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(54) **A DISTRIBUTED MODEL PREDICTIVE LIGHTING CONTROL METHOD FOR A STREET ZONE AND A DISTRIBUTED PREDICTION-BASED CONTROLLABLE LIGHTING SYSTEM**

(57) The present invention relates to a distributed model predictive lighting control method for a street zone including a plurality of streetlamps M and a distributed predictive controllable lighting system for the plurality of streetlamps M of the street zone. According to the present invention defined is the street zone including the plurality of streetlamps M each comprising a streetlamp controller device implementing a Model Predictive Control (MPC) algorithm configured to control of each streetlamp M and a Distributed Model predictive Control (DMPC) algorithm configured to adjust a light intensity level of each streetlamp M in the street zone satisfying local and global street zone constraints. The distributed local streetlamp controller devices are mutually and iteratively bidding towards a joint setpoint of the whole street zone based on a global optimization objective satisfying local and global street zone constraints.

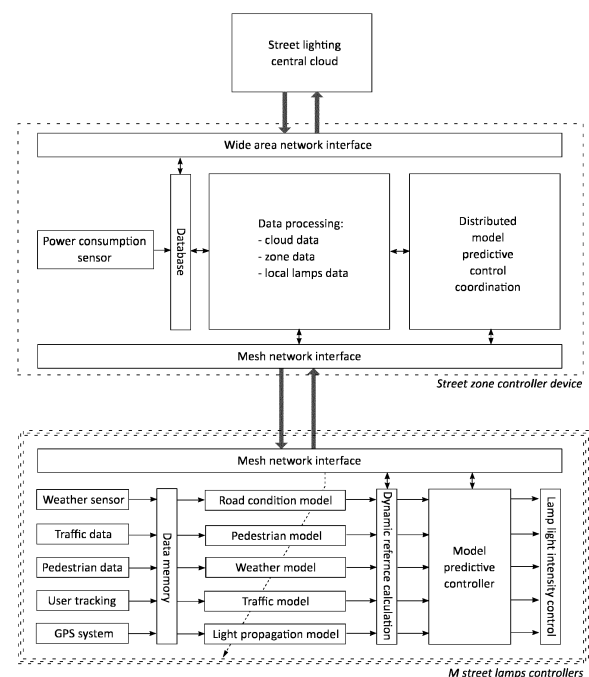


Fig. 13

Description

DESCRIPTION OF THE INVENTION

[0001] The present invention proposes a distributed model predictive lighting control method for a street zone to dynamically adjust a light intensity of streetlamps in the street zone for improving a comfort level of visibility for vehicles, pedestrians, cyclist, etc., in variable weather conditions, while minimizing an energy consumption of a system simultaneously. The present invention also relates to a distributed prediction-based controllable lighting system for the street zone.

BACKGROUND ART

[0002] The Streetlighting system, as one of the main infrastructures of modern urban cities, is technologically outdated, and poorly controlled. A real-time implementation of a centralized control system for streetlighting, even using very effective control algorithm such as Model Predictive Control algorithm (MPC), may not be economically feasible due to large number of distributed streetlamps. This is because it is computationally high demanding and requires communication network of several thousands of streetlamps for gathering all measurements in one location. The present invention provides a Distributed Model predictive Control (DMPC) algorithm to adjust a light intensity level of each streetlamp M in a street zone. This adjustment is based on dynamic reference values taking into consideration, traffic volume, pedestrian diversity, and weather conditions. In the proposed model, a group of streetlamps is considered as a subsystem or a street zone and each streetlamp is controlled with a streetlamp controller device based on a predicted setpoints. The distributed local streetlamp controller devices are mutually and iteratively bidding towards a joint setpoint of the whole subsystem based on a global optimization objective satisfying local and global joint street zone constraints. The DMPC algorithm is represented with a state-space model and optimized using Quadratic Program solver to calculate a light intensity (input sequence at each time step) of whole street zone and apply the control actions to each corresponding streetlamp. Each streetlamp problem is solved separately and independently. Solutions are passed to the central supervisor in the street zone controller device that makes additional decisions on global level and steers the distributed solutions towards the joint optimum. The main advantage of DMPC algorithm over the centralized MPC algorithm is that solving few smaller problems is often computationally faster than solving a large one. In this particular application, distributed approach enables fast zone digitalization as a practical benefit, with a usage of low power mesh wireless network. The simulation results indicate that the proposed DMPC algorithm can achieve a good performance of the whole system with a limited burden of communications. In addition, it strongly increases the system resiliency to security problems.

