Capacitive indoor positioning and contact sensing for activity recognition in smart homes

Miika Valtonen *, Timo Vuorela, Lasse Kaila, Jukka Vanhala
Department of Electronics, Tampere University of Technology, P.O. Box 692, 33101 Tampere

Abstract. In smart homes, unobtrusive monitoring of user position and activity are important but challenging tasks. With the current state of technology, this task is especially hard to carry out in private areas where video surveillance is considered undesirable or even offensive. Even though some alternative methods for passive and unobtrusive monitoring of people have been proposed in the past, we still do not have a simple method that could be used to measure user position and activities as a single practical solution. To fulfill this need, this paper presents a single privacy-preserving method to measure user position and activity which can easily be adapted to measure the subject’s height and posture as well. The system proposed in this paper can locate a person at floor level and monitor the subject’s interaction with common household items such as a bed, sofa, table or refrigerator. The measurement method is based on the conductivity of the human body and on capacitive coupling of low-frequency signals between electrodes embedded in the floor and the in the environment. A test system was built for the TUT Smart Home and was evaluated with multiple test subjects, including a two-week-long living test to show the system’s potential in long-term monitoring applications. The results show that a standing person can be positioned to within either 7 or 11-cm accuracy at a 90% confidence level using 30×30-cm and 60×60-cm-sized transmitting floor electrodes, respectively. For people walking, the respective accuracies are 17 and 33 cm. According to the long-term test results, the interactions with the environment were detected accurately. All the test data from this long-term living test, including the person’s position, contact with common household items as well as the user annotations, have been made public and are available for download.

Keywords: Indoor positioning, tracking, capacitive sensor, activity recognition, smart home

Pervasive yet unobtrusive human monitoring methods for smart homes and other intelligent environments have been researched for a number of years. Although this field has advanced rapidly, and researchers have developed many significant ideas to a practical and usable level, unobtrusive indoor positioning and activity recognition have still not developed as far as might be expected. In fact, many of the positioning systems of today are limited to merely tracking an object or a tag, which must be carried with the monitored person. Thus, they are hardly conducive for creating a homely environment, where people should be able to relax and feel free. In a similar way, the traditional use of video cameras can also be perceived as being intrusive in the home, and thus, in the opinion of the authors, should not be used for monitoring persons in this type of environment.

In addition to the above-mentioned problems, smart homes consist of many separate subsystems that sense different things in the home. To be used seamlessly together, they require a common architecture for communication as well as for collecting and collating data. Thus, the overall complexity of a smart home is usually much greater than the complexity of its individual parts. For example, certain data fusion techniques are often used to couple together the different types of sensory systems in order to get a comprehensive overall picture of what is going on inside the home [17,29,39,54].
Bearing these problems in mind, we have developed a single-solution system that can monitor a person’s position and actions in a passive and unobtrusive way without violating the privacy of the monitored individual with intrusive, vision-based methods. The system has been installed in the TUT Smart Home in the Department of Electronics at Tampere University of Technology (TUT), Finland, and is capable of positioning people on the floor, and detecting their contact with common household items such as a bed, sofa, table, or refrigerator. Although the system has been tested extensively with multiple adult subjects and has been found to work reliably over long periods of time. The system is currently limited to positioning one person at a time due to the slow update rate of the current measurement circuitry. However, the system has also been tested on a number of people at the same time, and directions for future improvements to enable the tracking of multiple people simultaneously are discussed in section 7. Furthermore, the system proposed here could easily be adapted to support unobtrusive measurement of a subject’s height and posture, thus enabling three-dimensional tracking and activity recognition in the TUT Smart Home [56].

These types of unobtrusive monitoring systems could be used in a variety of applications in order to collect large quantities of position and contact data about the user interactions in smart homes. Because position information is regarded as an essential factor in defining user context [2,15,32], the more accurate the information that can be obtained, the better the user context can be ascertained using computational methods. For example, with traditional home automation systems such position and contact data could be used to learn about personal routines and user activities, thus also enabling context-sensitive control of home equipment [6,9,10,14,27,44,51,54,57]. Similarly, in the healthcare sector physical and cognitive health could be monitored by observing patterns of activity [13,30,34,45,57]. Furthermore, there are many gaming and virtual reality applications which could also benefit from the input from these systems by enabling more natural movements for the participants as no devices or tags would need to be worn.

This paper will first introduce related work. Second, we will discuss the practical implementation and construction of the system with the aid of a capacitance model of the environment. Third, we will explain the system’s tracking algorithm and present the main hardware components needed to operate the system. Then we will present the experimental results from the four different tests, which will provide detailed data on the accuracy, reliability and feasibility of the system for short and long-term use. Finally, we will discuss the results as well as the properties of the system and conclude by referring to the long-term evaluation data that has been released for public use.

1. Related work

Video cameras have long been used to capture human actions and for positioning purposes [11,25,26,43,50,60,61]. As a result, efficient algorithms for detecting human body movements from a video stream have been available for a few decades. Although video-based motion capture is very efficient today, vision-based systems have difficulty in maintaining target identification, especially because of visual occlusion. For example, if one person stands in front of a single tracking camera, another person standing behind the first one cannot be tracked at all because of the line-of-sight requirement with vision-based systems. Of course, this situation can be remedied with multiple cameras, but the installation of multiple cameras would make the tracking system more complex.

Furthermore, video based solutions have a major drawback with regard to user privacy. The simple fact is, many people do not want video cameras to be installed in private places like their homes. Even though the video stream would not be fed outside the monitored room and would only be used, for example, for context analysis, the slight risk of hacking or intervention by an outsider prevents most people from accepting cameras in such places. That is why there has been so much research into alternative, wireless, positioning and activity sensing methods for monitoring people in their home environments [20]. These include ultrasonic [33,37,38,59], radio frequency [4,8,16,28,31,46,49] and inertial sensor-based [5,7,12,24,28] techniques that require the person to carry an active device. From the viewpoint of a home dweller, these techniques are not, however, practical or user-friendly because the user must always carry a tag or small electronic device on their person. Moreover, visitors cannot be located in the home without first equipping them with the necessary tags.

Therefore, lately there have been several studies of passive or tagless methods for positioning the person indoors without the violation of privacy caused by vision-based solutions. One interesting approach was taken by S. N. Patel et al. in 2008, when they pub-
lished their study of a sensing method located in the ductwork of a building in order to locate movements from room to room [36]. The idea in this study was to utilise the existing ductwork infrastructure of the central heating, ventilation and air conditioning (HVAC) systems found in many homes and detect the disruptions in the airflow. Even though the idea is fascinating, the method cannot be used to accurately detect movements within a room and the room-to-room transitions can only be detected with 75–80% accuracy.

Meanwhile, D. Hauschildt et al. have developed an infrared-based positioning system [19] that is based on passive infrared sensors placed in the corners of the monitored room. The sensors detect the thermal radiation of human beings and enable the tracking of either one or two persons in a 30 m² room with a maximum error of 26 or 68 cm, respectively. Although their system is reasonably accurate for general indoor positioning, it is prone to reflection and dynamic background radiation effects that cause the sensors to give out false readings.

In 2004, Y. Nishida et al. published a good alternative for the passive measurement of a person’s position and posture in indoor environments [33]. Their method is based on an array of ultrasound transmitters and receivers placed in the ceiling at intervals of around 18 cm. The pilot system they developed is able to position the subject three-dimensionally within the vicinity of the sensors and can calculate head position both horizontally and vertically with about 5 cm accuracy. Although that system gives promising results in terms of accuracy, it requires the installation of hundreds or even thousands of sensors in the ceiling, if whole apartments or houses are to be covered by the system, which is not a practical solution for tracking the users.

Consequently, capacitive methods for human positioning applications are interesting, because they provide a way of preserving personal privacy while passively monitoring the movements of a person, in addition to which their sensing electrodes need not be visible to the user. Furthermore, they can be implemented with large and cheap electrodes that can cover large areas. Indeed, as early as 1993, a simple electrode configuration for detecting the presence or movement of a person close to a robot was developed by N. Karlsson et al. in [23]. The purpose of this system was to stop the robot moving to ensure the safety of any person who came too close to it. Two years after Karlsson’s ‘person detector’, T. Zimmerman et al. from MIT Media Laboratory presented various ideas on capacitive applications [58], including a two-dimensional Finger-Pointing Mouse and a Person-Sensing Room. The floor of the Person-Sensing Room was covered by a transmitting electrode and four receiving electrodes were placed on the walls. Using the floor electrode, a measurement signal was capacitively coupled to the subject and the strength of the emanated signal from the subject was measured by the wall electrodes (this is called a transmit-mode measurement). The room was able to use this information to locate a person two-dimensionally on a floor plan. Later, in 1999, J. Smith from MIT Media Laboratory published his dissertation thesis [47] covering electric field sensing with different kinds of sensing applications. A separate article gave a detailed description of one of his most advanced applications, a three-dimensional mouse [48]. This mouse is able to capture hand position and alignment above the measuring electrodes with shunt-mode [58] measurements using a single transmitter electrode and three receiver electrodes arranged on a plane.

Over the last few years, we at TUT have also studied the use of passive and capacitive human tracking systems. In 2009, a description of the TileTrack system was published in [52,55], which utilised the same transmit-mode measurement as the Person-Sensing Room in [58]. However, instead of having a single electrode on the floor, a single receiver wire or plate next to the tracking area was used in conjunction with several transmitting floor segments in order to position the user two-dimensionally. More precisely, this system used the known physical positions of the floor tiles and the proportional capacitances between these tiles and the receiver in order to calculate the user’s position. Furthermore, in 2010, we published a method [53] for locating a person with electric field ranging. The system measures the capacitances between the user, standing on a transmitting floor electrode, and four vertically aligned receiver wires placed in the corners of the tracking area. The system converts the measured capacitances to absolute distances between the user and the receivers using a capacitance-to-distance conversion function in the horizontal dimension. Because the distances between the user and the static receivers are known, the position of the user can be calculated accurately.

