Robust, Low Cost Indoor Positioning Using Magnetic Resonant Coupling

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ABSTRACT
We describe the design, implementation, and evaluation of an indoor positioning system based on resonant magnetic coupling. The system has an accuracy of less than 1 m^2 and, because of the underlying physical principle, is robust with respect to disturbances such as people moving around or changes in room configuration. It consists of 16x16x16 cm transmitter coils, each able to cover an area of up to 50 m^2, and provides location information to an arbitrary number of mobile receivers with an update rate of up to 30Hz. We evaluate the actual accuracy of the positioning with a robotic arm and show quantitatively that even large metallic objects have little effect on the signal. We then present an elaborate study of the performance of our system for the recognition of abstract locations such as "at the table", "in front of a cabinet". It comprises four different sites with a total of 100 individual locations some as little as 50 cm apart.

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C.2.4 Distributed Systems : Distributed Applications

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General Terms
Algorithms, Design, Experimentation, Measurement

INTRODUCTION
Indoor localization is among the most researched problems in Pervasive Computing. Approaches range from leveraging inertial sensors in smart phones to elaborate, dedicated infrastructure such as RF beacons or floor integrated sensors and include sophisticated methods for considering background information (e.g. building plans) and fusion of different sensing modalities.

Indoor positioning has made significant progress in recent years and for some applications practicable systems with adequate performance exist. Thus, for example WiFi finger printing, possibly assisted by inertial navigation, is well suited for room level accuracy location. However, there are also many application areas where indoor positioning remains an open problem. One example is activity recognition within household, office, or factory environments. The design space for such applications is constrained as follows:

1. While room level accuracy is certainly useful, more exact positioning is often needed. Thus, for example, if the user is preparing a meal in the kitchen then the system should be able to recognize if he is in front of the fridge, the oven, or accessing a particular cabinet.
2. The environment tends to be cluttered and dynamic with people moving around, doors (often with metallic components) being closed and opened, and, over time, furniture being moved or added.
3. Cost and effort involved in system deployment and maintenance are crucial issues in real world applications.

In this paper we describe the design, implementation, and evaluation of a solution for the above application domain that is based on magnetic resonant coupling. The system is built around 3D transmitter coils (16x16x16 cm) and receiver coils (2x2x2 cm) operating in TDMA mode with RF synchronization (figure 1). A **single** 3D transmitter coil can cover an area with 8m diameter providing 3D position for the receiver badges with an accuracy below $1m^2$ and an update rate of up to 30Hz. Higher accuracies can be achieved by combining information from several transmitter coils. The synchronization protocol allows many transmitters to be combined to cover a large area or increase reliability. As described in section **Physical Background**, the basic physical principle behind the system (which is well known and has been used before for motion tracking, power transmission, or near field communication) makes it extremely robust as the signals are hardly influenced by the human body or objects in the environment (except massive metal objects which however have mostly local influence only).

Related Work
Giving an overview of research in indoor localization is clearly beyond the scope of this paper (see for example [18]). We thus focus this section on a quick summary of existing beacon based indoor positioning technologies (which are the di-

rect ”competitors” to our system) and other applications of magnetic resonant coupling.

Beacon Based Technologies

Beacon based systems compute user position from signal strength or signal delay to/from several (at least 3) beacons. Main technologies are ultrasonic, radio frequency and Ir light. Ultrasound based systems like Cricket [14] or Active Bat [20] rely on time of flight measurements to achieve a location accuracy of 3 cm. The main disadvantages of these systems are multi path and occlusion problems and the need to deploy at least three appropriately distributed devices in every room (since the signal is blocked by walls). Also the receiver can not be concealed on the body.

Similar issues (except for much less issues with multi path) arise with systems based on infrared (Ir) light such the Active Badge by Want et al. [19]. In addition such systems are easily disturbed by sunlight or artificial light sources.

Most popular RF approaches are based on WiFi infrastructure. Because of the complexity of RF signal propagation they use finger printing (e.g. [3] or [1]). A finger printing based system requires a calibration step in which the system learns the signal distribution at a discrete set of calibration points. A serious problem with such systems is that people moving through the building as well as changes in the configuration (even opening the door) alter the generated signal map and can lead to localization errors.

An RF indoor localization system which is often used for applications requiring high accuracy (see for example health care applications like presented in [7]) is the Ubisens system. This system uses ultra wide band pulses emitted by wearable tags. Time-difference-of-arrival and angle-of-arrival estimation between stationary receiver antennas allow a position estimation within an accuracy of 30 cm. However, metal objects like table frames or door frames interfere with the ultra wide band pulse and significantly disturb the position estimation process. Other issues are the high costs of the system and the high installation and calibration effort.

