Occupancy measurement systems to identify human presence

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A compilation of modern technologies and applications for determining human presence in residential buildings and how it can be used to create energy efficient homes

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Abstract

In Sweden, heating accounts for approximately half of the total energy consumption in the residential sector. Houses are often unoccupied during a large part of the day, which reduces demand for comfortable heat- and ventilation levels. Utilizing such a gap in demand, and reducing ventilation and heating during unoccupied hours, could reduce energy consumption by 30-42 %. This possibility raises the need for a robust and accurate way to measure occupancy and control HVAC. There are several techniques, both fully developed as well as those in idea stage, to measure human occupancy and each one of them has unique characteristics in terms of technical properties, accuracy and cost with varying suitability for implementation. This work contributes to the current research on this field by compiling existing literature and comparing different technologies to each other based on a number of aspects. Furthermore, associated privacy concerns associated with some of the covered sensor technologies are discussed and hopefully, this work will serve as the basis for future decisions on what type of sensor technology to be used in some selected projects at KTH.
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Nomenclature

Abbreviations

BMS Building Management System
CI Computational Intelligence
DUC Data Under Central
EM Electromagnetic
FLS Fuzzy Logic System
GA Generic Algorithm
HVAC Heat Ventilation Air Condition
IDS Intrusion Detection System
IoT Internet of Things
NFC Near Field Communication
NN Artificial Neural Network
OMS Occupancy Measurement System
PIR Passive Infrared System
PU Processing Unit
RFID Radio Frequency Identification Tag
TD Time delay
TMD Tomographic Motion Detect
1 Introduction

The rapid growth in global population as well as the economic development worldwide is resulting in a growing energy consumption in residential buildings (Energy information Administration, EIA, 2016). In Sweden, residential buildings account for 36% of the country’s aggregated energy consumption according to Energimyndigheten whilst the corresponding figure in emerging markets is much lower in general, and in China it is only 10% (Energiläget, 2015). However, the global urbanization is rising, and the figure is expected to grow with increasing individual wealth, where every one percent in rising wealth is associated with 0.76 percent increase in energy consumption per capita (Zhao et al., 2011). This is putting pressure on the demand for smart technical solutions and applications that could make energy consumption more efficient in households.

The ability to provide comfortable conditions and temperatures in households when its residents are present is crucial and heating accounts for approximately 50% of the total energy consumption in the residential sector in Sweden (Energiläget, 2015). Therefore, an important parameter in creating energy efficient households is the possibility of detecting human occupancy. By tracking patterns of human occupancy, smart applications could modify conditions of temperature and ventilation when the household is vacant, occupied, where its residents are asleep or awake and performing activities of varying intensity. This enable a more efficient use of energy and creates the possibility to decrease the overall energy consumption in residential buildings.

1.1 Purpose

Today there are several technologies for detecting occupancy both available commercially as well as in the concept stage with varying accuracy and cost associated with them. The aim of this thesis is to review these methods and determine their respective ability and effectiveness in creating energy efficient households in regard to various criteria’s that will be stated and described further on in the thesis. The target is to provide a solid and accurate basis when determining which technologies and applications to employ in both new and existing residential buildings.

The results of this thesis will serve as a foundation when implementing occupancy measurement systems in the newly constructed residential buildings in the project “KTH Live-in-Lab” located on the campus of the Royal Institute of Technology in Stockholm.

None of the studied technologies are entirely flawless and some are still in an early development stage resulting in higher costs and lower accuracy. For this reason, we believe that smart applications that combine various technologies, also known as sensor fusion, will present the best solution regarding accuracy as well as cost efficiency.

1.2 Scope of works

In this work, we have put our focus on sensors that are possible to implement in residential buildings. Residential buildings have criteria’s and requirements that differ from those of e.g. office buildings and commercial spaces. This limitation of scope ensures that our results will be valid as well as realistic when determining which systems and technologies that we propose for implementation in the KTH-Live-in-Lab project. As will be discussed later in
the thesis, computational intelligence (CI) - such as Artificial Neural Network (NN), Fuzzy Logic system (FLS), and Generic Algorithm (GA) - for processing the input data, plays a significant role in optimizing the performance of an OMS, and especially when combing sensor data.

1.3 Method

To achieve the goals and purpose of this thesis we review, analyze and present the different technologies and methods available today and used for determining human occupancy in residential buildings. Therefore, our method is a pure literature study where we collect data from previous research on the field as well from companies producing and selling the systems that are being covered in this thesis. Due to the limited time frame no interviews will be conducted.
2 Literature study

2.1 Fields of application

Our purpose is to collect and review information on technologies and applications that measure the human occupancy in order to create more energy efficient residential buildings. The following paragraph describes the technologies’ different fields of application and in what way they have a potential of reducing energy consumption.

In Sweden, there are regulations issued by Boverket which states specific requirements regarding ventilation and ventilation flows when constructing new buildings. One requirement states that the outdoor airflow shall correspond to at least 0,35 l/s*m² of living space. It also states that it is permitted to reduce the outdoor air flow to 0,10 litres per second and square meters of living space when no one is at home (Boverket, 2015). Through Miljöbalken, Folkhälsomyndigheten regulates air quality and air circulation in residential and commercial buildings. Moreover, additional regulations are stated in Arbetsmiljölagen (Svensk ventilation, 2014).