In 2011, we published a paper [56] on a practical measurement system for passive human height and posture recognition using a capacitive sensor. In this paper, a transmit-mode technique is used to create an electric field around the body with a floor electrode. The capacitance between the body and a ceiling elec-
trode, installed in a horizontal plane above the person, is measured using simple electronic circuitry. Because the measured capacitance between the body and the receiver changes inversely in proportion to the distance between them, the height of the person can be found by converting the capacitance to an absolute distance. The system was demonstrated to be able to measure a person’s height at 90% confidence with 5.2 cm accuracy when standing and with 14.3 cm accuracy in other postures.

Recently, H. Rimminen et al. has studied the use of electric fields for positioning people over a segmented floor electrode [40,41] and in 2011, Rimminen published his dissertation thesis [42] on these methods. Instead of using the transmit-mode measurement technique, he proceeded with the loading-mode measurement method, which measures the capacitance between a transmitter and the ground. Specifically, his systems scanned the floor area with the floor electrodes and toggled each electrode to transmit a measurement signal at a time [40]. When the electrode below the feet of the person was actuated, a measurable current flowed through the body to the surrounding grounded electrodes. The position of the person was determined using the physical locations of the electrodes and the level of current measured from each electrode. Although his systems achieved about the same level of positioning accuracy as the TileTrack system, the loading-mode measurement method used in his studies is not as easy to use to recognize interaction with objects in the environment and nor can it be modified to measure human height and posture, as is possible with the system described in this paper.

2. Objectives and system construction

The main objective of this study was to scale up the TileTrack system [52,55] and to create an unobtrusive, passive tracking system for the TUT Smart Home. The aim of this step was to show: 1) how these techniques could be used in a real residential environment for positioning purposes, 2) how the electrodes could be concealed in common household objects and be used for activity detection and 3) how re-sizing the floor electrode and changing the insulation material in the floor tile could affect the positioning accuracy and reliability of the system. The final objective was to perform living tests in the smart home and to acquire long-term data on the operation of the system. The following subsections will review the principle of the TileTrack measurement, introduce the TUT Smart Home and describe the physical construction of the system.

2.1. Measurement principle

The human tracking system in the TUT Smart Home is based on a transmit-mode measurement method whereby a measurement signal is sent to the person through transmitting electrodes and the signal strength is measured using a receiver electrode. In the TileTrack configuration, the transmitting electrodes are installed in the floor and the receiver is placed in the environment. The system described here uses a safe 32 kHz square-wave signal (see section 7.8 for discussion on safety) which is coupled to the human body effectively while the transmitting part of the system remains invisible to the person being monitored. In this study the receivers were placed in the ceiling and in common household objects in the TUT Smart Home, allowing the user’s floor position to be detected while also recognizing user activity through his or her proximity to or contact with the electrodes concealed in these objects.

The user’s position is calculated using the relative signal strengths from each transmitting floor electrode according to their physical location. The signal is stronger the larger the area of the electrode covered by the person’s feet. Therefore, the stronger the signal received from each floor electrode, the closer to the centre of that tile the person is assumed to be. Contact with the household objects is detected by comparing the measured signal values from the transmitters to predefined threshold values. Here, all the signal values are modeled as pure capacitances that decrease quadratically according to the distance between the person and the receivers.

2.2. TUT Smart Home

The TUT Smart Home is a 69 m² apartment on the fourth floor of a six-story office building on the TUT campus. The home, pictured in Fig. 1, was constructed in 2002 as a versatile laboratory for smart home research [22] and it has been used since as a test platform for a variety of systems. For example, various types of sensor, actuator, network and user interface designs have been studied and applied in the home, both at the hardware and software level. In addition, the environment has been used for system integration and user studies as well as for practical living tests.
This two-room apartment with a kitchen, sauna and balcony has a floor plan with plenty of open space, as shown in Fig. 2. It is furnished to resemble a typical modern apartment and the number of visible atypical devices and test equipment has been kept to a minimum in order to make the environment as restful and normal as possible. However, the environment was designed with easily modifiable physical structures that allow quick installation of new systems and appliances with minimal construction work. For example, the raised floor can be easily opened and closed so that electric cables or sensors can be fitted under the floor tiles. Similarly, a suspended ceiling houses controllable spotlights, electrical and network sockets as well as ample space for extra equipment. The rooms are separated by large movable shelves, which allow changes to be made to the room layout. Furthermore, the shelves have hollow ducts and space for cabling, which makes equipment installed later easy and simple to conceal.

2.3. Transmitting electrodes

The TUT Smart Home has two types of floor tiles with two different sizes of transmitting elec-
trodes. First, the smart home’s original 60×60-cm-sized raised floor tiles, shown in Fig. 4, have a 0.5-mm-thick uniform steel plate underneath that is used as the transmitting element. The upper surface of the tile is a 1.5-mm-thick plastic mat mounted on a 3.8-cm-thick graphite enriched layer of chipboard between the steel plate and the plastic mat. The tiles stand on metal pillars fitted to each corner, and there is a plywood spacer on top of these pillars to insulate the transmitting electrodes from the concrete floor or electrical ground as shown in Fig. 3, which is a cutaway picture of the environment.

Second, there are custom-built floor tiles, shown in Fig. 5 each of which is fitted with four roughly 30×30-cm-sized copper foil transmitting electrodes, which enable more accurate positioning in parts of the apartment. These 60×60-cm-sized tiles consist of a 2.8-cm-thick chipboard core and four 28.4×28.4-cm-sized copper foil tape electrodes attached to the bottom of the tile. The upper surface of the tile is covered with plastic mat. In addition to the chipboard, there are two plywood boards directly beneath the surface to stiffen the tile and raise it to the same height as the original raised floor tiles. The gap between any two of the copper foil electrodes varies between 1 and 1.5 cm due to installation tolerances.

As well as differing in electrode size, the two different types of tile have different electromagnetic characteristics. The original raised floor tiles of the smart home, marketed as electrostatic discharge (ESD) safe tiles, have a significant number of small graphite chips in the chipboard that separates the feet of the tracked person from the electrode underneath the tile. The graphite chips inside the chipboard make the chipboard fairly conductive, and the resistance between the upper and lower surfaces of the chipboard is only about 10-20 MΩ. Thus, with the large electrodes the only effective insulator is the plastic mat on top of the graphite enriched chipboard.

In contrast, the custom-built tiles with smaller electrodes have an infinite resistance between the upper and lower surfaces of the chipboard, which makes the capacitive coupling between the electrode and the feet much lower. In practice, this means that the signal to the receiver placed in the environment is much weaker. Consequently, this affects the accuracy and the tracking speed of the system (see section 7.2 for further discussion).

The different-sized electrodes were placed around the apartment according to the assumed usage frequency and application possibilities. Thus, the smaller electrodes were placed in the hallway, living room and kitchen, because those are the most frequently used areas. In addition, because there are audio-visual devices in the living room, the floor in that part of the apartment can be used for higher accuracy tracking in the future, for example, for gaming applications, in which body movements need to be tracked very precisely. The rest of the apartment, apart from the bathroom, sauna and balcony, were covered with the larger electrodes, which are less accurate but require less cabling and electronics and yield a higher update rate of
the user’s position [55]. Thus, the small and large electrodes provide contrasting levels of accuracy and scalability for the system. In addition, the installation and building costs can be reduced through the use of the larger tiles. The tiles and their placement are shown in Fig. 2.

In addition to the floor-tile transmitters, transmitting electrodes T1–T3 were fitted in the common household items shown in Fig. 6 to detect user touch. Indeed, the front steel surfaces of the freezer and the refrigerator, shown in Fig. 7, were used as transmitters T1 and T2, respectively. Whenever the person touched them, a signal was transmitted through the user’s body to the receivers, which recorded the contact. To improve the coupling between transmitter T2 and the user, copper foil tape was fitted to the back of the refrigerator handle. Thin wires were spread under the fabric covering the sofa to create transmitter T3, which could recognize sitting and sleeping on the sofa even when the feet of the user were not touching the floor tiles.

2.4. Receiving electrodes

Although the system requires multiple floor electrodes for accurate positioning, the receiver electrodes play a key role in this system in two ways. First, they are used to receive an adequate signal level from the transmitters in order to reliably position the user on the floor. Second, they are used for detecting periods of contact with common household objects. Due to the limitations in the electronic circuitry, all the receivers
In addition to the floor-tile-based transmitters, three object-based transmitters, T1–T3, were attached to common household objects to detect user touch. The metal doors of the freezer and the refrigerator function as transmitters T1 and T2, while T3 is a thin wire net under the fabric of the sofa. The five receiver electrodes, R1–R5, are spread out evenly around the apartment and are used for tile-based positioning and, in the case of R3 to R5, user touch recognition. The receivers R1 and R2 are conductive textiles hanging below the ceiling, while R3 is a conductive textile concealed under the bedsheets. There are also two copper foil receivers, R4 and R5, beneath the tabletops of the sofa and dining tables.

are interconnected at the measurement board and thus receive the same signal. Therefore, they should not be considered as separate in an electrical sense, although they are physically separated.

To achieve the goals of this study, the receivers were spread around the apartment evenly, as shown in Fig. 6. The silvered textile receivers, R1 and R2, were hung about 10–15 cm below the ceiling in the bedroom, hallway and kitchen. The kitchen ceiling textile material, shown in Fig. 8, is a semi-transparent loosely woven net, which is the same color as the ceiling above it so was virtually unnoticeable in its environment. The main reason for installing the electrodes below the ceiling, rather than in it, was because of the conductive steel framework of the suspended ceiling. The steel framework would have caused too high a capacitance between the receiver and the ground for the electronics used with this system (see [56, p. 330] for details). The height of the room below electrodes R1 and R2 is 252 cm, whereas the rest of the hallway, bedroom and the living and dining rooms is 289 cm high.