An alternative RF system was demonstrated by Patel et al. [17]. It uses power line installations as ultra wide band antennas and finger printing for position estimation with an accuracy 1 m^2. The main limitation is the limited range which requires the user to be close to a power line.

Applications of Magnetic Resonant Coupling

The underlying physical principle of resonant magnetic coupling is well known and has been used in many different applications. In addition to motion tracking [6], oscillating magnetic field applications can be found for example in keyless access to cars. In these applications a transmitter generates a low frequency (typically around 125 kHz) magnetic field and uses for example Manchester encoding to transfer information between transmitter and receivers(see [9] for details.). As another application a wireless power transmission system based on magnetic resonant coupling has been presented in [8]. The authors of [10] use oscillating magnetic fields to track the lives of underground animals. Paradiso et al. [11] propose an input device to play instruments.

Magnetic Indoor Positioning

The use of magnetic fields for indoor location has been explored by Prigge et al. [13]. However, whereas our system is based on highly energy efficient resonant coupling to filter out other magnetic fields, theirs uses a CDMA coding scheme in a non resonant mode. According to the authors the system needs about 100 W per Beacon and requires cables running between the Beacons for synchronization. Our system, on the other hand, uses only 2.5W per Beacon and relies on RF time synchronization (needing no cables). Furthermore, we use 3D transmitters which means that we can get rough localization with just one transmitter, whereas the Prigge setup requires at least 3. In summary, our system is much better suited for easy deployment in typical pervasive environments. One of the contributions of this paper is that we have evaluated it in such an environment including the recognition of semantically meaningful locations which is a key component of many activity recognition systems.

Paper Contributions

The system presented in this paper is based on our previous work in wearable motion tracking [12]. As opposed to commercial motion tracking systems which are bulky and expensive our previous work had demonstrated that an easily wearable, cheap receiver/transmitter pair is suitable for tracking the relative position of body parts well enough for complex activity recognition tasks. In this paper the system has been improved and adapted from on body motion tracking to indoor location and shown to work reliably in a variety of environments.

Our systems differs from other existing beacon based location approaches in that it combines the following properties:

1. It has an accuracy below 1 m^2 which could potentially be improved with more advanced magnetic field models.
2. Because we use 3 co-located perpendicular transmitter coils in a single beacon, such a single beacon limits the position of the receiver to a few points given by the symmetry of the magnetic field. Exact 3D positioning is possible with 2 beacons. A single beacon can cover an area of approx. 50 m^2.
3. High update rates (around 30Hz) are possible independently of the number of receivers.
4. The system does not require line of sight between the receiver and the transmitter.
5. The system is highly robust with respect to environmental factors such as people moving around, furniture etc., providing reliable positioning in real life environments.
6. Although we did not develop the required field models yet (and thus do not yet use it in our system), the signal contains information not only about the position but also about the orientation of the receiver.

On the technical level the contributions in relation to the motion tracking system we presented in [12] are: (1) improvements of the hardware and adaptation to large coils and longer range, (2) synchronization of several transmitters including the ability to detect synchronization errors and (3) a detailed evaluation in a variety of environments.

Overall we believe that a demonstration of a cheap, easily deployable positioning technology that has an accuracy of better than 1 m^2 and is insensitive to dynamics disturbances such as people or changes in room configuration is significant for a broad range of pervasive computing applications. To facilitate broad use within the community we have made the schematics and the firmware of the transmitter and receiver boards publicly available from **http://magnetic.wearcom.org**.

PHYSICAL BACKGROUND

Our system uses the principle of resonant magnetic coupling which is well known from near field communication and wireless energy transmission [8]. A transmitter generates an oscillating magnetic field with a well defined narrow frequency. The field excites a receiver which is essentially an oscillating circuit precisely tuned to the respective frequency. The strength of the excitation (=induced voltage) depends on the location of the receiver in the transmitter field, which is the basic effect that we use for positioning.

To understand the advantages and problems of this positioning principle it is useful to compare it with radio frequency (RF) systems such as WiFi positioning [3] or Ultra Wide Band (www.ubisense.com) devices. An RF based system generates propagating electro magnetic waves. Propagating means that the waves "separate" themselves from the transmitter and continue traveling "on their own", potentially towards infinity even if the transmitter stops oscillating. By contrast, in a magnetic resonant system propagating waves play no role in signal and energy transmission. Instead the vast majority of energy goes into a magnetic field that expands and contracts with the oscillations, but never "separates".

