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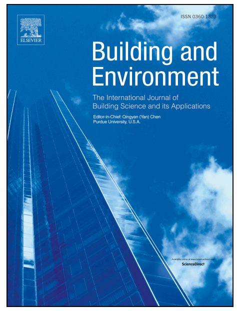

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Smart and dynamic route lighting control based on movement tracking

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Abstract

Intelligent LED lighting pilot was carried out along a light traffic route in a housing area in Helsinki. The goal of the research was to develop and test a lighting control system with an optimal lighting behavior, which saves energy without lessening safety and security of route users during the dark. The developed lighting control solution was based on tracking route users' movements and location along the route with passive infrared (PIR) sensors. Using this information, the system could create lighting conditions where the illuminated area reaches further in front of the user than behind. This was considered as an optimal solution from the perspectives of energy savings and user comfort.

The control was implemented on a real life test site used by pedestrians and cyclists consisting of 28 lighting posts with controllable LED luminaires. The recorded PIR data was analyzed to evaluate the performance of the developed system in northern outdoor conditions and to compare different lighting control schemes and their influence on energy consumption. The experiences gained during the piloting showed that the system could operate in outdoor conditions, but strong wind in a cold environment caused false sensor activity. The used arrangement of the three PIR sensors with wide field of view made the system sensitive to false detections, especially as installed high in lighting poles surrounded by foliage. The relative energy saving compared to the existing control solution of the area was 60 – 77% depending on the used smart control scenario and the calendar time.

Key words: LED, smart lighting, street lighting, dynamic, energy saving, sensing

1. Introduction

Driven by the rapid uptake of light emitting diodes (LEDs), applications of intelligent or smart street lighting are spreading to various types of urban context [1]. Besides the energy efficiency and long lifetime of the LEDs, easy control compared to the traditional street lighting technologies has generated new opportunities for smart features in lighting. Smart systems with increased functionality can change the lighting behaviour with dynamic functionality and the ability to adjust spectral content and light distribution for example [2]. If designed wisely, smart street lighting can, besides energy savings, offer added value for urban environments on various levels of experience [3, 4].

Lighting infrastructure is centrally located in city, close to people and activities. It provides excellent opportunity to collect and deliver information and services also beyond lighting. In this paper, we introduce smart lighting control system capable of tracking people movement in urban environment. Here, the information is used for dynamic street lighting control, but could be used for other services as well. Contrary to our previous work [5], the system can detect the direction of the movement and track the route that the person is taking enabling more sophisticated lighting behaviour with improved energy savings and user acceptance. The developed system is validated in real use environment along a light traffic route lighting in Siltamäki in city of Helsinki in which 28 control modules were installed. The performance of the system in real use environment is discussed and simulations and measurements are used to study the energy consumption of the developed system. Also, the data collected by the system is analyzed in the lighting design context as well as in use for other possible beneficiaries.

2. Background

The traditional way to control street lighting is based on a clock and/or daylight sensor adjusting the operating time. An active control of the light levels has not been feasible due to the difficulty to dim traditional light sources[6, 7] but with current LED luminaires software-controlled street lighting systems have emerged to the market [8, 9]. Sensors are typically used as part of the control system to deliver information about the use conditions. Office type indoor lighting is a typical example of wide-spread application of using sensors to turn the lighting on and off according to the presence of people. Depending on the control features of the system energy savings of 20-70 % have been reported. [10 -13] In street lighting, simple on-off functionality is generally not acceptable for safety and aesthetic reasons [6, 14 - 16] and more sophisticated controls with advanced dimming are required [6, 9, 15 - 17].

Currently, energy savings with smart control in street lighting have already been demonstrated in many case studies. Lau et al. [9] introduced a remarkable 90 % energy saving simulation compared with conventional control schemes with an adaptive street lighting algorithm based on traffic sensing to progressively control the brightness of street lighting. Ouerhani et al. [18] showed 56% savings in his real-world installation of dynamic street lights compared to classical static, time-based street lighting control, and Sun et al. [19] proposed a multi-sensor system with the average energy consumption reduction of 40 % for solar powered street lights. Although savings are impressive, they are often based on case studies rather than normal use installations, which would be rather complicated to execute as street lighting levels are often strictly regulated [7].

In our previous work, luminaires incorporated with sensors and low energy two-way wireless communication were installed on a pedestrian road in Helsinki. The system was able to deliver different lighting modes and record data including ambient temperature, LED board temperature, light reflected from the road, direct light from the LEDs, pedestrian presence sensor activations and, most importantly, energy consumption. This data were delivered to a web page that also served as a user interface for remote control of the pilot installation. Reduced power levels of more than 40 % were demonstrated for pedestrian street lighting in this installation. With light level sensing approximately 45 % less power could be used during the night with fresh snow compared with the previous night with no snow on the road while maintaining the same measured reflected light level. In the pedestrian sensing mode the luminaires operated on average at 40 % lower power than in the passive use mode during the five-day test period of pedestrian sensing. In this study, the luminaires were dimmed to 50 % drive current and raised back to passive use mode when an approaching pedestrian was detected. Due to the inability to detect the direction of the person’s movement, the lighting was symmetrically increased around detected person. [5]

In this work we present passive infrared (PIR) sensing solution for movement tracking. Human bodies are good sources of infrared radiation with some 100 W power emission in wavelength range of 5-14 µm [20]. Today, PIR sensors are commonly incorporated with lighting due to their low cost, small size and practical function to detect human presence by the thermal power emitted. Also, the detection does not depend on the amount of visible light and sensing does not need much computation. In many applications it is also appreciated that as the sensing provides only thermal characteristics of the objects it avoids privacy concerns. The drawback of the PIR sensing is that the detection can be disturbed by other sources of thermal energy, like engines and temperature changes in the ambience [21]. Also, as the detection is based on the change in temperature the target must move or special techniques, like chopping of infrared radiation or sensor rotation, must be used [22, 23]. Similar to our work reported in this paper, Lukkien and Verhoeven [24] used PIR sensor based system for dynamic street lighting control in their pilot installation in Eindhoven, Netherlands, and used collected PIR sensor data to simulate energy consumption of different lighting controls. Comparing dynamic lighting behaviour to static control of the same system the energy savings up to 28-38% were shown. Though the energy saving is significant, Lukkien and Verhoeven stated that the direct economic advantage per pole is limited due to the relatively low energy prices. Consequently, they proposed more versatile usage of the collected data to balance the extra investment. [24]

In this paper, the movement direction and people tracking was detected using low cost PIR sensors. Movement direction could be detected with vision-based camera recognition. However, compared to the proposed system such an installation is expensive. Also, operation of image recognition is affected by the surrounding illumination and the processing of a visual material requires a lot of computation capacity. In addition, people generally dislike camera installations for privacy reasons [25]. Sophisticated human tracking has also been realized with depth sensor (Microsoft Kinect) [26]. However, most of the reported applications are made indoors as the first version of the Kinect sensor was not suitable for sunlight conditions due to the structured light technique used in the detection [27]. Compared to such advanced detection systems installed in few critical locations, our system introduced in this paper is designed as part of street lighting infrastructure that would cover the environment widely. As such, the weaker detection accuracy could be compensated with the redundancy of the repeated installations. The approach is analogous to the results of Lovett et al. [28] stating that sensing value can be maximized by using multiple low-cost, less valuable sensors rather than fewer high-cost, more valuable ones. The luminaires acting as a communicating, sensing and reacting individuals is a classical example of 'Internet of things' combining many individual devices of everyday life into one communicating network [18]. It can be assumed that in future a significant number of these devices will be related to lighting as they already exist all around urban areas . Our research is one step towards this vision.