Determining the amount of people in a room is, for example, often used for adjusting the ventilation flow, which is done today by modern ventilation systems. An increase in total amount of people will result in more carbon dioxide and less oxygen, which calls for a larger air flow. Some technologies are based on determining carbon oxide levels, the same technology used in fire alarms, and its technology could also be used for increasing or decreasing ventilation flows. When going one step further, a house or apartment with zero occupants could lower the ventilation flow to the legally minimal boundary which in turn could reduce energy consumption.

Determining the amount of people in an area could also be used for controlling heating systems. A residence showing no occupants, or extremely low activity, e.g. during night time, lack the need of heating that operate in full. By tracking the residents’ schedules, a smart application could proactively adjust the heating systems to decrease temperatures according to occupancy and/or individual preferences to maintain a prominent level of comfort at the same time as it enables potential energy savings.

Moreover, simple occupancy detectors, which are limited in its field of application but at least can determine whether a room is vacant or not, can be used to turn on, off and dim lights in an area, which have proven to reduce energy by, on average, 30 % (Garg & Bansal, 1999).

2.2 Example of research and beneficial applications

Previous research validates the importance of occupancy measurement and gives indications of reduced energy consumption between 30–42 % when using sensor fusion (Tutuncu et al., 2016). The technologies available for determining and tracking human occupancy are widely studied and of meaning to various applications. Besides using sensors to track occupancy in buildings in order to adjust HVAC-systems they are used by, for example, retailers to track consumer patterns and in medical environments to ease patient care. Even though the technologies are the same, their field of application are endless and expected to grow as the systems becomes more accurate and data more accessible.
Teixeira et al (2010) uses a taxonomy in their study for summarizing occupancy measurement systems that enables a clear comparison between different technologies, where all the occupancy measurement systems are evaluated on the following conditions; detecting presence, counting amount of people, determining location, tracking individuals and being able to identify different individuals. Labeodan et al. (2015) expands this taxonomy to include measuring the activity of the present people to conclude which field of application this could be of use for. According to their research this is not possible for systems either using infrared, ultrasonic or acoustic sensors (Labeodan et al. 2015). Activity based monitoring has proved to be valuable in elderly homes and hospitals where the patients’ movements and medical status could be monitored at every moment to guarantee their safety and recovery.

Previous research tends to agree on that a technology that is used by itself, as a stand-alone system, shows too many limitations to be used as means of optimizing energy consumption in buildings. However, sensor fusion can overcome the drawback of each individual measurement technology and makes use of their respective strengths instead (Labeodan et al. 2015). For instance, (Agarwal et al. 2015), combined PIR sensors with a door reader to better determine presence in an office building, while (Erickson et al. 2013) made a case study to enhance accuracy by using image detection (cameras) together with PIR sensors.

Few previous studies have made cost estimations on the different technologies and - as will be shown further on in the thesis – the price varies quite significantly depending on technical properties and supplier. Without any experimental testing or previous studies to base assumptions on, the cost estimation will therefore be a quite large approximated price range.

### 2.3 Energy consumption in buildings

In the following section, we will go through what drives energy consumption in residential buildings and what is required in terms of regulations, directives and comfort from authorities. The main energy consumers in residential buildings are HVAC, appliances, water heating and lighting where the energy consumption of appliances is continuously rising because of smarter, connected, homes and an increase in electronic equipment in households.
2.3.1 HVAC

HVAC relates to heating, ventilation and air conditioning. This area is the most regulated and authorities have established requirements on minimum temperatures and air flows. In Sweden, for newly constructed residential buildings, Boverket sets minimum requirements for indoor temperatures when a building is occupied. This varies depending on geographical location and lower temperatures are allowed (however marginal) in northern Sweden.

For ventilation and air flow, there are minimum requirements even though the building is completely vacant. Since the indoor temperature does not change immediately following an adjustment in air flow, but rather takes time before the adjustment reaches full effect, there are requirements that ensure that the air quality fulfils comfortable conditions at all times.

As (Labedan et al.) states, the aim of optimizing HVAC systems is to keep energy consumption at minimum acceptable values while satisfying required conditions in terms of comfort.

2.3.2 Lighting

Lighting account for approximately 5-10% of energy consumption in households and active actions could reduce this figure (Energirådgivaren, 2015). Lighting is highly affected by the occupants’ behavior and because of the human factor, light risk to remain turned on during the course of the day even though there are no one at home. By turning lights off in rooms that are vacant and during the time when no one is present the energy consumption caused by lighting could be reduced by, on average, 30% (Garg & Bansal, 1999). However, this figure does not take into account the use of light-emitting diode (LED), which uses about 75% less energy than incandescent lighting and therefore reduces the potential of energy savings in regard to lighting. By replacing incandescent lighting by more energy efficient alternatives, such as LED lights, the energy consumption could be reduced even further. (U.S. Department of Energy, 2016)

Figure 2 Description on how a lighting system work through a PIR sensor
Source: http://pirsensor.blogspot.se/
2.3.3 Appliances

Activities such as washing, cooking, using the dishwasher and appliances such as refrigerator and freezer account for double the amount of energy consumption as lighting (Energrådgivaren, 2015). However, this is not as easily affected by occupancy detection systems and will therefore not be studied further in this thesis. However, it is worth mentioning that energy consumption could be reduced drastically by renewing this equipment and through active measures by the occupants.
2.4 Technologies used for occupancy measurement

2.4.1 Classification

We define occupancy detection, or human sensing, as any technical solution to extract information about presence in a certain environment (Teixeira et al., 2010). These technical solutions can be divided into various categories based on what information can be obtained through them. The focus of this study is to map current, as well as newly developed and promising, technical solutions. In this chapter, we will analyze and discuss the technical properties of OMS with focus on their accuracy and application field. Moreover, we will make a cost analysis of each technique and weigh it to its level of accuracy.