The Good News

From the point of view of indoor localization this has a number of advantages:

- Since nothing propagates, there are also no problems with multi path propagation which is a major issue in RF (and ultrasonic) systems, in particular (but not only) in time of flight measurement based approaches
- As no waves are generated, wave phenomena such as interference and refraction do not occur. In RF systems such phenomena are responsible for so called "fading" which means that signal intensity displays complex spatial variations that are much stronger than the distance dependent signal strength change used for position computation.
- Magnetic field is much more difficult to "block" than electromagnetic waves (at least within the spectrum range usable for positioning systems). In particular, water, which is the main component of the human body, has no relevant influence. Thus, presence of people which is a major factor in for example WiFi positioning, has no negative effect on a resonant magnetic system. In essence only massive metallic objects, in particular strongly ferromagnetic ones, have a significant effect on the signal.
- Even massive metal objects do not block the signal but have mostly local influence. While the influence of ferromagnetic objects on the field can be complex, on an abstract level it can be described as bending the field lines *running within the object*. To match the bending inside the object the field lines outside are also deformed but to a lesser degree and mostly in the proximity of the object. Thus we only see an effect if the object is close to the receiver or (to a lesser extent) to the transmitter. Unlike with RF systems the mere presence of the object in the vicinity has virtually no effect. This means that there is no need for finger printing to account for the specific configuration of furniture, walls etc.
- The magnetic field of a typical coil is elongated along the coil axis so that the field strength depends not only on the distance but also on where around the coil the receiver is placed. As will be discussed in section **Position Estimation** this means that using three perpendicular transmitter coils placed at a *single location* allows the receiver position to be restricted to a few points given by the symmetry of the magnetic field. Exact 3D positioning is possible with two beacon nodes. This is a major difference to other beacon based technologies where at least three beacons placed *at different locations* are needed for an accurate estimate and a single beacon only allows to narrow down the position to a circle rather than a small set of points.
- The strength of the signal induced in the receiver coil depends not only on the position within the field of the transmitter, but also on the angle between the receiver coil and the field lines. This means that the signal contains not only position, but also orientation information.

In summary, because of the underlying physical principle, magnetic resonant coupling technology is much less sensitive to disturbance typically found in indoor environments. Because of the structure of the field a single beacon only is needed for a basic position estimate and the signal even contains information about receiver orientation.

The Bad News

The physical principle of resonant magnetic coupling also creates some problems that need to be addressed by the positioning system design:

- The energy transmitted in the field decreases with $1/r^6$ which means that the system is inherently short range. The range depends on the size of the coil, the number of windings and the voltage of the transmitter. Given that the transmitters are stationary (which means that size is not that critical) and are operated from the mains (which means large voltages are feasible) we have been able to achieve a range of approx. 4m (covers a diameter of 8m) so that a single transmitter can in principle cover an area of approx. 50 m^2 (single large room). However this comes at the price of having to deal with a large dynamic range which complicates the design of the receiver.
- The receiver has a very narrow resonant range which is good in terms of being insensitive to noise from other sources of magnetic field. On the other hand it means that any variations in the transmission frequency or the resonant frequency have a critical impact on the measured signal. Such variations are common due to component manufacturing tolerances of the electronic components as well as from temperature effects and ways must be found to deal with them.
- The complex structure of the magnetic field means that

translation from the signal strength to position is not trivial and involves detailed modeling of the field.
- Because of the orientation dependence of the signal not only the transmitter, but also the receiver needs to have three perpendicular coils and we need to measure the signal from each transmitter coil on each receiver coil. To do this we need time synchronization between the receivers and the transmitters. Such synchronization must allow for multiple transmitters to be operating in the same area, overlapping in their fields.

OSCILLATING MAGNETIC FIELD SENSOR SYSTEM

System overview

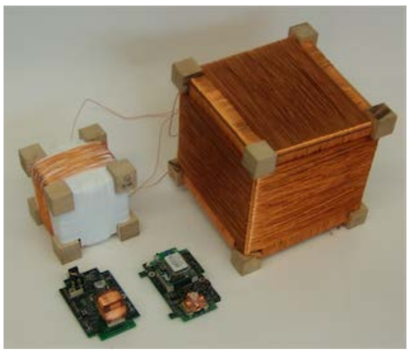


Figure 1. PCB on the left side: wearable transmitter, cubes: different transmitter coils (biggest cube is used in the experiments), PCB in the middle is the receiver with the 3D Receiver coil

