High accuracy indoor positioning system to monitor spatial use in dwellings

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Introduction

In recent years, occupancy sensing in indoor environments has been used in a wide field of applications, such as smart control of HVAC-systems, detection of humans in emergency interventions [1], assisted living [2], searching for lost people or objects, shopping behaviour, industrial applications [3], player tracking in sports, games, etc.. Three different levels of occupancy sensing can be distinguished: occupancy detection, occupancy counting and occupancy tracking [4]. Occupancy detection provides information about whether someone is present in a specific room or not, but not about the number of occupants or the spatial use within a room. It can be done by several techniques, such as infrared-detection [5] and sound-detection. . Occupancy counting, e.g. by CO_2-measurements, gives more information about the number of occupants in a room [6, 7]. The highest level of occupancy information is obtained by occupancy tracking, which gives, besides the presence and number of occupants, the exact location of occupants within a room and can be measured by indoor localisation techniques based on e.g. Bluetooth, Wi-Fi [4] and ultra-wideband (UWB) [1, 8]. Indoor localisation techniques are in general more intrusive for residents because they need to wear a tag [4], although some of them can be build-in in residents' smartphones (Bluetooth, Wi-Fi).

Nowadays, indoor localisation systems are mostly applied in large buildings with large spaces, such as office spaces, airports, etc.. For monitoring spatial use patterns in dwellings [9], a very precise indoor localisation system is needed which is able to track the position of residents in small rooms with a lot of obstacles. In this paper, system requirements for indoor tracking in dwellings are derived and an overview and evaluation of commonly used techniques for occupancy sensing in buildings are provided.. Four commercially available, ultra-wideband based localisation systems are compared. In a case study analysis, one commercially available system, Pozyx™, which provides accurate positioning and motion information, is used for monitoring spatial use patterns of residents in their dwelling.

Requirements for accurate indoor tracking techniques in dwellings

System requirements are crucial when selecting a sensing technology that is able to monitor the moving position of multiple residents over time separately. Mautz [10] defined several criteria which can be used for the assessment and comparison of different occupancy sensing techniques. In order to obtain the most fitting technique, the specifications of the system need to match the predetermined requirements which depend on the application. When searching the most suitable system, the different requirements have to be weighed against each other which is not a straightforward method [10].

When monitoring the exact location of residents in dwellings, some boundary conditions and difficulties have to be taken into account. First of all, the monitoring system has to deal with a small, but very complex environment with lots of obstacles, e.g. indoor walls and furniture that can disturb the location signal. Furthermore, the system has to be accurate enough (min. horizontal accuracy 1 m, min. vertical accuracy 2m), because, due to the small size of dwellings, small errors in accuracy can lead to large errors in the results, such as locating a person incorrectly in an adjacent room. Privacy is another critical issue when tracking residents in their own dwelling. The monitoring is rather intensive for the residents and can be perceived as intrusive, which can lead to drop-out or changes in their normal behaviour. Therefore, the monitoring system has to be as compact as posssible and may not restrict their normal living patterns. Additionally, some extra practical requirements are added, such as the possibility to set up the whole system in a relative simple and quick way (around 2,5 hours) and the need for limited infrastructure/devices. Lastly, the cost of the detection system has also to be taken into account. Table 1 shows a summary of the requirements which are derived for occupant tracking within rooms of dwellings.

Table 1: Requirements for occupant tracking within rooms in dwellings.

Criteria	Requirements
Coverage area (measurement area/volume)	Semi-large dwelling (2-3 floors)
Horizontal accuracy (position in a room)	<1m
Vertical accuracy (indication of the floor level)	<2m
Level of occupancy sensing (detection, counting, tracking)	Tracking
Output data (spatio-temporal data)	Coordinates with timestamp
Number of users (number of tags)	One family (1-5 tags)
Privacy (nature of gathered data)	According to ethical regulations
Intrusiveness (disturbing daily activities)	Low/Moderate
Size/weight (size/weight of measurement unit)	Handheld
Installation complexity (man-hours to install the system)	<2,5hours
Required infrastructure (devices/cables)	Moderate
Cost (price of the complete system)	Moderate

Evaluation of occupancy sensing techniques

Occupancy sensing in indoor environments can be achieved by using different sensors such as infrared-detection, CO_2-concentration measurements, cameras, indoor localisation systems (based on radio signals), although not all of them provide complete information about the location within a room. In Table 2, commonly used systems for occupant sensing and indoor localisation are showed, including the evaluation of their specifications according to the predetermined requirements.

