Occupancy Determination by Backscattered Visible Light Sensing

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***Abstract* - Demand driven control of heating or cooling, has the potential to reduce the energy consumption of buildings to a significant portion. One of the main cornerstones of such a demand driven control is the accurate determination of occupancy in the building or sub-areas of the building. In recent years many different approaches, founded on various technologies and sensing principles have been used to establish an occupancy detection system. Especially in existing buildings, retrofitting such a system can be associated with high installation effort and cost. Furthermore, some technological approaches, mainly camera-based systems are inflicting concerns in regard to the privacy of the users. In this manuscript, we present and discuss an approach for a lighting fixture that performs person recognition and occupancy determination based on the technology of Visible Light Sensing. In our implemented system by solely capturing reflections of the visible light, caused by bypassing persons, the occupancy, the movement direction and the walking speed can be accurately determined. Based on comprehensive real world experiments we will show how our system, fully integrated into an off-the shelf luminaire, is able to operate in different scenarios and ambient light conditions and only requires minimal installation effort without causing any privacy concerns.**

***Keywords* - Visible Light Sensing, Occupancy detection, Photonic remote Sensing**

I. Introduction

One of the key elements to fight the energy crisis is to make buildings more energy efficient in their operation. Worldwide, buildings are responsible for up to 40% of total energy consumption. Therefore, many efforts are made to reduce the energy consumed by buildings. To achieve this without reducing the comfort of the people in the building, technological innovations are needed in various areas. Reliable occupancy information is one of the most important aspects when it comes to tailoring the operation of Heating, Ventilation and Air Conditioning (HVAC) systems of a building. In [1] it is stated that implementing occupancy detection systems has the potential to realize energy savings between 10% and 40%.

In regard to new buildings, in planning or under construction, such occupancy detection systems are often already integrated, but especially in existing buildings the subsequent installation is often not feasible due to high installation cost.

In terms of presence and occupancy detection, the main approaches can be divided into three main categories, where each category utilizes again various methods and underlying sensor technologies.

The first category are so called active systems, where the user has to carry an active/semi-active device. The main technologies used are Wi-Fi [2,3], Bluetooth [4] or RFID [5]. The main principle is that the corresponding access point (e.g. Wi-Fi Router) recognizes the device or tag worn by the user and consequently, by counting the "connected" users, the occupancy of an area can be inferred. One advantage of such systems is that the existing infrastructure (e.g. Wi-Fi) can be used to gather this data, but this also outlines one of the main disadvantages. If a user does not carry the device, he also cannot be "counted".

The second category is based on environmental sensors. This category includes CO_2 sensors or smart-meter based approaches. [6,7] describe, how by monitoring the CO_2 concentration the number of persons in room can be inferred, since every human emits CO_2 by breathing. The main drawbacks of this approach are that the emission of CO_2 strongly depends on the activity and condition of the person [8] and that such systems have a quite long reaction time of about 20 minutes [9]. [10] and [11] demonstrate how the energy consumption, monitored by a smart meter can be used to infer occupancy or determine the activity of persons in a building.

The third category can be called passive systems. In this context, passive refers to the fact that the person is recognized based on physical effects, such as heat emitted by the person, its physical presence etc. Popular approaches in this category are Passive Infrared Sensors (PIR) [12], Ultrasonic Sensors [13] or camera-based systems [14]. While PIR and Ultrasonic based approaches show good performance in occupancy detection and the components are low cost, but nevertheless are also highly relying on an optimal placement [15], which again can lead to higher installation effort in existing buildings. Camera-based systems [16] are capable of providing detailed occupancy data, but nevertheless there are always privacy concerns.

One approach that can also be assigned to this category is to use the lighting infrastructure in combination with Visible Light Sensing (VLS) for inferring the occupancy. This approach has the main advantages that artificial lighting is almost omnipresent throughout buildings, the utilized components such as LEDs and Photodiodes are low-cost, no privacy issues anticipated and that the obligatory lighting remains unchanged.