3. Objectives and methods

The objective of the research was to develop and test control method capable of providing sufficient illumination for safety and security of the route users while minimizing the energy consumption of light traffic route lighting. The research hypothesis was that this could be achieved with adaptive lighting control, which keeps the lighting at low level when nobody is present, and when a person appears, brightens the lighting around the user and dims it again after he/she has passed. Optimally from the perspective of comfort and energy savings, the illuminated area would reach further in front of the user than behind. For this task, a system able to detect the direction of the movement and track the route that the person is taking was needed. The system should also be able to manage several road users at the same time. Furthermore, as the system is installed at every lighting pole, it should have low device cost and wireless communication to keep the infrastructure and installation costs minimal. As the dynamic lighting behavior could disturb the users [15], the control scheme needed to be designed so that the changes of the lighting level could not be perceived. In practice this would mean soft, low speed dimming ramps and wide enough brightened area around the road user. The area would be non-symmetrical extending further away towards the direction of the movement for optimized energy savings. The objectives of testing of the system were to evaluate its performance in northern outdoor conditions and to estimate energy saving potential with the developed system.

3.1 Research context and test installation

A sensing and control system able to fulfill the research objectives was developed and tested in real life pilot installation that situated along a light traffic route in Siltamäki housing area in Helsinki. The route was used by both pedestrians and cyclists. The route runs besides two and three story blockhouses and a kindergarten on the other end, then crossing a road, continues to run past another kindergarten, and finally runs alongside a park. The image of the pilot site is shown in Figure 1. There are some elevation changes along the route. The length of the walkway with pilot installation is in total 750 meters. The lighting control and movement detection was limited to only one dimension, and people entering and leaving from the crossing road and paths could only be detected when moving along this route. In the 6 m high lighting poles along the route, LED luminaires with a connecting device allowing DALI based lighting control, had recently been installed. There are plenty of big trees with leaves on both ends of the route. The trees come close to lamp poles and at some points partially surround the poles with branches. The existing lighting control in the area was based on central control. During the bright period of the day, lights were turned off, and during the dark period, all the luminaires were on at 100 % control level.

Figure 1. Pilot installation site at a light traffic route in Siltamäki housing area in Helsinki.

In our pilot installation, an intelligent lighting control system with the ability to detect the direction of movement of route users was tested. The lighting control was adapted to this information so that the lighting was brightened further ahead a walker or a cyclist than behind. The aim was to design and test an optimal lighting behavior which saves substantial amounts of energy without lessening traffic or moving safety or the sense of security of route users during the dark. In our experiments, the minimal lighting level was 20% when no road users were detected. Around the user the lighting was 100% and different scenarios of the size and dimming of the illuminated area was experimented (see Figure 12). Due to safety reasons, the smart lighting functionality was trialed only in shorter testing periods, while the developed sensing and control system could be experimented throughout the piloting season (03-2017 – 11-2017).

The developed system consists of sensor control units assembled in existing lighting poles and a wireless mesh network connecting the units together. A sensor control unit consists of a sensor module and a power module that was capable of controlling the LED luminaire via the DALI line. The sensor modules were installed to the poles at 4 meters height to protect the modules against vandalism (Figure 2). The power modules could be located at more convenient installation height of approximately 1.5 m as they were installed safe inside the poles similar to other cabling. A multi-wire harness running inside a pole connected the sensor module and power module together. Altogether 28 sensor control units were communicating to a single gateway that located in an electricity cabin along the road. The gateway was acting as a link between the system and cloud server in which the analysis of the data was made. The results of analysis, most important being the direction of the person's movement, was given to VirtuAUL dynamic lighting control software that created the lighting control commands. VirtuAUL design framework was developed in an earlier research project by the University of Oulu for the design, simulation and control of adaptive lighting [29 - 32]. Lighting control ecosystem called LightSense developed by VTT communicated the control commands to the luminaires via the gateway that located on the installation site, as shown in Figure 3. With this installation dynamic lighting behaviour adapting to the person's movement on the light traffic road was achieved.

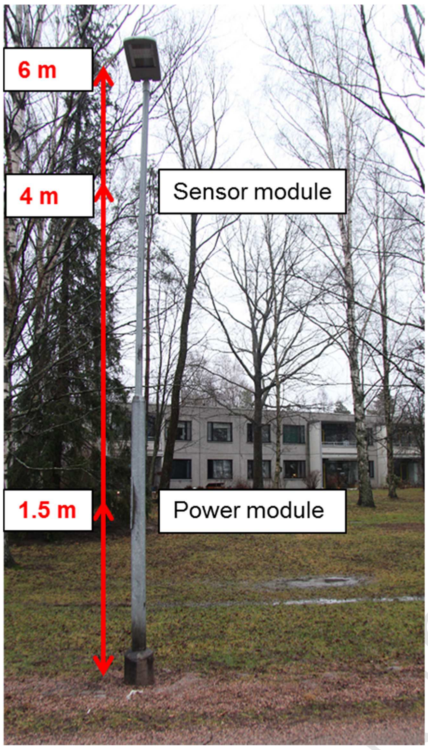


Figure 2. Sensor control unit installation in a lighting pole.

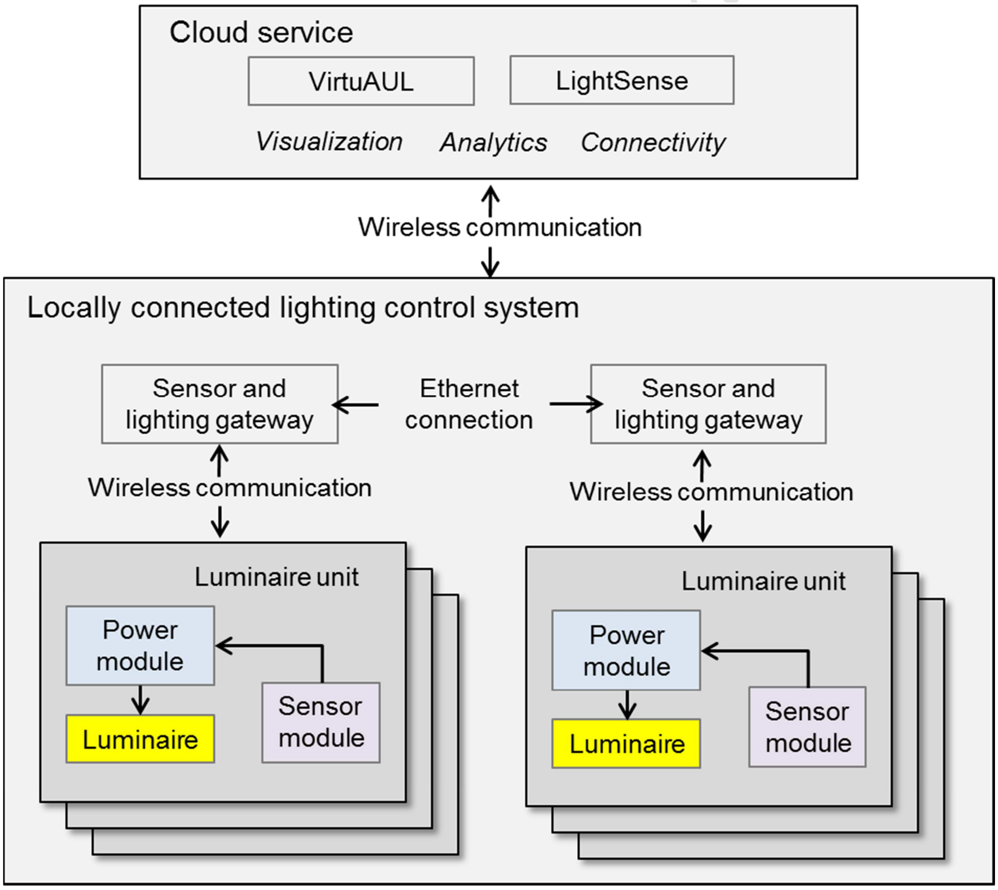


Figure 3. Sensing and control system parts and communication method used to provide adaptive lighting control to the real life test site Wired communication is shown with solid line while wireless communication and Ethernet is indicated with text. The arrowheads show the direction of the communication.

4. *Results*

4.1 Developed system

4.1.1 Motion sensor and control system

The motion sensing was achieved with a sensor module consisting of Nordic NRF51 microcontroller unit (MCU), three Panasonic PIR elements, omnidirectional antenna, and enclosure with cable harness. The role of the MCU was to process the PIR data and send it via mesh network to further processing. The MCU also handled the lighting control commands sent by the gateway by translating the received commands into DALI protocol that was used to control the OSRAM LED driver embedded in the luminaire. The gateway was able to address each of the sensor control units individually, which makes is possible to send e.g. direct DALI commands to a specific luminaire and to get reply from the luminaire receiving the command. In addition, the gateway was able to address desired group of sensor control units at once making it possible to do simultaneous lighting level changes to large number of luminaires. The gateway could also parameter updates to the luminaire units, for example to change the PIR detection window time.

