Indoor Localisation of Humans, Objects, and mobile Robots with RFID Infrastructure

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***Abstract*— The need for robust indoor localisation for all types of entities has been under continuous research by the ubiquitous community. Intelligent environments have to be supported with contextual information in order to facilitate intelligent behaviour. These contextual information include the location of humans and objects within the particular environment. Intelligent environments can be living areas with home automation, smart industrial plants, sensor-equipped office areas and indoor-emergency applications. So far technical solutions are either quite expensive or lack of precision for robust usage as components in intelligent service federations. We present rather low-cost localisation systems with great scalability based on active and passive RFID technology to locate humans, mobile service robots and objects of the daily use. The trade-off between technical effort and costs on the one hand and sufficient data accuracy for the application on the other hand is discussed. A motivation of our scenario, the technical concept and solution as well as the implementation and the integration that so far have been performed will be presented. Current prototypes of the proposed system are already being tested in a project aiming on development of smart assisted living environments.**

***Index Terms*— RFID, indoor-localisation, ambient intelligence, assisted living**

I. Introduction

Robust indoor localisation is one major key towards the development of intelligent environments. Knowing the location of humans and objects corresponds with knowing an important part of context. Especially the need for location information of humans, mobile helper systems and objects of the daily use in living areas is our current challenge within a joint project to set up a smart living environment for elderly people. Recent research in this area has already presented big opportunities, see [1] and [2]. But available systems so far neither are cheap and robust, nor easy to integrate. We present a set of systems all working with RFID technology. RFID hardware has become available during the logistics hype on that technology where the focus however was more on the identification than on the localisation idea.

GPS is the most famous system for outdoor positioning but works only with poor robustness within buildings. In industrial appliances several high precision systems based on rotating laser beacons, indoor GPS, such as ultrasonic triangulation systems, etc. are on the market. We however propose the setup of systems based on RFID technology. They are easy to implement, cheap, scalable, with medium measurement quality, and highly robust.

We use passive as well as active RFID technology for our localisation systems. Ceiling mounted active tags and floor mounted passive tags are the artificial landmarks used as fixed known coordinates. This idea is inspired by recent research in mobile robotics, see [3], [4], [5], [6]. Usage of large-scale passive RFID infrastructure has recently been proposed by [7], [8]. Passive tags on movable objects are markers to triangulate the location of these objects [9].

Chapter II starts with showing the intelligent environment where our systems are integrated. The three entities: humans, robots, and objects are categorised and their specific constraints regarding localisation are motivated. We lead over to the technological details of our localisation systems. In III the distinct solutions are elaborated regarding measurement quality, data accuracy, application satisfaction, and costs and scalability. The final discussion of the overall system as well as the outlook and further work are given in IV.

II. The Intelligent Environment and the Entities to be localised

A. Demonstrator

To allow joint software and hardware development in the domain of ambient intelligence, a demonstrator room has been established in 2005[1]. A fully-equipped living area has been set up for this task, see Figure 1. Research results especially in the assisted living domain are continuously integrated within this intelligent environment, see [10] and [11]. Special issues are health monitoring, daily routine check and helper services for elderly people. Within the project, facilities for testing and demonstration of sensor and software