II. Background & Solution Approach

In the most general sense, the technology of Visible Light Sensing (VLS) can be described as the approach to infer information from light received at a photosensitive device. VLS can be distinguished in 4 main categories [17], whereas in this work we will focus on backscattered scenarios, also referred to as Backscattered Visible Light Sensing (BVLS). Such scenarios are defined by the essential approach that no Line-of-Sight is given between the light source and the receiving element and that consequently only reflections from the object or person of interest are acquired at the receiving element. This approach has the big advantage that the light source and the receiving elements can be integrated into the same module or housing, without the need to place components into the rooms infrastructure, as described in [18].

In [19] the approach of presence detection based on BVLS has been described. In this work, the authors show that presence detection of humans can be achieved by detecting changes in the received signal strength (RSS) at a photodiode (PD). Furthermore, comprehensive experiments have been conducted to show the influence of different clothes, walking speeds and placement of light sources and receivers. This work shows in so-called pass-by experiments that a person walking through a hallway can be detected with 100% correct results. In comparison to this work, the results show on the one hand the feasibility of utilizing BVLS, but on the other hand do not investigate further into the influence of ambient light or when more than one person needs to be detected. Furthermore, our work extends the scope to also infer the walking direction of the persons and the walking speed. Especially determining the walking direction is an essential parameter in order to infer occupancy, since by determining the direction, the people entering or leaving an area can be counted.

[20] presents a system where the occupancy of a room can be inferred based on 16 sensing units (luminaires) in a room of 5 m x 6 m. In this work, the LED luminaires on the ceiling serve as both transmitter and as receivers (by putting the LED in reverse bias mode). By cooperative analysis of these 16 luminaires, an occupancy accuracy of 90 % is described. In contrast to our work the approach is based on non-moving persons in a room, as well as other ambient light sources are not present. Our work focuses on settings where people are moving in a hallway towards or away from an area, which in turn gives the big advantage that the occupancy can be inferred by a single adapted luminaire. Furthermore, this has the additional advantage that our luminaire can work stand-alone, meaning that the luminaire itself infers the presence, the walking direction, walking speed and consequently the occupancy.

A. Solution Approach

Our solution approach is based on the following theorems and assumptions:

- A person entering the Field-of-View (FoV) of a photodiode causes a clear deviation in the RSS compared to the RSS in the absence of a person
- The RSS deviation increases during the passage of the person until the person is located directly under the photodiode
- The RSS deviation caused by the person has a clear peak when the person is directly under the photodiode
- The RSS deviation decreases from the peak value in the further passage until the person has left the FoV of the photodiode
- By utilizing more than one photodiode the sequence of the RSS deviation peaks occurring at the respective photodiodes can be clearly separated
- Utilizing the known distance between the photodiodes and the time difference between the detected peaks, the walking speed can be inferred
- Additional ambient light has similar effects on all the utilized photodiodes
- The floor (e.g. material) is assumed to have the same properties under the whole length of the luminaire

Based on these theorems and assumptions, the hardware laboratory sample have been built and the software algorithm implemented, described in the following subsections.

III. Luminaire

The designed and constructed luminaire in our work consists of two main parts. First, we designed and manufactured a Printed Circuit board that is equipped with a visible light sensitive photodiode TEMD5510FX01 from the vendor Vishay, a Lumileds LMZ7-QW50 LED alongside the necessary Transimpedance Amplifier (TIA) to convert the photocurrent of the photodiode into a voltage signal as well as the driver circuitry for the LED. The output of the TIA stage is connected to an in-built Analog-Digital-converter (ADC) of a NUCLEO-WB55RG microcontroller board. In order to achieve a better directionality of the LED and the photodiode, CA10716 reflectors from the vendor Ledil with a spot beam of ~20° were placed over both the LED and the photodiode. Fig. 1 shows a 3D representation of the designed and manufactured PCB.