The power module needed for the sensing consisted of 230V AC to DC converter, DALI interface electronics, and DC/DC converter for the sensor module. The AC/DC conversion results in 16V DC, which was used to power the DALI bus. The DC voltage was then fed to DALI interface electronics and to DC/DC converter for sensor module that results in 3.3V. The interface electronics makes conversion between two wire DALI bus signaling and MCU signaling that consists of ground, receive, and transmit lines.

The sensor head consisted of three PIR components. Two of them had wide opening angle and long distance for detection as illustrated with A and B in Figure 4. They were adjusted so that the objects moving towards and away from the sensor can be detected as close to the maximum range of the sensor as possible. In the installation these sensors had the field of view along the route. The third PIR sensor in the middle had a narrow opening angle and short detection distance (C in Figure 4). In the installation this sensor was pointed down towards the ground. With this arrangement the detection areas of the sensors would not overlap and it was possible to distinguish direction of the moving object based on the order of the triggering of sensors and the time between the triggering events.

As the sensor modules were equipped with three motion detectors pointing at different directions, it was possible to distinguish different observation scenarios. When motion was detected by any of the sensors, the MCU on sensor node started a detection window that by default lasted for 10 seconds. During the window the MCU would store relative time from start of the window for each specific PIR event. After that, a message consisting of the time ordered events was sent to the gateway via mesh network. Figure 4 represents the motion sensor events numbered in red (1 - 7), and the derived position estimates. The events 1-3 would indicate detection made by sensor A in the left side of the lighting pole, the event 5 relates to sensor C detecting movement right underneath the pole, and the events 4, 6 and 7 would indicate movement occurring right from the pole. As the events were marked with a time stamp, they could be organized based on time of detection by the lighting control software. As such, for example, sequence of events 3;2;5 would be determined as movement direction to the right, where as 7;5 would indicate movement direction to the left. As the geographical location of each lighting pole was known (see Figure 8) this movement could be indicated on map and communicated to luminaires. The identity of reacting luminaires and the manner of behavior based on the movement direction was defined in the lighting control scenarios (see section 4.1.2).. Furthermore, the events were also linked with position estimates that were measured in a controlled environment before the actual test installation using five sensor modules installed in lighting poles. The measurements consisted of repeated test cases of different use scenarios: a single person walking by, a single person standing still, and a single person walking by and another person standing still in the motion sensor vicinity distracting the measurements. Total number of measurements for all the sensor modules in the position estimate testing was 75. A tape measurer was used to measure the 2.5 m detection distance for estimates 3 and 6 and 4.5 meters for estimates 1 and 4. Using these position estimates it was then possible to position detection in reference to lighting pole. Further, using the known locations of the lighting poles, the detected direction of the movement, and the generated position estimates it was possible to roughly track road users along the one dimensional installation at Siltamäki test site. Figure 5 represents the process that transforms the motion detections into track estimates that are generated using a Kalman filter. The tracks exist for 15 seconds if new detections are not added to the track. When a new detection occurs, its position is added to the nearest track estimate, which is less than 35 meters away.

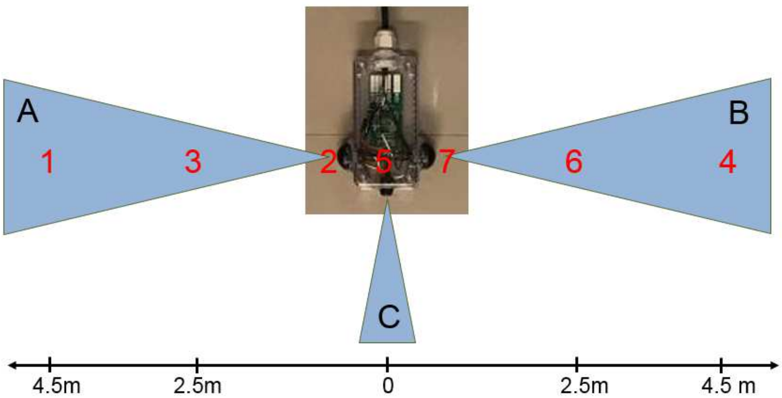


Figure 4. Motion sensor field of view (A looking towards left from the pole, B looking towards right from the pole and C looking down underneath the pole) was associated with events (1 - 7). Each occurring event would have a time stamp and a position estimate, which was gained in preliminary study. With this information events were used to generate movement tracking along the pedestrian route.

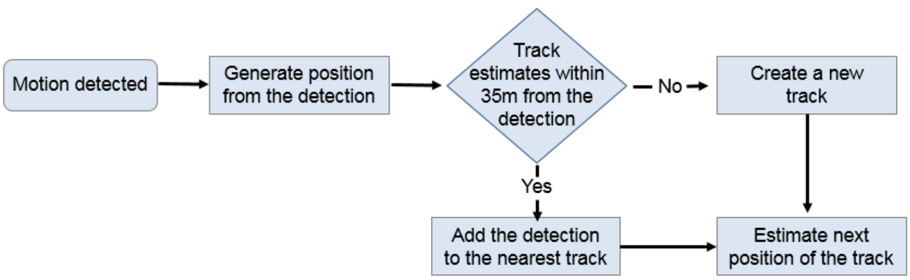


Figure 5. Process of transforming motion detection to track estimates.

4.1.2 Design tool and control data generator

The detected direction of movement was used in generating lighting control commands in the VirtuAUL software. The VirtuAUL was running in the cloud server with the LightSense server. The directions of movement were sent to the VirtuAUL, which generated lighting control messages for the LightSense server.

The earlier developed VirtuAUL design framework [29, 30] allowed the lighting designer to design adaptive lighting processes that generate lighting patterns based on sensor stimuli without the need for programming. The control and design methodology was based on the employment of network-based agents: designer controls and guides flows of agents in a virtually defined network, where lights and sensors act as the network nodes. The VirtuAUL Designer software allows for the designer to graphically define the adaptive processes that generate the lighting patterns by modifying the network nodes, topology, link directionalities, agent parameters and other design elements [29, 30]. The new version of the software is heavily based on the features of the previous version, except for the control methodology applying agents.

For the VirtuAUL Designer software, a new virtual PIR sensor type was developed based on the functionality of the real world sensor system, which could, in addition to motion detection, respond to the information about the direction of the movement. The sensor in the real world is triggered, when it detects motion and it outputs directionality of the movement as a left/right value into the VirtuAUL. Direction is related to the direction where the sensor is facing both in the real world and in the virtual model. In the simulation of VirtuAUL, a mouse pointer can be used to simulate directional movement. In the model, the virtual directional movement sensor is linked to a single lighting fixture, as in the real installation the sensor modules are situated in each lighting pole.

For the dynamic behavior of lighting in the networked virtual system, a new methodology was developed. Instead of dynamic computational agents moving from node to node, the lighting intensities are defined as percentages per linearly connected light fixtures down and upstream from triggered sensors. The down and upstream directions are relative to the direction of the user's movement; forward and backward, respectively.

In the VirtuAUL Designer software, the intensities of lighting fixtures can be defined graphically by the designer by using a ForceField controller node, connected to the sensor node. Each sensor node can have their individual controller nodes with individual values, or they can share controllers for similar values. The ForceField controller allows to define the intensity of the light directly connected to the sensor, as well as up to 6 light node links down and upstream. Percentages are given as a range of low and high value. Low value defines the passive intensity of the light and high value is triggered by movement detection. Separate fade-in and fade-out values determine the speed of the gradual change in intensity.

As light fixtures can be positioned in any direction related to each other, the directionality of left and right, and thus down and upstream of movement, cannot be solved just by evaluating the light fixtures' relative locations. Motion detected to the left might mean that the next light fixture downstream could actually be physically located behind, in front or even on the right side of the light. This means that the directionality of the movement must be explicitly defined in the lighting network, by stating the next connected light node in left and right direction. The down and upstream light nodes are determined by their linked connection distance to the origin node. Figure 6 presents screen captures of the software user interface.

