TileTrack: Capacitive Human Tracking Using Floor Tiles

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Abstract—**Accurate, simple and affordable methods for passive indoor tracking of human beings are still missing. In this article, we describe the development of an unobtrusive two-dimensional human positioning system based on low-frequency electric fields. The system's operation is based on measuring the capacitance between multiple floor tiles and a receiving electrode. The presented system is invisible to the user and uses a single-chip solution to measure the capacitances. The implemented system is evaluated with two different types of receiving electrodes and the results are presented. With the used tiles, the system can locate a standing human with at least 15 cm accuracy and track a walking person with at least 41 cm accuracy. The update rate of the system is 10 Hz.**

Pervasive positioning, pervasive tracking, human tracking, ubiquitous location systems, electric field, capacitive measurement

I. Introduction

Unobtrusive tracking of persons is one of the key functions required in future pervasive environments. Unobtrusive measurements of humans and their actions make it possible to create user-friendly and supporting environments in which a user can feel unobserved but still assisted. Despite the great attention these methods have received, there still exists a need for simple and affordable systems which could identify and track people in indoor environments. These systems can be used, for example, in context sensitive applications in future homes. Furthermore, they can serve as a tool for healthcare professionals to support assisted living of the elderly at home.

This paper presents a simple and robust method to position and track people indoor accurately. The method is based on the fact, that humans conduct a low-frequency signal well [1]. In our system, a transmitted measurement signal is coupled through a human body to a receiving electrode whose placement is almost arbitrary. The measurement is performed using a commercial single-chip capacitance-to-digital converter (CDC) [2]. The person is positioned on the floor using the physical locations of the floor tiles on which the user is standing and the measured signal strengths from these tiles. The developed system can be totally hidden from its users into the structures of the building, and its positioning accuracy does not depend on shoes or clothing.

The paper begins with a review of related work. Next, it presents the used electrode configuration with a capacitance model of the environment. Then, it continues by discussing the measurement hardware and the tracking method with the required calculations. Following that, the system is evaluated with two different receiving electrodes and with three persons. Finally, we discuss the test results, compare our system to previous work, and present a conclusion.

II. Related Work

Previously, many different kinds of indoor positioning systems have been built based on, for example, infrared [3] or ultrasonic sensors [4], or on ultrasound and RF transmissions [5]. A good comparison of these systems can be found from [6]. Further, [7] presents a recent survey on wireless indoor positioning techniques.

Despite the great number of existing systems, many of these systems require a user carrying a special transceiver and are thus called active systems. Active systems can be considered obtrusive and troublesome for continuous use, because one needs to change batteries to them or pay attention to them otherwise, for example, when changing clothes. Moreover, such systems cannot track people when they are not wearing the required equipment.

To overcome the problems of active systems, many passive positioning systems have been developed. Most of these are based on sensors that are embedded in the environment and thus do not require the user paying any attention to them. For example, video based systems [8] can operate in a passive way. However, they are hard to hide, because they require a line of sight from the user to the camera. Moreover, video cameras always raise privacy issues.

One way to build an unobtrusive tracking system is to measure the pressure under humans' feet. This idea became concrete already in 1997, when The Magic Carpet [9] was introduced. It used piezoelectric wires below the floor to measure position. In the same year, the ORL Active Floor [10] was published. It used pressure sensitive sensors below floor tiles. Later in 2003, an electret film [11] was proposed as a new technique to measure pressure signals. A year later, Z-Tiles [12] was published. It is a modular and pressure sensitive floor implemented with strain gauges.

The use of pressure as a measurable quantity has been a great step towards the invisible human tracking system. However, such systems are fairly complex and not very scalable in terms of installation, because pressure sensors need somewhat flexible floor and some installation space below the floor level to hide the sensors. Further, because of the

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mechanical structure of the pressure sensors, they are not optimal in terms of robustness and cost-effectiveness. Therefore, a need for more sophisticated techniques exists.

Capacitive sensors, on the contrary, provide a practical solution to the above problems. They use electric fields as their perception instrument, which penetrate non-conducting objects such as wooden or plastic floor coverings, furniture, or walls. Thus, the electrodes of a capacitive sensor can easily be hidden in the structures of a home, and the system made invisible to the users. Further, the electrodes can be constructed from very thin, cheap, scalable, and durable materials. For example, the electrodes can be built of plain aluminum foil, purchasable at any grocery store, and the foil can be cut in to proper pieces at the installation site.

Even though the electrodes are easily constructible, a correct measurement method must be selected for each application. Today, three primary methods or application modes for capacitive sensing are identified: transmit, shunt, and loading mode [13]. In transmit mode, a transmitting electrode emanates a low-frequency signal that is measured with a separate receiving electrode. If a person stands very close to either of these electrodes, his or her body electronically couples with the near electrode and thus prolongs the electrode dimensions. As a result, a capacitance change between the two electrodes can be measured. In shunt mode, a grounded human body blocks the electric field between the transmitting and the receiving electrode by draining the flowing current to the ground. In loading mode, a single electrode is used both to create an electric field between the electrode and the grounded human body and to measure the capacitance between these.

Equally important, the electrode layout and the electrical circuitry that measures these capacitances need to be carefully designed to create a workable sensing system. These problems have been researched widely over the last two decades. For example, in [14] the authors present an interactive table that reliably tracks multiple hands and fingers over a non-conducting surface using the transmit mode and a grid of wires as electrodes. Further, [13] reports many types of graphical applications, in which capacitive sensing has been used in its two primary modes: it describes a graphical screen that recognizes gestures by measuring the capacitances between the human and four receiving electrodes at the corners of the screen by using the transmit mode, and a 3D mouse that uses shunt-mode sensing to measure the 3D placement of a hand over a table. In [15], the author presents a workable measurement board called School of Fish for both transmit and shunt mode measurements. For those, that do not want to build their own measuring boards, [16] offers an open-source toolkit based on the loading mode.