[0003] Therefore, the present invention provides a further improvement of a centralized model predictive lighting control method (MPC) and a system thereof which has been described in the European application no. 22020553.8

SUMMARY OF THE INVENTION

[0004] The main objective of a distributed model predictive lighting control method for a street zone and system thereof is to provide an optimal utilization of the installed streetlamps in the street zone by adjusting their light intensities (brightness) considering the surrounding conditions. Such adjustment should, simultaneously, minimize an energy consumption of the control system and maintain a desired level of comfort visibility for vehicles, pedestrians, cyclists, etc. The method predicts a light intensity on a street surface over a prediction horizon N and adjusts the light intensity of the streetlamps according to it through an optimal solution of an energy efficiency and the comfort level of visibility.

[0005] In particular, it is the general object of the present invention to increase the energy saving in the field of street lighting system on an existing structure, without increasing significantly the costs.

[0006] It is a further general object of the present invention to provide a distributed model predictive lighting control method and a distributed lighting system that is predictive and adaptive.

[0007] The object of the present invention is solved by the subject matter of the independent claims. Further embodiments are shown by the dependent claims.

[0008] A basic idea of the invention is to define a street zone including a plurality of streetlamps M and to implement a Model Predictive Control (MPC) algorithm configured to calculate control light intensity of each streetlamp M and a Distributed Model predictive Control (DMPC) algorithm configured to adjust a light intensity level of each streetlamp M in the street zone satisfying local and global street zone constraints.

[0009] The present invention relates to a distributed model predictive lighting control method for the street zone including a plurality of streetlamps M , wherein the method provides a distributed prediction-based controllable lighting system for the plurality of streetlamps M of the street zone, the system comprising connectivity and telemetry exchange means to and between each streetlamp controller device of each streetlamp M and a street zone controller device,

wherein each streetlamp M light intensity is activated by a control action communicated by the street zone controller device. Each streetlamp controller device executes the following steps: obtaining of local historical weather, traffic, pedestrian and road condition data for each streetlamp M ; obtaining a local latest weather, pedestrian, traffic, and road condition data for each streetlamp M ; implementing a modelling method and generating local prediction data for a prediction horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions for each streetlamp M , the local prediction data are generated comparing a respective local historical weather, traffic, pedestrian and road data and the latest local weather, pedestrian, traffic, and road condition data, each generated local prediction data is implemented by the modelling method by one of the group consisting of physical models, machine learning methods, or neural networks; calculating a local spatial coordination-based model of light propagation at the predetermined set of points of interest p for each streetlamp M ; generating a local predetermined streetlight dimming scenario at the predetermined set of points of interest p for each streetlamp M for delivering a desired amount of light intensity over the prediction horizon N with the time resolution of T_s , the local predetermined streetlight dimming scenario is based on the generated local prediction data; selecting local dynamic reference values for the predetermined set of points of interest p for each streetlamp M , the local dynamic reference values are selected according to the generated local predetermined streetlight dimming scenario; and implementing a Model Predictive Control (MPC) algorithm configured to calculate a light consumption demand of each streetlamp M considering local dynamic reference values, assigned local weighting coefficients and calculated local spatial coordination-based model at the predetermined set of points of interest p for each streetlamp M , the Model Predictive Control (MPC) algorithm performs calculating a sequence of the control actions comprising light consumption demands over the prediction horizon N with the time resolution of T_s for each streetlamp M .