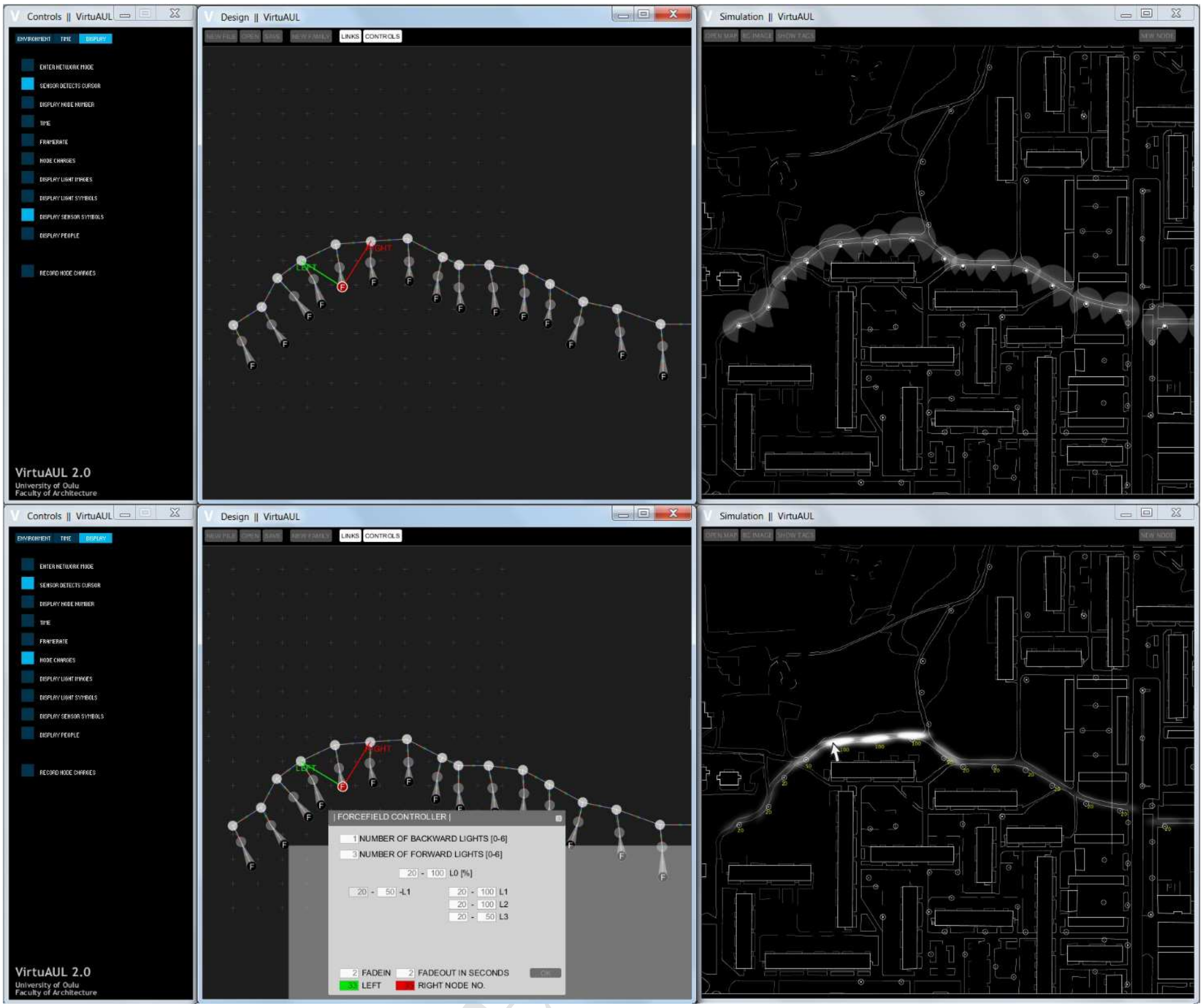


Figure 6. Screen captures of VirtuAUL Designer software (© Toni Österlund and Henrika Pihlajaniemi) with Control, Design and Simulation windows. In the Design windows, a network of virtual luminaires, sensors and ForceField controller nodes is created. With the Forcefield controller node, designer defines the details of adaptive lighting behaviour, which responds to the movement directionality. The upper simulation view illustrates the sensors on the map. In the lower simulation view, lighting behaviour is tested by moving the mouse arrow along the route from left to right.

The adaptive scenario designed with the VirtuAUL design software is saved as an xml-file, which contains all the defined control parameters of the scenario. The xml-file is saved to the lighting control unit, which runs the VirtuAUL controller software. The VirtuAUL controller runs the scenario, gets information about the sensor inputs and then passes the computed lighting intensities on to the lighting control system LightSense responsible for communicating the control commands to the luminaires.

With the design software, several scenarios of adaptive lighting responding to the movement direction were designed and then tested in the real installation in Siltamäki, both with the members of the research group and with local people. The printscreen captures from simulations of two tested scenarios are presented in Figure 7.

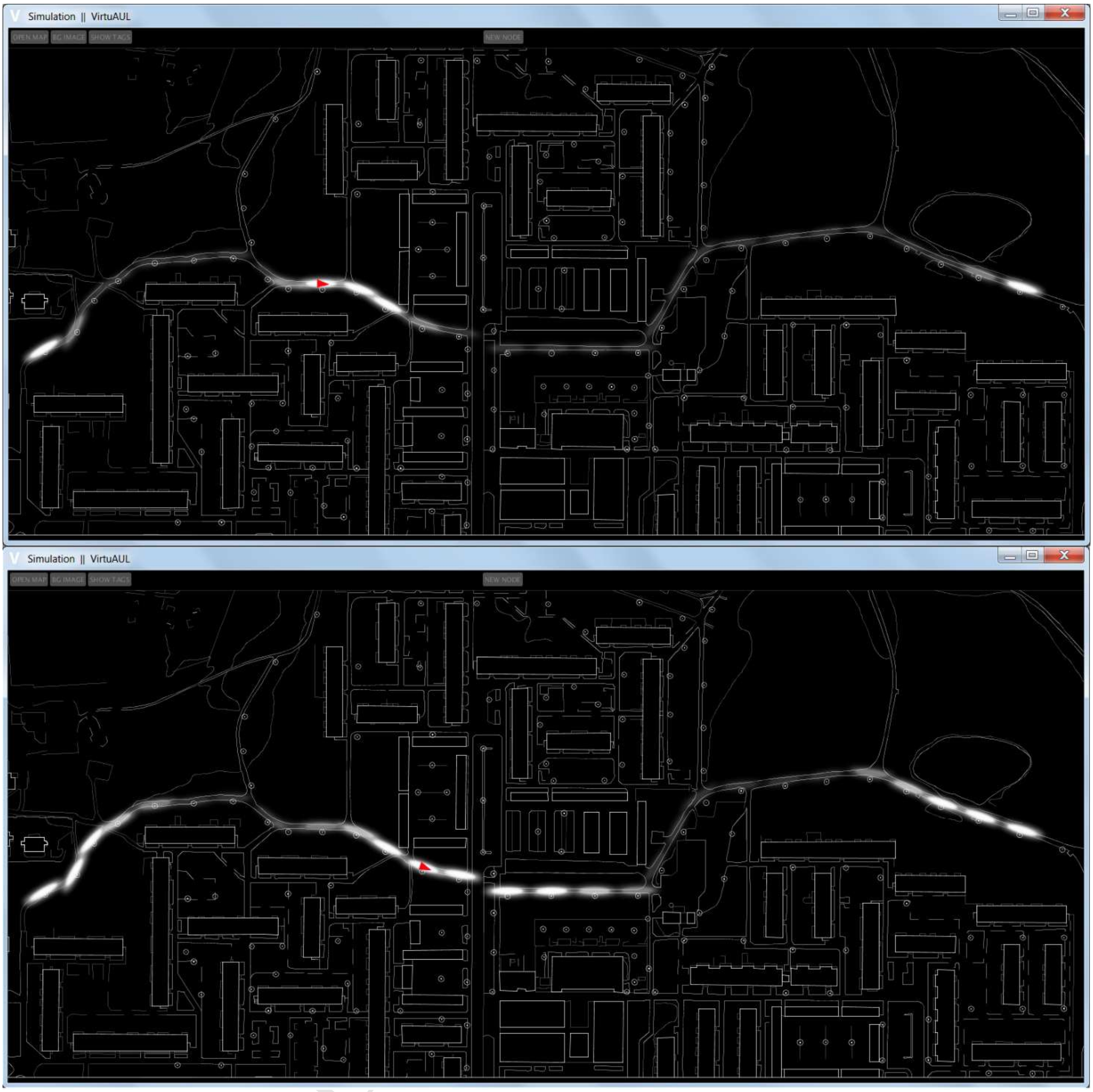


Figure 7. The print screens of VirtuAUL simulations of the two tested scenarios. The position and directionality of a route user is marked to the images with red arrows.