The system consists of 2 parts, a field emitter and a field receiver. The components are RF time synchronized. The oscillating magnetic fields are generated by three perpendicular transmitter coils, each with 200 turns of copper wire on a wooden frame. The stationary transmitter sequentially applies a square shaped $V_{pp} = 16V$ signal to the transmitter coil axes, the maximum current of the transmission cycle is 170mA . The impulse response of the axis is a sine shaped signal. The stationary transmitter is powered by a 24V 0.5A power supply. A mobile wearable transmitter which can be driven by a 9V block battery for 3 hours has not been used in these experiments but is also available. To overcome hardware tolerances of SMD capacitors the frequency of the applied square shaped signal lies in the interval of $[18.5kHz; 22.2kHz]$. The range of a stationary field emitter is approximately 4m, the mobile one covers approximately 1.2m.

The magnetic field receiver samples the field strength of the magnetic field using a 3 axis receiver coil with a highly permeable magnetic material. The receiver is battery powered using a LIPO battery, data can either be transferred using a serial USB cable connection or a wireless Zigbee based transmission. An on board microSD card also allows local storage of the collected magnetic field information for offline data processing. When battery powered the receiver part consumes at 3.7V 178 mA, when powered over USB (5V), 179 mA are drawn. Main power consumers are: Microchip Dspic (40mA), Microchip Zibee RF Node (40mA), analog amplification and battery circuits (120mA). When the receiver is battery powered (LIPO, 3.7V, 750mAh) it lasts for about 110 minutes when data is transferred wirelessly. There is significant potential for power management of the transmission part on the receiver side, however we did not explore it yet.

The high dynamic range of the induced voltages complicates the receiver design. Because of the $\frac{1}{d^6}$ dependence of transmitted energy on the distance between the transmitter and the receiver the induced voltage at low distances is around 1.6V, while at 4m it is below 10mV. A programmable amplifier (level between 1 and 128) is used to solve this problem. The system supports a sampling rate of $100Hz * \frac{1}{n_t}$ where n_t is the number of used transmitters visible in the same area.

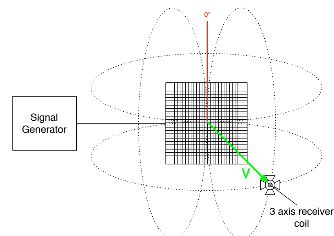


Figure 2. The transmitter sequentially generates an oscillating magnetic field in a certain frequency interval with three perpendicular transmitter coils. The three perpendicular receiver coils measure the induced voltage of the magnetic field.

Position Estimation

As we have 3 transmitter axes and 3 receiver axes, the resulting raw magnetic field data in a single transmitter system is a 3×3 matrix: Column i holds the voltage values of the receiver axes x, y, z $[x_i, y_i, z_i]$ sampled when transmitter axis i generated its magnetic field.

To illustrate how this translates into position estimation we consider magnetic field strength represented by field lines. A field line (as shown in Figure 2) is defined as a curve connecting all points with equal field strength. In a 2D setting a single field strength measurement (=voltage induced in the receiver coil) puts the receiver somewhere on a specific field line. If we add a measurement from a perpendicular transmitter axis, then the position is restricted to the intersection of the respective field lines. Because of the symmetry of the field around the coil axis, in 3D, a single measurement puts the location at a surface rather than a line. A measurement of a second transmitter axis then makes it a line and a third measurement from another axis reduces it to points at the intersections of the field lines. Adding another transmitter node j at a different location leads to another, independent set of points. Unless the second transmitter is placed in a very unfortunate way (co-planar, merely shifted along one of the coil axis), the two set of points (from transmitter i and j) are likely to have only one common element (point where the field lines of all axes of both transmitters intersect), which will be the location of the receiver.

In the above description we used the term "field strengths", not signals in the receiver coils. This is because the voltage induced in the receiver coil depends not only on the field strength but also on the orientation of the receiver coil with respect to the field lines passing through it. For simplicity we first consider a 2D system. Given the angle between the receiver coil x and the field line to be α, and the field strength to be f the measured field strength f_x

$$f_x = f \times cos(\alpha)$$

On a perpendicular receiver axis y the field strength f_y will be

$$f_y = f \times cos(90 - \alpha) = f \times sin(\alpha)$$

This gives us two equations with two unknowns from which the angle and the field strength can be computed. Alternatively we can use the fact that $sin^2 + cos^2 = 1$, and compute the field strength from f_x and f_y while ignoring the angle. A similar consideration can be done in 3D using f_x, f_y and f_z which explains why we need a 9 measurement matrix.