A third silverized textile receiver, R3, was placed in the bed under the bottom sheet. This provided good capacitive coupling with the human body when the person was sitting or lying on the bed, and even when walking around it. It also enabled the system to sense movements in the bed, yet during the long-term evaluation of the system, the subject was completely unaware of this electrode. In addition to the aforementioned receivers, two copper foil tape receivers, R4 and R5, were fitted to the undersides of the tables in the living room and dining room. Fig. 9 shows the foil tape and the cable attached to it underneath the living room table. In addition to positioning the person on the floor, these two electrodes can be used to detect when the user touches the tables or is sitting near them.

3. Capacitance model

A simple capacitance model was derived to explain the operation of the system. Fig. 3 shows this model with a cutaway picture of a person standing beside the dining room table. This model can also be expressed as a conventional circuit diagram as shown in Fig. 10. In the following subsections we will define the capacitances and discuss them in detail.
3.1. Body related capacitances $C^t_F$ and $C_B$

The capacitance model incorporates two capacitances that are formed between the electrodes and the human body. First, $C^t_F$ is the capacitance between the human feet and transmitter $t$ with the chipboard and the plastic covering of the floor tile acting as an insulator. However, with the larger floor tiles, $C^t_F$ mainly occurs between the feet and the graphite chips which are close to the upper surface of the tile, because of the existing resistance between the lower and upper surfaces of the chipboard. In contrast, with the additional transmitters T1–T3, $C^t_F$ can be considered as the capacitance between the transmitter $t$ and whichever part of the body is closest to it. $C^t_F$ increases as the common area between the person and the transmitter increases, and vice versa. Similarly, $C^t_F$ increases as the distance between the transmitter $t$, and the body decreases. Typically, $C^t_F$ ranges between 20–700 pF with both floor-tile types when shoes are not worn [56]. However, if shoes are worn, they insulate the person from the transmitting electrodes and thus act as an additional insulator. As a result, different types of shoes significantly lower $C^t_F$ and affect the measurement results. According to [56], $C^t_F$ can be up to 96% lower if shoes have 3-cm-thick soles.

Second, $C_B$ is the capacitance between the body and all receivers, insulated by air, textiles, or wood. However, it is formed mainly between the body and the closest receiver to the person, because the electric field is the strongest near the body from which it emanates. Furthermore, because only a single receiver channel is used in the hardware, the receiver signals cannot be distinguished from each other. Based on the data of [56], $C_B$ is about 4–8 pF when the person is standing below receivers R1 and R2, but can be significantly higher with receivers R3–R5 when the person is in actual contact with the electrodes, for example, when touching the table surfaces or lying on the bed.

Because the electronic circuitry measures the total capacitance between the transmitting and receiving channels, $C^t_F$ and $C_B$ cannot be distinguished from each other in the acquired result, and so they must be combined into a single term. Also, because only a single receiver channel is used in our hardware, these two capacitances are simplified in our model into one single capacitance $C^U_U$ for any given user. Because $C^t_F$ and $C_B$ are connected in series (see Fig. 10), $C^U_U$ can
3.2. Offset capacitance $C_{O}^t$

When nobody is in the apartment, there is an offset capacitance $C_{O}^t$ between each transmitter $t$ and the receivers. Because $C_{O}^t$ is in parallel with $C_{U}^t$ in the capacitance model, it affects the measured total capacitance $C_{TOT}^t$ between a transmitter $t$ and the receivers as in the equation

$$C_{TOT}^t = C_{U}^t + C_{O}^t$$

(2)

To remove the effect of $C_{O}^t$ and to get a reference level to which all future measurements could be compared, $C_{O}^t$ needs to be measured once before the person enters the measurement space. Then, this measurement can be subtracted from the measurement result to yield $C_{U}^t$ on its own.

3.3. Stray capacitances $C_{S1}^t$, $C_{S2}^t$ and $C_{S3}^t$

There are three fundamental stray capacitances with the ground. First, $C_{S1}^t$ occurs between each transmitter $t$ and the ground, depending on which parts of the environmental structure act as an insulator. With the floor-tile transmitters, the air acts as the insulator between the large bottom surface of the transmitting electrode and the ground. However, there is a significant capacitive coupling between the metal pillars and the ground, so the plywood spacers on top of the pillars also insulate the transmitters from the ground. With transmitters T1–T3, the non-conductive structures of the objects insulate them from the ground.

Because $C_{S1}^t$ between transmitter $t$ and a receiver is only measured by gauging the received current at the receiving electrode, the amount of current flowing into the environment from the transmitting electrode does not affect the result, as long as the signal source is able to drive the required waveform to the transmitter [35]. Thus, $C_{S1}^t$ does not affect the measured capacitance value with the buffered output of our hardware (see section 5.2) and its effect on the measurements can be discounted.

Second, $C_{S2}^t$ is formed between the human body and the grounded objects in the environment. An increased $C_{S2}^t$ can cause the received current to decrease, because $C_{S2}^t$ conducts a small part of the current emanated by the person to the ground and thus decreases the capacitance reading $C_{U}^t$. However, based on [56], $C_{S2}^t$ remains fairly constant even when large and grounded conductive objects are near the measured person. At most, these type of conductive objects increase $C_{S2}^t$ only by some tens of percent. Because the absolute value of $C_{U}^t$ is not of major interest and the error reflected in it is fairly constant as long as the person is not leaning against the walls, $C_{S2}^t$ can be neglected for position measurements. Likewise, because the appropriate levels for $C_{U}^t$ must be calibrated to recognize user contact to the household objects, $C_{S2}^t$ does not have a significant effect on the activity measurements since its effects are calibrated at the same time.

Third, $C_{S3}^t$ occurs between the receivers and the ground. With a static receiver position $C_{S3}^t$ remains almost constant at all times [56]. Thus, it only has a slight effect on the measured value of $C_{U}^t$.

All in all, because the used positioning method is not based on measuring the absolute values of $C_{U}^t$ but is instead based on the relative values of adjacent transmitters, any small errors in the measurement values are insignificant. Furthermore, because the reference values for contact sensing must be separately calibrated with each object, the environmental capacitances are already taken into account during the calibration period. Therefore, any stray capacitances in the proposed system can be neglected.

3.4. Cable capacitances $C_{CT}^t$, $C_{CR}$

The last two capacitances $C_{CT}^t$ and $C_{CR}$, shown in Fig. 10, are the respective capacitances formed
between the transmitter and receiver cables and the ground. \(C_{LT}^{t}\) is connected in parallel with \(C_{S1}\) and does not affect the measurements for the reasons provided in section 3.3 for \(C_{S1}\). Similarly, \(C_{CR}\) is in parallel with \(C_{S3}\) and has only a small effect on the measurement results. In addition, this effect is removed as a constant offset when the system is initialized (see section 4.1).

4. Tracking method

The basic measurement principle, presented in section 2.1, can be used to track multiple persons at a time in the TUT Smart Home. The following subsections explain the measurement process and the steps needed to operate the measurement system during the different tracking phases.

4.1. Initialization

Prior to any tracking measurements, the measurement system must be calibrated for the given environment so that the changes in \(C_{U}^{t}\) can be detected and compared to set reference levels. Specifically, \(C_{O}\) needs to be measured for each transmitter \(t\) once so that it can be subtracted from all future measurements. This is done 1) by measuring \(C_{TOT}^{t}\) for each transmitter six times when no one is in the measurement space, 2) by taking an average of the measured values of \(C_{TOT}^{t}\) for each transmitter \(t\) separately and 3) by substituting \(C_{O}^{t} = C_{TOT}^{t}\) for each transmitter, because \(C_{U}^{t}\) is zero when nobody is present. Finally, \(C_{O}\) is subtracted during tracking from all future measurements of \(C_{TOT}^{t}\) to obtain \(C_{U}^{t}\):

\[
C_{U}^{t} = C_{TOT}^{t} - C_{O}^{t} \tag{3}
\]

The measurement system only needs to be calibrated once prior to operation. However, if large conductive items such as tables or cabinets are moved in the environment, the system has to be calibrated again. During calibration, all movable and conductive furniture, such as chairs, should be placed as close as possible to their usual places to minimize tracking errors around the furniture. In addition, conductive items with volumes of several litres should be moved away from the measurement electrodes. However, errors caused by such small items are insignificant when tracking the user at floor level and are only minor when sensing contact.

4.2. New person detection

New persons can be detected in the TUT Smart Home either at the door or elsewhere in the apartment. In contrast to the basic measuring principle, where only one transmitter is measured at a time, 16 small electrodes have been virtually combined to form a single large transmitter in front of the door in order to detect new persons entering the apartment. These small electrodes transmit the same measurement signal at the same time and thus enable the measurement to be performed 16 times faster than when scanning a single tile at a time. Furthermore, this measurement method allows the receivers to receive a stronger signal, because the human body couples more effectively with these floor electrodes because of the wider electric field and larger \(C_{F}\).

When a person comes in through the front door, the measured result from the 16 tiles is compared to an experimentally determined \(C_{front\,door}^{detection\,threshold}\) that must exist between the large virtual transmitter at the door and the receivers to indicate that a person has entered the apartment. Because the detection and the initialization processes in the software for the new person can take a few hundred milliseconds, the newly located person’s coordinates are set to coordinates (465, 435) so that the measurements can keep pace with the person and the tiles ahead of the person can be measured as described in the next section. In other words, a person coming in through the front door “pops up” at the given coordinates. The origin of the selected coordinate system (X, Y) was the corner of the bedroom, as shown in Fig. 2.

4.3. Tracking

To measure the position of the person, that person is assigned a set of transmitters which will be measured one at a time in order to give a clear floor position for the user. Although scanning the whole floor area of the apartment sequentially would be a simple way to measure all the \(C_{F}^{t}\), the 11 ms update rate of the capacitance measurement circuitry (see section 5 for more details) would make scanning the whole apartment too slow to allow the tracking of even a single person. Thus, only the transmitters in the proximity of the person are scanned at any one time.