[0010] The control method further comprises executing a distributed model predictive control algorithm, by the street zone controller device, the distributed model predictive algorithm comprising a plurality of iterations n , wherein in each iteration n the street zone controller device receives light consumption demands from each streetlamp M and calculates an average light consumption demand σ , wherein the average light consumption demand σ is being sent to each streetlamp controller device; each streetlamp controller device performs calculating and updating light consumption demand by step of τ along a gradient $\mathcal{F}$ of cost function respecting global constraints and a multiplier vector λ and sends updated light consumption demand to the street zone controller device; and the street zone controller device performs calculating and updating the multiplier vector λ , wherein the distributed model predictive control algorithm is executed until a convergence is satisfied defined as an end condition:

$$\|u_{(n+1)} - u_{(n)}\| \leq \varepsilon_{toll}$$

where ε_{toll} is a number defining a trade-off between a suboptimality or an allowed execution time.

[0011] According to the embodiment of the invention a local dynamic reference values are selected according to a local predetermined streetlight dimming scenario, wherein an assigned variables and thresholds includes precipitation level, visibility data, traffic density, diversity and density of pedestrians.

[0012] According to the embodiment of the invention a Model Predictive Control (MPC) algorithm performs minimizing an objective function over a prediction horizon N with the time resolution of T_s , the objective function comprising calculating light intensity, light pollution, and a deviation from the desired lighting at the predetermined set of points of interest p considering local constraints.

[0013] Further, the invention provides implementing a local spatial coordination-based model being a weather-dependent spatial physical model of a light propagation in a space at a predetermined set of points of interest p , where the propagation of light regardless of weather conditions (V_u) can be uniformly generalized.

[0014] Further, according to the embodiment of the invention a distributed control algorithm performs iterative convergence of control actions and constraints, along their individual gradients, until an equilibrium point is reached, i.e., a global optimum.

[0015] Also provided is a computer program comprising program code that, when executed by a processor, enables a processor to carry out a Model Predictive Control (MPC) algorithm configured to calculate light consumption demand of each streetlamp M .

[0016] Also provided is a computer program comprising program code that, when executed by a processor, enables a processor to carry out a distributed model predictive lighting control method for a street zone.

[0017] Further provided is a record carrier storing a computer program according to the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Further characteristics and advantages of the present invention will become clearer from the following detailed

description of the preferred embodiments thereof, with reference to the appended drawings and provided by way of indicative and non-limiting example, wherein:

Fig. 1 illustrates a three-dimensional coordinate system of a streetlamp and pinpoints coordinates of a selected point of interest;

Fig. 2 illustrates a street zone and plurality of streetlamps M in the street zone of a distributed predictive street lighting system;

Fig. 3 is schematic illustration of a streetlight luminaire and corresponding geometry;

Fig. 4 is a schematic illustration of a distributed predictive control streetlighting system;

Fig. 5 illustrates an example flowchart for a distributed model predictive lighting control method for a street zone including a plurality of M streetlamps;

Fig. 6 illustrates an example flowchart for an iterative coordination between a street zone controller device and street zone controller devices of a plurality of streetlamps M ;

Fig. 7 are graphs illustrating illuminance intensity levels at a points of interest p ;

Fig. 8 are graphs illustrating lighting powers of streetlamps;

Fig. 9 are graphs illustrating comparison between a local and distributed control method;

Fig. 10 is a graph illustrating luminous intensity levels of the contributed lamps;

Fig. 11 is a block diagram of a streetlamp controller device adapted to be incorporated into each streetlamp M ;

Fig. 12 is a block diagram of a street zone controller device; and

Fig. 13 represents an overall logic flow of software modules of the invention according to aspects of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0019] The present invention relates to a distributed model predictive lighting control method for a street zone including a plurality of streetlamps M for controlling illuminance intensities of each streetlamp M considering local latest weather, pedestrian, traffic, and road condition data for each streetlamp M . The control method improves the energy efficiency (optimal utilization) of a distributed prediction-based controllable lighting system while maintaining comfortable level of brightness for safety and security reasons.

[0020] The term "local" generally refers to involving or affecting only one streetlamp M and an area nearby one streetlamp M .