Despite the great amount of research done on capacitive sensing in the past years, only a little research using capacitive sensors for positioning or tracking humans has been reported. Nevertheless, the first step in this direction was already taken in 1993, when a simple configuration for detecting the presence or movement of a person close to a robot using the transmit mode was introduced in [17]. The purpose of this system was to stop the robot to ensure safety when a person entered too close to the robot.

The second step towards human indoor tracking was taken in 1995, when a Person Sensing Room was presented with various other ideas of capacitive applications [1]. The floor of the Person Sensing Room was covered with a transmitter electrode, and four receiving electrodes were placed on the walls. Using the floor electrode as a transmitter, a signal was driven to the person and the signal strength was measured at the wall electrodes. With this information the room was able to indicate the location of a person on the floor.

After these two initial studies, capacitive sensing researchers concentrated much on other topics than human tracking. However, now the researchers are becoming active on this topic once again. To illustrate, a work on a Smart Carpet [18] was published in 2007. The carpet can track people walking over it and has 180 capacitive sensors embedded in it. Each sensor has its own sensing wire, placed in square 15 x 15 cm-sized squares, that can determine, by using the loading mode, if a foot is placed over the wire. With this carpet, a few classification methods were evaluated to identify footsteps and to estimate walking trajectories.

Today, the Smart Carpet is a commercialized product, SensFloor [19], that has been developed somewhat further. In SensFloor, the sensor modules deliver the acquired data to a central unit through a radio link and the modules can have up to 8 sensing wires connected to them. In addition, the sensing areas have been enlarged and their shapes have been modified from square to triangular ones.

In 2008, a human tracking system using a matrix of conductive floor tiles [20] was presented. This system uses the loading mode and sequences through all the tiles having one tile to transmit a low-frequency signal at a time, while all the other tiles are grounded. If a human is standing over a tile and thus functions as a transmitter, a current flow to the grounded tiles increases compared to the situation when the floor is empty. With this change, it is possible to determine, if a person is standing over a certain tile. Using the physical locations of the tiles, the authors compute a two-dimensional position of the person's location.

The last three approaches are somewhat similar to our system. However, instead of using the loading-mode sensing, we take the advantage of the transmit mode with a separate receiver, because this sensing mode allows us to neglect the stray capacitances formed with the environment. We will provide a more in-depth comparison to these systems in the discussion part of this paper.

III. ELECTRODE CONFIGURATION

Our tracking system builds up from several transmitting electrodes and from at least one receiving electrode that are used in transmit mode. With this sensing mode, the stray capacitances formed with the environment become negligible, because the capacitance between these electrodes can be measured by only measuring the received current at the receiving electrode. Hence, the amount of current flowing into the environment from a transmitting electrode does not affect the measured capacitance. As a result, we can use several types of electrode configurations, because we do not need to worry about the environment properties as long as we keep the

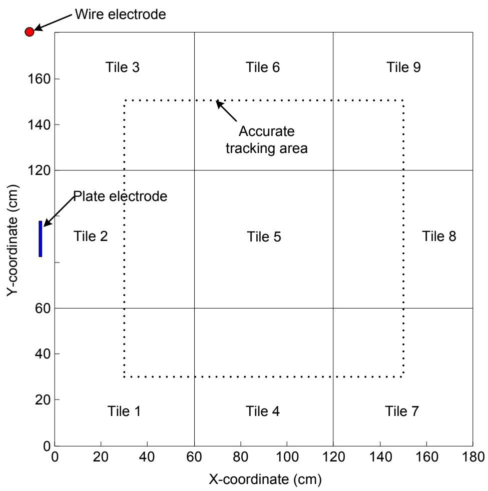

Figure 1. The tracking area of the system consists of 9 separately controllable floor tiles placed in a square shape. The dotted line shows the accurate tracking area. The positions of the two different kinds of receiving electrodes are also shown.

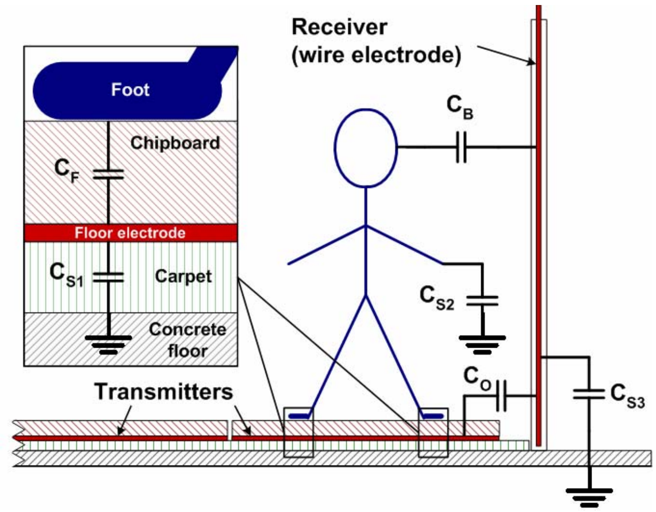

Figure 2. A cutaway picture of the measurement space with a capacitance model of the environment. A part of the floor electrodes are shown with the receiving *wire electrode* inside the stud of the wooden frame. The picture is not drawn to scale.

receiver in a reasonable place. Moreover, we can transfer the system to another environment and only with little calibration make the system to operate.

A. Transmitting Electrodes

We see that the optimal placement for the transmitting electrodes is on the floor, because people walk on it. The closer the floor electrodes are brought to the user, the better the achieved signal-to-noise ratio (SNR) is with the transmit mode, because the capacitance between the feet and the floor electrode increases when a person is closer to the electrode. However, theoretically the places of the transmitting and the receiving electrodes would be interchangeable without altering the system operation. But, the internal implementation of the CDC allows only 60 pF of stray capacitance to exist between the receiver and the ground. Because we measured the stray capacitance to be about 1.2 nF between a single floor tile and the ground, it was not even possible to consider the installation of the receiver on the floor without making some hardware modifications.

