

# Design of an Ultrasonic Localisation System with Fall Detection for use in Assisted Living Environments

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## Abstract

Indoor localisation offers an abundance of new services to be used within modern buildings. Amongst these, they provide more visibility, and can reduce routine tasks and human error, through information and server-side reactionary mechanisms. Herein we describe an RF- and ultrasound-based indoor localisation system useful within assisted living residences. The system-in-test uses an electronic name-tag that can be localised with an average accuracy of less than 10 cm deviation of its spatial position by reference nodes distributed throughout the environment. Extensible on-tag multi-use sensors provide additional input for scenarios such as fall detection. Preliminary prototype results for fall detection are exemplified through a demonstration software application frontend.

## 1 Introduction

In developed countries, elderly people represent the fastest growing segment of the population, growing twice as fast as the population as a whole. By the year 2035 over one-third of the population will be more than 65 years old with over one-ninth of elderly living beyond 85 years of age in countries like the United Kingdom [2]. Elderly people do not have as high dexterity, memory, and sensory capability as in younger years and thus often need help with medication, mobility assistance, and help during emergencies such as falling (the leading cause of death or serious injury). As more people over sixty join assisted living residences, the facilities themselves face shortages resources and of competent carers. One known method for solving such problems is to introduce technology and process automation to reduce burden on the carer staff, as well as reduce error and improve response time. Thus we present an indoor localisation system that serves as an enabling technology for numerous such potential services.

Localisation systems themselves have been known for some decades: GPS is an outdoor localisation system with 15-100m accuracy used since 1990 in cars and planes. Indoors where GPS cannot reach and where higher precision is needed, indoor localisation systems provide compactness, low power, and very high accuracy (3cm-3m at > 3°). Various techniques and technologies have been used to implement such systems

[1,3-6]. The most accurate system-types demonstrated in practice use radio messages with ultrasound or infrared to achieve 3-10 cm accuracy. Initial research includes Cricket, Calamari, and AT&T Bats in the 1990s-2000s. However, capabilities of embedded systems have evolved considerably since the development of the above-mentioned systems. Newer systems are smaller and extend beyond location data, with sensors for motion, tilt, temperature, environment status; and user feedback devices such as buzzers and speakers. Sensors such as accelerometers provide motion-detection and acceleration information that allows the detection of unusual movement patterns which may be caused by an accident or by an agility which differs from the normal behaviour of an inhabitant. In such cases a backend system may be programmed to alert family members or residence carer staff.

In this paper we present a fully functional ultrasound & radio-based system that provides location and sensory information. Our system offers considerable advantages in hardware size, cost, deployment effort and accuracy. The system is deployed within the isolated iHomeLab facility at Lucerne University of Applied Sciences & Arts.

The remainder of this paper is organized as follows: section 2 provides a system overview, sections 3 & 4 provide detail on hardware system components, section 6 & 7 describe the positioning algorithm and software components, section 5 describes deployment; and finally section 8 provides a brief summary.

## 2 System Overview

The system is composed of name-tags, detector nodes, and a position server. The name-tags use a system-on-chip with microprocessor and 802.15.4 software-programmed radio, rechargeable power cell, and ultrasound transceiver. Each name tag emits an ultrasonic pulse at a rate of 1Hz for localisation after synchronization and permission by radio signal on a time-division schedule. Tags enter a low-power mode when idle, allowing the tags to operate for several days without a recharge on a 25 mAh lithium cell. Each name-tag is equipped with a buzzer and with an accelerometer. The buzzer can inform the wearer of events, for example, as reminders to periodically take medicine or to visit reception desk staff or a computer console for messages or instructions. The accelerometer, besides delivering input for the power

management software, can detect user gestures and can detect unusual motion (e.g. potential loss of balance).

The reference nodes are constructed of a microcontroller, and 802.15.4 radio transmitter for sending synchronization messages, and ultrasound receiver. Nodes are inter-connected by a 2-wire bus, that serves as power supply and, by coupling UART signals to the power lines, also as serial multipoint connection. The bus is used for inter-node synchronization and for depositing onto the server sensor data (ultrasonic reception timestamps and other information).

The principle of operation from the hardware perspective is shown in Figure 1. One dedicated reference node broadcasts a synchronization data packet over the 2-wire bus periodically at a rate of 20Hz. Other nodes receive their signal, and their local clocks synchronize to within 1-2  $\mu$ s. Simultaneously by radio, the synchronization signal is also sent to the name-tags; the signal contains a sequence number indicating which tag should transmit an ultrasound pulse upon reception. The ultrasound pulse is received by ultrasound receiver sensor on surrounding reference node(s). Reference nodes record the reception timestamp and other information and immediately transfer them via the 2-wire bus to a gateway that in turn, forwards the data to a PC. The PC collects the reception times and calculates from the time-of-flight data the 3D spatial position of the name tag, which can be retrieved by the user application thereafter.