[0021] The distributed model predictive lighting control method is based on convex optimization and quadratic program with constraints and combines developed dynamic mathematical models of lighting, lighting requirements, models of location conditions and tariff conditions of electricity billing, with the common goal of minimizing labor and maintenance costs. The control method takes place in real time for the calculation of the corresponding control actions of individual streetlamps and an entire lighting system for a street zone considering local streetlamp and global street zone constraints.

[0022] In the following, an embodiment of the distributed model predictive lighting control method for the street zone is described and illustrated in Figs. 5 and 6, and Figs. 4 and 13 schematically illustrate a distributed prediction-based controllable system and an overall logic flow of software modules of the invention. The method for the distributed model predictive lighting control for the street zone including the plurality of streetlamps M providing a distributed prediction-based controllable lighting system for the plurality of streetlamps M of the street zone, the system comprising connectivity and telemetry exchange means to and between each streetlamp controller device of each streetlamp M and a street zone controller device, wherein each streetlamp M light intensity is activated by a control action communicated by the street zone controller device. Said connectivity and telemetry exchange means may be aided by suitable protocols which act as distributed control means, standards, frameworks, and mechanisms for self-regulating large volumes of distributed entities to achieve a collective objective or benefit. Said connectivity means typically include standard communication

technologies such as fixed and wireless telephony and mobile networks (GPRS, 1-5G, LTE), local communication technologies such as WiFi, Z-Wave, Zigbee, mesh networks, Powerline or signals carried over an electrical circuit, together with leverage of the Internet and remote servers, and cloud hosted components and technologies, and on end customer devices. Each streetlamp controller device executes the following steps: obtaining of local historical weather, traffic, pedestrian and road condition data for each streetlamp M ; obtaining a local latest weather, pedestrian, traffic, and road condition data for each streetlamp M ; implementing a modelling method and generating local prediction data for a prediction horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions for each streetlamp M , the local prediction data are generated comparing a respective local historical weather, traffic, pedestrian and road data and the latest local weather, pedestrian, traffic, and road condition data, each generated local prediction data is implemented by the modelling method by one of the group consisting of physical models, machine learning methods, or neural networks; calculating a local spatial coordination-based model of light propagation at the predetermined set of points of interest p for each streetlamp M ; generating a local predetermined streetlight dimming scenario at the predetermined set of points of interest p for each streetlamp M for delivering a desired amount of light intensity over the prediction horizon N with the time resolution of T_s , the local predetermined streetlight dimming scenario is based on the generated local prediction data; selecting local dynamic reference values for the predetermined set of points of interest p for each streetlamp M , the local dynamic reference values are selected according to the generated local predetermined streetlight dimming scenario; and implementing a Model Predictive Control (MPC) algorithm configured to calculate a light consumption demand of each streetlamp M considering local dynamic reference values, assigned local weighting coefficients and calculated local spatial coordination-based model at the predetermined set of points of interest p for each streetlamp M , the Model Predictive Control (MPC) algorithm performs calculating a sequence of the control actions comprising light consumption demands over the prediction horizon N with the time resolution of T_s for each streetlamp M . The Model Predictive Control (MPC) algorithm performs minimizing an objective function over the prediction horizon N with the time resolution of T_s , the objective function comprising calculating a light intensity J_{en} , light pollution J_z , and a deviation $J_{A...K}$ from the desired lighting at the predetermined set of points of interest p considering: calculated local constraints for street lighting norms requiring the least amount of light at the predetermined set of points of interest p at a street surface; generated local predetermined streetlight dimming scenario at the predetermined set of points of interest p ; calculated local spatial coordination-based model of light propagation at the predetermined set of points of interest p ; calculated local constraint for lighting transition dynamics limitations of each streetlamp M ; and technical specifications of each streetlamp M . The local spatial coordination-based model includes calculated light intensities in the predetermined set of points of interest p based on a steady-state light intensity distribution and a continuous, gradual transition between two levels of light intensities over two-time intervals, where a change of minimum allowed lighting intensity stemming from street lighting operators, management body or system manufacturer. A prediction of the light consumption demand of each streetlamp M at each of the predetermined set of points of interest p is based on the local dynamic reference values, weighting coefficients and the local spatial coordination-based model, the local spatial coordination-based model is a function of light intensities from one or more streetlamps at the predetermined set of points of interest p considering a distribution of the light intensities in a space in different weather conditions and taking into account reflections from all light sources. Weighting coefficients determine a significance of each point of interest p .