Initially, after the detection of a new person, the person is assigned a set of transmitters within a predefined 100 cm tracking range from the transmitter where the person was detected. Later, this same principle is used
when the tracked person moves around the apartment and only transmitters whose centroids are within the tracking range from the last transmitter which gave out the largest $C_U$ value are included in this set. Thus, the tracking set of transmitters for a given person is constantly changed as the person walks around the floor.

This tracking set is always scanned from left to right, one row of transmitters at a time, starting from the left upper corner when viewing the transmitters from above on the floor plan of the TUT Smart Home. During the scan, $C_{TOT}$ is measured for each transmitter $t$ in the tracking set in a time-multiplexed manner. In practice, a current flows from the transmitter to the body through $C_F$ and from the human body to the receiver through $C_B$ and the measuring circuitry measures the change in the current flow and converts it to a total capacitance value $C_{TOT}$ between the two electrodes. Given the stored value of $C_{TOT}$, $C_{TOT}$ can easily be calculated for each transmitter $t$ separately using Eq. 3. Now, when the person steps over a single transmitting electrode or even comes close enough to a transmitter $t$, $C_{U}$ between the transmitter and a receiver increases as a result of the decreased insulation gap between the electrodes.

If large enough values of $C_{U}$ are measured, above the ambient noise level of the installation environment, the position of the tracked person can be calculated. The $C_{U}$ values are filtered for noise with a constant threshold capacitance value $C_{measurement \ threshold}$, which every $C_{U}$ value must exceed before it is used in the tracking process. In our setup, the value of $C_{measurement \ threshold}$ has been defined experimentally for each part of the apartment. For example, the noise can be up to two times larger with the large transmitters than with the small ones, so $C_{measurement \ threshold}$ must be set about twice as high for the larger electrodes. However, the maximum differences in $C_{measurement \ threshold}$ are within 10% in the areas that are covered mainly by the same size transmitters. In other words, $C_{measurement \ threshold}$ is almost the same in the bedroom and the dining room, because they only have large transmitters and receivers R3 and R5 are placed in the centre of both rooms. Likewise, there is only a slight variation in $C_{measurement \ threshold}$ between the hallway, living room and kitchen areas because they are all mainly covered by the smaller transmitters.

Finally, with the filtered measurement results, the position of the person can be calculated using a simple center of gravity algorithm: the tracked person is positioned between the centroids of the transmitter electrodes’ coordinates in proportion to the measured values of $C_{U}$ for each transmitter. In practice, the signal strength or the value of $C_{U}$ is determined by how much of the foot is covering the transmitter. Thus, if one’s feet are placed on multiple transmitters at the same time, the received signal changes in direct proportion to the area of each transmitter which is covered. Furthermore, because a person has two feet, the person can always be positioned between the two feet, which corresponds well to the head position in a standing or walking posture.

After the position calculation, we perform an additional filtering of the position result with an exponential moving average (EMA) filter

$$P_t = \alpha * P_{t-1} + (1 - \alpha) * C_{tot},$$

where $P_t$ is the filtered position of the person on X and Y coordinates at time $t$, and $C_{tot}$ is the new calculated position of the person. The value of $\alpha$ defines the smoothing factor. To get a fairly well smoothed yet sufficiently fast changing position for the person, $\alpha$ was given a value of 0.92. This value of $\alpha$ is also used in the evaluation of the system in section 6.

Optionally, the last calculated coordinates of the tracked person can be used as the origin for the 100-cm-radius tracking range around the person. However, the method described above was found to work slightly better, because the EMA algorithm dampens the bouncing positioning result to a smoothly moving position and thus also causes the calculated position to follow the real position with some latency. This, in turn, makes it possible for a fast moving person to step out from this tracking range more easily, which causes the system to lose track of the person.

### 4.4. Contact sensing

The contact of the person with the bed, sofa, sofa table, refrigerator, freezer and dining table can be determined by measuring the signal strength associated with the electrode attached to the object. This sensing is possible and fairly easy to implement in the current positioning system because the magnitudes of the measured capacitance changes are directly related to the person’s proximity to the electrodes embedded in the objects. These changes are greater when the absolute distance to the electrode is small, but are non-linear with the changes in distance because the measured capacitances increase quadratically as the distances between the person and the electrodes become shorter.
The receiver electrodes R3–R5 in the bed and underneath the sofa and dining table tabletops give out a strong signal when the person gets close to them or touches the surfaces of these objects. In our implementation, the object proximity is given as a binary signal that is formed by comparing the sum of all $C_{U}$ in the tracking set of the person to a constant threshold capacitance for the object. The threshold has been defined to give a true signal when the person touches the object and a false signal when the object is not touched by the person. Furthermore, to generate a reliable detection signal and to be sure that the person is close to only one of the receivers (since they are physically interconnected), the person’s position has to be in the same room as the receiver.

In contrast to the above method, contact with the freezer, refrigerator and sofa are recognized through the object-embedded transmitters T1–T3. They transmit the same measurement signal as the floor transmitters and their respective $C_{U}$ values increase when the user comes close to the object. As with the object-embedded receivers, a constant threshold has been defined for each object. This threshold is used to give out a true signal when the person touches the object with any part of their body, and a false signal when there is no contact.

4.5. Lost person search

The implemented system may lose the track of the person, if all the $C_{U}$ values in the tracking set of the person go below the set $C_{measurement\ threshold}$, for example, when the person enters a room of the apartment in which no tracking system is installed (bathroom, sauna and balcony). If tracking is lost at the door of these rooms for a period of 2 seconds, the tracking system assumes that the person entered the room behind the door and changes the user coordinates to a static position within that room. For example, if the tracking is lost in front of the balcony door, the system continues to scan the last known position but simulates the person’s position with static coordinates of (1200, 270). When the person steps back into the scanned floor area, that person is detected from that position and normal tracking is resumed.

Furthermore, if the positioning system has lost the track of the person, for example, when the person sits on a non-conducting chair or takes their feet off the floor, the system will scan the apartment for the person. Thus, in addition to scanning the area around the last known position, the system will scan the whole apartment to make sure that the person will be detected, even if they should happen to jump from the chair quickly out of the tracking range. This scanning process through the apartment is conducted by using each of the floor electrodes as transmitters, one by one, and comparing the measured capacitance value to an experimentally set threshold $C_{detection\ threshold}^{all\ floor}$. If the threshold is exceeded, the lost person is placed in the center coordinates of the floor electrode giving out the signal and normal tracking process is resumed. If multiple persons are lost at the same time, the system cannot distinguish between the identities of the persons and the first tracked person of all lost persons will be set to the found position. While the whole apartment is being scanned, no lost persons can be detected within the tracking range of another person.

In all cases, to eliminate temporal electrical events that might cause a lost person to be detected wrongly, continuous new tracking data must be received for a period of 1.3 seconds to guarantee a valid detection signal. If such a signal is not received for this time period, the person is still assumed to be in the original lost position and the scanning is resumed from the original lost position.

4.6. Person removal

The tracking system tracks the person and assumes that the person is inside the apartment unless it recognizes that the person leaves the apartment through the front door. To do this, the system must track the person to the front door and lose the track in front of it. When this happens, the coordinates of the person are moved outside the front door to simulate the case when the person is outdoors. Then, if the person is undetected for more than 3 seconds, the person is removed from the tracking system and normal scanning in front of the door is resumed to detect any new persons entering the apartment.

5. Hardware

The hardware of the measurement system has been divided into multiple separate modules to make the system easily expandable and transformable. A central main module controls the measurement process for the whole apartment and communicates with control software on a PC. Multiple signal driver modules are placed around the apartment under the floor tiles to route the measurement signals to the transmitters. Re-
receivers are routed to the main module using coaxial cables hidden under the floor tiles. In addition, some cabling is needed to connect the drive modules to the main module.

5.1. Main module

The main module, shown in Fig. 11, consists of three separate sub-modules, each of which have their own task. First, a power and processing module is used to provide an appropriate power source for the digital components of the system, handling the measurement process and communicating with the PC. The digital power is provided either through an external power supply and an internal 5-volt regulator or through a USB-serial converter connected to the PC. An ATMega8 microcontroller handles the PC communication through a serial interface and controls the excitation signal to the transmitters. To get a good reference potential for the system, it is grounded to the mains power grid earth with a separate lead.

Second, a capacitance measurement module is built around a high resolution sigma-delta capacitance-to-digital converter (CDC) AD7746 [3], which carries out all the capacitance measurements in the system. It is connected to the microcontroller through a two-wire bus and performs a capacitance measurement between its transmitter and receiver channels every 11 ms, which is at 90.9 Hz. The transmitted 32 kHz, square-wave excitation signal from the CDC is routed to the third module, which consists of a signal multiplexer and buffering circuitry, which are used for buffering and routing the excitation signal and the drive module control signals to the correct drive module at a time.

Up to eight chains of drive modules can be connected to the main module, but in this implementation only a single drive module has been attached to each chain in order to optimize the system’s performance in terms of speed.

5.2. Drive modules

Each drive module, shown in Fig. 12, consists of two 20-channel Allegro A6812 signal drivers [1] that are used to route the excitation signal to the desired transmitters. The A6812 drivers have an internal latched shift register which is programmed serially with the microcontroller prior to measurement. The drive modules are able to withstand voltages up to 60 V and are therefore well suited for driving the 48 V signal that is supplied to the drive modules through the main module.

The A6812 chips are slew-rate limited to 10 V/µs. When they are driven with 48 volts, the maximum transmitted frequency component of the signal is thus limited to about 200 kHz. This guarantees that the transmitters emit virtually no magnetic field, and the system functions in a low-frequency mode with only an electric field present in the environment, because the wavelength of this frequency is about 18 times longer than the largest dimension of the floor tiles.