4.1.3 Energysimulator

The pilot installation site at Siltamäki was part of a larger lighting control area of the city of Helsinki and the energy consumption of the test luminaires could not be distinguished. Therefore, the lighting control ecosystem LightSense was used to simulate energy consumption of different lighting control scenarios. The simulations used laboratory measured luminaire power consumption and presence data recorded at the pilot installation site. Additionally, the sun rise and sunset times retrieved from online weather service were included in simulation by turning power off in between these times. All the presence (PIR) data collected by the developed system during a selected testing day was used in the simulation. The testing day was selected to represent typical presence at the test site analyzing the presence data during timeframe of 23.3.2017 – 6.5.2017.

The LightSense simulation system could simulate the lighting situations as they were performed in real life at Siltamäki pilot site. The accuracy of the simulation depends on the speed it is run. For quick demonstrations, the simulation can be accelerated 1000 times, simulating a full day in 1.5 minutes. However, at this speed, simulation artefacts occur in individual luminaire levels, i.e., at some points, some luminaires may have been turned off when they should have been on. This generates approximately a 10% error to the total simulation. The simulations used here were accelerated to double speed, which generates no errors at all, and a full day could be conveniently simulated during out of office hours. A more detailed description of the simulation system is published in [33].

4.2 Data analysis

4.1 Presence data

The pilot installation site is shown on map in Figure 8. The analysed area marked with a rectangular covers 12 sensor nodes. Only this area was provided with 24h electricity to the lighting poles so that the PIR sensor data could be retrieved throughout the day. Also, the sensor nodes located at the road crossing point were discarded from the data analysis because crossing traffic would cause false detections on the investigated light traffic road. The timeframe of 23.3.2017 – 6.5.2017 was used in the data analysis to coincide with user surveys done on the same installation. Consequently, there would be also qualitative information available to support the analysis. The results of the user survey will be published in another paper. Here, the data was analysed for two main objectives: 1.) to analyse the performance of the developed system and to identify factors that would affect the performance, and 2.) to analyse pedestrian presence on the light traffic road in order to discuss and compare different lighting control schemes and their influence on energy consumption.

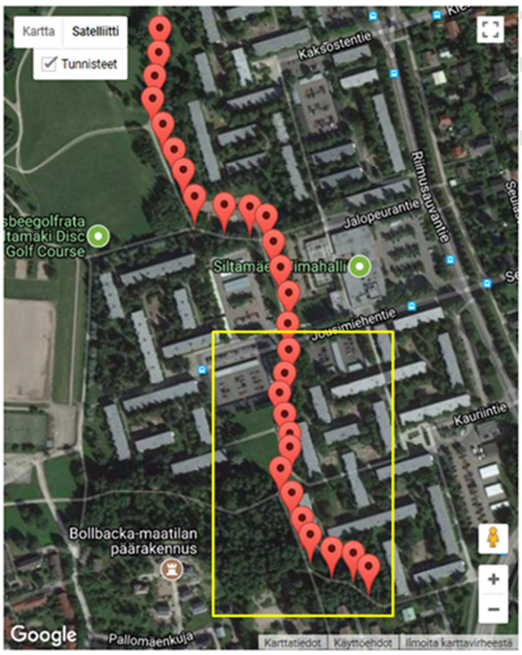
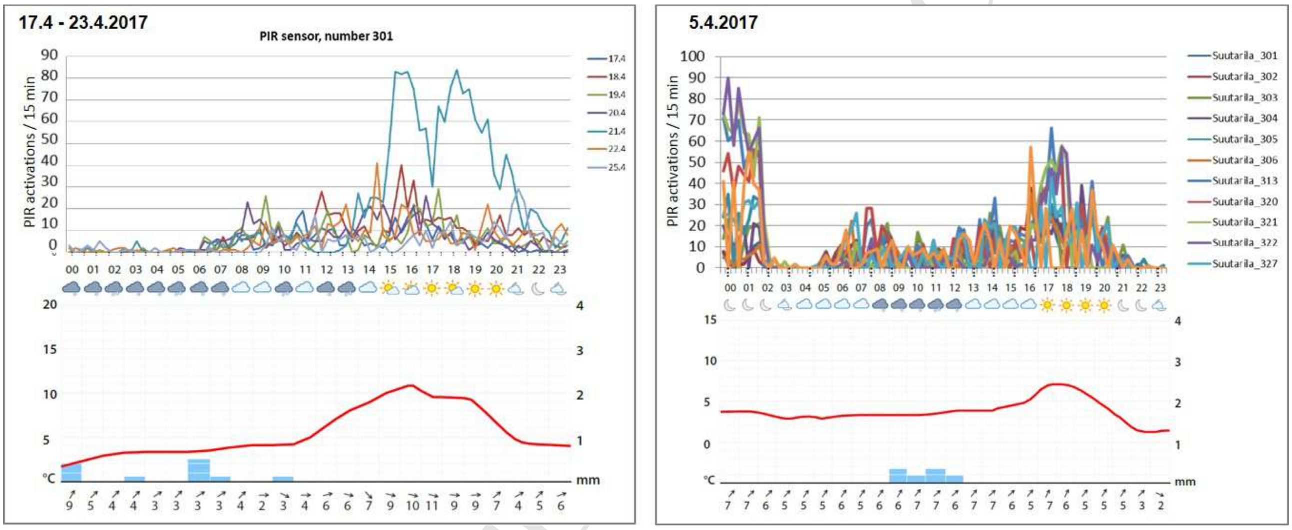


Figure 8. Siltamäki test site. Alltogether 28 sensor control nodes indicated with red items where installed. The area used in the data analysis is marked with a rectangular. This area had 24h electricity supply to the lighting poles so that the data could be retrieved throughout the day.