In summary, given our 9 element measurement matrix we can first compute the field strength received from each transmitter axis independently of the receiver orientation and narrow down the receiver position to a few points given by the symmetry of the field. The latter requires a model of the magnetic field. Given that our coils are hand made prototypes a reasonable approximation with an analytical model seams unlikely. Instead we use an industrial robot to build a look-up table on a coarse grid (5 cm). Exploiting field symmetry and a transmitter range of 4 m the table needs to cover a volume of 4mx4mx4m which leads to $80^3 = 64000$ entries. These can be sorted and searched using binary search which is not an unreasonable effort.

Note that the above lookup table approach is fundamentally different from the fingerprinting method used for example in WiFi location. In our system a lookup table is created for a coil. The table is independent of the location in which the coil is deployed. Thus, once it has been created, the coil can be used in any location without further data collection. On the other hand, finger printing approaches require

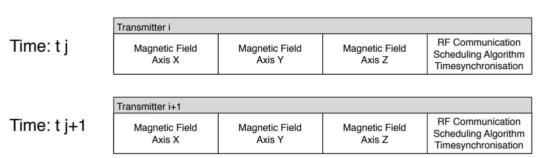


Figure 3. Tasks performed on the transmitter nodes when generating a magnetic field.

As described above, our position estimation method requires that

1. the transmitter sequentially generates a field on each of its three axis and
2. the receiver knows when the transmitter activates each axis to be able to enter the measurements into the correct slot in the measurement matrix.

In a system with several overlapping transmitters we also need to make sure they do not interfere with each other, since the magnetic fields of two simultaneously active transmitters add up losing all information about the individual field strengths. To this end each transmitter is assigned a unique time slot that is made known to all nodes in the system during the initialization phase. This means that the transmitter and receiver nodes need to synchronize their local hardware

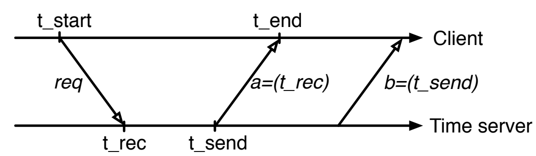


Figure 4. The client requests a synchronization process. In addition to the originally proposed algorithm we remove the server side processing time from the round trip time to increase time synchronization accuracy.

Even with synchronized clocks there remain several issues that need to be addressed:

- Which node of the sensor network is the time synchronization server?
- What happens when the time server is removed or fails?
- How can we support a large scale sensor network in which there are nodes which do not have a direct bilateral RF connection?

Time Server Election

Time synchronization in sensor networks is a well researched problem and many different approaches have been proposed [16] (Broadcasting the timing information, time synch protocols or tiny sync/ mini sync). Time synch protocols usually use hierarchical sensor network structures which use spanning trees to find timing sources (e.g. Van Gruennen et al. [5], Sichitiu et al. [15] or Awerbuch [2]). Our approach uses local network connectivity information to assemble a global connectivity graph which can then be used to gather timing sources for the local nodes.

In our method each transmitter and receiver holds (local) information about its current RF neighbor nodes. When the node receives a packet from an other node, the network table is updated. This local connectivity information has to be transferred to other nodes to build a global connectivity graph. In the beginning a node broadcasts its known local neighbors. When a node receives this subgraph, it adds these edges to its local version of the global network graph. The updated information is then re-broadcasted. When there is no update in the global network graph after receiving a message - or after a time out - the data collection step is finished. To achieve good overall time synchronization accuracy we need to establish a central node to act as time server since each hop introduces a clock offset of at least 50 μs. To this end we apply the Floyd Warshall algorithm to calculate the

Location	Events with Synch errors	Events	Percent
Office	123	292	42.12
Apartment	65	186	34.94
Living Area	130	427	30.44
Cellar	131	424	30.90

Table 1. Statistics for Synchronization errors at different locations

center of the network connectivity graph. The center of the graph is the set of nodes which have the minimum distance to all other nodes. If there are several possible nodes in the center set, we use the node which has the minimum id.
When the Center is not part of the local neighborhood, the node uses a neighbor node which has the minimum distance to the center and which has the minimum id. This information can also be derived from the Floyd Warshall algorithm.

Detection of synchronization problems
During data evaluation we encountered randomly occurring, major disturbance of the signal. An example is shown in the lower plot of figure 5. In the continuous data stream (of the transmitter magnitudes m_i) "rectangular" signal changes can sometimes be found. These disturbances occur when there is at least one part of the sensor system (either the transmitter or the receiver) out of time sync. The receiver then samples the magnetic field at the wrong time and correlates this (wrong) data with the current transmitter.