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.

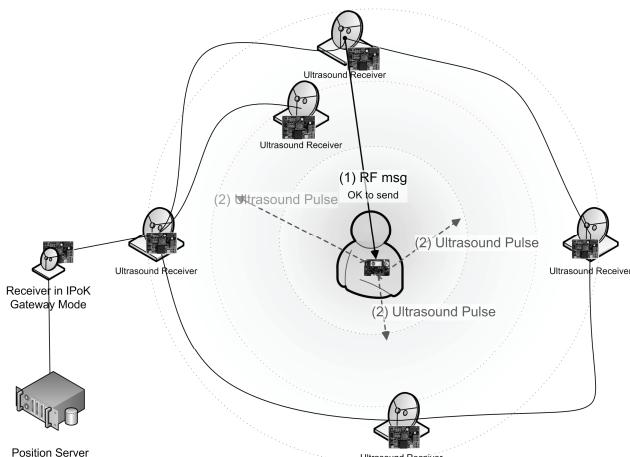
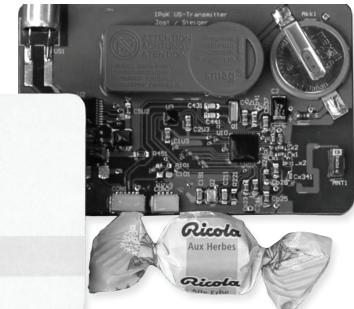


Fig. 1. Five ultrasonic reference nodes receive an ultrasonic pulse after the specific name tag has been sent an RF signal to transmit the pulse. Time of reception is recorded by the ultrasonic receiver nodes, and forwarded to the IPoK gateway, to be forwarded to the position server via ethernet.



i Home Lab

Stefan Knauth

Fig. 2. Name Tag: with system-on-chip, a chip antenna, a rechargeable cell, accelerometer, ultrasound transducer (top-left), and recharge port (bottom).

### 3 “Name Tag” Hardware

The main components of the system are the name-tags and reference nodes. The name-tags (Fig. 2) are constructed of a PCB which holds on one side the electronics and on the other side the name label. Each name-tag is uses a TI-CC2430-SoC with 8051 based micro-controller and IEEE802.15.4 transceiver for message reception. The design choice is based on the device’s very low standby current (1  $\mu$ A), small form factor, and for already available expertise, development tools and documentation.

On the name-tag, one 40 kHz ultrasound transducer is connected to two RS232 line drivers that contain a charge pump and low-power mode to reduce energy consumption. The synchronized name-tag sends out one ultrasound pulse each second - an operation that takes about 5 ms and 20 mA. In addition a Bosch SMB380 accelerometer is attached to the micro-controller for fall and gesture detection. The SMB380 has a low-current standby mode where it is able to detect movements of the name-tag, for example to wake up the main controller if the device is moved. 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  $\mu$ A 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 after a few minutes for a location update.

### 4 “Reference Node” Hardware and Bus System

Since reference nodes are line-powered and therefore are designed for minimalist wiring during installation, since a large number of these devices are deployed in such a system.

Communication between the nodes is done through “IPoK”, or “IP over Klingeldraht”, a protocol we recently developed 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. RS485) and to also supply power (7-30V) via the same two lines. Power and data are decoupled by an inductor and 3.3V DC-DC converter. 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 reception, the signal is AC coupled to a comparator or 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 uses a IEEE802.15.4 transceiver to broadcast synchronisation packets. The name-tags do not need to receive each synchronisation packet; they 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 signal.

## 5 On-site Deployment

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. In practice, the density of reference nodes should be as high such as the distance to the farthest node does not exceed five meters, and that each point is covered by more than 3 nodes. This is due to the fact that the ultrasound signal needs line-of-sight for propagation, and can be shaded for example by the body of the wearer of the tag or other objects in the same room. In the iHomeLab, twenty nodes were initially placed in the two rooms and the entrance (Fig. 3). Recently, the density has been increased to about 50 nodes to further increase the accuracy and coverage of the system. These 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, all of the ultrasound transducers (Fig. 4) were mounted separate from the node electronics and wired with normal shielded audio cables.