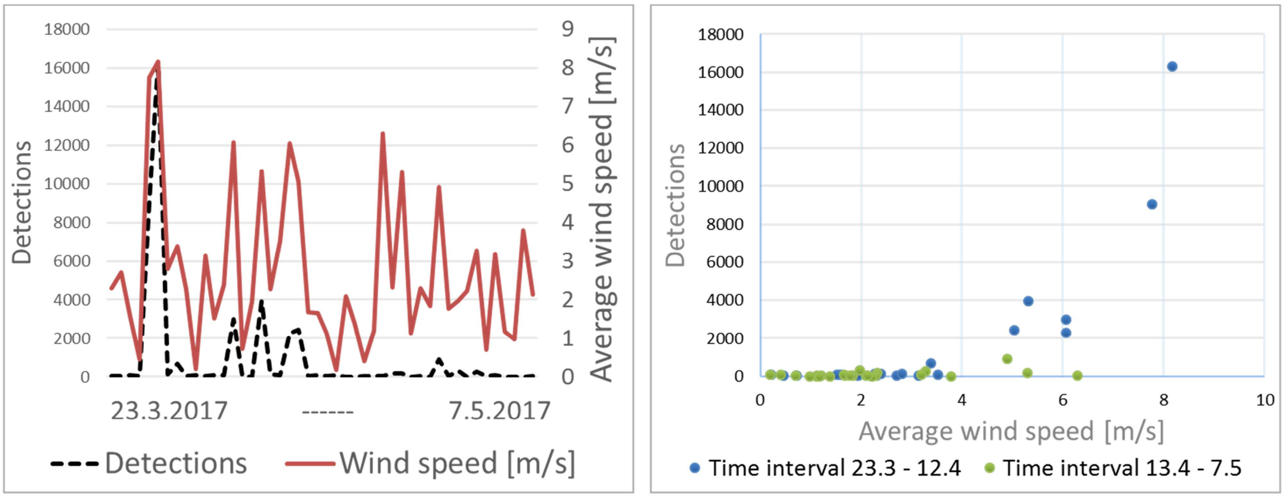
Analysis of all the collected presence data shows that pedestrians use the road typically in between 05.30 am - 10.30 pm. However, very high activity peaks sometimes appear in the data. These peaks occur in occasional days and sometimes during quiet hours over night with no clear explanation of some unusual activity at the site. Therefore, the peaks were considered to be false PIR activations with no guaranteed person presence. To investigate this matter further weather data during the testing period was reviewed. The weather information was retrieved from www.Foreca.fi. – weather service from Helsinki-Vantaa airport weather station that is located about 6 km distance from the Siltamäki pilot site. Left in Figure 9, PIR activations recorded by one sensor node (number 301) during week 16 (17.-23.4.2017) are shown. The activity detected by the sensor remains below 40 activations / 15 minutes with the exception of Friday 21.4.2017 when very high number of PIR activations are experienced between 3 – 9 pm. The timing corresponds with weather data showing change in both sun and wind conditions. Right diagram in Figure 9 shows another example of the data. Here, detections of all 12 PIR sensor nodes during Wednesday 5.4.2017 are shown. Again high activity observed between 4 – 8 pm corresponds with sunny weather and the temperature increase. However, the high activity detections overnight cannot be explained by the thermal gradient of sun.



A B

Figure 9. Comparison of collected sensor data (upper chart) and weather information (below chart). A) A single sensor node data during 17. - 23.4 2017 is shown in the left. The different colours in the sensor data graph represent different days during that period. B). All the sensor data collected during 5.4.2017 is shown in the right. The different colours in the sensor data graph represent data collected by the different sensor nodes during that day.

To explore the effect of weather a more carefully analysis on data correlations between different time series during 23.3. – 7.5.2017 was carried out. The weather data used in the correlation analysis was retrieved from Finnish meteorological institute open data bank [34]. The first time series consisted of all the PIR detections between 0 am - 6 am collected from the sensor nodes in the Siltamäki test area. The second time series contained wind speed, cloud coverage and temperature data respectively at Siltamäki during the same overnight hours. The Pearson correlation over the full timeframe of 23.3. – 7.5.2017 for the PIR detection and wind speed was 0.69 indicating correlation between these time series. Furthermore, as shown in Figure 10, the correlation seems to decrease with time. The peaks in the detections figure (dashed line) appear only during early months of March and April and disappear towards the summer. These peaks also occur simultaneously with high average wind speed indicated solid line. If the timeframe is divided into two intervals, the first interval of 23.3 – 12.4.2017 would have Pearson correlation of 0.81 while the second interval of 13.4 – 7.5.2017 would only constitute Pearson correlation of 0.44. The same effect can be seen in Figure 10B where green dots indicating the latter timeframe (13.4 – 7.5.2017) show only small number of associated detections while the blue dots of former timeframe (23.3 – 12.4.2017) indicate some occasional high detections at high wind speed. The environmental factors typically related to this timeframe in Finland include the melting of the snow (in April) and appearance of the foliage (in May) that could explain the detected outcome. Other investigated weather parameters did not show correlation with PIR detections.



A B

Figure 10. The correlation between average wind speed and detections overnight during 23.3.2017 - 7.5.2017 reduced with time. A) High detection peaks shown with dashed line only occur in early part the of test period and simultaneously with high average wind speed shown in solid line. B) The earlier timeframe (blue 23.3 – 12.4.2017) show that there was a high amount of detections associated with high wind speed. During latter timeframe (13.4 – 7.5.2017) the number of detections remained low regardless the wind speed.

In figure 11, the presence detection ratings (indicated with solid line) at the Siltamäki installation site were compared to a typical dimming schedule of outdoor LED lighting in Finland (indicated with dashed line) [35].
The national guidance instructs to keep the lighting at 100% between 7:00 and 21:00 (switched off during day with natural light) and to dim down to 40-75% during quiet hours of day. The timing can change according to the availability of natural light. However, no guidance adapting to the presence of road users is currently given. The presence detection rating recorded at the pilot installation site at the selected day (19.4.2017) is shown for a single node (nro. 301) in gray and as an average of all the nodes in black. Also, the average of one node (nro. 301) during the whole week 16 (17.-23.4.2017) in shown in orange. The Friday 21.4.2017 with the known error in data is excluded. All the data curves show similar activity at the installation site. When compared to the advised control schedule (indicated with dashed line), it can be noticed that overall the period with 100% control level corresponds nicely with the detected active period in the area in the morning. However, in the evening the active period is much shorter than with the typical control schedule dimming down from 100% control level only after 9 pm. Consequently, energy savings could be realized by adaptive lighting behaviour in between 6pm and 9 pm when the activity in the area is dropped practically in half.

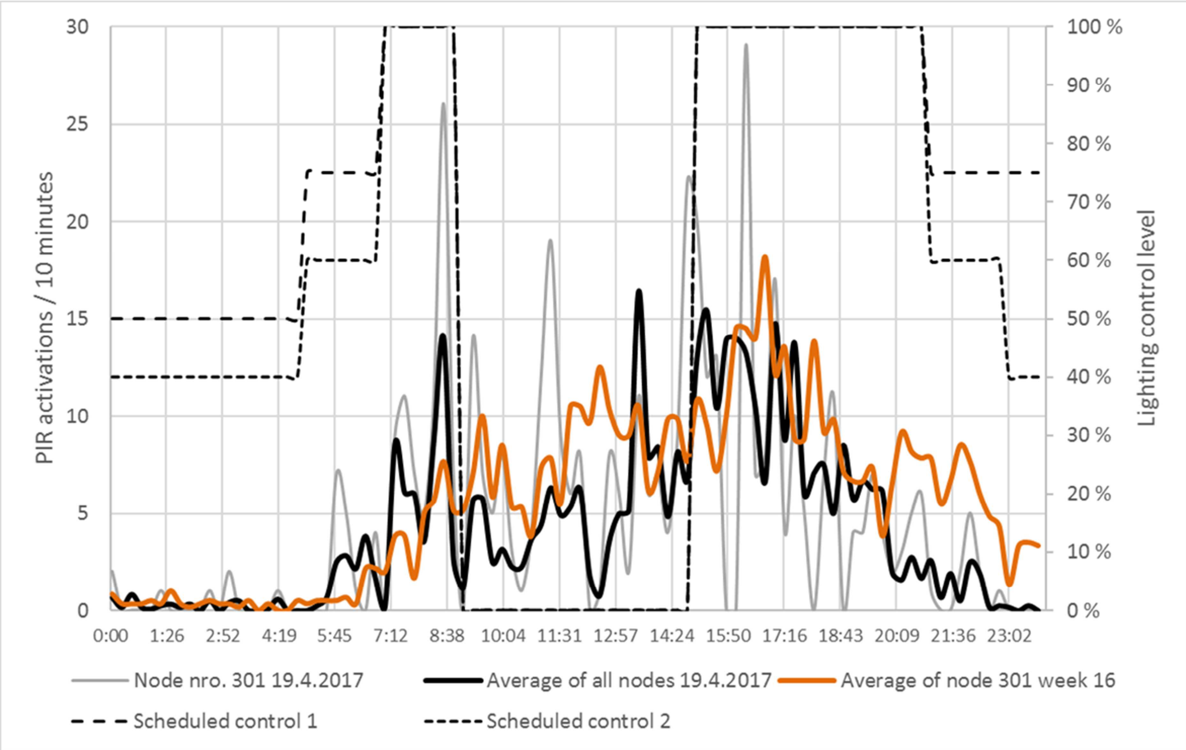


Figure 11. The presence recorded during the day at the pilot installation site (solid line) compared to two different typical dimming schedule of outdoor LED lighting used in Finland (dashed line). The presence data of a single node during the reference day is presented in gray, during the reference week (average of all days) in orange and the average presence data of all nodes during the reference day is presented in black. All the presence data shows similar use pattern on the road.