Category	**Techniques** / **Requirements**	*Level of occupancy sensing*	*Horizontal accuracy*	*Vertical accuracy*	*Coverage area*	*Output data*	*Number of users*	*Privacy*	*Intrusiveness*	*Size/weight of the tag*	*Required infrastructure*	*Installation time*	*Cost*	*References*
Sound	Ultrasonic	Detection	mm	mm	Scalable	Distances	NA	High	Low	NA	High	High	High	[10, 11]
	Audible sound	Detection	Room	Room	Scalable	Presence	NA	Med	Low	NA	Med	Med	Low	[10, 11]
Concentration	CO_2-concentration	Counting	Room	Room	Scalable	Presence	NA	High	Low	NA	Med	Low	Med	[6, 7, 12]
Infrastructure	Pressure-sensors/computer activity	Detection	Zone	Zone	Scalable	Location	NA	High	Low	NA	High	High	High	[11, 13]
Image detection	Visual	Tracking	dm-mm	dm	Scalable	movie	High	Low	Low	NA	High	Med	High	[2, 10, 11, 14, 15]
	Infrared-detection	Detection	Zone	Zone	Scalable	Presence	NA	High	Low	NA	Med	Med	Low	[2, 10, 11]
Radio frequency signals	GPS	Tracking	25m	X	NA	Coordinates	High	Med	Med	Small	Low	Low	Low	[16]
	Wi-Fi	Tracking	3-10m	Floor	Scalable	Coordinates	High	Med	Med	Small	Med	Med	Low	[4, 10, 17, 18]
	Bluetooth	Tracking	1-3m	Floor	Scalable	Coordinates	High	Med	Med	Small	Med	Med	Med/high	[10, 19, 20]
	Ultra-wideband	Tracking	dm	dm	Scalable	Coordinates	Med	Med	High	Med	Med/high	Med	Med/high	[1, 3, 8, 10]
	RFID	Tracking	1-3m	Floor	Scalable	Coordinates	High	Med	Med	Small	Med	Med	Low	[10]

Table 2: Commonly used techniques for occupant sensing

If the aim is to investigate spatial use within rooms, the exact location of residents needs to be monitored and, therefore, some of the techniques of Table 2 need to be excluded. Ultrasonic sound-detection, audible sound-detection, infrared-detection and CO_2-concentration measurements only provide information on the level of occupancy detection or occupancy counting [3, 10]. These techniques can be valuable for other studies in which -the exact location of residents within a room is not needed, as they are in general cheaper and less intrusive to the residents. Infrastructure-based techniques, such as pressure tiles, can deliver fine-graded information about the location, depending on the number of sensors [13]. These techniques are most suitable to situations where occupant information is needed for a specific place such as a desk or a conference room [11]. Visual camera-detection can offer very detailed information about the location of occupants and even their activities and actions, but privacy concerns related to camera detection will be very high. Additionally, the image processing and required infrastructure will lead to a large cost [11].

Most techniques that can determine the exact location of residents are radio-frequency based, but there is a large difference in accuracy between those techniques. Most techniques require the resident to wear a tag (or smartphone) [4]. The most well-known localisation technique is GPS (global positioning system), which can reach an outdoor accuracy up to a few meter by using satellites. Once indoor, GPS cannot be used anymore because GPS-signals cannot penetrate solid walls and it will lead to inaccurate results [3]. Therefore, other radio-frequency based signals are commonly used which can work in an indoor environment, such as Wi-Fi, Bluetooth, Ultra-Wideband and RFID (Radio-frequency identification).