For these reasons, the transmitting part of the prototype system is built of 9 floor electrodes. To allow easy construction and scalability, commercial raised floor tiles are used, even though any conductive material with some dielectric on top of it could have been used. For example, plain aluminum foil and plastic floor covering should work as well.

The square 60 x 60 cm-sized tiles are made of 3.85 cm-thick chipboard that has a 0.5 mm-thick steel coating on the bottom surface. The tiles are placed in a three by three square providing a tracking area of 1.8 x 1.8 m and have a spacing of about 5 mm. A thin furnishing carpet insulates them from the floor covering of the building, which is in our laboratory covered with a plastic electrostatic mat. The layout of the tiles and the placement of the receiving electrodes are shown in Fig. 1. In addition, the figure shows the accurate tracking area, which will be explained with the tracking calculations in section VI.

The used floor tiles make the person stand about four centimeters away from the transmitting electrode. Because the SNR decreases with the increasing distance between the person and the electrode, the thick floor tiles are not optimal. On the other hand, the use of these tiles demonstrates that the tracking system can work even with many centimeters of insulating material between the person and the electrode. In practice, even thick furnishing carpets or thick shoe soles do not inhibit the tracking of people.

B. Receiving Electrodes

Our system supports virtually an arbitrary number of receiving electrodes. However, all the receiving electrodes must be connected together at the measuring circuitry. Further, the placement of the receiving electrodes is somewhat arbitrary. The closer to the person the electrodes are installed or the bigger they are, the better the achieved SNR is.

In this study, we evaluated two different kinds of receiving electrodes installed in different places. First, a square copper plate with a side length of 16 cm over a printed circuit board (PCB) was used as a receiving electrode. This copper plate was attached to a wooden frame next to the floor tiles and its long side was put along the Y-axis. In addition, it was aligned vertically and its top was set at 180 cm from the floor. The installation point of this small receiving electrode, to which we will refer with a name *plate electrode*, is shown in Fig. 1.

A standard power-line cable installed inside a vertical stud of the wooden frame was used as the second receiving electrode. The cable runs vertically up from the floor level to about 190 cm height. The placement of this receiver can also be seen in Fig. 1. In the following conversation, we will refer to this receiving electrode with a name *wire electrode*.

IV. CAPACITANCE MODEL

We use a simple capacitance model of the environment to show how the important capacitances form in the measurement space. This model is shown in Fig. 2 with a cutaway picture of the environment.

The model incorporates two capacitances that form between the electrodes and the human. First, C_F is the capacitance between the human feet and the transmitter, having chipboard as an insulator. In addition, if shoes are used, they insulate the person from the floor electrode and thus act as an optional insulator. Second, C_B is the capacitance between the body and the receiver, insulated by air. Because the human body is an almost perfect conductor at the used 32 kHz measurement frequency, we model human as a conductor with no internal impedance.

These two capacitances are the only ones that change when a person moves in the tracking area. Moreover, they define where the human is positioned. Indeed, when a person is standing over a tile, the C_F increases and the transmitted signal is coupled to the human body. The transmitted signal or current then flows through C_B to the receiving electrode. The CDC measures the current flow coming in from the receiving electrode and converts it to a capacitance value, which is the total capacitance between the electrodes. In other words, the total capacitance is the series capacitance of C_F and C_B parallel with C_O. Here, C_O represents the offset capacitance that exists between the electrodes even without a human.

In addition to these capacitances, some stray capacitances with the ground exist. First, C_{S1} exists between the transmitter and the ground, having carpet as an insulator. Second, C_{S2} forms between the body and the ground, and third, C_{S3} between the receiver and the ground, both insulated by air. Two of these, C_{S1} and C_{S3}, stay always constant, but C_{S2} varies a little with the human position.

All of these stray capacitances can be neglected in operation, because the capacitance between the transmitting and the receiving electrodes can be measured by measuring only the received current at the received electrode. Hence, the current flowing to the environment from the transmitting electrode through C_{S1} or from the human body through C_{S2} does not affect the result calculated by the CDC. Thus, the only capacitance, that could affect the result, is C_{S3}. It, however, stays constant all the time, because the receiver is not moved.

V. HARDWARE

Our measurement board consists of three primary components. These are a high resolution sigma-delta CDC AD7746 [2], an ATMega8 microcontroller, and a signal multiplexer. The CDC performs the capacitance measurement and delivers the result to the microcontroller when requested. This, in turn, delivers the result to a PC, which takes care of the tracking calculations. Additionally, the microcontroller controls the distribution of the transmitted low-frequency signal with a multiplexer. The signals are routed to and from the electrodes using coaxial cabling to prevent unintentional coupling between the transmitted and received signals, and to shield the signals from noise.

A. Capacitance Conversion

Capacitance-to-digital conversions with the CDC are performed according to a predetermined routine. This routine is both controlled and initiated by the microcontroller and it consists of three major steps. These are multiplexing, measuring and data retrieval.

The floor electrodes are sequenced through one at a time, starting from tile 1 (see Fig. 1). So, the first step is to select an appropriate transmitting electrode. The microcontroller takes care of this by adjusting the multiplexer output. Second, it requests the CDC to perform a single capacitance measurement through an I^2C bus. Then, the CDC excites a 32 kHz, 5 volt square wave excitation signal to its output port, which is now routed to the appropriate floor electrode through the multiplexer. At the same time, it measures the capacitance between the electrodes, converts it to a digital form and informs the microcontroller of the finished conversion. Third and the last, the microcontroller reads the result from the CDC and sends it to the PC through a serial interface.