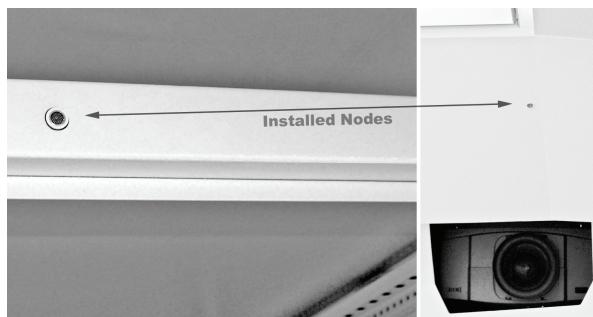


Fig. 4. Ultrasound transceivers in iHomeLab: (a) Rack-mounted and (b) wall-mounted (with projector on right for size comparison)

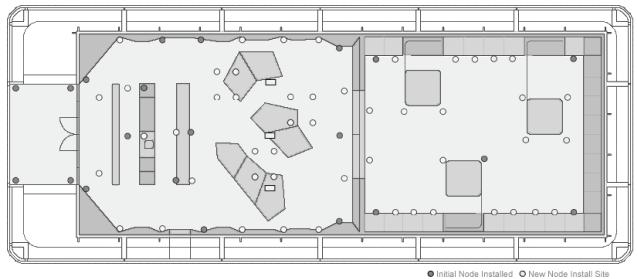


Fig. 3. Node deployment map with new node install sites for increased node density. Environment is 32 meters by 10 meters, at height of about 2 meters.

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 was placed at positions of a well defined grid 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.

## 6 Position Calculation Methodology

For a name-tag, 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 10 values are obtained. Since a least-square calculation leads to poor accuracy since it averages over all measurements (good and bad) with unit weights; we adapted a linear averaging method since it performs well on gaussian error distributions. However, repeated measurements for a given tag position showed that about 95% of the “correct” values fell into an interval of 2 cm. Errors occurred 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 range measurements with distance values, each from a different reference node at position; and find the three ranges needed for trilateration by computing all possible permutations of range measurements. Next, 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, also a so-called stability factor is calculated; only positions for which the stability factor does not exceed a defined threshold are taken into account for the further calculation, and the position with the lower stability factor is chosen as the real position of the tag.

To compute the 3 best range values from all permutations is a compute-intensive algorithm, 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 is selected out of the measurements. The approach has been chosen because we observed that a reported range(s) 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 name-tag. The position may of course be used as input for further processing with state estimators and propagator models (e.g. 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.

## 7 Software Services and Visualisation

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 persons carrying the name-tag. Fig. 8a displays a screen shot of a 3D representation of a laboratory room. Fig. 8b displays a screenshot of the top-down display right after a fall event. Detection of falls has already been performed using the position information and the accelerometer included in the name-tag. If a name-tag (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.

Note that the visualisation component is attached via the software-interface (currently .NET) to the position server and is therefore decoupled from the hardware system.

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.

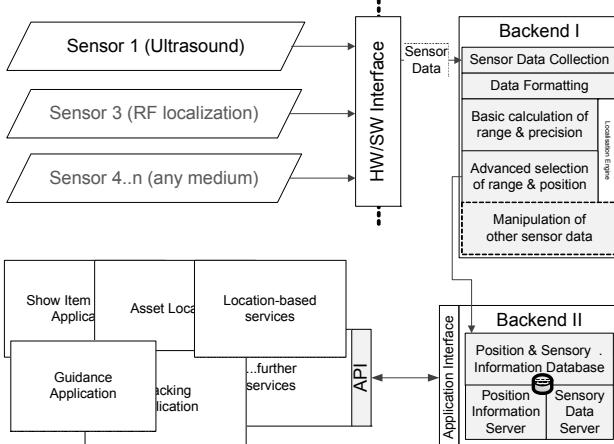


Fig. 7. High-level overview of the indoor localisation system with emphasis on software perspective. Sensor data collected by the backend is processed and stored, to finally be made available to a user-level application.

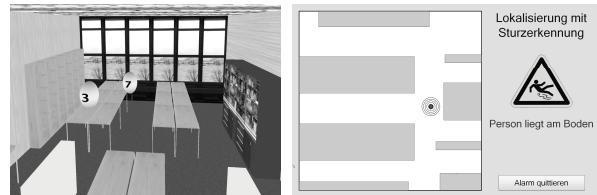


Fig. 8. (a) 3D position: Tags 3 and 7 (x,y,z) position is plotted in room.  
(b) Top-down view: Alert rendered for Tag 1 that has fallen.

## 8 Conclusion

An ultrasound and low-power radio-based localisation system has been designed. Careful hardware- and software-design has shown the system to install easily into an on-site facility for testing at a moderate cost. The system shows reliable operation in initial prototyping stages, providing through a selective data-fusion algorithm, position detection accuracy under 10 cm. Due to the consideration of software data-access mechanisms and an application interface, simple software applications were written in .NET to demonstrate the location capabilities of the system for position of name-tag and also for fall detection.

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