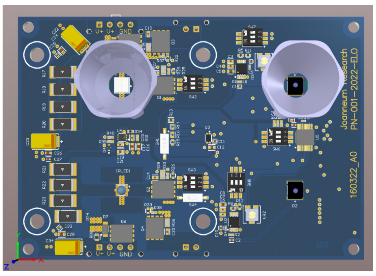

Figure 1: 3D representation of the designed and manufactured PCB

In the following, we integrated 3 of those PCB's into an off-the-shelf luminaire with the size of 120 cm length and 28 cm width. The placement of the PCB's and respectively the LED and photodiodes where chosen to be at the two outer borders of the luminaire and one PCB in the middle of the luminaire. Fig. 2 (left) shows the luminaire with the three integrated PCB's, with descriptive text added to the figure, marking the photodiodes the LEDs. Please note that the other visible reflectors in the picture are placed over other sensors, which are not used in this work and are consequently marked as such. Fig. 2 (right) shows the luminaire finally mounted in one of the laboratory rooms.

As mentioned earlier the output of the TIAs of the photodiodes (PD 1 to PD 3), see Fig. 2 (left), are connected to a NUCLEO-WB55RG microcontroller board also integrated in the luminaire. This microcontroller board runs the algorithm, described in the next subsection.

IV. Algorithm

Based on the theorems given in chapter II, the algorithm was implemented in the NUCLEO-WB55RG microcontroller.

Following the first theorem, that a person entering the Field-of-View (FoV) of a photodiode causes a clear deviation in the RSS compared to the RSS in the absence of a person a triggering mechanism was implemented, that is used to determine a "steady" state from a "non-steady" state. The "steady" state in this regard means that no person is currently passing through the luminaire, while the "non-steady" state means that the presence of a moving person is detected. The triggering mechanism is based on a rolling average calculation by an array of 1001

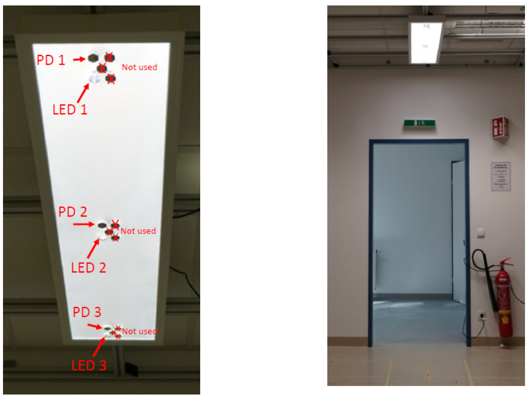

Figure 2: (left) Detailed view of the Luminaire with descriptive text (right) Luminaire mounted in the laboratory

values at the chosen sample rate of 3.2 Ms/s by each photodiode. By comparing the previous value of the rolling average with the current value of the rolling average and applying a threshold level of +/- 1 % difference, the current state is determined. If the threshold is exceeded, the "non-steady" state is triggered by the corresponding photodiode and the next steps in the algorithm are performed. One thing we want to point out in this regard, is that by applying a relative threshold level already one big advantage of our approach can be highlighted, namely being independent from the static reflections caused by the flooring material or the presence or absence of ambient light. As we will show later in our experimental results, therefore no adjustments of changes had to be made to the algorithm although the scenarios differ in terms of present ambient light or flooring material.

When the "non-steady" state is triggered, by for example, PD 1, the algorithm starts computing the derivate from the acquired values from PD 1. By computing the derivate, a simple peak detection is achieved, since the value of the derivate equals 0 at the peaks of the underlying values. When a peak (derivate equals 0) has been detected the corresponding timestamp and photodiode (e.g. PD 1) is stored. Following the theorem that a person causes a peak at every photodiode it passes, the result will be three stored timestamps from the three utilized photodiodes. In order to illustrate this, please see Fig. 3, that exemplarily shows the passage of a person from PD1 (blue line) to PD 2 (red line) towards PD 3 (green line) under the luminaire with the digital "raw" values of RSS of each PD given on the x-axis and the time in seconds on the y-axis.

