Development of the Detection Module for a SmartLighting System

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Abstract: The research presented in this paper focuses at the human detection means for lighting areas. In particular, analysis of output sensors signal and software signal processing, analysis of ambient conditions influence on detectors functionality is given. The performed research is based on experiments, conducted at the Future Internet Lab Anhalt. The main goal of this paper is development of the human detection module for a SmartLighting system that satisfies a set of requirements of reliable human object detection. The given tests have been performed using ultrasonic, radio wave and infrared sensors. The analysis of the performed experiments allows us to define a degree of sensors conformance for the aimed SmartLighting applications. As the result of the performed experiments it is also shown that the combination of different detectors provides the most informative parameters about moving object in a control area than any considered single detection method. The hardware design and signal processing algorithm of the detection module have also been implemented in the course of this work. We found out that the sensors combination provides an error probability of less than 1% of human movement detection at distances up to 10 meters.

1 INTRODUCTION

According to International Energy Agency (2006), the street lighting is 53 % of worldwide outdoor energy consumption for lighting. Therefore, modern lighting systems have strict requirements for energy consumption and resource efficiency. These requirements can be satisfied by using smart lighting systems.

Smart lighting systems have a set of advantages in comparison to legacy ones. While conventional lighting systems have default lighting time that is independent from time of day and weather. In particular, lighting will not be activated automatically in required environmental conditions (e.g. at foggy or rainy weather). Also, switching on/off of conventional lighting systems do not depend on presence of pedestrians and moving cars, which leads to excessive energy consumption during all the dark time of day (Srivatsa et al., 2013).

The key element of smart lighting systems is a motion detection module. Accuracy and reliability of this unit have high impact on workability and efficiency of a smart lighting system. The registration of human motions in a controlled area by means of collection and processing of informative parameters is performed by a detection subsystem (Matveev et al., 2015).

Contemporarily existing detection means which are used in smart lighting systems have a number of significant disadvantages, particularly a high detection error rate. Their detection reliability heavily depends on operating conditions. Therefore, an approach for compensation of interfacing factors influence on detection reliability is studied in current work.

Currently, the prototype of a smart lighting system is being developed within *SmartLighting* project at the Future Internet Lab Anhalt of Anhalt University of Applied Sciences (Dugaev et al., 2014). The project is aimed at developing an autoconfigurable mesh networks across street lighting systems which passes motion detection messages across the network and performs intelligent handling on motion activities on the street. In particular, a specific routing scheme for wireless mesh lighting networks along with a detection subsystem is there under development (Dugaev et al., 2014), (Dugaev and Siemens, 2014).

This paper is focused on experimental research of different sensors types which are acceptable for human movement detection. That includes investigation of sensors parameters as operating range, probability of detection errors, triggering error, informative signals.

2 RELATED WORK

Existing detection means, which are used in smart lighting systems, are usually based on single control method (Sung, 2013). Hereby, workability and accuracy of the detection system are limited by disadvantages of method, for example, false triggering or small working distance (Goponenko and Matveev, 2015).

Two kinds of widely spread motion sensors are passive infrared (PIR) and ultrasonic (US) sensors (Yavari et al., 2013). Passive infrared (PIR) sensors are compact, have low cost and low power (Zappi et al., 2007), however, they are highly dependent on the ambient temperature and brightness level (Fardi, et al., 2005). Ultrasonic technology enables obtaining distance information to the motion object, which can be used for the object motion speed calculation (Canali et al., 1982). One of the main disadvantages of these sensors is the multipath reception that could distort measurements of the distance between emitter and receiver. Also, these sensors are sensitive to temperature changes as it has a significant impact on the sound speed (Mainetti et al., 2014).

In contrary to the said two sensor kinds, radio wave (RW) sensors are commonly used for object detection in security or surveillance systems. RW sensors have high sensitivity (Yavari et al., 2013) that can cause incorrect work of a detector, for example, by vibrating equipment or small animals. The efficiency of RW sensors depends on the ambient conditions. Usage of RW detector requires resource demanding filtration, demodulation and processing algorithms due to specifics of the output signal (Matveev et al., 2016). However, it ensures large number of informative parameters, which can be used for motion analysis.