4.2 Energy efficiency

The energy consumption simulations were used to evaluate the energy performance of the developed system. The simulations combined the measured luminaire power consumption, the presence data recorded at the pilot installation site (at 19.4.2017), and sun rise and sunset times. The presense data used in the simulation was recorded at the pilot installation site in the area marked with a rectangular in figure 8 covering 12 sensor nodes. Only this area was provided with 24h electricity to the lighting poles so that the PIR sensor data could be retrieved throughout the day. Also, the sensor nodes located at the road crossing point were discarded because crossing traffic would cause false detections on the investigated light traffic road. The data is visualized in Figure 11. In simulations, three different control scenarios as illustrated in Figure 12, were used. All the scenarios were designed in a way that the adaptive functionality of lighting could not be detected by the road user or was hardly noticeable. In practice this would mean that the illuminated area on the route would be long enough to cover most of the user's field of vision. With the smart lighting control 1, the lighting was at 100% control level around the route user and two luminaires ahead of him/her. After that, the third luminaire was dimmed to the 50% control level as well a the luminaire behind him/her. Otherwise in the area the lighting was dimmed down to default level of 20%. With the smart lighting control 2, the luminaire by the route user and two luminaires ahead and behind of him/her were at 100% control level. Beyond the 100% area, the next (third) luminaires in both directions were dimmed to 50 % control level and all the other luminaires stayed at the default 20% level. As the illuminated area is symmetric, this control scheme could be realized with standard presence detection without knowing the direction of the movement. With the smart lighting control 3, the illuminated area around the road user was the largest. This time the luminaire by the route user and three luminaires ahead and one luminaire behind of him/her were at full 100% control level. Then, the next luminaires in both directions were dimmed to 75 %, and the next luminaires after that would be at 50% lighting level. The default control level beyond the brightened area around the user was 20% in all the control scenarios. As the system was able to track several people at the same time, all the road users could have their own illuminated area and the areas could overlap. The smart lighting control 1 would optimize the energy performance with the smallest illuminated area but would require the lighting system to be able to detect the direction of the movement. The smart lighting control 2 has symmetrical attributes around the road user so it could be realized with standard presence detection technologies.

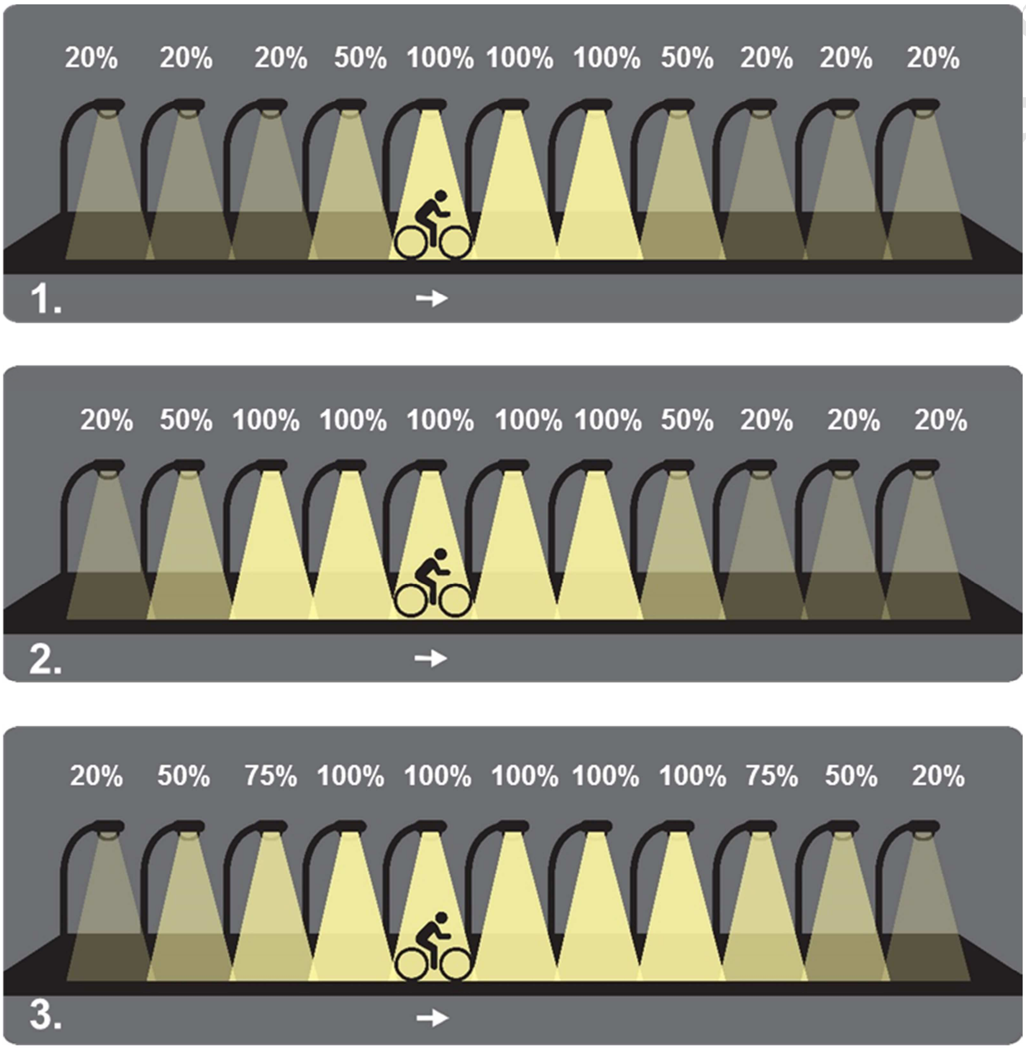


Figure 12. The simulated smart lighting control scenarios with varying amount of brightened luminaires around the route users. Beyond the brightened area, the luminaires were at 20% control level in all the scenarios.

Table 1. Simulated energy consumption and energy saving (of each luminaire) compared to normal, static street lighting control. PIR data collected 19.4.2017 is used in the simulation.

Date	Energy consumption / luminaire	Energy saving/luminaire with smart control compared to normal control (100% power over night)

	Smart control 1 (kWh)	Smart Control 2 (kWh)	Smart Control 3 (kWh)	Normal control (kWh)	Smart control 1 (kWh)	Smart control 2 (kWh)	Smart control 3 (kWh)	Smart control 1 (%)	Smart control 2 (%)	Smart control 3 (%)
1.1.2017	0.15	0.18	0.19	0.48	0.34	0.30	0.29	70	62	60
8.2.2017	0.12	0.14	0.15	0.41	0.30	0.27	0.27	72	66	65
15.3.2017	0.08	0.10	0.10	0.33	0.24	0.23	0.23	74	71	70
19.4.2017	0.06	0.06	0.06	0.24	0.18	0.18	0.18	76	75	74
1.6.2017	0.03	0.04	0.04	0.15	0.12	0.11	0.11	77	76	75

In figure 13 and table 1, the dynamic smart lighting control scenarios are compared with normal (static) control of the area in which the lights are off during the bright period of the day, and at 100 % control level during the night. The luminaire (Greenled Sirius) was measured to consume 6 W at 20% level, 10W at 50% level, 17W at 75% level and 27 W at full 100 % power. In all simulations, real PIR data collected during 19.4.2017 was used. The representative day was selected based on data analysis introduced in the previous chapter. The values for the other dates shown in figure 13 and table 1 were generated by using sun rise and sunset times of the corresponding time.

