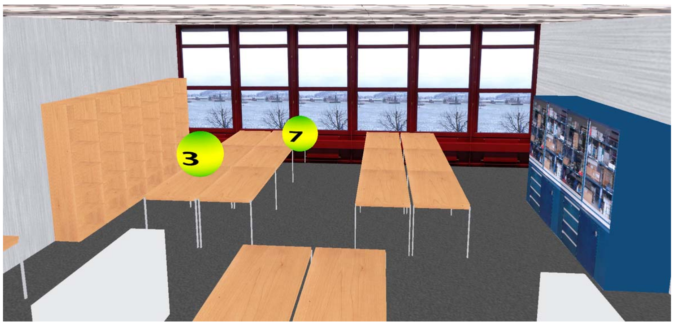

Fig. 9. 3D Position Visualisation: Tags 3 and 7 are visible.

Acknowledgements

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Laboratory

The work has been performed at the iHomeLab (www.iHomeLab.ch) at Lucerne University of Applied Sciences, Switzerland. The iHomeLab is the Swiss think-tank and research laboratory for intelligent living and building automation. Special attention is given to the issue of Ambient Assisted Living. Core competencies are applications of automation networks that are user-friendly, appropriate for the masses, and efficient in terms of cost-benefit ratio (value). Energy efficiency, comfort, and safety are the key design aspects. The iHomeLab is a networking platform for interested universities and companies, offering information exchange, information and marketing oppo-rtunities by partner programs. Funded research projects, such as this one, are done on behalf with industry partners and carried out in the 210 m^2 lab.

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