We will study mainly three parameters when analyzing the technical properties of each OMS. Those are:

1) **Presence**

   This is the most basic property of any OMS and is strictly binary - *Is the environment empty or not?*

2) **Count**

   This property is critical to a more precise OMS – *How many people are present in the given environment?*

3) **Location**

   Where, in the given environment, is the person located?

For other application fields, for example the above-mentioned field for retailers to track consumer patterns and in medical environments to ease patient care, it is relevant to further analyze properties such as the system’s ability to track and identify. However, for the purpose of this study, these two parameters become redundant as they do not have any explicit impact on heat- and ventilation demand.

2.4.2 Passive Infrared Sensors – PIR

Passive Infrared Sensors is an electronic system which processes radiation from objects at infrared wavelengths, which is emitted by all objects at a temperature above absolute zero degrees. The sensor detects changes in the infrared radiation which trigger the detector. These changes can occur when an object, with different temperature than the surrounding, is moving within the detector’s field of view, thus resulting in a temperature rise or fall which triggers the detector. Changes in incoming infrared radiation can also occur when an object with different surface characteristics is displayed in the detector’s field of view and thus emit infrared light in different patterns than the surrounding which then also triggers the detector (Ecosiris).

These characteristics of the Passive Infrared Sensor have historically made it a suitable application for Intrusion Detection Systems (IDS) in buildings, as well as lighting control indoors and outdoors because of its binarity; these application fields, and intrusion systems in particular, work fine with singular information if an individual offset the detector. Their
ability to detect human presence is however limited due to several factors; for example, it cannot detect the number of people present which plays a role in determining ventilation flow and heat demand. Moreover, it can be offset if individuals are stationary – the system requires constant movement to fully function (Teixeira, G. Dublon, A. Savvides, 2010).

![Figure 3 Representation of functionality of a IR](http://pirsensor.blogspot.se/)

For full accuracy, there is a need for a PIR in every closed environment in a building, so the cost for one PIR sensor should be multiplied with, at least, the total number of rooms. However, the sensor can be installed with a time delay (TD), to ensure that it is not falsely off- triggered when a person is in another area for a certain time or sitting still. 

PIR sensors have proven to have high accuracy in terms of detecting presence. Since it is a binary technology it lacks the ability to identify and track individuals, but given that installed sensors are able to cover the studied area the accuracy of detecting human presence range between 90 and 99% (Yun J., Lee S., 2014).

The cost of a single infrared sensor varies in the range between SEK 50 to SEK 1000, depending on function. It is important to bear in mind that a sensor should be installed in each room in order to establish a complete and fair estimation of occupancy, and in some cases more than one sensor is required in a single room depending on its geometry. Therefore, the final cost ultimately depends on size and geometry of the residence as well as the need to get a comprehensive system that is able to detect presence in the whole building.

### 2.4.3 Ultrasonic Sensors

Ultrasonic Sensors are, in contrast to Passive Infrared Sensors, active. The sensors emit ultrasonic sound waves at a frequency of 25 – 40 kHz and receive the reflected sound. When an object is hit by the emitted sound waves, the reflected sound waves received by the sensor will have a different wavelength which triggers the sensor. The advantage with Ultrasonic
Sensors, over Passive Infrared Sensor, is that Ultrasonic sound can be propagated by reflection to all areas in a building (and thus has a higher coverage), where Passive Infrared Sensor only can detect movement in their field of view (Guo X., 2010). Thus, it is more effective than the PIR, but – in similarity with PIR technology – it is not able to determine the exact location of a person, nor is it able to determine how many people are present in the environment.

While Passive Infrared Sensors are susceptible to false off-triggers, Ultrasonic Sensors are highly sensitive and therefore vulnerable to false on-triggers. They are exposed to risks of being triggered by minor movements such as wind from an open window, or from some small objects falling off a counter which alone limits their practical feasibility as an accurate occupancy measurement system (Evans et al., 1989).

As ultrasonic sensors are well-developed on a commercial stage and not regarded as very technically advanced equipment, they are inexpensive. The cost for a sensor ranges between SEK 300 and SEK 1500. The range depends on the technical abilities and of course its sensing range. As in the case with PIR it is noteworthy that multiple ultrasonic sensors are needed, increasing the total installation cost.

### 2.4.4 Carbon dioxide (CO$_2$) concentration measurement sensor

CO$_2$-detectors measure the concentration of carbon dioxide in air. The sensors are sometimes used to measure the concentration of carbon dioxide in buildings for the sole purpose to assess the air quality and control the air flow. However, it has also been shown to have an extended application. Given there is accurate information about the inflow air and room size, as well as assumptions on CO$_2$-emissions, the sensor could be used to give an indication of the occupancy in a room. Unlike Passive Infrared Sensors and Ultrasonic Sensors, CO$_2$-based detection systems could give an estimation of how many occupants a room has and thus lead to a more precise heat demand estimation (Labeodan, 2015).

Drawbacks with solely relying on carbon dioxide concentration to estimate human occupancy are the many unknown disturbances that highly affects the outcome. These parameters include air change rate through infiltration, window and doors, as well as the assumption of the concentration of carbon dioxide in outdoor air (Meyn et al., 2009).
(Jiang et al., 2016) performed a test using \( \text{CO}_2 \) sensors in an office space with 24 cubicles and 11 open seats, and was able to show an accuracy rate of 94% with three or four incorrectly estimated occupants of a total 35 occupants.