It can be seen that the smart control generates significant energy savings. This is because of the low default level (20%) and long quiet hours with no or only very few pedestrians at the route overnight. Also, the overall presence of users on the route is rather low. The relative savings compared to the normal control increase towards the summer with significant amount of natural light in northern latitude. Consequently, artificial lighting is needed only during midnight hours with practically no users. For the same reason, the amount of energy saved with smart control radically decrease towards summer despite the increasing relative saving. When comparing different smart lighting control scenarios, only little difference between them can be detected. As expected, the highest energy consumption is with the scenario with the largest illuminated area. One of the scenarios (Smart control 2) is such that it could be realized with a simple presence detection. Compared to that, the advanced control able to adapt based on direction of movement provides only small benefit (1 - 8 %). The difference between the smart control schemes reduces towards summer implying that the low overall presence in our test site contributed to this small benefit. As such, the advanced solution would be more useful in some other applications (with more road users). Still, there is a question whether the higher cost of the advanced solution would ever be justified only by the energy saving argument.

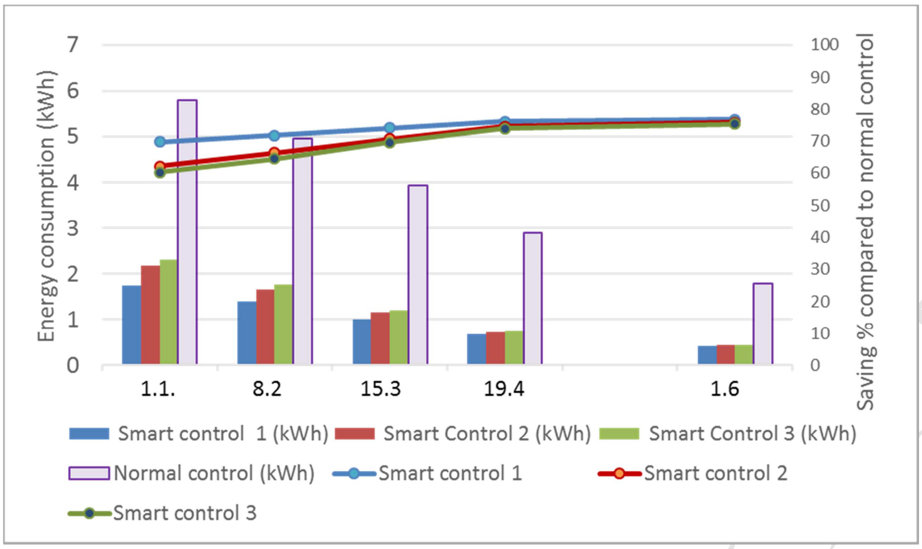


Figure 13. Energy consumption of the test area (12 luminaires) was simulated with the PIR data recorded 19.4.2017 , the measured luminaire power consumption and the sunrise and sunset times of the corresponding dates. The columns represent different control scenarios and associate with energy consumption shown in left y-axis. Lines with markers show energy saving compared to the normal control. Different colors represent different smart control scenarios and refer to saving in percentages shown in the right y-axis.

5. Discussion and conclusion

The developed sensing and control system, which was piloted in the real use environment, demonstrated to be able to implement the dynamic and adaptive lighting as planned. The experiences gained during the piloting season (03-2017 – 11-2017) showed that the system was robust enough to remain functional in outdoor environment. However, some false sensor activity was discovered and deduced to be caused by the environmental conditions. The data analysis showed that the strong wind correlates with the high presence activity detected at night time. Strong wind would make objects of the environment, such as tree leafs and branches, move. This movement on the PIR sensor view would be detected whenever there is a temperature gradient associated with the movement. The effect of wind was more pronounced in the earlier time interval with colder weather circumstances. It can be speculated that because the second time interval was later in spring, which makes the thermal environment more uniform, the wind caused less false detections. Additionnally, the sun is considered to cause false alarms during daytime as objects with different color can cause thermal gradient to the environment in the sensor field of view. However, as the data is not needed for lighting control during daytime the effects of sun are considered less detrimental in this application.

The used arrangement of the three PIR sensors in the developed sensor module made the total field of view of the sensor device very large making the system sensitive to false detections. In addition, as the sensor module was installed at 4 meters height it would sometimes be surrounded by foliage that could be detected to move. Dense foliage, as well as the metallic electricity cabin in which the gateway located, would also attenuate the wireless communication signal. Assembling the sensor module lower in the pole would make the installation easier and might also have positive influence on detection reliability as the immediate environment of the sensor would be more static. However, such assemblies are in danger for vandalism. Optimized solution could be assembly inside the pole that would protect the sensors against both weather and vandalism. However, this would need some kind of sensor window to be developed for the pole allowing wireless communication and detection signals to pass through the pole structure. Another, practical solution would be to use collar to limit the field of view to more focused area.

Here, the detection error is false positive causing increased level of lighting in occasions when nobody is truly present. This would increase energy consumption but, on the other hand, would not deteriorate the end user experience. If the system would be trimmed less sensitive, the risk of false negative detections would increase. This would mean that lighting would stay in 20% and not increase to acceptable level every time people are present. In many considerations this would risk the safety and be more detrimental than the loss of energy savings, especially as the LED lighting already is rather efficient, when compared to old technologies [3]. However, in this test installation the number of false detections at windy weather could be significant. Thousands of messages send via the wireless mesh network could overload the system causing the control to crash or behave otherwise unstable way. To prevent the overloading to occur , a cooldown feature making the system to wait for predetermined time before successive message delivery was developed.

The relative energy saving compared to the static 100% control at the dark time of the day was 60 – 77% depending on the used smart control scenario and the calendar time. The result was realized by simulation using measured luminaire power consumption, presence data recorded at the pilot installation site, and sun rise and sunset times retrieved from the weather data bank. The energy saving is significant and was achieved by dimming the lighting down to 20% power level when no one was present and allowing the normal 100% lighting only in the vicinity of the detected pedestrians and cyclists. With this approach, the low pedestrian or cyclist presence in the pilot installation site, especially in between 6 pm and 9 pm, cumulated the savings. During those hours, a typical dimming schedule of outdoor LED lighting in Finland recommends a 100% control level [35]. Similar to this result, in his studies of energy performance in buildings Yang et al. discovered that the true presence differs from generally used statistical use profiles and this might have significant energy performance effect depending on the application [36].

Contrary to a generally used dimming schedule, which provides decreased lighting levels at night time [35], with our system the user would always experience the normal 100% lighting regardless the time of the day he/she uses the road. Also, with the large illuminated area around the road user, it was guaranteed that a user would not be able to detect lighting level change around him/her, that can be experienced unpleasant [15, 16]. The effect of the different smart control scenarios was discovered to be rather minimal. The smart lighting control 1 with the smallest illuminated area had the best energy performance, but the difference to the other investigated scenarios was less than 9 % being largest in January with the shortest natural light time. So, instead of focusing on optimizing the smart control with the lowest possible energy consumption it could be more important to optimize it for the pleasant user experience. The practical solution could be to use normal, static 100% lighting during active hours and dynamic smart control during quiet hours of the night. However, the challenge is that the achieved energy savings would not quickly cover the increased infrastructure costs of the advanced sensor and control technology and the payback period would be rather long with today's energy prices. This means that the cost savings might not be the biggest driver of IoT technology for street lighting after all. A more versatile use of collected data is needed to cover the additional costs and truly benefit from the smart technology in urban environment.

Dynamic and adaptive street lighting makes the lighting environment change. This is a new feature and design parameter in outdoor lighting and more research is needed to find out optimized control scenarios for different application. The dynamics should never disturb the user and hinder the safety and security of the people and traffic [37]. Currently there is no standards nor regulations on presence based lighting control. It is an important and interesting research question whether such systems would affect the user safety while targeting energy savings. For example, the current guidance would allow only 40% over night regardless there could be someone on the road, while our scenarios would always provide 100% lighting to road user. There is a risk of malfunctions though, which should be considered in the further development of the control system. Additionally, there is a risk that the dynamics could influence negatively other parties beyond route users, for example, people living close to dynamically illuminated areas might experience the changes in the lighting level. However, such a fluctuation might not always be experienced negative as the natural light is not static either. So, new technologies in lighting provides interesting research questions on end user experience investigations as well.

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Highlights

Smart and dynamic route lighting control based on movement tracking

- Dynamic route lighting was shown to save more than 60% of energy.
- The relative savings compared to the normal control are higher during summer.
- Direction of the movement can be tracked with low cost PIR sensors.
- Strong wind causes false detections on PIR sensors especially during cold season.