[1] **http://www.belami-project.org/**

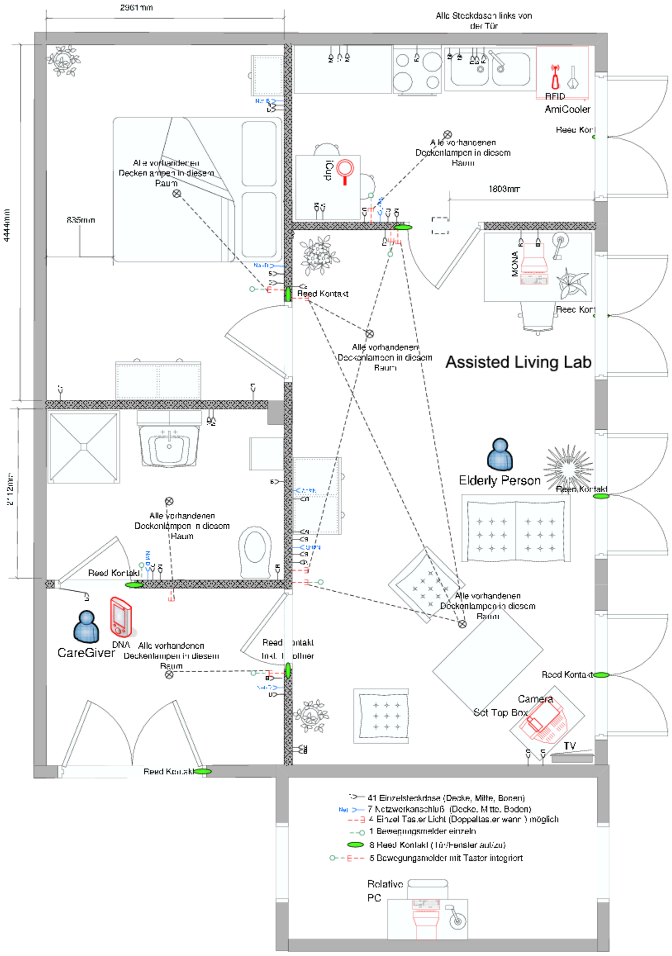

Fig. 1. Demonstrator Setup

systems are available. Assisted living systems however shall not replace human care but extend its capabilities in the areas of:

- Remote Interaction with Relatives
- Comfort and Entertainment
- Emergency Diagnosis
- Household Services
- Behaviour Analysis

This shows the need for localisation of human beings, objects of interest and sources of information being part of the context of common daily activity as well as exceptional emergency events.

B. Humans

Evaluation of appliances that may benefit from human location information resulted in a necessary precision not more than 50 cm. In particular this is enough to select for example the right display or audio unit for information delivery, to check in which room the inhabitant is present, to check if the inhabitant is moving around in certain time intervals, and so on. Also, typical pathways in an apartment around and between furniture are not narrower than this distance. There are two main types of measurement principles: human-centric and environmental. In the following the problems and benefits these two design concepts are elaborated.

a) Human-centric: At least one component of the measurement system is mounted on the human himself. Systems based on receiving and processing information from active landmarks are included here. These systems can consist of field strength detection [12], [13] and signal runtime measurement as in the Global Positioning System. The gathered information has to be radio-broadcasted before being accessible by other services. Important issues about the design and layout of the part of the system the human has to wear therefore are:

- Size
- Energy Consumption
- Weight
- Wireless Capabilities
- Costs

On the one hand one always tries to avoid manipulating the human but the concept also has strong advantages: The position information is derived locally and it is generally decidable whether or not it should be made public. Additionally the identity of the detected human is known by concept as the data acquisition unit can add identifying information. After all, if the human does not carry a sensor device, even more technology has to be integrated into the building which increases the costs of the system but enhances usability and acceptance. Currently we are using two human-centred technologies, described in III-A and III-B.

b) Environmental: No manipulation of the human is necessary as he is recognisable for example by computer vision, movement sensors, by reasoning on interaction activities and so on. The system is truly ubiquitous and hidden and the human does not have to carry a badge, sender or mark on his body. The disadvantage lies in weak measurement accuracy and a lot of cases were the human is technically undetectable. This scenario aims more at the direction of supervision than the human-centric way where a decision is up to the user whether or not information about his position should be published. Another disadvantage is lack the of human identification. That means in cases where more than one human is present in the observed environment, these systems might not work properly. Movement sensors cannot distinguish between humans or even pets for example.

