Vehicle and Pedestrian Aware Street Lighting Automation

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***Abstract*— The emergence of LED luminaires that can be dimmed rapidly and frequently enables radical innovations in street lighting automation. It is possible to save considerable amounts of energy by adjusting street lighting according to the movements of individual road users. Since the same lights are often used for illuminating both vehicle lanes and sidewalks, it is necessary to detect both vehicles and pedestrians. A simulation of vehicle and pedestrian traffic is interfaced to a distributed street lighting system based on the IEC 61499 standard, in order to quantify the energy saving potential of a street lighting automation system that exploits real-time sensing information of individual road users while conforming to traffic safety related requirements for road lighting.**

Keywords*— *Intelligent Street Lighting, IEC 61499, pedestrian cellular automata, LED, Energy Efficiency

I. INTRODUCTION

As smart cities are investing in intelligent LED street lighting and traffic monitoring systems, new applications of distributed automation technology are possible. LED luminaires may be quickly dimmed and adjusted back to full power to provide the optimum level of light at the right time [1, 2], even reacting to the movement of individual road users without damage to the luminaire, as is indicated by recent patents (e.g. by Philips [3]). In our previous work, traffic simulation was integrated with street lighting automation, and significant energy savings were reported, especially at low traffic volumes [4]. In this paper, the approach is extended to cover bi-directional traffic as well as pedestrian sidewalks on both sides of the road, resulting in changes to both the IEC 61499 control software as well as the traffic simulation. The paper presents simulation-based results on energy saving as a function of vehicle and pedestrian traffic volume.

II. RELATED LITERATURE

The application presented in this paper could be implemented with various control software technologies. Since the system will be distributed over very broad geographical areas, it will need to support interoperability of components from different vendors and it should be possible to reconfigure the system, e.g. due to new or broken sensors with minimal downtime and interruption to the rest of the system. In this paper, the IEC 61499 is chosen as its purpose and ongoing research related to it is aimed at applications with these characteristics. IEC 61499 is being applied to automation of geographically distributed systems such as the smart electric grid [5, 6] and distributed hybrid electric and gas grids [7]. Interoperability of software and devices developed by different vendors [8], automatic re-configurability [9] and co-simulation of the automation with the system to be controlled [10-13] are all active areas for the IEC 61499 research community. Smart virtual metering, similar to the approach described in [14], will be used to quantify energy savings.

Energy savings from smart traffic lighting have not been presented with IEC 61499, but some proposals based on other technologies exist. With a few exceptions [15, 16], the approaches are based on detecting vehicles. Statistical information on traffic volumes makes it possible to degrade the level of lighting at times when traffic volumes are expected to be low [17], and a recently reported application follows this approach in a way that conforms to relevant and up to date street lighting regulations [18]. A few authors have proposed automation that exploits data from sensing individual vehicles, but these approaches ignore and violate traffic safety regulations [19, 20]. In this paper, the idea is to always provide a sufficient length of fully lit road in front of each vehicle, so that road lighting regulations are not violated. Our earlier work has considered a one-directional road without pedestrian sidewalks [4]. In this paper, the approach is extended to cover two-directional traffic as well as pedestrian sidewalks on both sides of the road, resulting in changes to both the IEC 61499 control software as well as the traffic simulation. Our work was limited so far mainly to roads without junctions. In case of a junction, it would be necessary to know or predict which way a road user intends to turn. If such information is available, the algorithms here could be configured to roads with junctions in further research. A suitable algorithm for this purpose has very recently been presented in [21] and validated in a real urban setting, so further work on this approach could integrate the lower level distributed control presented in this paper to the computationally expensive prediction algorithms presented in [21], which could be executed in a cloud environment with appropriate processing resources.

III. MODELING OF THE CELLULAR AUTOMATA MODEL

A. Vehicle Traffic Modeling

One of the most accurate and simplest ways to model vehicle traffic is cellular automata (CA) model. The principle of CA is that vehicles move in a road segment, which is modelled as a one-dimensional lattice of cells. Every cell can be either empty, or occupied by just one vehicle. Vehicles assumed to be moving in one direction in this lattice of cells. Each vehicle moves with velocity v_v, with integer values ranging from 0 to v_{max}. The position and velocity of each vehicle is updated every time step, which is taken to be 1 second.

In [4], a single lane with one-directional moving was modelled. Change of velocity is regulated by a set of three rules, described in NaSch CA model [22].