As can be easily seen from Fig. 3, by a simple comparison of the stored timestamps the walking direction consequently can be inferred.

Furthermore, Fig. 3 also shows how after the person has left the FoV of the corresponding PD the "steady" state is reached again. With the known length of the luminaire (120 cm) and the stored time between the start and the end of the "non-steady" state, finally the average walking speed of the person is calculated.

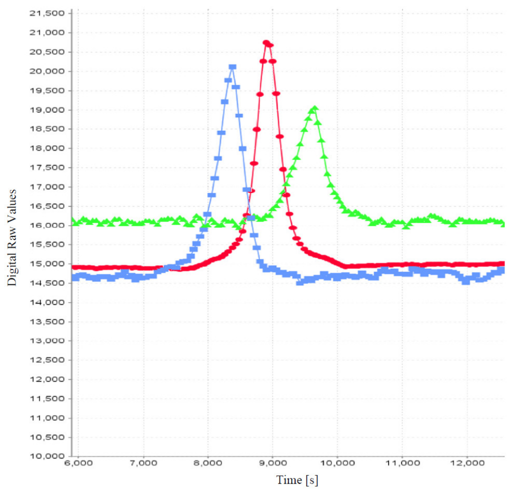

Figure 3: Exemplary data of a person walking under the luminaire

Given by the theorem that additional ambient light has similar effects on all the utilized photodiodes, the algorithm for mitigating the effects of sudden ambient light has been derived. Sudden ambient light changes, for example turning on or off the preexisting room lighting, will cause a change from the "steady" state to the "non-steady" state at all the three photodiodes at the same time. Our designed algorithm therefore monitors if a change from "steady" state to "non-steady" state occurs only at one PD or at all PD's at the same time. If all three PD's exhibit the change, the occupancy determination algorithm is paused until all three PD's have reached the "steady" state again. Please note that this mitigation is aimed at sudden light changes, whereas slow changes in ambient light, e.g. sunlight during the day, must not be mitigated separately, since the rolling average value will of course rise or fall over time, but will not exceed the threshold level in order to trigger a "non-steady" state.

With the described algorithm implemented in the microcontroller of the luminaire, several experiments in two settings where conducted in order to verify the validity of our solution approach. The achieved results are given in the following chapter V.

V. Results

In order to verify our solution approach experimentally, two basic scenarios and different test cases were conducted. We would like to emphasize that during the different test cases and the scenarios, neither the luminaire, nor the implemented algorithm were changed or adapted.

The first scenario, which we further on call "room entrance", was built to resemble the determination of occupancy when persons enter a room, please see Fig. 2 (right). In the first test case, a person (male, 180 cm height, black curly hair), referred to as TP1, enters the room by walking in a straight line directly centered under the luminaire, entering the room and then leaving the room again. Consequently, the occupancy of the room should first be 0, then after TP1 passed under the luminaire should be increased to 1 and then after leaving the room go back to 0. We will refer to this sequence in the following as one Run. The occupancy determination is only considered correct when the numbers are correctly determined throughout one run.

In the first test case, TP1 conducted 40 runs with the ambient light off and walking in a straight line centered under the luminaire. With the ambient light (preexisting room lighting) off and shades of the laboratory closed to block sunlight, our luminaire was the only active light source. The achieved results show that for all 40 runs, the occupancy, the direction and the walking speed was determined correctly. In regard to the walking speed, please note that the speed was varied from walking slowly to running and the assessment was done on a subjective rating if the determined speed corresponds to the performed action.

In a second test case, the same test person repeated the same 40 runs with the ambient room light (fluorescent tubes) on. To illustrate how this affects the lighting situation, the Lux values were measured with a handheld spectrometer at the same points with and without the ambient light. For example under the left upper corner of the luminaire, the measured illumination on the floor was 511.2 Lux without the ambient light and 997.2 Lux with the ambient light on. Nevertheless, we can report that for the 40 conducted runs, again the occupancy, the direction and the walking speed were determined 100 % correct.