C. Mobile Autonomous Units

The second entity that is in strong need for localisation technology is a mobile service robot. Within the particular application of assisted living we want to integrate mobile robotic systems for transportation tasks and human interaction services. Our robot is called ARTOS (Autonomous Robot for Transport and Service). It is under development for several aspired services within the assisted living demonstrator, see Fig.2. For example it shall autonomously approach or follow the humans position to perform simple transportation tasks. With its small size with a length of 50 cm, a width of 30 cm and a height of 25 cm it is suitable for indoor application especially in home environments. Therefor interaction, tele-operation for emergency recognition, transport services and human-behaviour monitoring for health supervision are the main goals in development. The internal control software of ARTOS regarding drive control, anti-collision sensors, human-detection sensors, interaction multimedia, and camera-vision are developed in MCA [14]. For control it offers interfaces for approaching locations, and delivering speech messages from other system components.

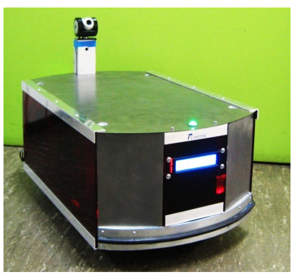

Fig. 2. ARTOS

For the robot entity only self-localisation is a serious option as it already carries sensor and computational capabilities. Although this topic is as old as mobile robotics itself, one has to spend some effort again each time a system is set up. Localisation is done with artificial landmarks implemented as a grid of passive RFIDs in the floor, see Fig.3. The system is explained in III-A.

D. *Objects of daily use*

In assisted living environments it can be useful to technically monitor the location of objects of the daily use. Especially elderly people tend to loose track on certain objects like their glasses, medicine etc. Mobile robots can serve as base platform for object position tracking. The main advantages of object detection via RFID tags compared to “conventional” computer vision approaches are the speed, reliability and individuality of the detection process. Thus supporting vision-based object recognition by RFID technology is subject of many research projects. Mainly the last item should be emphasised: Even in the case of two objects which are equal in size, shape and colour (e.g. two white cylindric cups of same size and material) tagging them with RFIDs facilitates a distinction of each individual.

In [15] a custom setup of several tags is examined to estimate the 3D pose of objects and in [9] a combination of consumer camera and RFID reader is employed to detect and localise tagged objects in the video stream that is generated as the user randomly moves the sensor system in 3d space. One application is the tracking of nomadic (infrequently, passively moved) objects.

Especially some ideas from this last reference play a role in our scenario of object detection and tracking in office and home environments. The goal is to provide a list with tagged objects to the mobile robot which then has to actively search these objects within its working space and to keep this knowledge as up-to-date as possible. Thus in contrast to [9] the motion of the sensor system is actively controlled as the RFID reader is mounted on the robot and search strategies for finding a certain amount of important objects within a target time period are subject of research. The motion control components have to enable the robot to decide where to search for objects first (e.g. table tops and shelves are good candidates for object locations) and how to explore hardly accessible places (i.e. reachable though narrow passages) if the amount of found objects drops below a certain threshold. The gained information (object positions with timestamps) is stored in a database on the mobile unit which facilitates knowledge preservation at downtimes (during re-charging of robot batteries) independent of memory size of the applied RFID tag. That way the input information is a set of tag IDs and corresponding description of raw object properties as size, shape and colour.

The object localisation system is based on a recently developed autonomous mapping approach for office environments (see [16]) which enables a mobile robot to extract a topological map of an arbitrary a-priori unknown environment without user intervention. Consequently the developed system can be used for service and transportation tasks in home, office and industrial environments as it can provide useful hints about object positions (e.g. file folders, coffee cups or glasses), survey assets or pick and deliver goods according to user demands.

This application scenario and accompanying research focuses are currently elaborated. In section III-C the applied sensor technology and mobile robot are described.