The cost of a \( \text{CO}_2 \)-detector varies quite significantly depending on supplier, but are usually in the range of SEK 1000 to SEK 5000 for the sensor. Thus, a carbon dioxide sensor comes at a higher cost than PIR and ultrasonic systems.

### 2.4.5 Image processing sensors

Image detection systems such as video cameras and regular cameras traditionally are used for security purposes in buildings, ranging from residential to commercial spaces. Image detection sensors are able to identify, track, count and detect variations in activity in buildings and are therefore able to gather comprehensive data that in turn could be used for creating smart applications for determining human occupancy (Labeodan, 2015). The analytical algorithms used to process and analyze occupancy information are still in preliminary stages of development but shows great promise (Benezeth et al., 2011).

An image detection system always requires line of sight to function properly, creating a need for multiple devices. This technology might prove more suitable for office spaces as well as in commercial buildings but might prove difficult in residential buildings where rooms are smaller and seldom as openly planned as, for example, an office floor. The need for multiple devices will increase cost due to use of expensive hardware. Using image detection systems also raises questions regarding privacy since information is gathered in forms of graphic images whereas an ethical dilemma might arise as user privacy is exploited and registered (Ghai et al., 2012).

In (Benezeth et al., 2011), an 83-93 % accuracy rate for occupancy detection was shown. In another study performed in a laboratory environment, the accuracy rate was proven to be 71.2 % (Erickson et al., 2011). Based on these two studies, the accuracy rate if ranging from approximately 70 % - 90 %. This accuracy term includes identifying and tracking individuals.
It proves difficult to state a specific price on image processing sensors as it may vary from SEK 100 to one hundred times that. Depending on product specification and what requirements are needed the price is volatile. For example, view angle, data storage and display resolution are some specifications that affects the price. However, in order for a video camera to be used for occupancy measurement there are possibilities of finding a suitable product in the price range of SEK 100-1 000. The technology has some similarities with PIR systems since it always requires line of sight in order to return a correct value of the occupancy, which creates a need for multiple devices.

2.4.6 Acoustic systems

Though at an early stage in development, acoustic systems, or sound detection systems, are being evaluated if they are able to be used in applications for detecting human occupancy. By registering sound waves emitted from the people located in the building, they provide information regarding presence and location (Huang et al., 2016). At the moment, the technique is being tested and developed where the algorithms are continuously improved. One of the drawbacks of the technology is that the sensors react to other sound sources than humans meaning that the system could actively change the surrounding environment due to false premises. It could also register false data when premises are occupied but there is no activity. It might prove difficult to use acoustic systems as standalone systems, but given the right complement it could prove to be an effective technology to be used for occupancy measurement. One of its advantages is that it will react solely based on emitted sound, making it non-intrusive. Moreover, no individual tags are needed, as when using RFID technology, at the same time the technology is considered to be unadvanced, making it very cost efficient and user-friendly (Huang et al., 2016).

In order for a sound detection system to work the only technology that is needed besides the smart BMS (building management system) is a microphone and a microcontroller. The researchers in 2016 used a Gaussian Mixture Model (GMM) speaker recognition system while optimizing its algorithm to achieve a system that could separate the different speakers. In this way, the technology proved to be able to not only detect occupancy, but also determine the number of people in a room provided that they were all speaking at some time. These are usually inexpensive and could be bought at a price below SEK 90, while still giving more than reasonably accurate information about occupancy levels. Although at an early development stage, the technology shows progress and looks promising.
It proves difficult finding previous research on what level of accuracy acoustic systems shows regarding presence- and or occupancy detection. (Jiangfeng et al., 2005) performed a study using both microphone and PIR and achieved an 87 % accuracy rate for detecting occupancy.

### 2.4.7 Electromagnetic signal detection systems

The electromagnetic signal detection systems, consist of systems that could be used by transmitting and receiving electromagnetic pulses. This technology could be found in WIFI, Bluetooth, Radio Frequency Identification tags (RFID) and Near Field Communication (NFC). This means that the user’s mobile devices transmit electromagnetic pulses to a static receiver which then registers presence, count and activity (Li et al., 2012). This technology can provide highly individualized information that could be used for occupancy detection.

Since it is always transmitting pulses the user is always monitored which reduces privacy, creating the same drawback as with image detection systems. It might also provide false data if each user has multiple mobile devices, where one might be left at home when the user leaves the building. It will also present incorrect data if the mobile device and the user are not in the same part of the building, meaning that activity and presence as a result will be registered incorrectly.

(Li et al., 2012) performed an experiment using RFID tags and could show an 88 % accuracy rate for detection occupancy. In another study, the accuracy rate was shown to be 93 %. Based on those two studies, the accuracy rate lies around 90 % (Zi-Ning et al., 2008).

The cost for electromagnetic signal detection systems vary depending on if it is a simple RFID tag or if it is already present in some other technology, e.g. a mobile phone. For low-frequency RFID tags with a possibility for storing data, the price might vary between SEK 30 and SEK 1 000. However, one of the advantages with this technology is that it seldom requires external hardware, since a clear majority of people today carry some sort of technology that are RFID tags or contain NFC or Bluetooth. This means that it is safe to say that the cost of the hardware, besides the BMS, is negligible.