1. IF $v_{vi} < v_{max}$ THEN $v_{vi} := v_{vi} + 1$
2. IF $v_{vi} < g_{vi}$ THEN $v_{vi} := g_{vi}$
3. IF $v_{vi} > 0$ AND $V = 1$ THEN $v_{vi} := v_{vi} - 1$ (1)

where v_{vi} is vehicle velocity of vehicle i, g_{vi} is the number of cells between vehicle i and the vehicle going ahead. V is a variable with random value either 0, or 1, and is needed as an uncertainty parameter.

In this paper, we continue to work with the previously constructed model [4], updated for the needs of two-directional vehicle moving. A second lane with identical parameters was added. The only differences are that vehicles move in opposite direction to the first lane, and, accordingly, vehicles appear from the opposite side of the cell lattice. As a result, the model updates positions and velocities of vehicles on two separate lanes simultaneously each time step. An assumption we made is that vehicles still may not overtake each other. So one cell still may not be occupied more than one vehicle moving in the same direction, but certainly two vehicles moving towards each other may locate in the parallel cells on different lanes.

B. Pedestrian Modeling

The pedestrian behaviour can be modelled by Cellular Automata technique as well as the moving vehicle. However, there are significant differences between the vehicle and pedestrian models since the pedestrians move differently than cars. The speed of the pedestrian is less, they move in several directions within a single lane, they can accelerate to a maximum speed instantly, and stop as quickly.

Significant research efforts relating to the modelling of pedestrian movement behaviour have been carried out by several groups in recent years. In the works of J. Dijkstra [23], Blue [24], J. Kwak [25], the principles and rules for pedestrian behaviour were described. The principles in [24] are chosen for the basis for our work.

The pedestrians move in two dimensions, i.e., forward /back and left/right within a single pedestrian lane. Thus, the road segment is considered to be a lattice of square cells with fixed size. Cell size in the reference model is designed to be in accordance to the minimal requirements for the personal space as described in the USA Highway Capacity Manual (1994) and it is chosen to be 0.5 m to closely synchronize with the vehicle CA model.

For each pedestrian who appears on any edge of the road, the initial velocity vpi for moving forward is assigned. This value is 2, 3 or 4 cells per time step corresponding to speeds of 1 m/s, 1.5 m/s and 2 m/s respectively. The three different initial velocity values were used to divide pedestrian flow into three groups – Slow Walkers (2 cells per time step), Standard Walkers (3 cells per time step) and Fast Walkers (4 cells per time step). The pedestrian speed distribution was chosen in accordance to works of Blue, Adler and Lovas [26], as 5% probability for fast walker, 90% for standard, and 5% for slow walker. The time step is 1 second and the pedestrians move according to the following rules:

1. **First parallel update: Lane change**
   a. If 2 walkers are close enough, they may not walk into one cell.
   b. If there is an opposite direction walker ahead, change the line (step out) when the gap is := 0.
   c. If there is the same direction walker and opposite direction walker ahead, step behind the same direction walker in any available line.
   d. Ties of equal maximum gaps ahead are resolved according to:
      i. 2-way tie between adjacent lines: 50/50 random assignment between 2 lines.
      ii. 2-way tie between current lane and single adjacent line: stay in current lane.
      iii. 3-way tie: Stay in current lane.
   e. Moving. Move 0. +1 or -1 lateral steps.

2. **Second parallel update: Step forward**
   a. If there is a gap to walker ahead, then update velocity: v_{pi} := gap.
   b. Exchanges. If cell occupied by an opposing walker, then react on it and possibly increase the gap. For example:

      IF gap = 0 or gap = 1 AND gap := gap_occ

      THEN v_{pi} := gap + 1 with probability p_exchg.

      ELSE v_{pi} := 0. (2)

   c. Moving. Move v_{pi} cell forward.

Thus, a walker moves forward with his own velocity, and may slow down and do sidesteps to avoid a collision with other walkers. However, for an intelligent lighting system, not all of these complex rules are necessary. Smart lighting system is assumed to regulate the lighting in accordance to the presence or absence of people on the road. When there are a lot of walkers on the road segment, the lights will always be on, because people will move tightly enough to each other. As a result, in each lighting zone will certainly be a pedestrian and light regulation does not make sense. When there are not many pedestrians on the road segment, they all move with constant speed and avoid the collisions in advance, without losing time. As a consequence, the rules for lane change can be neglected in this case. For the same reason, we do not need rules for changing the speed (Step Forward) according to the gap, because faster pedestrian will change his lane in advance and will overtake slower walker without speed losses.