The hybrid systems based on US - PIR (Pfeifer and Elias, 2003) or RW - PIR (Bai et al., 2013) combination of sensors are focused on indoor object detection and localization that makes such systems hardly acceptable for street lighting related applications.

3 REQUIREMENTS FOR THE MOTION DETECTION MODULE

Given the significant role of the detection module as a part of SmartLighting system (Siemens, 2014), requirements and conditions for the following requirements of motion detection have to be fixed.

Requirements for error probability. One of the significant problems, which can appear during SmartLighting system operation is incorrect triggering of the detection module. Errors can be divided into two classes of errors:

Error of human detection. The error is occured when motion is not detected in presence of a human object. This error class has high influence on the reliability of the detection module therefore error probability has to be as low as possible. We believe that the value of the human detection error probability for the detection module has to be less than 1% in operational SmartLighting systems.

False triggering error. This error occurs when motion is detected while no human motion is present in control area. Such errors are typically caused by bad weather conditions and caused by non-human motion sources like trees oscillation etc. The value of the false triggering error is less critical than error of human detection, since it leads only to unnecessary energy consumption and doesn't negatively impact the public security, so we set the target threshold for the detection module to be less than 5%.

Detection range requirements. The human motion has to be detected early to provide necessary lighting area for a pedestrian. The taken detection distance is equal to 10 m and chosen based on analysis of street lighting systems parameters for pedestrian areas which are represented bellow.

The typical distance between lighting poles is 25 - 50 m. Lamp type is light emitted diode (LED), high-pressure sodium (HPS) or fluorescent (FL). Power of lamps varies in the range of 70 - 150 W. Lamps installation height is 5 - 8 m (Transport Canberra and City Services, 2007), (Lighting Orient Co., n.d.), (Standard Development Specification, n.d.).

Necessary informative parameters (status). The information about existence (movement or occupancy) of an object in area of lighting. The status is an obligatory information which is necessary for proper operation of the SmartLighting system.

Complementary informative parameters (speed). The parameter can be used with the aim of SmartLighting system reliability and accuracy increase, e.g. for calculation of object location between lighting units.

Flexibility of the system. The module is developed as integrated unit for SmartLighting system. The flexibility of the detection module assumes compatibility of interacting interfaces and system architecture which is convenient for further extensions and modifications.

4 EXPERIMENTAL RESEARCH

In this section the operation range and reliability of US, RW and PIR sensors are researched independently on each other. Acceptability of chosen detection means for usage in detection module has been defined experimentally.

4.1 Experimental Setup

In order to perform the analysis of dependence between human motion and the responses of sensors an experimental setup as follows has been designed. The positioning of sensors on the experimental board is shown on Figure 1. The board with sensors is installed on a tripod with 2 m height. The distance between sensors is 0.1 m.

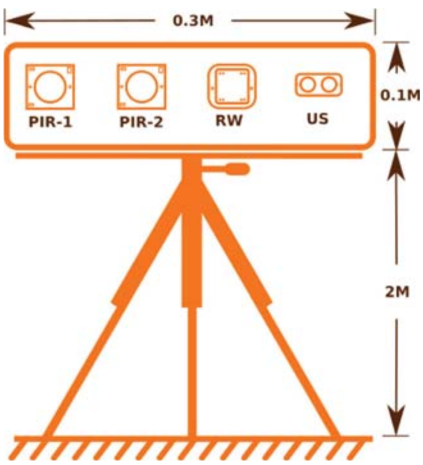

Figure 1: Location of sensors on the experimental board.

Three types of detectors have been used. Two PIR sensors: “PIR-1” - produced by SeedsStudio and “RK410RQ” - produced by Rokonet). A radio wave detector “X-band motion detector” produced by Parallax and an ultrasonic sensor “SRF08 ranger”. In further text, the “PIR-1” is referred as PIR-1, the “RK410RQ” as PIR-2, “X-band motion detector” as RW and “SRF08 ranger” - US.

The structure of the experimental setup is represented on Figure 2. A main control device of the test setup is a Beaglebone Black (BBB) microcomputer. The BBB provides power supply for detectors, executes the measurement program, polls the sensors, process received data, and transmits collected data to a workstation.