The update frequency of the tracking system is limited by the conversion speed of the CDC. With the fastest setting, the CDC can perform a single conversion in 11 milliseconds. By using this setting, we get a 10.1 Hz update rate for human position, because the sequencing through all the 9 floor electrodes takes a total of 99 milliseconds. As a result, the system can provide a good update rate for general tracking applications, but it is not fast enough, for example, for virtual reality applications.

B. Transmitter Cabling and Buffering

The floor electrodes are connected to the PCB using RG58 type coaxial cables and BNC connectors. The inner wire carries the excitation signal from the CDC to the transmitting tile. The shield of the coaxial cables is connected to the circuit ground at the PCB end and is left unconnected at the end of the tile. The use of coaxial cables allows the excitation signal to remain shielded until the floor tile and not to transmit any signal to the receiving electrode before the transmitting tile.

Depending on the cable length, some extra capacitance is formed in the cable between the excitation wire and the ground, and between the transmitting electrode and the ground. These capacitances are fairly large and make the excitation signal to deteriorate, because the CDC cannot supply enough current to keep the waveform square. For example, a 10 meter long coaxial cable attached to a single tile can increase the total capacitance between those and the ground up to 2.5 nanofarads. Hence, a high current buffer was implemented to counteract this effect. Now, when the excitation signal is buffered, we cannot see any difference in the received signal, even if long coaxial cables are used.

C. Receiver Cabling

The receiving electrodes are connected to the PCB with a thin coaxial cable. The inner wire carries the received signal and the shield is connected to the circuit ground at the PCB end. This cable has no connectors at the electrode end, but uses a crocodile clip for easy connecting to different types of electrodes. At the PCB end the cable has been soldered directly to the PCB.

The length of the receiver cable is approximately 2.9 meters. We have tested different lengths of cables, but as long as the cable length stays below about 10 meters, we cannot observe any difference in the received signal. The measured offset capacitance, however, builds up with the extra capacitance formed with the ground.

D. Optocoupling

The PCB is galvanically separated from the PC with an optocoupler. This is done to prevent the noisy signals from the PC entering the circuit board and decreasing the SNR. As a result of disconnecting the PCB ground, the ground floats and the CDC cannot measure the capacitances correctly. To keep the circuit ground at a constant potential we have connected it to the power-line ground with a separate lead.

VI. Tracking Calculations

The tracking calculations of the system are performed on the PC. These calculations consist of a short initialization phase and of simple filtering and tracking steps. During the initialization, the tracking software measures the offset capacitance C_O formed between the receiver and each floor electrode, one at a time, and stores the values into memory. In this phase, the tracking area must be empty, so that the measured total capacitance value represents only the offset capacitance of a floor tile and the receiver.

In operation, the microcontroller sends a ready conversion result to the PC always, when the CDC has finished a conversion. Thus, the PC receives the measured total capacitance value between a single floor electrode and the receiver, one at a time. Because the series capacitance of C_F and C_B is in parallel with the constant offset capacitance C_O, we can easily compute the series capacitance of C_F and C_B from the total capacitance by subtracting the respective stored offset capacitance value from the received total capacitance value. This series capacitance can then be used in the next step after it has been low-pass filtered to give a more stabilized reading. To filter the noise out, we take a moving average of five successive measurement values for each floor tile separately. This gives us a position result that oscillates from about 0.1 cm to about two centimeters with both receiving electrodes, the amount of noise depending on the distance from the electrode. We have determined this noise to be normally distributed.

The actual tracking is performed with these low-pass filtered values using a simple algorithm. When a person moves or stands on the tiles, the capacitances C_F and C_B change. More specifically, these capacitances increase when a person enters the tracking area, because the human as a conductive object decreases the size of the air gap between the electrodes. As a result, the measured total capacitance increases and a change in the received signal can be measured.

At this point, we must divide the received values into two categories, to strong and weak signals, because we also receive small signals from the neighboring tiles that are located around the tile that is used as the transmitter. This effect is caused by the fact, that the floor tiles are installed so close to each other. The small 5-mm gap is not enough to decouple the floor electrodes from each other and thus the transmitted signal is also slightly coupled to the neighboring tiles. In practice, we divide the signals into these two groups with a preset threshold. The threshold is set so that a strong signal is only received from a tile that has a foot over it even partially.

Subsequently, we want to reject the weak signals, because they are not needed in the position calculation, because the user never stands on the tiles giving out weak signals. Thus, we do the actual positioning and tracking by using only the strong signals. Further, if a person is standing only over a single tile, we position the person in the centroid of that tile, because it is the only tile we are receiving a strong signal from. On the other hand, if a person is standing over more than a one tile, we calculate a center of gravity with all the tiles that give out a strong signal. More specifically, we position the user between the centroids of the tiles that give strong signals in proportion to the signal strengths. To have a single two-dimensional, point-sized position for a human, we have defined the position of the person to be at the centroid of the person's body. That position corresponds well to the position of the top of the head if the person is standing or walking.

Because of the center of gravity algorithm, which only pulls the position result closer to the tiles' centroids in proportion to the signal strengths, the system can only end up with a position result within the dotted "accurate tracking area" marked in Fig. 1. However, in larger scale implementations a much larger percentage of the floor can be used accurately, because only one half of the edge tiles reside outside the accurate tracking area. Moreover, these edge tiles in a room installation are usually next to a wall, and thus no person can stand closer than about 15 centimeters to the wall with the above definition of the person's position. Therefore, this algorithm causes at worst about 15 cm deviation in the position result at the edges of the tracking area if installed, for example, to a home.

In practice, if a person stands only over tile 5 (Fig. 1), no other tile is used for calculating the position and the centroid coordinates of tile 5 are given as the result. Also, if the person stands in the intersection of tiles 2, 3, 5, and 6 so that his or her feet are over all of these tiles, then the position of the person is calculated based on how his or her feet are placed on these four tiles. In this case, the user is most likely positioned close to the intersection of these four tiles.