5.3. Cabling

The measurement signals are routed to and from both the transmitting and receiving electrodes using coaxial cabling to shield the signals from noise. The transmitters are connected to the drive modules with
5.4. Operation

The low-level software in the microcontroller handles the measurement of each tracked person’s transmitters separately. Specifically, the tracking set for a single person is updated by the PC control software to the microcontroller memory. The microcontroller routes the measurement signal to the appropriate transmitters constantly by cycling through the tracking sets of the tracked persons using an interleaved method, where the transmitters for each person are measured alternately. In the same way, searches for new or lost persons are handled by the microcontroller as if they were virtual tracked persons, and thus, these searches are interleaved with the tracking of the persons.

6. Evaluation

The system was evaluated in four different ways to determine how it performed in practice. First, the received signal strength was measured in the TUT Smart Home by walking around the apartment to map it. Second, the positioning accuracy and precision were studied in multiple static standing positions. Third, the dynamic properties of the system were analyzed by having test subjects follow different paths around the apartment. Fourth, a test person was asked to live in the apartment for a period of two weeks and the activities of that person were recorded.

Because we have previously evaluated the positioning accuracy with the 60×60-cm-sized transmitters using the TileTrack system with the same type of floor tiles and a remote receiver [52], it was not necessary to remeasure these figures for this new implementation. Therefore, only the results from our previous work will be cited when discussing these figures. Equally importantly, all these new tests were conducted without shoes to make the results comparable with the previous results.

6.1. Received signal strength

The received signal strength varies greatly according to the person’s position because of the quadratic degradation in the received current as the person gets further away from the receiver and when the person approaches grounded objects. To demonstrate this phenomenon in the TUT Smart Home, the relative signal strength was measured over the whole tracking area.

A 190-cm-tall test person was asked to walk around the home covering all parts of the floor not blocked by furniture. He was asked to take short steps in order to make the calculated position change slowly. The position of the person and the largest \( C_U \) in the tracking set of the test person was saved for each position measured during the test walk. The same test was repeated with the same person two more times and the acquired data was averaged and smoothed to highlight the major trends. The results are visualized in Fig. 13 with the contour levels representing a percentage of the largest received signal in the whole apartment.

As is clearly visible from Fig. 13, the largest measured capacitance \( C_U \) between the user and the environment occurred next to the dining room table because the receiver electrode R5 is there, while at the same time the person is well away from any conducting building structures, thus keeping \( C_{S2} \) small. For the same reasons, signal values of up to 60–80% were received close to the living room table and by the bed. The minimum values were received close to the walls, because the \( C_{S2} \) is greater there and conducts the majority of the measurement current to the walls.

The practical minimum signal strength for tracking a walking person was found to be about 10–20%. However, it was possible to track a slowly moving or standing person even at about 5–10% signal levels. Nevertheless, if the person walked fast enough through the weak spot in the tracking area, the track of the person would be lost at least for a moment. A good example of this is discussed in section 6.4 where the person was lost in the middle of the apartment close to the end of the cabinet, where the signal strength falls below 20%.

6.2. Standing test

To evaluate the accuracy and error distribution of this system in a standing posture with the 30×30-cm-sized transmitters, we asked a 170-cm-tall test person (person 2 in Table 2) to stand in 13 different positions over the tracking area. The test person was guided to align his feet as precisely as possible with the prede-
Fig. 13. The variation in the capacitive coupling between the tracked person and the receivers is demonstrated in the figure as a percentual received signal strength map. The map was obtained by walking slowly around the apartment and by saving the largest measured $C_T$ for each position. The maximum signals were measured beside the dining table as shown by the darkest contour lines but the positions of other receivers are also well recognizable.

Fig. 14. The accuracy and precision of the system were measured in 13 different standing positions over the small transmitters. The determined spots shown as footprints in Fig. 14. These places were carefully selected to show how different kinds of standing positions in different parts of the environment affect the positioning accuracy.

After aligning the feet, the calculated position of the person was recorded and saved for further analysis. The whole test was repeated three times with the same person to detect any possible outliers or major errors, as well as to get more data on the repeatability of the measurements. The measurement results are shown in Fig. 14 with the assumed true position of the person’s head. A cumulative error distribution...
function in Fig. 15 shows the distribution of the errors from the true position. According to these two figures, it is clear that the results lie close to the true position with a good accuracy in more than 90% of the cases because the maximum error with that confidence level is 7.0 cm. However, the maximum error of 18.5 cm was measured in position 12, where Fig. 14 shows a clear right bias in the calculated position. The reason for such a large error is probably caused by the fact that the received signal strength is only about 40% of the maximum measured signal (see Fig. 13) and thus some of the transmitters’ measurements were not taken into account when calculating the user’s position because the measured $C_tU$ did not exceed the set $C_{\text{measurement threshold}}$. In this case, only the measurement results from the transmitter under the true position of the person and the one to the right were giving out strong enough signals to be used for position calculation. Thus, the person is only positioned by the results from these two transmitters and the results from the transmitters under the person’s toes or left heel are not used in the calculation.

Even though the signal is even weaker in position 13, the person is only standing over a single transmitter and the surrounding transmitters give out only a weak signal, so the calculated position is much closer to the true position in all three measurement rounds. Nevertheless, we can conclude that the measurement accuracy goes down when the measured $C_tU$ values approach the set value of $C_{\text{measurement threshold}}$ for the given environment. Thus, the receivers must be placed carefully in the environment to ensure that a strong enough signal to maintain maximum accuracy is received at all times.

The 60×60-cm-sized floor transmitters were tested in [52] with the TileTrack system using the same method as that described above for the smaller transmitters. Because the results with the TileTrack setup were similar to this setup, we will only report here the results from the previous experiment. In short, the accuracy with the 60×60-cm-sized transmitters is never less than 14.3 cm as shown in Fig. 16.

The results from both of these tests are summarized in Table 1 with the mean and standard deviation of errors. From this table, we see that the mean and standard deviation are almost the same for both transmitter sizes. However, the maximum errors differ significantly because of the weak signals from the small transmitters in test position 12, as discussed above. Likewise, if figures 15 and 16 are compared with each other between the 0 and 90% confidence levels, we can see that the slopes of the almost linearly distributed errors are different and the smaller transmitters have 38% smaller error at the 90% confidence level.

6.3. Walking tests

The dynamic properties of the system with the 30×30-cm-sized transmitters were evaluated by having three persons walk along three paths (paths 1–3) a total of three times at three different speeds (slow, normal, fast). The test persons were the same ones as were used for the TileTrack system to make the results easily comparable to the results already achieved with
the larger 60×60-cm-sized transmitters. However, to ensure a more constant speed over a path, the test persons were asked to define their own personal walking speed in steps per minute so that the longitudinal speed would not need to be approximated from the recorded data as was done with the TileTrack setup. Furthermore, with the set step rate we did not need to define any step markers on the floor and thus allowed the walk of the test persons to be as natural as possible. Moreover, this permitted the measuring of multiple walking speeds with natural stride lengths. The personal properties of the test group are shown in Table 2 with the personal step rates and the measured average walking speeds on all paths.

The three walking paths are shown in Fig. 17 with the arrows showing the direction of movement. The start and finish lines of the paths are also marked with the coordinates for start and end positions. All the paths are linear in shape so that the true position of the person, both in the longitudinal and transverse directions, can be estimated more easily and precisely than would have been possible with curved paths. For this experiment, the kitchen and living room carpets were removed and the living room chairs were moved out of path 3 to make the results uniform for each room and unaffected by the carpets.

The three different speeds provided a way to analyze the performance of the system in terms of different walking speeds and to see how the simple positioning algorithm would work in different situations where people walk at different speeds. To help the test persons maintain a constant speed during each walk on these paths, a personal step rate for the measured speed (see Table 2) was provided to the walker audibly through the speakers of the TUT Smart Home.

The first walking path, path 1, was defined in the kitchen, starting at coordinates (900, 480) and ending at (660, 480). The chosen path was just at the borders of the transmitters to see how the measured position would fluctuate alternately between the left and the right side of the path since the left and the right feet would pull the positioning result from one side to the other at each step. In addition, because the kitchen was found to have a fairly poor signal strength (see Fig. 13), this path should give a good picture of the system’s performance in non-optimal conditions. For the same reason, path 2 was also selected to be in the kitchen. However, it was defined to go through the centroids of the transmitters on the path to see how the results would compare to the errors induced by path 1. The start and end coordinates of path 2 are (900, 465) and (660, 465).

The second path, path 2, which simulates walking through the centroids of the transmitters on the path to see how the results would compare to the errors induced by path 1. The start and end coordinates of path 2 are (900, 465) and (660, 465). The third path resembles a more common situation where the person walks somewhat diagonally to the transmitters. The start and end coordinates for each path are shown.

Table 1
The mean (μ) and standard deviation (σ) of the measured errors with the errors at different confidence levels.