The mobile device is used for a remote system control and for starting the experiment. The application on mobile device simplifies the operation of the experiment - in particular, one person is able to control the system remotely and to be an object of sensors response. Also, the problem of timing of people's motion in the experiment is resolved by the mobile device.

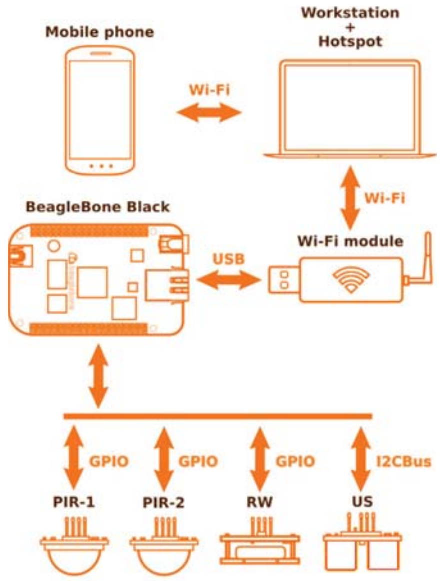

Figure 2: Diagram of the experimental setup.

A Wi-Fi hotspot has been deployed on a workstation that receives the data from the BBB at the end of experiment for further processing and analysis.

4.2 Methodology of the Experiment

The experiment has been performed under environmental conditions that are close to expected operational conditions of the detection module at a street area with 10 m length and 14 m width. Motion vectors are oriented to sensors radiation direction with 1m grid density. Experiments have been performed at twilight and night time to avoid false triggering of PIR sensors during the day, because the level of brightness affects response time, sensitivity and operating range of sensors significantly.

The temperature range during experiments was 18–25° C, approximate wind speed range - 7–23 km/h.

Each experiment run takes 30 s: 0–5 s - no motion; 5–15 s - motion in one direction across control area; 15–20 s - no motion; 20–30 s - motion in opposite direction across controlled area.

4.3 Experimental Results

As a result of experiments, the feasibility of sensors usage in the human detection module has been analyzed. PIR-2, RW and US sensors were not able to cover the aimed detection range. The PIR-1 sensor detects movement at distances up to 10 m. However, PIR-1 can react on warm object outside the control area, that leads to increased triggering error probability.

4.3.1 Ultrasonic Sensor

The given experiments have revealed that the US sensor is not usable for the target application. The sensor responds only when significant motion occurs in the control area. The sensor is able to detect reliably an object on a distance which is less than 1.5 m with 30° angle of scanning.

However, such data, as a distance to the object, is an important information and can be used for an object speed calculation. The US sensor will be not used in the developed detection module, due to the given disadvantages.

4.3.2 Passive Infrared Sensors

Two PIR sensors have been used to define variation of detection parameters as range, angle, triggering delay and errors probability values, for different models of PIR sensors.

The PIR-1 and PIR-2 output signals are high when continuous motion is detected. This can be simply analyzed without need of further processing.

The detection graphs for PIR sensors are represented on Figure 3. These graphs show response of sensors while human motion is performed during of the experiment run.

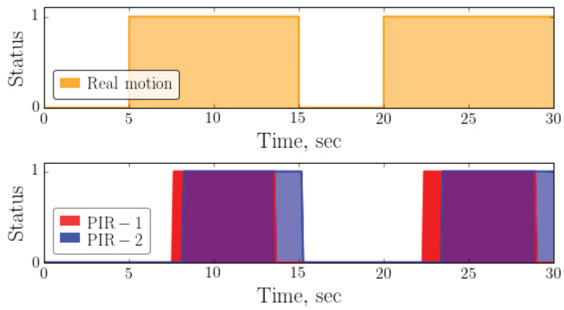

Figure 3: Motion detection diagrams for PIR-1 and PIR-2 sensors. Motion across control area on two meters distance to the experimental setup.

The time shift between real motion and detected signal can be explained by limited operation angle and triggering delay. So, it takes 2.5 s to overcome the distance from border of polygon to the area of detection, covered by PIR-1. Triggering delay value for the sensor was determined experimentally and equals to 0.3 s. The PIR-1 is able to detect movement on distances up to 10 m. The operating angle is 140°. The human detection error probability of the sensor was equal to 0% (according to 200 experiment samples). The disadvantage of the PIR-1 is that sensor can react on warm object outside the control area, such as cars, because the IR radiation intensity from engine of a car is more than IR radiation intensity from a human. Triggering of the detector caused by non-human sources of IR radiation leads to increase of triggering error probability.