VII. Evaluation

We evaluated our tracking system with two different receivers and with three persons of different sizes. In addition, we measured the SNR of the system when the test person was standing at different distances from the receivers with and without shoes.

A. SNR test

The SNR of the measured signal depends a lot on the distance of the person from the electrode. Also, the shape, the size, and the installation position of the electrode matters. Thus, we measured the SNR at three distances with both electrodes

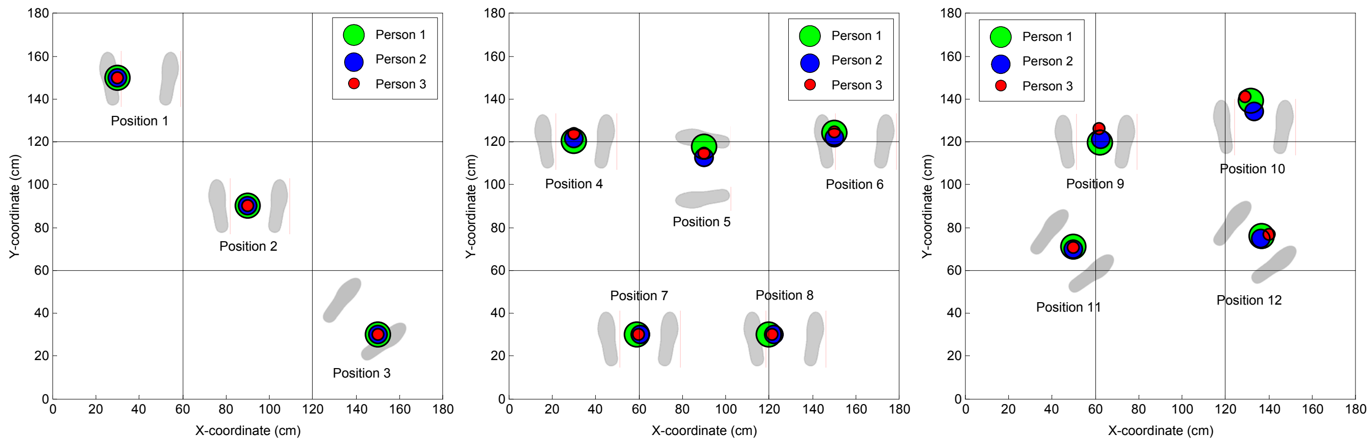

Figure 4. Recorded positions with wire electrode for the test persons standing A) over 1 tile, B) over 2 tiles, and C) over 3 or 4 tiles

by having a person to stand in the middle of three tiles for a period of 30 seconds. This was first done having our test person (Person 2 in Table 1) to wear socks only, but repeated with ordinary shoes, to prove that the system can receive a measurable signal in that case as well. Fig. 3 shows how the SNR depends on the distance from the receiver with and without shoes.

The SNR in decibels seems to decrease somewhat linearly as the distance between the user and the receiving electrode increases. By looking at the data from these measurements, we can see that the amplitude of the noise increases when a person comes closer to the receiving electrode. This shows that the received noise does not only contribute from the environment or from the receiver itself. If this would be the case, the amount of noise would be about constant when the person moves towards the receiver. Moreover, the SNR should increase quite rapidly as the signal amplitude increases. Evidently, this is not the case. Thus, it must be concluded that the transmitter also acts as a considerable noise source, at least when the signal is coupled through the person to the receiver.

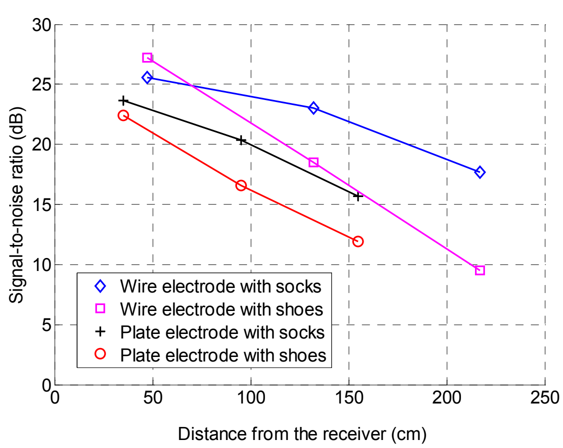

Figure 3. The signal-to-noise ratio decreases when the distance between the receiving electrode and the person increases.

Looking at Fig. 3, the SNR of the *plate electrode* is at all distances at least a few decibels smaller than the SNR of the *wire electrode*. For example, at 100 cm from the electrodes, the *wire electrode* gives about 24 dB SNR with socks, while the *plate electrode* gives only about 20 dB in the same case. This happens, because the parallel surface area of the *plate electrode* with the human is much smaller compared to the *wire electrode*, which, in contrast, runs vertical. Thus the *wire electrode* is in the same orientation as the standing human and provides a better SNR.

On the other hand, the SNR seems to decrease more rapidly with shoes than with socks when the distance increases between the person and the electrode. However, the measured SNR of the system with the *wire electrode* and shoes at about 50 cm is better than without shoes. This is a little surprising, since the actual measurement value without shoes is about 1.6 times larger than with shoes. We repeated this test twice with the same person and shoes to verify the result and got similar results. Thus, a little better SNR can be achieved very close to a receiving electrode with shoes on, because shoes seem to decrease the amplitude of the noise more than the actual signal.

Summing up, the SNR decreases somewhat linearly when the distance between the user and the receiver increases. Further, the *wire electrode* seems to give a little better SNR than the *plate electrode* at all times. Also, in general, shoes act as a dielectric between the user and the floor plate and reduce the received signal strength. As a result, the noise becomes more remarkable compared to the actual signal and thus decreases the SNR with shoes.