Two most commonly used measuring principles for positioning techniques are (multi)lateration and (multi)angulation. Lateration, trilateration and multilateration rely on measuring distances to calculate the position (Figure 1a). For two-dimensional environments, minimum three distances are needed, while, for three-dimensional environments, minimum four distances are needed. Lateration can be used in combination with algorithms to calculate the distance between the transmitter and receiver, such as:

- Received Signal Strength: RSS-based algorithms measure the signal strength of the received signals to estimate the distance between the transmitters and receivers. RSS is sensitive to NLOS-situations (not-line of sight) and multipath environments which leads to less accurate results in these environments and makes them less attractive for accurate indoor localisation [3, 10].

- Time Of Arrival: TOA-based algorithms estimate the distance by calculating the traveling time between the transmitters and receivers and divide them by the wave speed. Therefore, the clock between the transmitters and receivers has to be precisely synchronized [3, 10].

- Time Difference Of Arrival: TDOA-based algorithms measure the difference between the time of arrival measurements and has as advantage that only the transmitters have to be synchronized [3, 10].

- Two Way Ranging: TWR-based algorithms are measuring the traveling time from a transmitter to a receiver and back. In this way no time synchronisation is needed between the devices, which leads to lower complexity and lower cost. As drawback of TWR, measurements of different devices need to be managed sequentially to avoid interference [10].

Multi-angulation (Figure 1b) calculates the position by forming triangles from receivers wherefrom the location is known. Angulation can be used in combination with Angle Of Arrival (AOA) algorithms [1, 3, 10].

- AOA-based algorithms measure the angles to the reference points which leads to higher complexity compared to other algorithms and they are more sensitive for errors which can lead to inaccurate results [3, 10].

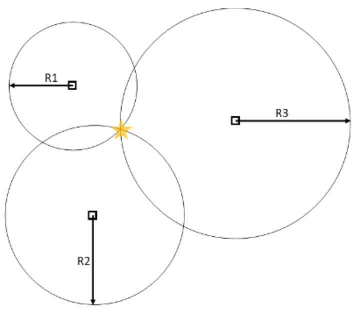

Figure 1a: Positioning by trilateration

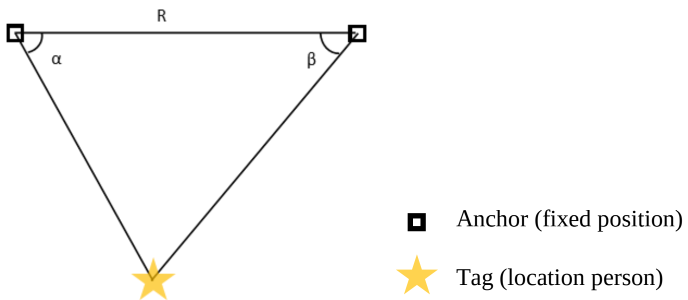

Figure 2b: Positioning by triangulation

Bluetooth-, Wi-Fi-, RFID-based localisation mostly rely on the RSS-algorithm which is more sensitive for obstructions such as internal walls [10] which leads to lower accuracy and is not high enough to get insights into the circulation within a room. Bluetooth-based systems mostly have very small and low-power tags or can be integrated into a smartphone [10, 20]. Wi-Fi-based systems has a wide coverage range between 50 and 100m and can use the existing network. RFID can also be used for proximity positioning where the position is equated to the anchor point with the strongest signal strength. Hereby the accuracy depends on the density of the anchors and signal range. They can all localize a large number of occupants because no time management is needed. Nevertheless, RSS is less reliable for high accurate measurements in an indoor environment [3, 10].

Ultra-wideband (UWB) is a radio frequency technology for short range and high-bandwidth (larger than 500MHz) communication with less multipath interference and a signal that passes through walls and objects [3, 10]. UWB can be used for accurate indoor positioning by using different positioning methods, such as TOA, TDOA, TWR and RSS. The first three methods are more reliable for measuring distances in indoor environments because they measure time instead of signal strengths. UWB-based systems have also some drawbacks: They operate outside the licenced radio frequencies, causing that the power has to remain below 12dB (Europe) [3]. The cost of UWB system is mostly higher than similar systems which are using Bluetooth or Wi-Fi. However, UWB is a good technique for high accurate indoor localisation and has been used for this research to gain insights into the spatial use of residents within a room in a dwelling.