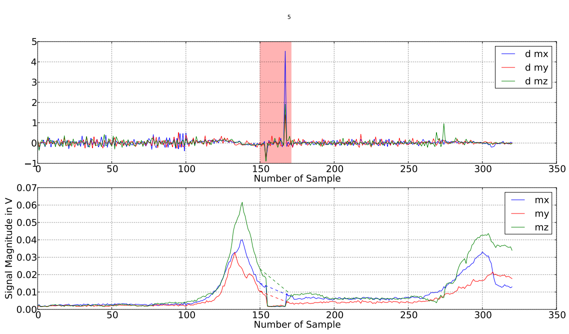


Figure 5. Synchronization problem found in data. Upper plot shows signal deviation, lower plot depicts the raw magnitude values. The red area highlights the found synchronization problem.

This kind of synchronization problem can be detected if the first derivate of the signal is analyzed. To deal with the high dynamic range of the signal, the first derivate is also normalized. The falling edge is visible in the first derivate of the signal as a distinct peak. When the sensor system is synchronized after several seconds, there is another peak (in the opposite direction) which usually is even more intensive than the start peak. Smaller signal disturbances resulting in small peaks in the first derivate are ignored using a threshold. Time shift (resulting in attenuation or amplification of the signal of a transmitter) cannot be detected with this approach as time shift lead to continuous "soft" changes in the signal. During the processing steps a script automatically marks these synchronization problems and discards them in location estimation. Table 1 gives an overview of the synchronization problems found in the dataset.

Scalability
An important issue with respect to any time slot based algorithm is scalability with respect to the number of nodes. Specifically, in our system the question is how the number of transmitters impacts the location sampling rate which is given by the time needed to generate and receive the signal from all beacons. Clearly, if we increase the number of transmitters visible in a given area, the maximum achievable sampling rate decreases linearly. However, there is little point in having more than three to four transmitters covering the same area (see table 2). At the same time, the characteristics of the field propagation (energy decreasing with $\frac{1}{d^6}$) means that the range of the transmitters is limited (in our case the limit is around 4 m). Thus, if the time slot algorithm takes into account the spatial distribution of the transmitters, there is no scalability issue since transmitters deployed in the same environment can share the same time slot as long as they are more than approx. 8m apart. To avoid tedious, static adjustment of the synchronization scheme we are currently working on a scheduling algorithm which dynamically builds up a visibility map of the transmitters and adjusts the slot distribution accordingly.

Health and Safety Considerations
Health and safety considerations are an important aspect of any practical system. In our case the obvious concern are the generated magnetic field strengths. The German Federal Office for Radiation Protection[1] guidance for safe field strengths of low frequency dipole magnetic fields are between 2T and 5T. Hair dryers or electric shavers emit between 1.5T and 2T at a distance of 3cm (which is how they are used). The theoretical magnetic field strength (see Biot Savart Law) for 200 turns of copper, a frame size of 12x15 cm and I=0.176A is at 30 cm approximately 3.6T, at 1m 0.097T. This means that the magnetic field exposure caused by our system is comparable to the exposures produced by home appliances and well within safe limits.

EVALUATION

Accuracy Evaluation using a Robot Arm
To evaluate the basic accuracy of our position estimation we again use an industrial robot (Figure 6). The robot is positioned between four transmitter nodes and has a receiver fixed to its arm tip. The robot arm is 1.5 m long so that it can reach a maximum distance of 3m from each coil which is a bit less than the maximum range of the transmitters (4 m). For the evaluation we select 1000 random robot arm positions and compare the estimated position given by our system with the ground truth provided by the robot controller. We perform the position estimation using 1, 2, 3, and all 4 coils to see the effect of additional transmitters on location accuracy. The results are summarized in table 2.

Sensitivity to Disturbances
To demonstrate the robustness of the system with respect to changes in the environment and obstacles in the path of the

[1] `http://www.bfs.de/de/elektro/nff/anwendung_vorkommen/vorkommen.html`

Figure 6. Distance evaluation using a robot. Attached to the arm of the robot, two receivers are rotated in the magnetic fields generated by four magnetic field emitters.

Number of Transmitters	Mean Error	Std. Deviation
4	4.39	6.32
3	9.57	8.94
2	32.40	24.41
1	44.32	33.23

Table 2. Localization errors in cm when using different numbers of distances / anchors in localization process.

field we have investigated the influence on the distance estimation when different objects are placed between the transmitter and the receiver. The measurement with the obstacles were compared with a reference measurement with no obstacles.