### 2.4.8 Tomographic Motion Detector

Tomographic Motion Detector (TMD) is a quite newly developed technology. The system consists of two parts: nodes and a processing unit (PU). The nodes can be imbedded in walls or behind objects in the area and are together creating a fully connected mesh network, which means that the nodes are all connected to each other. The nodes are not sensors themselves; they need to connect to each other to create sensing lines which is done by the nodes transmitting and receiving radio waves to and from each other. When an object is moving past the sensor lines they are disrupted which triggers the system. The PU is in communication wirelessly with the nodes and are constantly receiving information about the received signal strength between the nodes, which is then processed and notified to a connected control panel (Artelisy).
The main benefit with TMD is its full coverage of an area. In contrast to the PIR that relies on a line of sight, the TMD cannot be blocked by solid objects or walls, thus resulting in a higher coverage. Because all nodes are connected to each other, the number of links (sensor lines) is given by \( N(N-1) \) where \( N \) is the number of nodes. The TMD is also able to track where a person is located. Another characteristic with the TMD is that the system itself can be completely hidden, impeded in walls or behind objects which could be an esthetical benefit. The TMD’s ability to fully cover an area is a clear advantage but one drawback is that it might not be able to differentiate two or more people standing closely next to each other.

The motion detection area is also being completely isolated by the coverage of the nodes because of the communication in between them, which minimizes the risk of fake triggers by moving objects in surrounding environments that the system is not meant to be covering. However, the characteristic of TMD adds more value in applications such as intrusion alarms where there is a specific, fully defined area, that are being protected.

For an area of approximately 500 square feet (46 m²), the requirement for full coverage is about 6 nodes which together with the PU has an estimated cost of $400- $500 (SEK 3600 – SEK 4500) (Xandem).
2.5 Combining sensors and smart technologies

The previous section has given a technical description of the different technologies that are available on the market today. In this section of the thesis, focus will be put towards examining how these technologies are being combined in applications and how a combination of different sensors/technologies can be used to reduce the shortcoming of each technology and thus improve its accuracy. Furthermore, privacy issues related to the usage of smart occupancy measurement systems will be addressed.

2.5.1 Sensor fusion and learning systems

Sensor fusion combines sensory data to produce enhanced data in form of an internal representation of the process environment. Since each technology presents a number of drawbacks they are often insufficient as stand-alone systems. Some systems prove to be valuable in open spaces where others might be better suited for other types of indoor geometries. By combining technologies into a sensor fusion system, the benefit of taking advantage of the single strengths of each system while reducing the impact of their respective limitations is accomplished. Sensor fusion systems are able to present more fine-grained data and take different views into account when acting as a learning system. By using one single main system with the options to retrieve and analyze data from different technologies, cost could be kept at reasonable levels (Elmenreich W., 2002).

In short, the accomplished achievements of sensor fusion are - among other abilities - a more robust system, increased temporal and spatial coverage, reduced ambiguity and uncertainty, and, to not say the least, improved resolution rendering in better detection accuracy. This vouches for higher accuracy in terms of occupancy calculations and improved occupancy driven control systems with increased energy efficiency as a result.

When gathering data from multiple sources as done in sensor fusion, an interesting aspect is the processing of the data acquired. Computational intelligence (CI) - or soft computing, often used to solve complex problems that cannot be handled by rule-based program – plays a significant role in optimizing the control system performance (Kukolj et al., 2001, Martins & Coelho, 2000). An example is ANN which is a biologically inspired model and is based on a major network of connected units called artificial neurons. The neurons are most often connected in layers (see figure below) where the signals are travelling from the input layer to the output layer. In the input layer, the data is gathered by the model, in the hidden layer the data processing takes place and in the output layer some results based on the input is produced. Some Neural Network algorithms that are being used are for example Hebbian, Perceptron and Back- propagation. In the back- propagation algorithm, the input reaching the output layer is compared to a desired output and potential error is propagated backwards and finally optimized such that the loss function is minimized (Ekwevugbe T., 2013)

Applying CI – such as Neural Networks, Fuzzy Logic Systems or Generic Algorithms – does have exciting potential in optimizing demand driven HVAC control, although this area is still quite unexplored regarding its use for residential buildings. It could be argued that behavioural patterns are more easily predicted when they are in aggregated forms, such as the occupancy in office buildings or malls – where the occupancy load often follows some form of cycle/pattern. Predicting one or a few people’s behavioural pattern could be perceived as more challenging.
There are several studies that have been exploring the opportunities with different combination of sensors and their performance together with the use of CI. For example, (Ekwevugbe T., 2013) used a machine learning model for sensor data fusion, implementing sensor technology such as CO₂, PIR- and acoustic sensors which was then combined with a neural network. The experiment showed that the system overall had an 84.59 % accuracy rate of detecting occupancy. In another study, using the combination of CO₂-, light-, acoustic-, and PIR sensors, an accuracy rate of 98.4 % for occupancy detection was shown (Hailemariam et al., 2011) which by far is the highest percentage of accuracy presented in this thesis.
2.5.2 Smart applications and privacy concerns

The technologies that have been covered in this thesis can be viewed as enablers; technologies that can form an output that reveals information about occupancy in an enclosed environment. Over the last decade, we have been witnessing a growing development in smart technologies, which unsurprisingly also has emerged within energy efficiency. By employing predictive algorithms that allows the system to learn, and forecast, occupancy patterns, a more precise and smart occupancy measurement can be obtained. For example, by utilizing opportunistic data sources - such as GPS and smart phones - a system could learn to estimate the likelihood of expected occupancy (Pritoni et al., 2016). Moreover, collections of data gathered from any of the above covered techniques could be used to estimate behavioural characteristics of inhabitants - in terms of when, and when not - a person is at home. This gathering of data could be regarded as privacy intrusive which could limit its application field in the future, due to stricter legislation and a stagnation in customer acceptance.