Comparison of commercially available ultra-wideband indoor positioning systems

Requirements / ***System***	*Level of occupancy sensing*	*Horizontal accuracy*	*Vertical accuracy*	*Coverage area*	*Output data*	*Number of users*	*Privacy*	*Size/weight of the tag*	*Required infrastructure*	*Installation time 4 anchors/1tag*	*Cost 4 anchors/1tag*	*Positioning algorithm*
Ubisense ™	Tracking	15cm	15cm	Unlimited	Coordinates	>1000	Location	38x39mm, 25g (incl. battery)	Tags, anchors, timing cable	10'	High	AOA + TDOA
Eliko™	Tracking	30cm	30cm	scalable	Coordinates	10 (4Hz), 40 (1Hz)	Location	85x55x18mm, 54g (incl. battery)	Tags, anchors, master	30'	Medium (±€1800)	TWR
Open Rtls™	Tracking	30cm	30cm	Scalable	Coordinates	>1000	Location	75x50x17mm (incl. battery)	Tags, anchors	/	Medium	TDOA, TWR
Pozyx ™	Tracking	10cm	30cm	Max 16 anchors	Coordinates, Free platform	Frequency/tags	Location	60x53 mm, 14g (excl. battery) 58x70x33mm (incl. battery, self-made)	Tags, anchors, master tag	30'	Low (±€600)	TWR

Table 3: Commercially available ultra-wideband positioning systems

Table 3 shows an overview of four different commercially available ultra-wideband based positioning systems which are compared according to the requirements which are discussed earlier. All four listed indoor localisation systems achieve the requirements, although they use different algorithms which have an influence on the number of tags and the required infrastructure.

Ubisense™ offers an indoor localisation system based on a combination of AOA and TDOA to calculate the position of a tag [21]. Therefore, the time between the different anchors has to be configured, which can be done by a timing cable between the anchors [22]. The system is able to cover a large area and can locate many tags because they can be measured individually and do not interfere with one another. The compact tag of Ubisense™ is the smallest compared to the other systems and has a long life battery, which has a positive effect on the intrusiveness for the residents. Eliko™ offers an indoor localisation system which is based on TWR, with the advantage that no time synchronisation is needed. Hence, multiple tags have to be located sequentially to prevent interference between the different tags. The tags of Eliko™ are larger with a rechargeable battery, but are still portable for users [23]. Open RTLS provides real-time location and can be synchronized for TDOA or TWR, in case of TDOA there is a wireless synchronisation. The tags of open RTLS™ are comparable with those from Eliko™. Pozyx™ is a commercially available system which offers an indoor localisation and motion sensing system (accelerometer, gyroscope, magnetometer, pressure sensor) which works according to TWR. Tags have to be managed by a master which also gathers and saves all the collected data. These tags are compatible with the open Arduino platform which make it able to collect raw data [24]. Pozyx™ offers a development kit without a case or battery and the kit cannot be handed over to the residents directly. The Pozyx™ system is used in the research project to monitor the circulation patterns of residents throughout the dwelling because of its open platform, development possibilities and its low cost. Practical implications and some preliminary results are shown in the next paragraph.

Spatial use monitoring in a dwelling using Pozyx™

To gain insights into the spatial use within rooms in Flemish dwellings and their seasonal variations, spatial use patterns, actions of residents and the indoor climate in the dwelling are monitored for nine consecutive days in each season. Pozyx™ is used as indoor localisation system. It consists of minimum four anchors (Figure 2_{left}) for three-dimensional positioning (lateration), one tag (Figure 2_{middle}) for each resident and one master (Figure 2_{right}) to control and readout the data of the tags carried by the residents. The master will send a signal sequentially to one of the tags carried by the residents. Where after, the resident's tag sends a signal with a time stamp to the anchors that send the signal back to the resident's tag (principle of two-way ranging). The resident's tag calculates its position and sends it to the master tag [24] which saves it on an SD-card. After this cycle, the master sends a signal to the next resident's tag, and this process is repeated continuously during the whole monitoring period when the residents are at home and awake. The number of anchors depends on the design and structure of the dwelling. Therefore, the accuracy has to be tested during each set up. Generally, four anchors are needed for each floor level but the presence of obstacles (walls) can result in the need for more anchors to obtain the same accuracy. The location of the anchors can be gathered by the anchors themselves or need to be measured manually and loaded into the program. Pozyx™ offers a development kit without standard battery, on-off switch or case. For carrying the tags, a case has been designed with the Pozyx tag, a 3700 mAh battery and a charger to charge the battery and to switch the tag on and off. According to the technical description, the tags should use 200mA which leads to a theoretical autonomy of 18,5 hours. Due to the conversion of 3.7V to 5V, a reduced autonomy of 12-14 hours is mostly obtained.