Obstacles we used are furniture with metal frames and legs, 3 persons and two metal tower-computer bodies as shown in figure 7. For each object we recorded 10000 samples at three different distances. We placed the disturbances approximately 40 cm from the receiver. After converting the raw magnetic values to distances, the distances are compared to the reference measurement. Figure 8 shows the results. The disturbances caused by metal objects are around 4%. Furniture with wooden frames or metal parts of chairs have a much lower influence.

We also conducted a test using the robot to slowly move a ferromagnetic cylinder towards the receiver coil. The magnetic field is altered by the cylinder when the distance between the receiver and the cylinder is lower than 6cm. The robot hardly influenced the magnetic field as it is made of aluminum which is a non ferromagnetic metal.

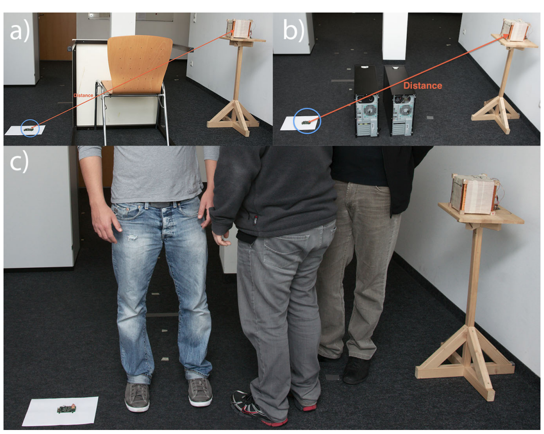


Figure 7. Obstacles are put directly between the transmitter and the receiver. a) Furniture b) Computers c) Persons. As can be seen, the obstacles are in the line of sight between the transmitter and the receiver.

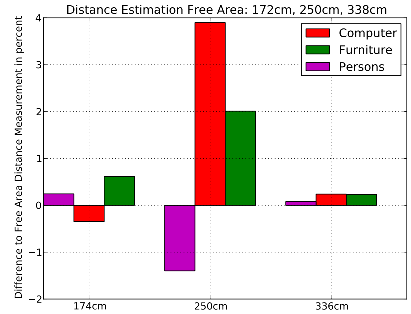


Figure 8. Results of distance estimation where different obstacles are placed between the transmitter and the receiver.

Performance in Location Classification

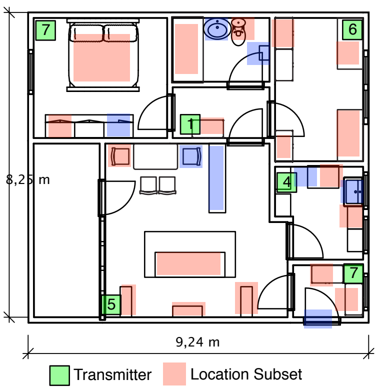
As described in the introduction our system targets activity recognition where user location often needs to be known at the level of relevant parts of a room: e.g. at the table, in front of the fridge, in the armchair, at the sink etc. In this section we evaluate the usefulness of our system for such applications. The focus of the evaluation is on the following aspects:

1. Being as close as possible to the way a system would be deployed in a real activity recognition system. Thus we do not just place the receivers at predefined points in space. Instead we give them to test subjects and ask them to spend some time in some locations defined in human understandable terms (e.g. in front of this cabinet).
2. Covering different environments. The system has been evaluated in 4 different settings: an office floor with an area of $230m^2$, a large apartment ($100m^2$) of a house, the cellar of the same house, and a small apartment ($68m^2$) in a different house (see figures 9,10).
3. Testing the limits of the system. Thus we have defined two sets of locations. One is pushing the performance to the limits with some locations being very close (around 50 cm) to each other (see figures 12, 13, 14 and 15). Overall this data set contains 33 locations in the office building, 20 at the house, 17 at the cellar and 25 at the small apartment. The data set tries to respect the 1m system accuracy taking into account that we have to consider not just the distance between the locations but also the range within which people would move when considering themselves at the location. The second set has 22, 20, 11 and 17 locations respectively.