III. Technologies

A. *Passive HF RFID Localisation*

As already stated in section II-C a grid of artificial landmarks consisting of passive RFID tags has been implemented in the floor. The idea of using RFID technology for localisation is not new. In [5] passive UHF tags are used as artificial landmarks to support 2D environmental mapping in combination with a laser-scanner based SLAM[2] approach. Recently the German vacuum cleaner and carpet company Vorwerk[3] has started to sell prototypes of smart floors components to enhance the speed and coverage of vacuuming

[2]simultaneous localisation and mapping
[3]**http://www.vorwerk-teppich.de**

Fig. 3. RFID Underlay

Fig. 4. Foot-attached RFID Reader

robots. To have some options we decided to implement a rather narrow grid of RFID tags within the carpet. Our grid density is 12.5 cm (5 in). In future tests we will try to stepwise reduce the grid density through hiding of the tags by software until the services' qualities reach their limits. This of course would lower the costs for such an installation. About 4,000 tags were mounted in an apartment of 60 m^2 (600 sq.ft.), see Figure 3. This does not sound very cost efficient but considering the goal of RFID industry to approach prices per tag in Cent areas and the carpet companies being major clients when smart carpets become successful products, the costs can be expected to be negligible, compared to the costs for the carpet itself. Standard ISO15693 tags (13.56 MHz) are used as they and their readers are easily available and have satisfying characteristics [17]. RFID reader hardware is provided by FEIG Electronics[4] The human-attached reader is assembled from components of a mobile bluetooth reader device for appliances in logistics. Our wireless reader unit can be mounted on top of a human foot, see Figure 4. Experiments showed that within a sensing range of about 10 cm (4 in) at least two tags are in detection range with the mentioned grid density. This implicates that if standing in the tagged area and keeping the feet on the ground, the localisation information can always be derived, there is no blind area due to shielding, diffraction, reflexion or other field strength issues observed in all other wireless localisation systems.

$$N = \text{RFIDs in range} \tag{1}$$

$$Pos_{x,y} = \frac{1}{N}\sum_{i=1}^{N}\begin{pmatrix} x_i \\ y_i \end{pmatrix} \tag{2}$$

As derived in equation 1 the current position Pos of the RFID reader is simply determined as mean value of the 2D positions of all N RFIDs in range.

[4]**http://www.feig.de**

Of course the passive RFID landmarks also allow the robotic unit to continuously perform a robust self-localisation. The robot carries a small RFID reader board of 5 cm to 5 cm, also from FEIG, with integrated antenna connected over UART interface. Orientation determination which is a major part in robot navigation can only performed during the measurement of several landmarks while moving. A combined arithmetic and heuristic calculation is performed to update the robots orientation estimation. One has to consider at this point that the RFID position measurement accuracy is about 10 cm. Unfortunately the sensing information cannot be mapped to an exact point in time due to indeterministic measurement delays which makes it difficult to localise precisely during fast motion.

Our experiments however have shown that the robots pose estimation is fully suitable for indoor navigation. Again the major benefit of our localisation principle arises from the high robustness of the system. When an RFID tag is located the information is perfect with a known maximum error. When no tag is located this information is also valid. This is a big difference to all triangulating systems where one always gets a result from the system never knowing the maximum error that might have occurred.

B. Active UHF RFID Localisation

For rougher position measurement ceiling-mounted active RFID tags are used. Advantages of the system are the high availability of position data and the small size of the reader device that is designed as CF-card for handhelds, see Figures 5 and 6. Also the system is far more scalable than the carpet solution as mounting tags at the ceiling is an easy process and the installation may be extended at any time to other rooms in proximity. Alas, a major disadvantage is the poor quality of derived data accuracy which deviates up to several meters from the correct position. Therefor this human-centred system is mainly useful for determination of the room the inhabitant is located.

The idea to use this technology is originated in a system, developed by the German Research Centre for Artificial Intelligence (DFKI) [18]. Active RFID tags from Identec Solutions[5] are mounted in the ceiling of the demonstrator rooms. Their transmission range is about 6m at 868 MHz in