The PIR-2 sensor is designed for alarm security systems. The sensor operates within 4 m range, which is low for typical IR based sensors. Triggering delay of the sensor is about 2 s, which is not acceptable for usage in the detection module because a lighting area for a pedestrian should be provided timely. The operating angle is equal to 140°. Due to the disadvantages, the PIR-2 sensor will be not used in the developed detection module.

4.3.3 Radio Wave Sensor

The output signal of RW sensor is a dependence of signal frequency and duty cycle from the size and speed of a moving object. The dirty cycle is defined as the ratio between the pulse duration and the time distance between the beginning of the current pulse to the next pulse. However, the raw RW signal needs further processing for being used for motion and speed detection. A segment of raw signal from RW sensor during 8 - 8.6 s of the experiment, when the person enters detection area of RW sensor, is represented on Figure 4.

The frequency transformation is performed as follows. Based on raw signal, the period of each impulse T_{imp} is defined, then inverse value $f_{imp} = 1/T_{imp}$ is calculated. The resulting impulse frequency is registered on y axis with corresponding time values on x. The signal frequency correlates with object speed - the higher frequency, the faster object is moving. This conversion allows plotting a frequency transformation graph and estimate object movement intensity (figure 4).

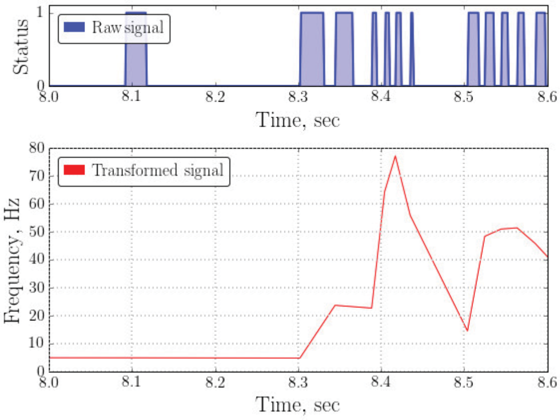

Figure 4: Raw and transformed signals from RW sensor.

Such signal conversion allows the definition of a frequency level, that is typical for a human motion, and set this value as a level for a human detection. Values of signal frequency higher than the defined level indicate the human presence in control area.

The performed tests have shown that the RW sensors reacts very sensitively on insignificant movements, for example, on trees or grass oscillations caused by a gust of wind. Also, electromagnetic interferences affect sensor performance significantly (Combined detectors for alarm systems, n.d.). The frequency filtering is based on calculating a mean and standard deviation values of the signal frequency:

Mean value of a sample allows to define average signal frequency during a defined window size. The sample is an array which contains calculated frequency values of impulses. Given the relation between signal frequency and movement intensity, mean value is used as first human detection criteria.

$$\overline{x} = \sum_{i=0}^{n} x_i \cdot \frac{1}{n} \quad (1)$$

where $\overline{x}$ - mean value;
x_i - observed value of the sample items;
n - sample size.

Standard deviation is used to quantify the amount of variation or dispersion of a set of data values (Bland and Altman, 1996). This value allows filtering out of areas of rapid frequency changing.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2} \quad (2)$$

where σ - standard deviation
x_i - observed value of the sample items;
$\overline{x}$ - mean value of the observations;
n - sample size.

Human detection is performed only when the following conditions are satisfied: calculated mean signal value is more than established mean criteria value and standard deviation value is less than corresponding criteria value;

$$\overline{x} > m_{cr} \cup \sigma < st_{cr} \quad (3)$$

where $\overline{x}$ - mean value of a sample;
m_{cr} - mean criteria;
σ - standard deviation value of a sample;
st_{cr} - standard deviation criteria;

Figure 5 represents mean and standard deviation plot of signal frequencies taken when motion occurred at two meters distance from the experimental setup. The standard deviation value in areas of human motion has gradual increase behavior therefore such areas are not subjected to be filtered. The result of detection for the RW sensor is shown on third graph of figure 4, where high levels correspond to a detected motion.