<table>
<thead>
<tr>
<th>Test</th>
<th>Transmitter size (cm)</th>
<th>μ (cm)</th>
<th>σ (cm)</th>
<th>90% (cm)</th>
<th>Max. (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing</td>
<td>30×30</td>
<td>4.2</td>
<td>4.5</td>
<td>7.0</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>60×60</td>
<td>5.8</td>
<td>4.2</td>
<td>11.3</td>
<td>14.3</td>
</tr>
<tr>
<td>Walking</td>
<td>30×30</td>
<td>9.4</td>
<td>6.5</td>
<td>17.3</td>
<td>51.1</td>
</tr>
<tr>
<td></td>
<td>60×60</td>
<td>17.5</td>
<td>11.3</td>
<td>32.8</td>
<td>40.7</td>
</tr>
</tbody>
</table>

Table 2
Test group properties and measured average walking speeds on all paths

<table>
<thead>
<tr>
<th>Sex</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Shoe size (European)</th>
<th>Step rate (steps per minute)</th>
<th>Walking speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Slow</td>
<td>Normal</td>
</tr>
<tr>
<td>Person 1</td>
<td>Male</td>
<td>183</td>
<td>86</td>
<td>43</td>
<td>80</td>
</tr>
<tr>
<td>Person 2</td>
<td>Male</td>
<td>170</td>
<td>70</td>
<td>40</td>
<td>88</td>
</tr>
<tr>
<td>Person 3</td>
<td>Female</td>
<td>157</td>
<td>61</td>
<td>37</td>
<td>84</td>
</tr>
</tbody>
</table>

Fig. 17. The dynamic properties of the system were analyzed by having the three test persons walk three different linear paths. The first path demonstrated the maximum error situation, where the feet of the person would alternately be placed on the transmitters on each side of the path. In contrast, the second path simulated a situation where the person walks through the centroids of the transmitters. The third path resembles a more common situation where the person walks somewhat diagonally to the transmitters. The start and end coordinates for each path are shown.
Fig. 18. An example of the measured walking tracks on path 1 at different walking speeds with person 2. The gray arrow in the background shows the beginning and ending of the path.

and (660, 465), respectively. Both of these paths were 240 cm in length.

Path 3 was set in the living room and hallway areas to create a long diagonal track, representing a more common situation where the floor is crossed in an arbitrary direction. The start and end coordinates were set at (630, 185) and (390, 393) respectively, giving the path a length of 318 cm. In comparison with paths 1 and 2, the received signal strength would be a little higher at the beginning of the path, but close to the kitchen levels at the end of the path.

Before each measurement, all the test persons were instructed to practice walking along the test path with the metronome giving their personal beat (see Table 2) in the background. The intention was to let the subjects learn to walk to the beat and to maintain a constant stride length, in order to provide a constant speed over the whole measurement path. After a few test walks the test person became acquainted with the walking rhythm and was allowed to perform the actual measurement walk. In fact, the test person was instructed to stand well away from the start of the path before beginning the walk to allow time to accelerate to the constant walking speed. In the same way, the test person was instructed to continue walking at the practiced constant speed beyond the finish line to ensure that the constant speed was maintained over the whole length of the path. For the sake of consistency, the walking times between the start and end positions were monitored during the walks with a timer. If the walking time was not found to be consistent with the others, the test person was asked to repeat the walk again. Finally, all the measurement data was fed into a computer for analysis.

Figures 18–20 show examples of the recorded tracks with person 2 on all three paths. As predicted, the recorded position of the person on path 1, as shown in Fig. 18, fluctuates strongly between the left and right side of the path at all walking speeds. In fact, the positions of the steps can be easily recognized from the tracks, because they always turn from one to the other side of the path with each step. Predictably, this increases the number of errors between 0 and 15 cm, as is shown by the cumulative error distribution function for path 1 in Fig. 21, because the centroids of the transmitters adjacent to the path are 15 cm away from the straight path. Anyhow, for any given application the data could be smoothed to get a nice straight track, although this would compromise the real-time response of the system. In numbers, the dynamic error could be up to 51.1 cm, but is only 17.6 cm at 90% confidence level on path 1.

If we analyze the straightness of the paths on path 1 versus the walking speed, we can recognize that the slow walking speed has resulted in the straightest track. This is probably due to the measurement system having enough time to scan the area around the person more times than with the normal and fast walking speeds. Thus, the system has been able to use the readings from multiple transmitters instead of the transmitter immediately below the foot to measure the movement of the foot in the air, and use these measurements...
for positioning the person more closely on the path. This deduction is also supported by the other test persons’ data, which show similar behavior.

On path 2 the transverse error is not as great as on path 1 and the measured tracks become straighter at higher walking speeds. This can be explained with similar reasoning as with path 1: at higher speeds the system has less time to scan the tiles around the person and to recognize any changes in the measured capacitance in the adjacent transmitters next to the transmitters on the path. Path 2 gives the best results in terms of errors as shown by Fig. 21: the accuracy is at least 31 cm and 15.8 cm at 90% confidence level.

The tracking results with path 3 shown in Fig. 20 look much the same as with path 2. Here, the measured track at slow speed fluctuates only a little in the transverse direction and follows the path closely until near the end, at which point it deviates sharply from the path resulting in a large transverse error. The reason for this large deviation around the path’s end point is probably the fact that at this point the left foot is partially covering a large transmitting tile, and the system does not have enough time to scan the smaller tiles on which the left foot is placed. Thus, the result is pulled towards the centroid of the large transmitter.

Furthermore, on path 3 the normal and fast walking speeds result in straighter tracks than at the slow speed, but interestingly both of them show a situation where the measured position is coming backwards on the path. That is, the calculated user position moves nicely forward with the test person on the path but at one point momentarily jumps backwards about 10–15 cm and then continues advancing along the path with both the normal and fast speeds. Again, this deviation is presumed to be caused by the limited scanning speed of the system and the simplicity of the measurement algorithm, which does not optimize the scan in any way. The maximum error is almost the same as with path 1, being 51.3 cm, and at 90% confidence level the accuracy is 17.9 cm.

In addition to analyzing the differences in the paths, the errors in the measured data can be analyzed in terms of walking speed and personal differences between the test persons. First, Fig. 22 shows how the slow walking speed gives somewhat better accuracy than a walk at normal or fast speeds. In figures, the maximum errors are 46.5 cm with a slow walk and

![Fig. 21. Cumulative error distribution functions for the three test paths with all persons and speeds.](image1)

![Fig. 22. Cumulative error distribution functions for different walking speeds with all test paths and persons.](image2)

![Fig. 23. Cumulative error distribution functions for the three test persons with all paths and speeds.](image3)
about 51 cm with the higher speeds and at 90% confidence level the accuracies are 14.1, 17.1, and 20.1 cm for the slow, normal and fast speeds, respectively.

Second, all three test persons seem to get similar results and the errors do not differ much. From Fig. 23 we can see, however, that the smallest test person (person 3) did get slightly worse results than the other two. From the raw data we see that the errors with person 3 were somewhat greater on paths 1 and 2 than on path 3. However, we were not able to verify any single reason for this slight difference, but the reason might be in the different walking style or in the shorter stride length. In figures, the maximum errors are about 47 cm for person 1 and 51 cm for persons 2 and 3. At 90% confidence level the accuracy is 15.7, 15.9 and 18.8 cm with persons 1–3, respectively.

When looking at figures 21–23 or analyzing the results from Table 1, it is important to understand that the depicted results contain the dynamic errors that include both the longitudinal and transverse errors of the positioning system. Indeed, by analyzing the data carefully, we have found out that the maximum errors in the order of tens of centimeters are caused mainly by the longitudinal errors in the measurements. Thus, if no real-time response is required for a given application and the information about the walked track is sufficient, a much better accuracy can be achieved. For example, the maximum transverse error on paths 1 and 2 are only 27 and 23 cm at 100% confidence level, and 14 and 10 cm at 90% confidence level, respectively. Moreover, by smoothing the measured data e.g. with a moving average filter, very straight tracks with very little error can be recorded. Thus, it is up to the application developer to select the correct amount of filtering to compromise between the response time and the tracking accuracy of the system.

The results with the 60×60-cm-sized transmitters had already been measured in TileTrack [52], but are summarized in Table 1 with the new results. With TileTrack, we found that a person was positioned with 40.7 cm and 32.9 cm accuracies at 100% and 90% confidence levels, respectively. Thus, the measured maximum errors in the user position are somewhat lower with the larger transmitters, but between 0 and 90% confidence levels the smaller transmitters are roughly two times more accurate. We see that the largest errors with the small transmitters are caused by the limited scanning speed of the system and the simple tracking algorithm, because the system cannot keep up with the tracked person as well as with the large transmitters (see section 7.2 for further discussion).

6.4. Two-week living test

The positioning system described in this paper was put to a long-term test by having a test person living in the TUT Smart Home for a period of 14 days. A 19-year old, 163-cm tall and 64-kg-weight male with European foot size 40 was selected for the task and instructed to live as normally as possible in the apartment. The position of the person was recorded with the system at its full speed and the data was logged into a central repository. Due to some bugs in the software, the positioning, or some other component of the control software of the TUT Smart Home stopped working a total of three times during the test. This prevented the collection of the data, causing small gaps where no position data is available. Nevertheless, all the position and annotation data that was collected during this long-term test is available at [21] and can be used freely for any purposes.

The test person worked part-time during the test period and was mainly away from the apartment in the daytime. He was asked to stay at home in the evenings as often as possible so that more data could be acquired during the test. Fortunately, he spent most of the evening hours in the apartment and about 12 days worth of position data were recorded during the whole test period. In addition, the test person was asked to record all major actions and activities when they were about to take place, on a digital voice recorder. In order to fulfill this requirement, he carried the recorder anywhere he went in the apartment, except the shower and sauna. All recorded voice data was timestamped by the recorder and so it is in sync with all other data. Thus, the voice recordings can be used as an annotation to all the measured position and activity data in the TUT Smart Home during the test period and provide a means to check the validity of the measurement results.

Fig. 24 shows an example of the measured position data during a one-hour period on the third evening of the test. Both the raw position data and the smoothed walking tracks of the person show clearly in which parts of the apartment the person walked or stayed in. This smoothing has been performed by taking a moving average of seven consecutive measurement values.

Fig. 24 also shows the timestamps at several locations so that the position data can be compared with Fig. 25, which shows the measured activity data from the environment as contacts with the common household items during the same one-hour period. The latter figure also shows the annotation recorded by the test person.
Fig. 24. An example of the acquired raw and smoothed walking tracks during the long term living test. The data was gathered between 20:00 and 21:00 hours on the third day of living in TUT Smart Home. The activities during this hour are shown in Fig. 25.