There is a clear conflict between creating smart and energy efficient homes, that requires gathering of data, while at the same time not being privacy intrusive. We have been witnessing a growing debate regarding these issues, through articles in various newspapers (The Guardian, 2014), and perhaps the clearest concern is for commercial entities, where companies could have incentives to use behavioural data to learn more about customer behaviours. As long as it is in aggregated form, it might not be perceived as a privacy issue. On the other hand, aggregated data naturally consists of amounts of personal data that in theory could be analyzed in a separate form.

In the summation below, the main privacy concerns we have identified is explained

1. **Illegal use** - Criminal people, thieves etc. stealing data to know when a house is unoccupied
2. **Law enforcement use** - using data gathered from video etc. to detect illegal activities in homes
3. **Use by family members** - Household members tracking other household member’s activity, for example a partner spying on his or her partner, or a parent keeping track of their children’s behaviour in a way that violates privacy

2.6 Energy efficiency and OMS

In the following section of the thesis, energy efficiency and the impact of occupancy measurement sensor will be addressed. Previous research shows that two of the most crucial factors of succeeding in creating more energy efficient households are the ability of measuring occupancy levels as well as incentives for energy efficient behaviour for the residents (Heinonen J., Junnila S., 2014).

While energy consumption caused by lighting could be reduced by, in average, 30 % as mentioned in chapter 2.4.1, the other valuable aspect to investigate is reduced energy consumption by HVAC systems. One study show that smart applications enable a reduction of energy consumption by the HVAC system by approximately 18 % by using a system that detects occupancy by connection between the occupant’s phones and the Wi-Fi network (Balaji et al., 2013). Moreover, the typical HVAC systems that is used in office buildings
assume low, or even none, occupancy during the time of night while occupancy is assumed to be maximum between regular office hours. As argued above, a fine-grained system should adjust HVAC systems on a room-to-room basis since geometry and activity levels usually vary depending on time of area. In residential buildings, and more specifically older buildings, it is not uncommon that HVAC systems stay at constant temperature set points regardless of occupancy levels.

One of the key topics to address relating to reduced energy consumption due to occupancy measurement is the time delay (TD) of the sensor. The TD is defined as the time between the last detected motion and when the system acts. Adjusting the TD is an active precaution that could enable energy savings but it must be taken by residents since standard TD’s tend to be unnecessary long. A reduction of TD has proved to increase energy reduction by 100 % in relation to using the standard TD (Floyd et al. 1996). However, a too short TD risk resulting in false off-triggers, where the system will respond too quickly. This will create several adjustments by the system, resulting in increased energy consumption. Garg and Bansal show that smart occupancy measurement sensors with the ability of adjusting the TD based on the occupants’ different activity during the course of day could reduce energy consumption further by 5 % (Garg V., Bansal N.K., 1999).

Agarwal et al. (2010) show that adjusting room temperatures from standard temperatures during typical unoccupied and occupied hours have the possibility of reducing HVAC energy use by 10-15 %. While conducting further studies, Agarwal et al. (2011) had the system driven by real-time occupancy estimates and turned the system off during unoccupied hours, which yielded savings up to approximately 16 % in electrical energy consumption.

Furthermore, during a simulation Pavlovus (2004) kept ventilation at maximum levels during occupied hours and lowered the air flow during unoccupied periods which yielded energy savings up to 20 % in ventilation energy use. As discussed above, fine-tuning the system for real-time occupancy driven control in combination with adjusted temperature and ventilation levels on a room-to-room basis could be enabled by smart occupancy driven systems. Erickson et al. (2009) used a dynamic approach when calibrating their system which accounted for real-time occupancy in each room and reported reduction in energy consumption by HVAC systems by 14 %. Equivalent results were reported by Klein et al. (2012) when calibrating a system to act upon real-time occupancy detection and knowing the user preferences in advance. Ekwuegbu (2013) uses real-time based occupancy driven ventilation control and accomplished energy savings amounting to 53 % in regard to ventilation and heating consumption.

Previous simulations and case studies show that the use of occupancy driven HVAC and lighting systems have a substantial impact on energy use in buildings, both residential and offices. Active measures from the end-consumers and users prove to have a significant impact on the total saving potential since systems based on standard settings risk reducing savings potentials. The critical factors for success is being able to detect occupancy and activity on a room-to-room basis while customizing the system to match individual preferences and schedules.
3 Results

In the following section, a summary of our review on existing literature will be presented to get a clear overview of the different technologies that have been covered. The results should reflect the advantages and drawbacks of each technology to gain a comprehensive assessment that will serve as basis for our recommendation when choosing an OMS.