B. *Standing Test*

To evaluate the positioning capabilities of our system, we asked three test persons to stand in 12 different positions over the tracking area. The three test persons represent different sizes of adults. Their personal properties are shown in Table I.

In this test, the test persons were guided to align their foot as precisely as possible with the predetermined places shown in Fig. 4 with footprints. These places were selected carefully to show how different kinds of standing positions affect the positioning accuracy. After the feet alignment, the system calculated a position for the person. The measurements were first done with the *plate electrode* and then with the *wire electrode*. However, because the positioning results did not differ almost at all, we only present the results with the *wire electrode*.

Fig. 4A shows the first three measured standing positions and the calculated positions for all test persons with both electrodes. The centers of the circles point the exact positioning result. These measurement results suggest that the person is always positioned by the system in the middle of a single floor tile, no matter where his or her feet are placed, as long as they lie within a single tile. For example, in position 1, the test persons stood very close to the edge of tile 3, but were still positioned in the middle of that tile. This operation is exactly what we expected to have, because only one received signal is used here for positioning.

Next, to see how the system works in a case, where a person is standing over two tiles, we continued the measurements with positions depicted in Fig. 4B. Now, the system uses two signals received from two different transmitters or tiles. Then, it computes the position of the person using center of gravity algorithm. As the two neighboring tiles always have either the same X- or Y-coordinate, the positioning result lies on a line between the centroids of these two tiles. For example, with the position 5 shown in Fig. 4B, all the positioning results are on a line between tiles' 5 and 6 centroids. Therefore, the position on this line is only defined by the placement of the person's feet over the border of these two tiles.

In practice, the positioning works almost only by the division of footprint area over these tiles. Indeed, the calculated position for all test persons in positions 7 and 8 is almost at the boundary of the tiles involved, because the footprint area on both of these tiles is similar. On the contrary, in position 5, the test persons' feet are covering more area on tile 5 and thus the positioning result is closer to the centroid of tile 5 than the centroid of tile 6. Also, by looking at the results for positions 4 and 6, it can be perceived that all the test persons had more area on the tile on the toe side compared to the heel side of their feet. However, this is quite self explanatory, because the area under the toe side of humans' feet is bigger than on the heel side. Thus, it can be concluded, that the persons stood so that the mid-point of their feet was at the border of the tiles.

TABLE I. PROPERTIES OF OUR TEST GROUP

	Sex	Height (cm)	Weight (kg)	Shoe size (European)
Person 1	Male	183	86	43
Person 2	Male	170	70	40
Person 3	Female	157	61	37

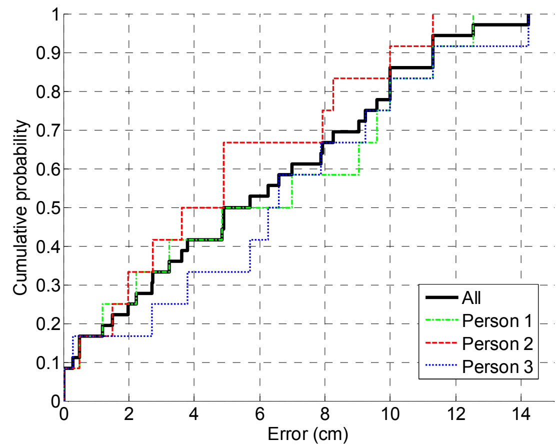

Figure 5. Cumulative error distributions in all 12 standing positions for all test persons

Further, we measured how the system positions the persons, when their feet are over three or four tiles. These calculated positions are shown in Fig. 4C. Yet, the same principles apply in these positions.

To evaluate the accuracy and precision of the system with standing persons, we calculated the error distance between the calculated and the true positions of the persons. The true positions were approximated using the footprints shown in Fig 4. Using these error distances, we plotted a cumulative error distribution function for each test person standing in all of these 12 positions; the plot is shown in Fig. 5. In addition to these functions, the figure shows cumulative error distribution function combined for all test persons.

According to the graphs shown in Fig. 5, the system can position a standing person, with the used tile size, with at least 14.3 cm accuracy and with 10 cm accuracy in 80 % of the cases. The biggest errors occur in positions 3, 5, 6, and 8, where the person is neither close to the centroid of a tile nor standing over a boundary of two or more tiles. Because the graphs are fairly linear, we make a conclusion that the combined error probability distribution for all test persons is almost constant.

C. *Walking test*

After the positioning tests with standing persons, we proceeded to measure walking tracks with the same test persons. We wanted to confirm, that the same principles that apply for standing persons, can be applied on walking persons as well. Thus, we defined three simple paths and marked the footsteps for the test persons on the floor. Then, we asked them to walk the path at a normal walking speed and recorded the calculated track. Again, the measured tracks with both of the electrodes were so similar, that we only present the measured tracks with the *wire electrode*. The results are only analyzed within the accurate tracking area shown in Fig. 1, because the system cannot end up with a position result outside that area.

On our first path, we asked the test persons to stand on tile 4 and walk a straight line through tiles 5 and 6 out of the tracking area. The results from this first path are shown in Fig.