An analysis of the raw tracking data in Fig. 24 shows that it sways from one side to the other of the smoothed walking track. Even though it seems somewhat erratic, it meticulously follows the footsteps of the tracked person. In contrast, the smoothed track shows clearly the path that the body or head of the person most probably followed.

If the track of the person is lost, the position of the person might even seem to jump through a wall or cabinet, because the positioning algorithm did not take into account the walls or other large practically unmovable obstacles in the environment. An illustration of this can be seen in Fig. 24, which shows that the recorded path of the person jumped through a cabinet when he walked in the hallway towards the bathroom, just before the weak signal reception area in the middle of the apartment shown in Fig. 13. By carefully looking at the positioning data, we have determined
that the person was lost for a period of 23 seconds at 20:47:49 at the south end of the cabinet, but then found again 20:48:12 in front of the bathroom door. This data is also supported by the annotation data recorded at 20:47:56 which confirms that the test person was in the bathroom at the time of the recording. Thus, with our simple tracking algorithm the calculated position of the person moved from the lost to the found position and the corresponding line was drawn in Fig. 24 through the cabinet.

The annotation data matches well with the recorded activity data of Fig. 25 when it is analyzed together with the plotted tracks of the person shown in Fig. 24. In fact, if the inaccuracy in the timestamps of the annotations are taken into account, we cannot find any discrepancies between the annotation data, measured walking tracks and the activity data shown in these figures. However, it has not yet been possible to go through the whole 12 days of data to confirm that there are no errors in the data at all. Nevertheless, based on this example, we can conclude that the embedded electrodes in the transmitters and the receivers can well be used for reliable user activity measurements.

7. Discussion

According to the presented actual results, the positioning system can be used to position a single person reliably if the person is standing or walking in the apartment. Further, this system is able to recognise user contact with the common household objects that have been embedded with hidden electrodes. Although this system can function as an input for many different types of applications and can capture human actions with reasonable accuracy, to get a better picture of the system’s applicability to different application areas, the properties and the use of the system will be discussed in detail in this section. The discussion is divided into several subsections which examine its pros and cons from different points of view, compare this system’s properties to those of previous studies, where possible, and provide indications for future developments.

7.1. Accuracy

In comparison to previous systems, this passive system cannot measure a person’s position with the same accuracy as many of the active systems where the person must carry a small device or a tag with them. For example, the two well-known ultrasound-based location systems, Cricket [38] and Bat [59], can position a person with about 10 cm and 5 cm accuracy, respectively. Likewise, a commercial Ubisense location system based on UWB (Ultra-wideband) technology can track a person with about 15 cm accuracy [20]. However, the system presented here gives more accurate results than many of the traditional radio frequency based techniques [46,20], whose accuracy is typically above one meter.

Furthermore, this system has somewhat better accuracy than the passive infrared system of Hauschildt et al. [19], which can only position a single person with an accuracy of 26 cm. On the other hand, this system is not as accurate as the passive ultrasound system of Nishida et al. [33], which can track a human head with less than 5 cm error. However, it is important to note that in its current state of development the system of Hauschildt et al. suffers from reflection and dynamic background radiation issues, and the ultrasonic system of Nishida et al. would require the installation of hundreds of sensors in the ceiling of the TUT Smart Home in order to cover most of the rooms.

If the accuracy of this system is compared to the capacitive positioning system of Rimminen et al. [40,41], this system has a slightly better mean accuracy than Rimminen’s system. Indeed, Rimminen et al. use 25×50-cm-sized electrodes on the floor to obtain a mean accuracy of 21.2 cm for walking persons while this system obtained a mean accuracy of 9.4 cm and 17.5 cm with the 30×30-cm-sized and 60×60-cm-sized floor electrodes, respectively. Furthermore, the standard deviations of this system are slightly smaller: 13.2 cm for Rimminen’s system versus 6.5 and 11.3 cm respectively for the small and large transmitters used in this system. The main reason that this system is more accurate than the Rimminen one, even with the larger electrodes, is probably due to the fact that Rimminen et al.’s system had wiring between the electrodes [42, p. 10] on the floor surface. This meant that the available electrode area on the floor surface was reduced, which led to an increase in the positioning errors. Nevertheless, our results are supported by the findings of Rimminen et al. and can thus be considered valid and accurate.

7.2. Reliability

As already discussed in the evaluation section of this paper, this system can sometimes lose the track of the person. Typical reasons for this are 1) insufficient sig-
nal strength over a certain area of the apartment, 2) a person moving too fast and 3) a person moving in an unusual way, such as leaping on the floor, jumping from a nonconducting chair to another or crawling on the floor in areas of low signal strength. Although fixing all these problems is challenging, the first two problems could be fixed, or at least alleviated in many ways. First, a better receiver network could be established by placing more receivers in the environment. If the receivers could be placed, for example, in the furniture, the contact with these items could also be recognized. Second, the structure of the floor tiles could be changed to yield a greater $C_{f}^{U}$. This could be done, for example, by moving the transmitting electrode closer to the surface of the tiles. In an installation in an old house this could be achieved by spreading the transmitting electrodes directly over the existing and nonconducting floor surface and by installing a new, thin floor surface directly on top of it. Also, the use of thinner carpets on the floor would help with this issue. Third, by decreasing the total number of transmitters, for example, by using only the larger $60\times60$-cm-sized electrodes, the scanning speed of the current implementation could be increased significantly. And fourth, new electronic circuitry that would enable faster scanning of tiles could make a significant difference.

In addition to the above improvements, the tracking algorithm of the system could be enhanced significantly to help with the speed issues. Because the current tracking algorithm only scans the transmitters from left-to-right and a single row at a time, and the tracking set is updated to the microcontroller at unknown times, it is possible that some of the transmitters in the tracking set are not scanned at all before moving on to the next set of transmitters. In other words, we cannot guarantee that the transmitters under the person are always scanned. For example, the scanning order causes transmitters under the person to be measured more often when the person walks to the left and/or upwards on the floor plan. Conversely, walking to the right and downwards causes the measurement system to measure more transmitters behind than ahead of the person. Unfortunately, this perfectly fixable software issue could not be addressed before the long-term living test and so tracking was sometimes lost during the test.

7.3. Multiple occupancy

Although the presented system was implemented to be able to position multiple persons in the TUT Smart Home, the implementation was not tested with multiple persons because of the issues discussed in section 7.2. The main reason for this was found to be the limited scanning speed of the hardware. This is because the number of transmitters that need to be scanned increases sharply with the number of persons, especially if the persons are not close to each other. As a result, all of the tracked persons can easily be lost, for example if they all walk at the same time. This issue could be tackled, however, with the steps mentioned above in section 7.2. Despite all the issues with the current implementation, we later tested the system with multiple persons using the methods discussed in section 7.9 and found that with a modified receiver in the dining room, the system was able to position at least three walking persons accurately.

7.4. Contact sensing

Both the transmitters and the receivers of the environment were shown to work well with regards to touch recognition during the long-term test. However, it is important to understand that no transmitter can be used effectively if there are no good receivers nearby. Thus, it would be more efficient to use receivers to recognize contact with the objects in the environment, because the floor is already covered with transmitters. Similarly, the measured $C_{f}^{U}$ is high close to the receivers, so the proximity to the receiving electrode could be measured much more easily, even a few meters away from the receiver [52]. However, if multiple receivers are installed close to each other, for example so that the person can touch them at the same time, they cannot be distinguished from each other. This is because, although they are separated physically, they are connected to the same wire running to the measurement circuitry. For these reasons, contacts with the kitchen and living room tables are distinguished only by the calculated user position. That is, the two receivers are far enough from each other not to be touched at the same time by the same person. However, if multiple persons touch the same or different receivers at the same time, they can still be easily distinguished if the persons have different positions and thus different transmitters under them sending the measurement signals.

In contrast, transmitters can be distinguished from each other even if they are installed close to each other. If two people are standing near the same transmitter at the same time, and one of them touches the transmitter, we cannot tell with our current algorithm who is
touched by either of the persons touching the transmitter. In other words, either of the persons touching the transmitter could conduct a recognizable current to the receivers. However, if the current implementation of the algorithm were altered so that both the transmitter in the object and the one under the person could be actuated at the same time, but at different times for the two persons, the received signal would appear only for the person touching the transmitter. Thus, the separation of multiple persons could be achieved merely by changing the algorithm.

Even though the proximity or distance to the electrodes could be measured from the data by observing the signal strengths, we did not analyze this because it would be necessary to establish a capacitance-to-distance conversion function for each electrode separately, using for example the methods of [53]. In the case of the receivers, however, it is best to observe the sum of all $C_i$ within the tracking range of the person and compare this sum to a calibrated reference level. With transmitters, the individual signal strengths from individual transmitters can be directly compared to a calibrated reference level.

To minimize errors in contact sensing, large items close to the object-embedded electrodes should be removed prior to the system calibration. For example, large jugs of waters should be removed from the tables that are used for contact sensing. However, the effects of these types of items are usually much lower than that of the people whose contact to the electrodes are sensed, so their practical effects are usually insignificant. For example, in the TUT Smart Home the calibration reference levels for touch detection need not be changed, even if items with volumes of several liters are placed on the living and dining room tables.

### 7.5. Construction, cost and complexity

The physical construction of the electrodes is simple, because they consist of single layers of conductive material which is easily available. For example, the floor electrodes could be built from aluminum foil placed underneath the floor surface, which could be either wood, plastic or ceramic. Similarly, the receiver electrodes could be built out of almost any conductive solids, textiles, or even from a sparse wire net. In fact, we have successfully tested a 0.22 mm-thick wire-net receiver in the ceiling of the TUT Smart Home with wires running in parallel through the room with 60-cm spacing. This installation is discussed in detail in section 7.9.