We can greatly simplify the rules above since we do not need to consider side stepping and the cell lattice can be transformed into a vector with certain number of cells. The cell size remains at 0.5 m, but now only in the longitudinal direction. Since pedestrian walkways are typically at least 2 m in a width, we allow more than one walker to occupy the same cell at one time step. The final rule for pedestrian motion is now expressed as:

$$X_p := X_{pi} + V_{pi} \quad (3)$$

Where x_{pi} is the current walker's position and v_{pi} is the walker's velocity. Since we assume that there are no obstacles to pedestrian, his speed is expected to remain constant. So, every walker will move with own constant velocity, given initially according to (5: 90: 5) distribution. The rule (3) is applied for both directions

C. *United Vehicle and Pedestrian CA Model*

United model consists of two vehicle lanes, developed in [4] and the pedestrian lane, described in Section *III B*. All these lanes modelled in one dimension, as a road segment in longitudinal direction. One vehicle cell is equal to 7.5 m size, while one pedestrian cell is taken to be 0.5 m; thus, the road segment 1.8 km consists of 240 vehicle cells and 3600 pedestrian cells in parallel. The time step is equal to 1 second for both cases, so the state of all vehicles and pedestrians updates simultaneously every second.

The arrival process for new vehicles was implemented exactly the same as in our previous study [4]. With probability *p*, a new vehicle is generated into the first cell in the direction of movement of the lane at each time step. The pedestrian arrival process is made in the same way, with one difference that new walkers may appear from both boundaries of the pedestrian lane.

IV. SYSTEM AND CONTROL

A. *Street Lighting Design and Lighting Control*

The parameters and settings for street lighting equipment was taken unmodified from previous study related to one-lane vehicle model and described in details in [4]. The road is chosen to be class ME4 of UK road classification standards [27]. The luminaire remains to be of type GELIGHTING 85344 ERS4-0-TX-EX-5-57-1-G-CP [28], maximum Wattage is 258.0 W.

The road is divided into sensing zones. Each of them is controlled by two vehicle detectors and two pedestrian detectors, for both directions. For simplification, we assume that there is only one sensor mechanism that fulfils the role of these four separate detectors. The sensors are located at the borders of sensing zones, and the controller regulates the control signal for the lights in the zone *k* based on presence or absence of objects moving:

$$u_k(t) = \vee_{j=k-M}^{k+N} x_j \quad (4)$$

where M is the number of zones behind the zone k (in the direction of traffic movement), N is the number of zones ahead of the zone k. For vehicles, we continue to use values M = 4, N =1 [4] for both direction lanes. For pedestrians the values M = 1 and N = 1 was chosen. The power of lighting P_k is set by the following rule:

$$f(x) = \begin{cases} P_{max}, & u_k(t) = 1 \\ \beta P_{max}, & u_k(t) = 0 \end{cases} \quad (5)$$

where P_{max} is the maximal available light power, and β is the parameter for dimming of the light, with values ranging from 0 to 1. When there are no pedestrians and cars on the road, the light can be dimmed to a certain level in order to save the energy and reduce consumption. Due to the safety factors, the luminaire should provide some amount of light even if the road is empty, so β cannot be 0.

The sensor in the lighting zone can detect a vehicle or pedestrian moving in the certain zone. For each time step, the information about the presence of vehicles and pedestrians in every lighting zone is transferred to the street lighting control system. The length of one zone is taken as 60 m, as in the work [4]; that corresponds to 8 vehicle cells or 120 pedestrian cells in the CA model.

B. *Updated Sensor Value*

The CA model in this work has been extended to include two vehicle lanes and a pedestrian path. With the introduction of an extra lane and a pedestrian path, the use of a binary integer to represent the sensor value in [4] is no longer sufficient. The sensor now indicates the direction of the vehicles in both lanes and the pedestrian lane. Since the lighting strategy introduced in this paper is largely dependent on the direction of the vehicles and the pedestrians on the path, the sensor value encode the directions of the vehicles and pedestrians (Table I). In total, there are $2^3 - 1$ possible encoded combinations. The 0^{th} bit represents vehicle/s traveling towards the right. The 1^{st} bit represents vehicle/s travelling towards the left and lastly, the 2^{nd} bit represents the pedestrian/s. The direction in which the pedestrian is traveling is not distinguished in the sensor value as the lighting strategy is the same for both directions.