[5]**http://www.identecsolutions.com**

Fig. 5. Active RFID

low-sensitivity mode. In the general case, the mobile reader receives about one to four tags and calculates the expected current position based on the distances to the according transponder positions with a merging function which considers the recent history. A tags coordinate can be stored on the tag itself or together with the tags ID within a database. A combination of both methods can be used to improve the estimation of distance to the particular tag because the detection of a tag in the scan range appears to be more reliable than reliable data exchange. However, this requires more development and testing. The use of the signal strength to get the distance to particular tags is possible but the quality is lowered by the behaviour of the underlying RFID technology which is driven on the edge of its specification in our scenario. In our tests in various real-world scenarios under the described conditions, the distribution of signal strength appeared to be very inhomogeneous and hardly comprehensible on the first glance. Therefore, a more reliable way is the measurement of discrete tag detection events and monitoring of the average detection rate over few scan cycles. This implies a deviation from the real position when faster movement of the tracked object occurs. A simple approach to merge the data and consider the history with adjustable dynamic behaviour is represented by the function 3. The weight parameters used to merge the previous positions are empirically determined during tests in real world environment.

$$\begin{aligned} N &= \text{RFIDs in range} \\ H &= \text{History of calculated positions} \\ W &= \text{Weights for historical values} \\ Pos_{x,y} &= \frac{1}{N}\sum_{i=1}^{N}\begin{pmatrix} x_i \\ y_i \end{pmatrix} + \frac{1}{W}\sum_{k=1}^{W}(w_k h_k) \end{aligned} \quad (3)$$

C. Passive UHF RFID Localisation

RFID-based object localisation is our latest field of research in the field of localisation. For object localisation we use passive UHF RFID technology. Outstanding features of the passive UHF RFID technology are the provided read range of up to 5 meter with purely passive tags, i.e. it combines a working range similar to active RFIDs with the advantage of tags without extra power supply. The reader is an UHF long range reader unit from the `OBID i-scan` product family of FEIG Electronics (see figure7). As it

Fig. 6. Handheld with RFID Reader

Fig. 7. Passive UHF RFID reader module from FEIG Electronic

belongs to the same series as the passive HF readers the software components for reader control can be exchanged easily. The reader has a size of about 170x210 mm^2, maximum power consumption of 30W and provides an adjustable radio power from 100mW up to 3W in steps of 100mW. Thus the read range can be fine tuned during operation dependent on the actual application needs.

As supported originally by the reader EPC Class 1 Generation 2 RFID tags in two different sizes are evaluated in actual experiments (see figure 9). They only differ in their antenna area which is 27x97 mm^2 resp. 15x97 mm^2. The tags are flexible enough to stick them to objects of different shapes, e.g books, cups and bottles. As with all passive RFID tags they do not work on metal surfaces. But in many cases a

Fig. 8. Passive UHF RFID antenna from FEIG Electronic

Fig. 9. Passive UHF EPC Class 1 Generation 2 tags from EURO I.D.

thin plastic underlay of 2 mm thickness is sufficient to make them work even under these circumstances.

As in [9] the fact of detecting a certain tag in the actual reading or not will be used to refine the estimated 3D pose of the tagged object. Compared to the mentioned work our setup has two advantages: Firstly the movement of the sensor system through the environment is actively controlled. Thus we can decide when to look in which direction with the RFID antenna to restrict the potential object position. Secondly as we use two antennas with small overlap of radio fields and actively control which antenna is used for reading we can derive further information from the fact that a tag is present only in the field of the left or of the right or even of both antennas - even without moving the sensor system. Finally also an adjustment of the radio power for a refinement of estimation results is possible.

IV. Conclusion and Outlook

As motivated in this work, supportive services for comfort, convenience and care in assisted living environments are deeply improved by knowing the location of the inhabitant. Localising objects of the daily is also considered a very convenient application. Mobile robot units being part of such a service federation can therefor on the one hand increase their usefulness and can on the other hand improve their self-localisation and navigation capabilities with external localisation infrastructure available.

To implement robust and useful applications however it is mandatory to rely on localisation technology with certain qualities that can be modelled and understood at runtime. We gave a short overview on general aspects of position measurement systems for location-based services in ambient intelligence environments concerning advantages and disadvantages of human-centric and environmental data determination.

Future tasks concern the integration of the UHF reader to evaluate the performance of object pose estimation based on tag readings with different antenna configurations and a static and dynamic sensor system (i.e. with and without robot motion). Consecutively search strategies for a reasonable robot motion control as basis for object tracking will be developed.

V. Acknowledgements

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