Unfortunately, the current design requires a single coaxial cable for each electrode, which means that the amount of cabling required to cover a house can be large. In the case of the TUT Smart Home, about 400 meters of coaxial cables were installed to feed the measurement signals to and from the electrodes. One solution to this problem would be to replace the cabling and the electrodes with, for example, the thin sensor laminate made by UPM-Kymmene Oyj shown in [42, p. 11]. This 150-µm-thick laminate was made from a 13-µm-thick aluminum film that was laminated between two PET (polyethylene terephthalate) films. All the wiring to the 36 × 30-cm-sized electrodes were incorporated into this laminate using etching techniques and were made accessible at the end of the laminate using a standard connector. Thus, this type of sensor material has already been commercially produced and could well be used with the system presented in this paper.

Because the current electronic implementation does not have a large component count, the electronic implementation of the system becomes affordable. Indeed, the single AD7746 CDC chip used in the current implementation only costs about $5 when purchased in bulk. Also, by using newer CDC chips, for example Analog Devices AD7142, the price of a single CDC unit with 14 channels is reduced to $1.37 in large quantities. In fact, almost any cheap microcontroller in the price range of $1 to $2 could handle the communication to the CDC and the attached PC. Although the production of Allegro A6812 signal drivers has been discontinued, their function could be implemented with other affordable components. Therefore, the total cost of the electronics hardware could be a two figure sum in dollars. Equally important, the power consumption of the hardware is low because not much power is needed for either the components or for driving the electrodes.

The above compares well with the costs involved using ultrasound sensors. The ultrasound sensors of Nishida et al. [33] would require a large array of sensors installed close to each other in the ceiling. As a result, the installation and operating costs of such a system would be more expensive than with this system. However, the infrared sensors of Hauschildt et al. [19] could be cheaper, as only eight of them would be required in a room.
7.6. Shoes

Although the effects of shoes were not studied in this paper, they can have a significant effect on the ability of the system to track people and on the accuracy of the results [56]. This happens, because $C_t F$ gets smaller in inverse proportion to the distance between the feet and the transmitters, and the insulation characteristics of shoes cause negative effects. For example, if the person walks in the kitchen with shoes on, the measured signal strength with the receiver can be only tens of percent of the magnitude without shoes. Based on the findings of [56], the received signal strength even directly under the receiver R2 can drop from about 20% to 10%, which would make tracking a person less reliable due to the increased possibility of losing track of them entirely. Furthermore, in the weak signal reception area in the middle of the apartment shown in Fig. 13 the signal strength drops to 10% or less if the subject is wearing shoes, causing the system to sometimes lose track of the person in that area. To combat this issue, the receivers should cover the whole apartment more evenly, for example with the receiver setup discussed in section 7.9, to ensure an adequate received signal strength in every part of the home.

Furthermore, $C_t F$ could be increased with and without shoes, if the transmitting electrodes were to be brought closer to the surface of the floor. For example, by covering the floor with a thin plastic mat or wood laminate and placing the electrodes directly underneath the surface of the floor, the current flow to the receivers would be increased.

7.7. Privacy

If the proposed implementation is compared to video-based methods, the level of privacy is much higher. In fact, we believe that not many people would accept a video camera in their bedroom or bathroom, even if it was only used for monitoring that person, without any human intervention, because the inhabitant might not have any control of the equipment. Particularly, if the inhabitant is not technically oriented, it is hard for him or her to confirm that the video material is not fed out from the building for anything other than the intended purposes. Thus, because the proposed capacitive methods can be implemented in an unobtrusive way which does not violate one’s privacy, the system is well suited for use in any home or residence.

7.8. Safety

The system can be considered completely safe to human beings, because the electric and magnetic fields in the human body are well below the International Commission on Non-Ionizing Radiation Protection (ICNIRP) set restrictions [18]. The commission has set the limit for maximum internal electric field strength in the human body to 4.32 V/m at the 32 kHz frequency and the first harmonics of the used square-wave signal. Because the human body conducts these frequencies well, the potential difference between the feet and other parts of the body is only about one volt as shown by our simulations with the models of [56]. Hence, the internal electric field within the human body remains under 1 V/m, which is well below the set limit.

Because the wavelength of the 32 kHz square-wave signal and its harmonics are in the order of magnitude of kilometers, while the used floor electrode dimensions are measured in meters, the emanated magnetic field from the transmitter is virtually nil. Thus, the human body’s exposure to magnetic fields in this system is negligible.

Equally important, the current levels in the human body need to stay below the ICNIRP set reference levels for general public exposure [18]. To prove this, we simulated the current in the neck with a 170-cm-sized body model of [56] having the head grounded. According to the simulation results, the current in the neck is only 225 $\mu$A. Because the maximum current set by the ICNIRP for the 2.5–100 kHz frequency range is 6.4 mA and the simulated current remains well under the set limit, the used measurement currents do not pose any safety risks.

7.9. Three dimensional tracking

Because $C_t U$ changes according to the distance between the person and the receiver, it could be used to measure the height of the person if the receiving electrode could be installed above the tracked person, in the ceiling, and the measured capacitance could be converted to an absolute distance between these objects. Thus, by measuring $C_t U$ with the method proposed in [56], the positioning system of this paper could be modified to determine the height and posture of the person simultaneously with their position on the floor. Further, by using the same receiver configuration in the ceiling, the received signal strength would be equalized in the apartment and the problems of losing the track of the person would be minimised.
Supporting sticks

Wire receiver

Fig. 26. The positioning system was briefly tested with a loose enamel wire net as a receiver in the ceiling of the dining and living rooms. This practically invisible wire net, supported by 9-cm-long wooden poles, can be used to equalize the received signal strength in the apartment and thus make the system more reliable. The simultaneous measurement of user height and posture with the user position also becomes possible using the techniques of [56].

To check the above-mentioned idea, the same loosely woven, enameled copper wire net used in [56] was used as a receiver in the TUT Smart Home. This wire receiver, shown in Fig. 26, was installed 9 cm below the ceiling and supported with wooden poles. The wires of the receiver were run back and forth in the dining and living room areas parallel to each other with a spacing of 60 cm.

Because the proposed height and posture measurement methods had already been found to be feasible with a moving person in [56], we only tested the wire receiver briefly in the dining room area with three persons simultaneously walking around the room wearing shoes. During this short test, the system was found to track all three persons well in every part of the room, even though a few times two persons with intersecting tracks changed their identities or were lost for a while. However, it is important to note that no efforts were made towards solving this problem in this study, and the tracking algorithm could certainly be improved to deal with intersecting tracks much more efficiently. For example, by applying some computer vision algorithms or other models that could predict user position, the tracking algorithm could be made much more robust. Nevertheless, because of the large $C_f^p$ with the 60×60-cm-sized transmitters, the setup with the wire receiver was found to be usable and fairly reliable, even with shoes and multiple persons. Therefore, it appears likely that the system proposed in this paper could well be integrated with the methods of [56] and should enable the implementation of three-dimensional tracking of multiple persons in the TUT Smart Home in the future.

7.10. Practical performance

Although no specific tests were performed with this system to analyze how it would work in practice in some general use scenarios, this subsection will present some of our thoughts on these matters. First, the system should be able to track whole families, including children and large pets, with the same methods that were used with adults. In practice, however, the receiver electrodes would need to be placed somewhat more densely in the measurement space to enable an adequate $C_f^p$ for tracking children and pets. Nevertheless, with the wire network in the ceiling, the height of each tracked person or pet could be measured as discussed in section 7.9. Whatever the case, more tests would need to be performed with both children and pets to be able to verify the necessary receiver configuration for robust tracking.

Second, we found no problems in tracking people even if they interacted with each other as long as they stayed on different tiles. However, if people stood on the same tiles, the current tracking algorithm could not position the people as accurately as it could have done otherwise. For example, in cases where people shake hands, hug, help each other with coats, or stand next to each other talking, the positions of the people can still be measured, but the achieved accuracy might momentarily decrease.

8. Conclusion

The main objective of this study was to show that both human position and activity can be measured accurately and reliably using capacitive transmit-mode sensors hidden in the environment. This paper presented the construction of such a measurement system and verified its operation in the TUT Smart Home with both short and long-term tests. The paper concluded with a detailed discussion of the main advantages and disadvantages of the system.

The short-term tests of the system showed that the system can position a standing person with 7 and 11-cm accuracy at 90% confidence level using the 30×30-cm and 60×60-cm-sized transmitting floor electrodes, respectively. A walking person can be po-
sitioned to within 17 and 33 cm accuracies using these different sizes of floor tiles at 90% confidence level. Furthermore, if no real-time information is needed and only the walked track of the person is sufficient for a given application, the large longitudinal errors along the walking path, now included in the above figures, could be ignored. By only taking the transverse errors into consideration, more accurate results could be obtained. Equally important, the long-term living test showed the system to be capable of monitoring a single person for two weeks in terms of position and contact with the common household items such as a bed, sofa, dining table and refrigerator. During this two-week test a large amount of data was collected and has been made available for free download at [21].

The main advantages of the system presented here are its ability to monitor a person unobtrusively without compromising the person’s privacy. In addition, the user of the system does not need to wear any tags and his or her position and contact with common household objects in the installation environment can be measured passively in all the places where the system electrodes have been installed. In addition, the system can easily be combined with the system of [56] to implement three-dimensional positioning and posture recognition over large areas. Although it was unfortunate that the system could not be fully tested with multiple people, we were able to show that this should be possible if the issues of receiver coverage and the limited scanning speed of the electronics could be addressed. Indeed, by moving the receivers of the system from the tables to the ceiling, we enabled three-dimensional positioning and were able demonstrate that the tracking of multiple persons was possible even with the current electronics.

The unobtrusive measurement methods of this paper are well suited for a wide range of applications. For example, personal activity routines could be automatically learned with the support of this system and could be utilized with modern home automation systems. In addition, the monitoring of physical and cognitive health through the observation of home activities over long periods of time could enable new types of healthcare services for elderly and/or disabled people who need continuous support in their life. Finally, multiple gaming and virtual reality applications could benefit from the unobtrusive measurement methods used in this system.

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