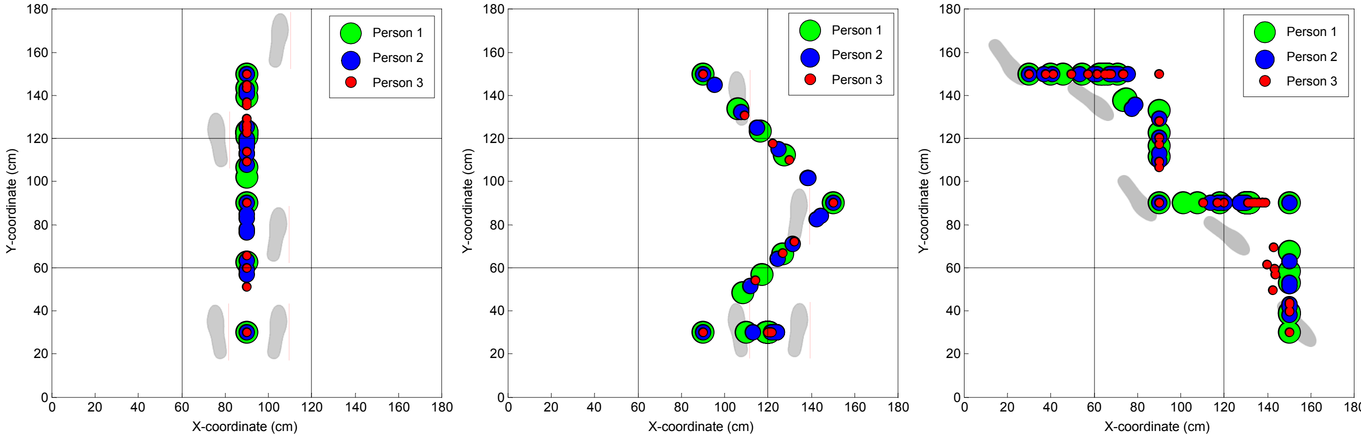

Figure 6. Recorded tracks with the wire electrode for all test persons on A) path 1, B) path 2 and C) path 3

6A. As expected, the system positions the standing user in the middle of tile 4. Then, when the persons proceeded over tile 5, the system tracked them over the border of tiles 4 and 5. Next, the tracking continued to the middle of tile 5, to the border between tiles 5 and 6, and finally, to the centroid of tile 6. Because there are no tiles after tile 6, the tracking system cannot position the user beyond the centroid of tile 6.

Second, we measured a very similar path compared to the first one, but increased the stride length a little and moved the path 30 cm to the right, where a person stands over two tiles. The footsteps for this path are shown in Fig. 6B. On this path, the test persons first lifted their right foot off the ground. At the same time, the received signal from tile 7 decreased and the tracking result deviated to the left. At one point, the signal amplitude decreased below the threshold set for the strong signals and the only tile giving out a strong signal was tile 4. Hence, the tracking position remained a while in the centroid of tile 4. After a while, the right foot came in contact with tile 8 and caused the tracking result to move towards the centroid of tile 8. Again, as the left foot was lifted up and placed on tile 6, the recorded track moved through the centroid of tile 8 to the centroid of tile 6.

Third, and the last, we recorded a diagonal path so, that the test persons started their walk outside the tracking area and also finished outside it. The results form this path, shown in Fig. 6C, seem to be rather rectangular than a straight line through the tracking area. This, however, shows the nature of our system quite well: the system always positions a person to the centroid of a tile or between the centroids of the tiles in proportion to footprint areas.

The first path gives errors only along the Y-axis, because the path goes through the centroids of the tiles 4, 5, and 6, which have the same X-coordinate. Therefore, the cumulative error distribution function combined for all test persons on the first path, plotted in Fig. 7, has the smallest errors compared to the other paths, whose cumulative error distribution functions combined for all test persons are also shown in Fig. 7. All of these functions were produced by approximating the true position of the person from the predefined foot positions and the measured temporal data.

On the contrary to the first path, the second path was created to see what the largest tracking error the system gives out is. The largest tracking error realizes with the second path, because the error along the X-axis is the highest, since the position result fluctuates about ± 30 cm on both sides of the actual track. In addition, the second path has about the same errors that were produced on the first path, because of the test persons' natural movement along the Y-axis during their walk.

The third path resembles the most an actual walking path in a real environment, because it does not go along the coordinate axes. However, because it goes somewhat diagonal to the tiles, it gives a fairly linear cumulative error distribution function.

According to the combined cumulative error distribution function for all test persons and all paths, shown in Fig. 7, the recorded track is always less than 40.7 cm from the actual track. In fact, in normal walk, where the human body is located between the person's feet, this maximum error is about the same as the diagonal distance between the centroid and the corner of a tile, because the person cannot be any further from a tile's centroid without being on another tile. The error probability distribution for the walking test seems to be fairly

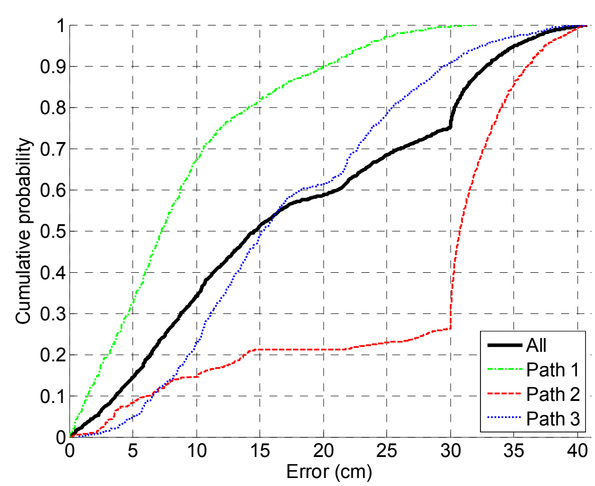

Figure 7. Cumulative error distributions for tested paths with all test persons

constant or a little exponentially decreasing with the error distance increasing.

VIII. Discussion

A. Comparison with previous systems

Below, we highlight the major differences with the Smart Carpet [18], SensFloor [19], and matrix of conductive floor tiles [20], which were already shortly presented in the related work section. However, because the tile sizes and/or shapes in these works are different from ours, and these works present very little or no accuracy and precision data, we cannot reasonably compare the accuracy and precision of our system with these works.