Figure 2: modules to locate multiple persons: anchor (left), tag (middle), mastertag (right)

One way to present the gathered data of the localisation system is as a heat map (Figure 3), which visualises the use intensity of places by a resident during the monitoring period. The figure shows that some areas are only partially used while others are not used at all. This heat map does not make a distinction between use patterns where the residents have been staying on one place or when they are just passing multiple times at a certain spot. To discover the difference between those, more research on 'stops', i.e. places where residents stay for a longer time, has to be done. Additionally, circulation patterns which visualize the effective walking line can be derived. Figure 4 shows the circulation pattern of one resident during a time frame of 23 minutes while coming home. The resident starts his tag at the door, passes the dining table, where after he goes to the kitchen, stay for a relatively long time at the extra work table and then goes upstairs for a couple of minutes. This figure shows where the residents has walked as well as where the resident has stayed for some minutes e.g. the work table and kitchen table.

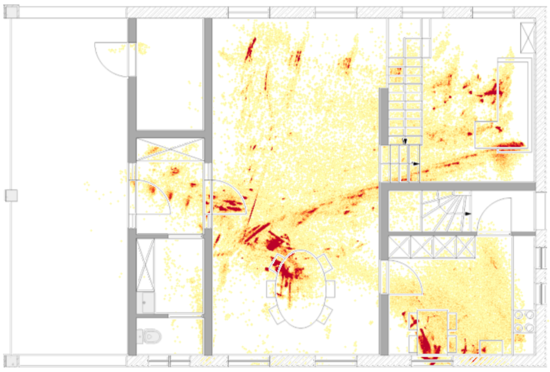

Figure 3: heat map of spatial use of one resident

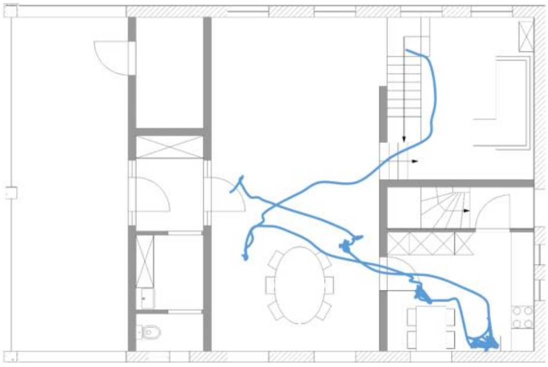

Figure 4:Circulation pattern of one resident during 23’

Conclusion

Many techniques can be used for occupancy sensing and can be used in a lot of research areas. However, for monitoring detailed spatial use patterns within rooms in dwellings, a more advanced monitoring technique is needed because most detection systems give only insights in the occupancy of a room as a whole. A literature review has shown that ultra-wideband has the most potential for accurate indoor positioning in dwellings. Characteristics of UWB, such as large bandwidth and short pulses, makes it able to penetrate obstructions, such as walls, more easily and therefore UWB is more suitable for complex indoor environments. UWB-based systems mostly use time measurements to calculate the location of a tag. When Two-Way Ranging is used, no time synchronisation is needed. Comparison of four ultra-wideband indoor positioning systems showed that they all meet the requirements and they all are highly accurate. For a research project on spatial use patterns in dwellings, the indoor localisation system Pozyx™ is used and some preliminary results are presented as a heat map and as a circulation pattern. In further research, a distinction between movements and stops will be made to get better insights into the areas where the residents are staying for a longer time instead of areas where residents pass multiple times.

Ethical statement

The case study has been submitted to the ethical committee of Hasselt University. Before the residents take part in the research, they are informed about the complete research process and about their right to stop their participation at any time. Each resident signs a document which guarantees that all the data will be processed confidentially and gives permission to use floorplans and pictures for the analysis and to publish results of the analysis.

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