Table I. Sensor Decoding Table

2^{nd} Bit	1^{st} Bit	0^{th} Bit	Integer
0	0	0	**0**
0	0	1	**1**
0	1	0	**2**
0	1	1	**3**
1	0	0	**4**

1	0	1	**5**
1	1	0	**6**
1	1	1	**7**

C. Distributed Smart Lighting Control System

The intelligent lighting controller is implemented in IEC 61499 function blocks. IEC 61499 is the reference architecture for the design of distributed systems and is suitable for an intelligent lighting control system where sensors and lighting actuators are geographically dispersed. The design methodology of the street lighting controller is similar to the one in [4]. A single street light function block controller controls a single street light and instantiated multiple times for each sensor in the CA model to take advantage of the object orientation offered by IEC 61499. Fig. **1** shows an excerpt of a single street light controller and its interconnections to the eight most immediate controllers. For the reason of clarity, only the event and data connections are shown.

For the case of two-lane bi-directional vehicle traffic and a pedestrian path, each controller must communication with eight of its neighbouring controllers. The lighting strategy used for a single vehicle is to light four of the street lights ahead of the current zone and one street light trailing the current zone. With two lanes, one in each direction, each street light controller must forward its sensor value to four of the immediate leading controllers and four of the immediate trailing controllers. When a street light controller receives a sensor value for its zone, it will then immediately forward the sensor values to the eight other street light controllers via the *Sensor_Pos* event signal. Each *Sensor_Pos* event signal is associated with the *SensorPos* value (with the sensor value), which is also forwarded to the connecting street light controller. At each simulation step, each street light controller receives its sensor value from the CA model and eight additional sensor values from its immediate surrounding controllers. Each controller then processes all nine sensor values to determine whether it needs to switch its street light to the dimmed state or to the fully lit state. The functionality of virtual metering is also implemented in each street light controller. Each controller tracks its power consumption at each simulation step, which is aggregated to compute the total energy consumption over the course of the simulation.

V. RESULTS

A co-simulation framework adopted from [5] was used to validate the IEC 61499 control system where the CA model was developed in MATLAB and the IEC 61499 control was developed in nxtStudio [29] interfaced by UDP communication. The parameters of the simulation are as follows: The length of the street in the CA model is 1.8 km long separated into 30 zones. Each zone consists of a sensor, which detects the vehicles in two lanes and the pedestrian path. At each simulation step, a total of 30 sensor values are sent to the IEC 61499 function block control model. In total, 36 simulations were performed with different combinations of arrival probabilities for vehicles and pedestrians. The arrival probabilities used for the vehicles and the pedestrians are shown in Table II.