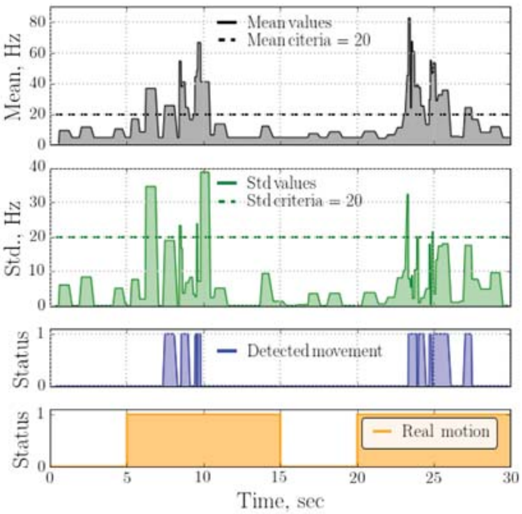

Figure 5: Processed signal for RW sensor. Motion across control area on five meters distance to the experimental setup.

A two-dimensional detection area for the RW sensor using given filtering is represented on Figure 6. The black spot at coordinates [0, 7] is the position of the tripod with sensors. The blue elliptical shapes are the points where human motion is detected by the sensor. The highest level of detection is allocated within the gray elliptical area on the figure. The human detection error probability in the whole gray area is less than 3%, the triggering error probability is approximately 10%.

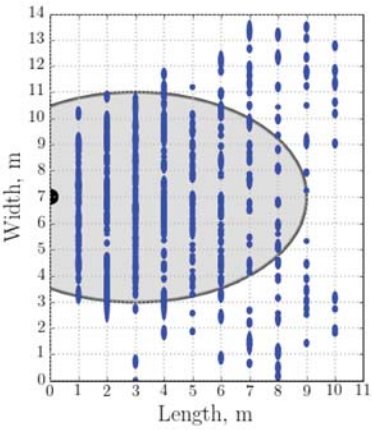

Figure 6: Detection area for RW sensor (m_{cr} = 20 and st_{cr} = 20).

The aimed human detection error probability of is less than 1%, are given when filter criteria are equal to m_{cr} = 30 and st_{cr} = 15 (Figure 7). The triggering error probability for these criteria is approximately 5%. The detection range for these parameters is up to 4 m. The triggering delay range is 0.1 - 0.2 s due to signal processing time.

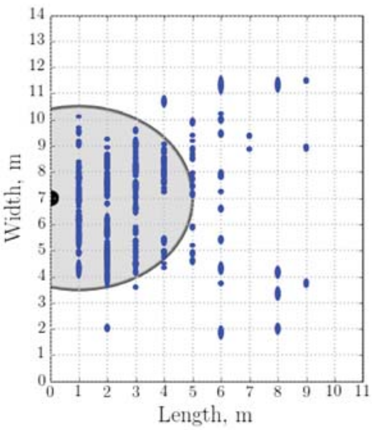

Figure 7: Detection area for RW sensor (m_{cr} = 30 and st_{cr} = 15).

However, a significant disadvantage of the senor is its high sensitivity to insignificant motions in a control area. Also, the detection distance, when 1% of the error probability is provided, is insufficient to the operating distance requirements for the detection module.

5 PROPOSED COMBINED DETECTION MODULE APPROACH

As experiment result, an improved combination of sensors for usage in the detection module has been found. This combination consists of the PIR-1 sensor and the RW sensor. Due to sensors disadvantages, obtained signals separately do not allow to estimate human motion or presence precisely.

One of the possible solutions is a dynamical filtering level adjustment of the RW detector. The concept is based on RW sensor signal level reduction for the filter, when a human motion is detected by the IR sensor. Such approach allows to compensate detectors disadvantages and to reduce errors probability. The human detection is only performed when both sensors detect human motion.

The chosen detectors have following informative parameters in respect to human detection purpose. Binary signal from the PIR detector identifying a warm object motion in the controlled area. Frequency and duty cycle data of the RW detector based on object movement intensity in a control area.