First, Smart Carpet is built on a fabric that has an embroidered sensing wire in each 15 x 15 cm-section of the carpet. Altogether, the 2.4 x 2.0 m-sized carpet has 180 sensing wires and sensor modules, consisting of a microprocessor, external memory and several other components, for each section. In contrast to having such a large number of modules buried in the floor, we only need to have thin electrodes with some wiring under the floor level. The thickness requirement of the floor covering is not much different for Smart Carpet or our system, because the sensor modules take a few millimeters of space vertically within the carpet and thin coaxial cabling takes about the same space. However, the Smart Carpet's modules are fairly expensive to manufacture and have a limited life time, while our electrodes and cabling are cheap and practically everlasting. Further, we could implement a similar-sized floor with the same sizes of floor electrodes only with a single measurement PCB and thus get the total cost and the power consumption of the system remarkably lower than in Smart Carpet.

Second, our system does not require any data routing, group communication or power distribution algorithms that are used in Smart Carpet and partly in SensFloor. Also, we do not use radio links to transfer the measurement signals like SensFloor does. Instead, we route the measurement signals to a single PCB with coaxial cables. As a result, our system is much less complex and has less fault-prone parts.

Third, in contrast all of these three works, we do not use loading-mode sensing but transmit mode. By using this mode for sensing, we are able to neglect the stray capacitances formed with the environment. This in turn provides a good transferability and scalability for the system in terms of installation space and electrode sizes. In fact, if we would measure the capacitance between a single electrode and the ground potential in loading mode like in these three works, the maximum measurable capacitance would be defined by the bulk or the offset capacitance formed between the electrode and the environment, which can be considered to be at a ground potential.

B. Problems

Although the system has been demonstrated to work here, the system has some problems that require future work. First, the contact area of the person's feet only defines the position of the user. Thus, if a user is not in a normal standing posture and is, for example, sitting on the floor legs straightened, the system can solve the position of the user only with decreased accuracy. Also, if a person has only one foot on the floor, like when walking, the positioning result becomes less accurate. For the same reason, if a man sits on a chair, he will be most likely positioned in front of the chair, assuming that he keeps his feet down on the ground. If he does not, he can still be positioned, if the chair conducts a small but measurable current. This is luckily the case with many office chairs, because many of them are made out of plastic and steel.

This problem could be overcome, if the system could understand on postures. Indeed, it would be desirable to be able to determine the user's posture at times. To measure this with our system, some signal processing should be applied on the received signal. For example, with the *wire electrode*, some height information could be recovered from the signal strength. A weak signal from many tiles could indicate that a person is lying on the floor, and a decreasing signal from a set of tiles could reveal a person crouching down to sit on the floor or on a chair.

Second, As conductive furniture can help tracking a sitting person, it and other similar objects can also cause some problems. For example, if a person moves the place of a steel table, the operation should be recognized and the table distinguished from the people. To do this, one option would be to apply some temporal filtering to resolve the non-moving objects form the moving objects.

Third, if a user is standing only on a single tile and not over any tile boundary, the person cannot be positioned anywhere else but in the centroid of the floor tile. This happens, because the used center of gravity positioning does not take the small signals into account at all. This could possibly be overcome, if the small signals from the neighboring tiles could be used more wisely. Another simple way would be, of course, to use smaller or even non-rectangular tiles so that a person would step on the borders of the tiles more often.

If the tile size would be decreased, more cabling would be required to connect all the tiles to the PCB. However, the number of coaxial cables could be reduced by using some matrix type measurement method like in [14]. Nevertheless, smaller tiles would increase the system's accuracy, because the center of gravity algorithm works better when a person's feet are crossing the tile borders. Therefore, tile size and positioning accuracy can be traded with each other.

C. Future Work

In addition to the previously described problems, the system could be improved by adding new features. First, in a large deployment with hundreds of tiles, the update frequency would drop significantly, if the system were scaled in the naive way of simply adding more tiles. The scaling can be, however, done in a more sophisticated way without affecting the update rate almost at all. Indeed, if the person's current position is known, we only need to measure the tiles that lie around the current position. In other words, we can move the demonstrated 9-tile section virtually in the building with the person and thus keep the update rate high. If the person should be lost, for example, because of laying on a bed, the system could cycle through all the floor tiles (or only the ones around the bed, if the system would be aware of the bed's location) to find the person again.

Second, the deployed system can track multiple persons, if they stay at least a tile away from each other. However, because the tracking space used in this implementation is so small, we have not implemented such a tracking algorithm to this system. Nevertheless, we expect to implement this functionality to some future version of our tracking system.

However, if a multiple person tracking algorithm should be implemented into a large scale deployment, we see that it would be wise to check the doorways for incoming persons and "attach" a 9-tile tracking area around each person, if detected. Although this is possible, this would decrease the position update rate inversely proportional to the number of tracked people if only a single measurement channel were used. To overcome this, the system could be fitted with multiple CDC chips and each chip given a single person to be tracked. However, these chips should be time-multiplexed, because they disturb each other if operated simultaneously. On the other hand, if these chips would be replaced with other types of measurement techniques, for example with the one used in [14], different measurement frequencies could be used to track different persons, and thus the update frequency would not drop at all.

IX. Conclusion

In this paper, we have presented a simple and passive tracking system for indoor use that can reliably track different sizes of people. The presented tracking system is robust to environmental changes and offers good transferability. Moreover, it is scalable and can function with many types of electrodes. In figures, the system can position a standing person, with the used tile size, with at least 14.3 cm accuracy and a walking person with at least 40.7 cm accuracy.

Because of the system's simple construction and transferability, it could be easily replicated using raised floor tiles or other conductive and segmented floor materials to many application areas. For example, the ambient assisted living researchers and practitioners could benefit from the system. With it they could, among other things, help the elderly people live independently at home. Furthermore, the developed tracking system could be used to enhance the context sensitive services of a smart home or to track people in public places like in shops, offices, and schools.

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