Experimental Setup

Depending on the size of the test site we used 6 to 8 transmitters as shown in figures 9, 10, and 11. This means that in the small apartment the transmitter density was quite high

whereas in the office floor we had fairly sparse transmitter placement. We chose the positions of the transmitters to be next to a power supply and made sure that there is at least one transmitter in a room. The locations that we are recognizing have been chosen to cover most common tasks for the specific environment (e.g. in the office: desks, printers).
All locations from both sets and the placement of the trans-



nent. Locations and

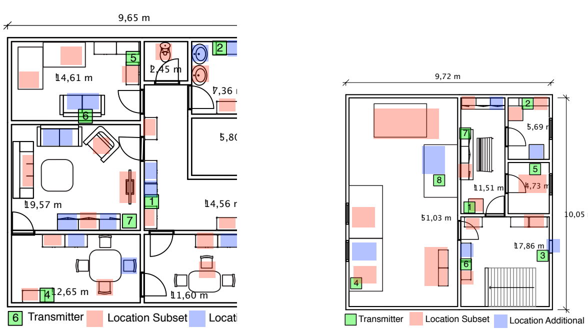


Figure 10. Floor plans of the living area environment on the left side and the cellar environment on the right handed side.The overall number of locations was for the living area 20, for the cellar 17, the limited number of locations was 35 and 17.

Classification Process

The evaluation described below is meant to investigate how the system would work in its intended application which is

Figure 11. Floor plan of the office environment. The number of classes when all locations have been used was 33, 22 locations have been used when the subset location classification was done.

activity recognition. This involves recognizing that a person having the receiver on the body and moving freely is within a certain mostly loosely defined semantically meaningful area (e.g. in front of the cupboard). Defining such areas in terms of manually specified coordinates makes little sense and is never done in practical applications, no matter what positioning system is used. In fact, the translation of physical coordinates to semantic locations is a research area of its own.
As a consequence, we rely on a standard supervised classification approach rather than direct specification of coordinate boundaries. Note that this does not mean that we use finger printing for the location system itself. Instead the training is used to map the output of the location system to the human interpretation of the places. We use a standard decision tree (CART) that is trained directly on the output of the location system without any further features calculation. Obviously not all transmitters are visible at all locations. In fact depending on the density of the transmitters mostly 1 to 3 transmitters provide useful signals at each location. Including non visible or non reliable (because of too large distance) transmitters in the feature vector would clearly reduce performance. Thus, in the first training stage for each location we determine the set of valid transmitters. We do so by requiring a minimal signal strength that we set at 0.003V. In the next step we put together locations, that share the same set of transmitters. Then we take each of these transmitter sets and train a dedicated classifier to distinguish between the corresponding locations. During the testing phase we then first use the valid transmitters to select the classifier and then use the classifier to distinguish between the possible locations. If a particular classifier had only one location associated with it the second step could be skipped. However, in our data this was not the case. The above classification is done on a frame by frame basis with a frame rate of 30Hz. We then use majority decision over the entire time period when a person stayed at one location to classify that location.

Classification Results

Results are based on training data from two subjects being tested on the third one (averaged over all combinations of

Figure 12. Pictures taken in the living area of the house. The white crosses mark the different locations Notice that we also included the metal bathtub as possible location.

Figure 13. The upper picture pair depicts the kitchen of the house and the storage room in the cellar. The lower picture pair shows the heating system with metal water tubes on the left side and part of the garage part of the cellar with metal tools.

Figure 14. Depicted in these two scenes are on the left hand side the registry with cabinets for bureau supplies, on the right hand side a typical office with two seats, storage room and a cabinet. Notice the spatial relation between the rack in the upper right side and the cabinet.

Figure 15. In this room there are two partitions in the upper left part of the picture, a book rack and a table are in the lower and the right part of the picture.

test and training subjects). For the more challenging (”full”) set their results are between 81.4% (for the house) and 94.9% (for the cellar) with an overall rate of 88.2%. For the reduced, more realistic set we get between 87.2% (for the house) and 97.1% for the office floor.

It is interesting to note that misclassifications were not concentrated in specific locations, but more or less randomly distributed across locations. Most locations would have no more than a single misclassified sample. This is a strong indication of synchronization issues due to loss of RF Packets rather than measurements problems (e.g. disturbances to the field or issues with the field model) being responsible for the misclassifications.

CONCLUSION

The main thesis of the paper is that magnetic resonant coupling has the potential to implement cheap, easily deployable, yet very robust positioning systems with sub room level accuracy that are suitable for a broad range of activity recognition applications. The results of the location classification study strongly support this thesis. The achieved accuracy is well within what can be expected given a broad definition of the locations, their proximity, and variations in the way people interpret them. While not perfect, it is clearly enough to support complex activity recognition.

The main topic for future work are further improvements to the magnetic field model which should lead to even better accuracy. In addition, we will work to exploit the receiver orientation information. On the hardware side the range could be further increased with higher transmitter voltages and more advanced coil design. Finally, our new version of the receiver contains gyroscopes and accelerometers which could be used to identify erroneous signals due to e.g. synchronization errors.

Finally by making the hardware design and the firmware publicly available we hope to stipulate further research and improvements by the community.

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