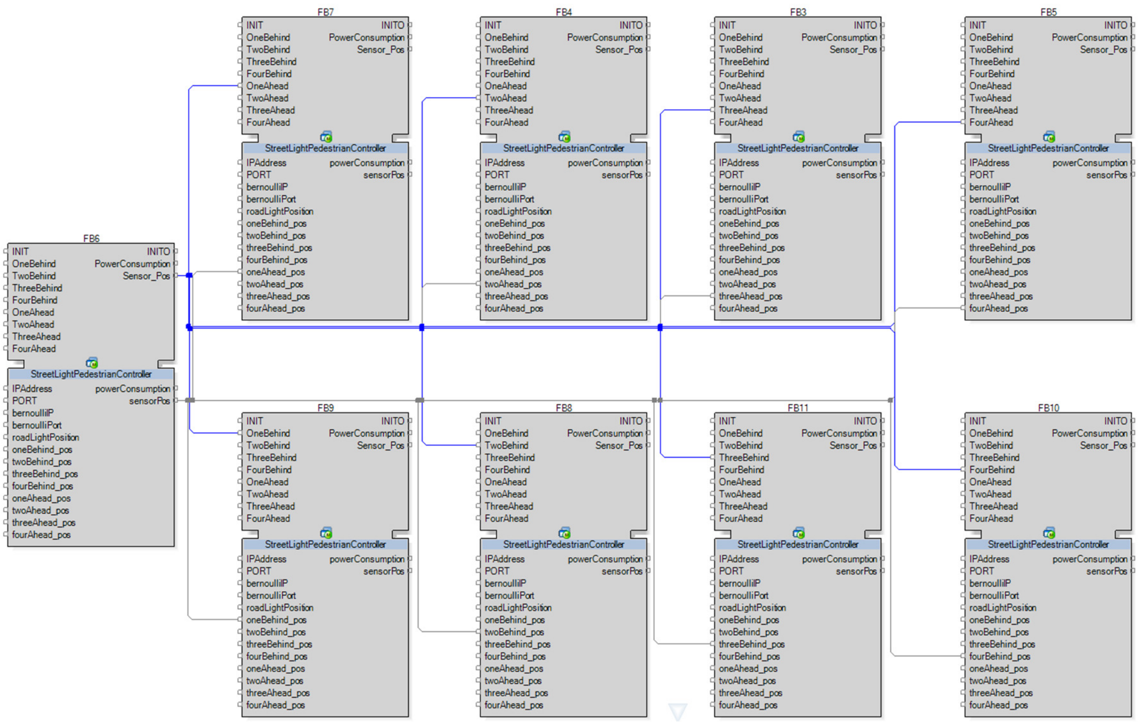

Fig. 1. An excerpt of a street light controller and its interconnections to four of its trailing and leading street light controllers

Table II. Arrival Probability Values for Vehicles and Pedestrians

Vehicles		**Pedestrians**	
Veh/h	**Probability (*p*)**	**Ped/h**	**Probability (*p*)**
0	**0**	0	**0**
10	**0.002778**	7.5	**0.002083**
50	**0.013889**	15	**0.004168**
150	**0.041667**	30	**0.008333**
300	**0.083333**	60	**0.016667**
500	**0.138889**	90	**0.025**

The graphical result of the simulation with the above combinations of the average number of vehicles and pedestrians per hour are shown in Fig. 2.

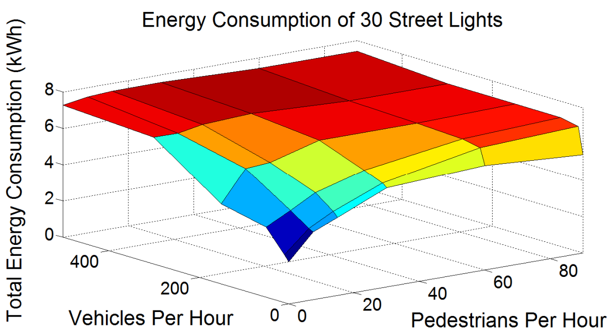

Fig. 2. Energy consumption for a 1.8 km street for one hour as a function of vehicles per hour and pedestrians per hour

It is clear from the plot that the greatest benefit of having an intelligent street light controller is when the vehicle and pedestrian traffic is light. Without intelligent lighting (where there is no dimming of street lights and the street lights are lit at 100%), the energy consumption is 30 x 258 W x1 h = 7.74 kWh, where there are 30 street lights and each street light consumes 258 W of power. With intelligent lighting where the street lights are dimmed to 30% of full consumption, when there are no vehicles and pedestrian on the street, the energy consumption is 30% x 30 x 258 W x 1 h = 2.32 kWh. In addition, significant savings in energy consumption can be seen in Fig. **2** when there are only pedestrians on the street. Even at the highest average number of pedestrians in our simulation run, the energy consumption is approximately at 70% of the full energy consumption if smart dimming were not deployed.

VI. CONCLUSION

Smart street lighting is enabled by the emergence of LED luminaire technology capable of being dimmed rapidly and frequently, paving the way for major innovation in the lighting automation system. In this study, the potential energy savings for the scenario of two lane streets with pedestrian paths is investigated. We have quantified energy savings as a function of vehicle and pedestrian traffic volumes. Results are presented in kWh for the chosen luminaire type [28] and can easily be updated for a different luminaire based on the specifications for maximum power consumption of the said luminaire. If there exists statistical data on vehicle and pedestrian traffic for other two-lane roads, it will be possible to use the results in Fig. **2** to quantify the savings in energy consumption before deciding to invest in traffic based street lighting automation for that road. These results are an estimate, which is based on traffic simulation. The CA does not provide accurate simulation of the movements of individual road users, but the focus of this study is on traffic patterns. The CA is established in the traffic engineering community as an accurate solution for monitoring traffic patterns, including platooning of vehicles [22].

Further work integrating the approach in [21] can provide accurate estimates for districts including junctions; the introduction of such computationally expensive algorithms, which need to be performed only infrequently, are a motivation for further research on the automation architecture to integrate the geographically distributed control in IEC 61499 presented in this paper to an architectural component that resides in the cloud.

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