Table 1 Illustration of results

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Presence</th>
<th>Count</th>
<th>Location</th>
<th>Occupancy accuracy</th>
<th>Cost</th>
<th>Privacy concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIR</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>Low</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>Low</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>✓ ✓</td>
<td>✓</td>
<td>94 %</td>
<td>High</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Image</td>
<td>✓ ✓ ✓</td>
<td>✓</td>
<td>70-90 %</td>
<td>High</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Acoustic</td>
<td>✓ ✓</td>
<td></td>
<td>Not clear</td>
<td>Low</td>
<td>No/Yes</td>
<td></td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>✓ ✓ ✓</td>
<td></td>
<td>88-93 %</td>
<td>Medium</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Tomographic</td>
<td>✓ ✓ ✓</td>
<td></td>
<td>Not clear</td>
<td>High</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

The table above summarizes the properties that each technology that has been covered in this thesis possesses. Moreover, based on existing literature, the accuracy for detecting occupancy (presence and count) is illustrated for those that fulfil the criteria. As seen in the table, no reliable and unbiased data was discovered for occupancy accuracy for Acoustic sensors and Tomographic sensors. In chapter 2.55 a study was presented, claiming an 87 % accuracy rate for occupancy detection using both PIR sensors and Acoustic sensors. However, limited conclusions regarding only the Acoustic sensor’s accuracy can be drawn from this.

All sensor types fulfil the criteria of the ability to detect presence which could be viewed as the most basic criteria for an OMS. The sensors abilities to count are limited to CO₂ sensors, Image sensors, Acoustic sensors, Electromagnetic sensors and Tomographic sensors. The sensors abilities to determine exactly where a person is located are only fulfilled by Image sensors, Electromagnetic sensors and Tomographic sensors.

When it comes to accuracy, it should be made clear that it is a fairly subjective categorization. The existing studies that have been presented in this thesis, all have had different lab environments, different equipment, software and models that have been used to approximate the accuracy of each technique. Thus, the %age accuracy presented should be taken with a grain of salt when comparing different sensors to each other.

The cost for each sensor has been categorized in three levels - low price, medium price and high price. Because prices fluctuate quite substantially depending on supplier and quality - and because we have not had the opportunity to practically test several devices - the cost level has been determined by comparing products of similar technical data to find a somewhat industry benchmark price. By this, we have found that CO₂ systems, Image processing systems and Tomographic systems belongs to the highest price level, whereas
Electromagnetic systems are to be considered in the middle price range and finally PIR, Ultrasonic, and Acoustic in the lowest price range.

The table also illustrates if there is any privacy concern associated with the sensor.
4 Discussion

When establishing a proper comparison criterion in order to evaluate which technologies are most promising we found that a trade-off between cost and accuracy was not enough. Privacy concerns has been a recurring topic and at the same time as technologies are advancing they are able to present more fine-grained information regarding users and user data (Parmas J., 2017). This raises the question if perfect accuracy is desirable. Image detection systems have the full capability of locating, tracking and even identifying users, but at the price of impairing privacy. They are also, as seen in Chapter 3, priced high. Privacy issue in combination with high pricing made it clear for us that they are not the technique to invest in going forward, at least not until stored data can be guaranteed to be completely secret and safe.

Privacy is also a topic concerning ICT. Through individual tags within mobile devices (e.g., RFID) individualized data is retrieved by central systems that have the possibility to identify each individual. As the area and field of applications using EM is growing, privacy related issues have to be addressed properly. Such efforts are, for example, seen by official authorities where restrictions on what data that could be collected are introduced and in what way this data may be used (Information Age, 2015). Our results show that the EM technology and its endless field of application is promising and the preferred technology. Furthermore, due to its compelling ability to detect presence in combination with the low cost associated with the technology at the same time as regulations are introduced and developed regarding data storage, we firmly believe that this technology is superior and shows promising progress as it develops.

In our research, we have found that one of the more recent developments regarding occupancy driven control systems seems to be the learning systems. Early methods that have been in use until now have previously been functioning in one of two ways, either through a time schedule which has created a binary system that works in one specific way during a specific period and in another way during the rest of the day. This could be regarded as the predecessor to occupancy driven control systems. The other function is that of true occupancy driven control systems, but usually in a binary manner. When occupancy is detected, the lighting and HVAC systems will act upon the retrieved signals in the DUC, and adjust itself when the building, or room, is regarded as vacant with a predetermined TD.

Smart applications possess the ability to collect and analyze occupancy data from its users, making it possible to proactively adjust lighting and HVAC systems. Learning systems go one step further, and will not only react upon activity, but rather anticipate it by collecting data on user habits and learn by its patterns. For example, based on previous data, temperatures could be set to a lower level inside a house or apartment in the morning before the building is completely vacant. Since adjustments do not occur instantaneously, it will take a while for the system to reach its target temperature. Smart applications therefore enable for proactive measures that could lead to potential savings in energy without sacrificing comfort. The learning mechanism from smart applications will likely see rapid development in the years to come, rendering in more accurate actions and more effective energy usage.

The target of this thesis has been to review and compile the technologies, both available today and in an early development stage, and no case studies have been performed by the authors during this research. Consequently, a result is that there are limitations in determining cost efficiency and accuracy as these are based on previous work. The definitions of accuracy
and efficiency vary, and in most cases, there are only one or two technologies that have been studied simultaneously, further aggravating comparison between the different systems and its underlying functionalities.

In addition to above, saving potentials are likely to be affected by the geometry of the residence as well as its total volume. A somewhat efficient geometry, without limitations in visibility, would likely decrease the number of stationary sensors. As an effect, the cost baseline would subside for the presented technologies with required visibility. Therefore, there are difficulties manifesting that the use of occupancy measurement systems certainly results in realized savings in energy consumption, since building geometries vary in a wide range, both in single-family houses and multi-residential buildings. The same result applies when considering building volume. An increased volume has both positive and negative effects. On the downside, the need of sensors will in most cases increase with size. On the other hand, each sensor has the possibility of serving a larger area, further streamlining energy consumption. This does in turn demonstrate that one specific set of technologies and applications that have the possibility of realizing energy savings in multi-residential buildings may not have the same effect in single-family houses.