These results substantiate that one of our major goals in this work was successfully reached, namely that independent from the overall ambient lighting conditions, the occupancy can be inferred correctly. In order to further investigate the robustness of our approach, further test cases, where the test person is not passing centered under the luminaire were conducted. In these experiments, the test person was walking displaced by 40 cm to the left from the centered line for 20 runs and 40 cm to the right for 20 runs, with the ambient light on. The results show that also when the test person is not walking centered under the luminaire, again 100% correct results in terms of occupancy, direction and speed approximation was achieved.

In order to experimentally verify the applicability of our solution in regard to the second major goal, namely being independent from the persons in terms of hair, clothes and height, we introduced a second test person (male, height 175 cm, baldhead), further on referred to as TP2.

In these test cases, the two test persons were entering and leaving the room one after another with a distance between TP1 and TP 2 of 1 meter. First 20 runs were conducted in the absence of ambient light, and then 20 runs in the presence of the ambient room lighting. The achieved results show that in 17 of the 20 runs and respectively 18 of the 20 runs the occupancy, the direction and the walking speed were determined correctly. Investigating the incorrect runs shows that the direction was determined correctly, but that the occupancy was incorrect by 1 person. This means instead of 2 persons entering and leaving the room the occupancy count was only 1 person. This miscounting was caused by the circumstance that the persons were walking closer together as the targeted 1m. Nevertheless, the results still show that our occupancy determination renders good results with the two differing test persons and with and without ambient room light present.

For the second basic scenario, the luminaire was mounted in the corridor towards our laboratory rooms. Fig. 4 shows this setup, where we would like to point again that neither the hardware nor the algorithm was changed, only the luminaire was relocated.

Figure 4: Corridor experimental setup

In this second scenario, the test cases were repeated with the same procedure and by the same test persons TP1 and TP2. Please note that in this scenario the ambient light (sunlight + preexisting fluorescent tubes) was always present (see Fig. 4).

The achieved results are summarized in Table 1.

TABLE I. RESULTS CORRIDOR SCENARIO

Corridor scenario		
Test case	***Runs***	***Correct***
TP1, centered	40	40
TP1, 20 cm to the left	20	20
TP1, 20 cm to the right	20	20
TP1 and TP2, 1m distance	20	19

With almost identical results as compared to the "room entrance" scenario (see Fig. 2 (right)), we can show that our built occupancy determination successfully works also in much changed scenarios (flooring material, furniture, etc.) without the need for adaption or recalibration, etc.

One limitation that was encountered during the experiments, as mentioned earlier, is the miscounting of persons when the moving persons have a distance of below 1 meter. Overcoming this limitation is one of the main goals in our future work. The key starting point to solve this, is to narrow the FoV of the utilized photodiodes. Based on initial tests with adapted reflectors, we can report that the achieved results are very promising in overcoming this limitation.

VI. CONCLUSION

In this manuscript, we presented an approach for realizing an occupancy determination system based on the technology of Backscattered Visible Light Sensing. Based on low-cost off-the-shelf components we were able to fabricate a luminaire that with fully integrated photodiodes can be easily installed and consequently can reduce the installation effort to a minimum. The implemented algorithm was tested in two much different scenarios and test cases, showing that not only satisfactory results have been achieved, but that additional ambient light or differing test persons do not have a negative effect on the results. Furthermore, our solution approach of employing BVLS does have the big advantage that no concerns in regard to privacy is raised as compared to other technologies in the field of occupancy determination systems.

In combination with another aspect followed in the "Vilipa" project, namely realizing the communication of our luminaires by the means of Powerline Communication (PLC), we can outline our vision, where a multitude of connected BVLS enabled luminaires throughout a building delivers occupancy data to effectively reduce the energy consumption, by only causing minimal installation effort.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK), the FFG and the funding program "Stadt der Zukunft" - Project "Vilipa"

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