Application of dynamical detection criteria allow to increase sensitivity and detection distance of the RW sensor. Such approach allows to increase detection range of RW sensor and while avoiding false triggering errors of the PIR sensor. Also, the probability of false RW sensor triggering is reduced, because the sensor sensitivity is only increased when human motion is expected.

Usage of the sensors combination and efficient detection algorithm allow to detect human motion in a control area with approximate error probability of 0.5%.

False triggering probability of the detection module (due to interfering factors) depends on the environmental conditions. In the described experiments, the error value equals to 3%, when an approximate wind speed is up to 25 km/h.

Signals which are received from the detection module, when dynamical human detection criteria are applied for the RW sensor, are shown on Figure 8.

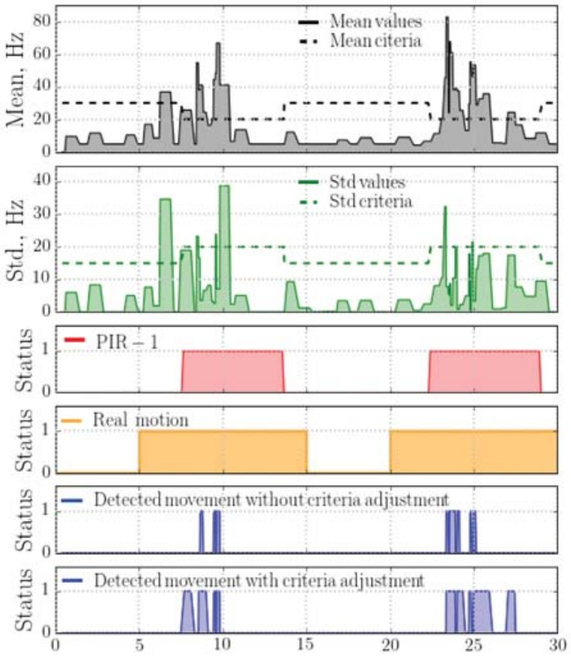

Figure 8: Dynamical human detection criteria adjustment.

The resulted detection area of the detection module is represented on Figure 9 as a gray elliptic area.

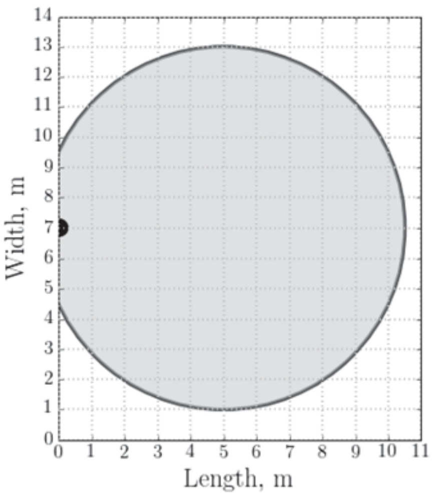

Figure 9: Operating area of the detection module.

6 CONCLUSION

The experimental research has been performed to test the feasibility of the given sensors for motion detection in the SmartLighting environment. It enables engineers to analyze detectors' responses, the investigation of areas of detection with its respective error rates. Using this, a significant improvement of the reliability of motion detection by using of a combination of PIR and IR sensors for a human detection could be tested and its benefits have been proven.

Using the combined methods with the given filter parameters the detection error probability can be reduced to 0.5% whereby false triggering error probability can be kept at 3%. Thus, resulted values of errors probability satisfy the error probability requirements for the detection module. Resulted detection range of the detection module is equal to 10 m. That satisfies the operating distance requirement.

The prototype's hardware provides extendibility and flexibility. The implemented approach allows to easily integrate the detection module to the SmartLighting system that satisfy flexibility requirement for the detection module.

The following research tasks to the detection module are supposed to be considered in further activities. Other models of US sensors are going to be considered with the aim of an object speed calculation. Development of improved filtering algorithm that allows to increase performance of the detection system has to be done. Also, of an algorithm for system adaptation to ambient conditions based on statistical data analysis could further improve the motion recognition reliability. Power consumption reduction via algorithm optimization (decrease of redundant calculations) is going to be performed. Integration of brightness detection elements that provides the SmartLighting system activation in required weather and climate conditions which influence on the ambient brightness level has to be done.

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