For reasons stated above, we see the need for additional experimental studies in both multi-residential buildings and single-family houses that highlight which technologies are most prominent depending on its application in a specific environment.

Within the scope of this study and serving as basis for our results, we have studied the effects and potential seen in multi-residential buildings, e.g. apartment buildings. Research showed that shared areas, such as stairwells, elevators, laundry rooms, account for 21% of total energy usage in multi-residential buildings (Finch et al., 2014). By deploying an Electromagnetic based application, connecting to the apartment through the Wi-Fi network, a blind spot would be established in terms of determining the total potential energy savings since WiFi networks are seldom global in the way that they serve an entire building. This of course excludes those residences located at a university campus where the public network could be used throughout the building, but instead raises the topic of individual comfort preferences and efforts in decreasing energy usage. This creates a need for stationary sensors, more specifically inexpensive ones which are able to assess consumption in common areas and implement the necessary actions to realize energy savings. For this particular use, PIR sensors would be preferable due to low installation and maintenance costs.

Furthermore, we have reached the conclusion that the area covering learning applications collaborating with applications deriving its technology from mobile devices that is connected through Wi-Fi networks is still not fully discovered. This is by far the most interesting area in our opinion since no stationary sensors are required if the technique is used as a stand-alone system. As a result, the cost is negligible, apart from the main control system, at the same time as the technology meets all the criteria in terms of acknowledging presence, location and count. Future research should study the effects of using this technology and its strengths and weaknesses in relation to other technologies.

When conducting our study, we found scarce research that study the effects of combined use of OMS and active energy control. The latter has been even more enabled by more rapid development of technology and smart applications than seen before, where portable/mobile devices are playing a significant role. By connecting the household appliances to cloud based
services, residents are able to retrieve real-time snapshots of the total energy consumption around the clock, which appliances are using the most electricity and take action and control the appliances from an application in your mobile device. In our research, we have drawn the conclusion that accurate OMS have large, but varying, energy saving potentials but as aforementioned, energy savings potentials increase when the user are able to monitor and study their energy usage. We propose that future research study the impact of realized energy savings where an OMS is implemented in combination with the usage of active applications that monitor and can control household appliances from distance. We believe that energy savings potential could be substantially higher due to earlier mentioned reasons. We are experiencing a time where Internet of Things (IoT) is expanding and continuously finding new areas of application, where occupancy-driven energy control is one of them. Smart technology in collaboration with mobile devices enables a more energy considerate approach in a way that is also economically justifiable.

Among the applications that combine the features as stated above are Nest, Ecobee and ESA. They are learning systems that make sure energy is allocated to where and when energy is due, based on user preferences while also providing the user with the possibility monitoring and act based on real-time snapshots of the energy consumption.
5 Conclusions

The scope of this thesis was to review previous research on different technologies with the ability to detect and measure human occupancy levels in residential buildings. These technologies were then to be evaluated in terms of technical abilities, accuracy and cost efficiency to determine which technology or fusion between technologies would be superior in realizing energy savings based on occupancy flows. As a consequence of omitting commercial buildings from the scope we were able to draw the conclusion that traditionally used technologies in e.g., office buildings would not be as efficient in apartments and single-family homes. The distinctive advantages of these technologies are often derived from its abilities to handle public and open spaces with high visibility, which is seldom needed in residential buildings apart from common spaces.

In our research, we concluded that depending on the geometry and volume of the household, the preferred technical abilities differ. Energy savings are, apart from those that stems from HVAC, in most cases enabled by a smarter and more conscious way of using lighting and household appliances. Studying the use of the latter has not been within the scope of this thesis. Previous research show that occupancy-driven control systems in commercial buildings have a large energy saving potential in regard to lighting, which largely depends on the fact that lighting is operated automatically and not operated manually by the users. In residential buildings, where the user is economically responsible for the electricity bills, lighting is often regulated depending on preference, actual occupancy and activity. We therefore conclude that the savings potential in this specific area is lower inside the homes of residential buildings than in commercial buildings. Moreover, it might lead to discomforting on-triggers as aforementioned in Chapter 2. Specifically, in smaller apartments, which are the main scope of this thesis, the risk of leaving a light on during zero occupancy hours is moderate, and even if this happens sporadically, the overall savings are considered to be limited. For this reason, we believe that sensors controlling lights inside the homes are redundant in smaller residences, but deserves to be further studied through experimental analysis. However, in shared areas where lighting is often adjusted by a building management system we suggest the implementation of occupancy sensors with binary use, in eg. passive infrared or ultrasonic systems, since these technologies are inexpensive and considered to be sufficient in terms of addressing demand.

We consider applications based on electromagnetic signal detection systems to be superior to other technologies as connection through a Wi-Fi network in interplay with the GPS that mobile devices offer, deliver high occupancy accuracy and require no stationary sensors. HVAC systems could then be controlled by smart central systems with learning abilities that react both based on historic occupancy patterns as well as actual presence. This is also considered to be the most promising technology going forward as it advances with a high correlation as the development of Internet of Things.

We propose that future research study the realized savings in energy consumption in residential buildings through electromagnetic signal detection systems. In addition, in order to obtain a comprehensive understanding of the saving potentials, both single-family homes and multi-residential buildings should be studied. This is an increasingly important global topic as energy consumption by the residential sector are continuously growing as the emerging markets economies are expanding.
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