[0023] The method further comprises executing a distributed model predictive control algorithm, by the street zone controller device, the distributed model predictive algorithm comprising a plurality of iterations n , wherein in each iteration n the street zone controller device receives light consumption demands from each streetlamp M and calculates an average light consumption demand σ , wherein the average light consumption demand σ is being sent to each streetlight controller device; each streetlamp controller device performs calculating and updating light consumption demand by step of τ along a gradient $\mathcal{F}$ of cost function respecting global constraints and a multiplier vector λ and sends updated light consumption demand to the street zone controller device; and the street zone controller device performs calculating and updating the multiplier vector A , wherein the distributed model predictive control algorithm is executed until a convergence is satisfied defined as an end condition:

$$\|u_{(n+1)} - u_{(n)}\| \leq \varepsilon_{toll}$$

where ε_{toll} is a number defining a trade-off between a suboptimality or an allowed execution time. The multiplier vector λ is a non-negative parameter that secures adherence to global joint constraints $Gu \leq w$ of the street zone where u is a vector of streetlamps consumption extended on the prediction horizon N .

[0024] The method further comprises setting of a prediction horizon N , time resolution T_s , street zone and number of the predetermined set points of interest p for each streetlamp M in the street zone, weighting coefficients determining a significance of each point of interest p , parameter τ represents a size of a step taken in the direction of a gradient, and

allowed execution time as maximum allowed time available to perform iterations defined by available hardware resources or the sample time T_s .

[0025] The latest local weather, pedestrian, traffic, and road condition data are being continuously saved and used for updating the local historical weather, traffic, pedestrian and road data. The local historical weather, traffic, pedestrian and road data have been collected and processed at least for a three-month period to establish different occurrences. The latest local weather and road condition data can be obtained from onsite measurements of meteorological sensors or remote sources on meteorological information and combinations thereof; pedestrian data can be obtained from surveys, pedestrian mobile phones, wearable devices, traffic counters, video and acoustic sensors, or from remote sources on traffic information and combinations thereof; and the latest local traffic data are obtained from onsite measurements of traffic counters, video and acoustic sensors, and from remote sources on traffic information, and combinations thereof.

[0026] According to embodiment of the present invention, generating the local predetermined streetlight dimming scenario, for each streetlamp M , is based on local scenario conditions, the local scenario conditions are depending on a day light duration, weather, traffic and pedestrian conditions, wherein the each of said conditions has an assigned variable and threshold used for selecting the dynamic reference values. Further, the local predetermined streetlight dimming scenario is continuously and real-time updated over the prediction horizon N with the time resolution of T_s .

[0027] Weather phenomena examined to establish different scenario conditions being Temperature, Precipitation, Visibility and Humidity. Precipitation is any product of the condensation of atmospheric water vapor that falls on the ground. It can be divided in 2 categories - liquid precipitation (rain) and solid precipitation (snow). The weather phenomena highly related to precipitation is humidity. That is the amount of water vapor in the air, expressed in %. In meteorology, by definition visibility is the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background, or the greatest distance at which lights of 1,000 candelas can be seen and identified against an unlit background. Weather conditions used for the scenarios are: clear, dry weather; rain; snow and ice, and fog. Clear, dry weather is characterized by high visibility and no precipitation.

[0028] According to the local historical traffic and weather data, street lighting norms, together with empirical aspect of city users and street lighting technology provider, available local scenario conditions are determined for each streetlamp M . Table I below comprises a list of examples of the local scenario conditions with a characteristic of each.

Table I. EXAMPLES OF THE SCENARIO CONDITIONS

e				Local Conditions	
	Year period	Weather conditions	Traffic	Characteristics	Variables and Thresholds
1	Summer	Clear, dry	Light or no traffic	Short night	Lighting duration < 10h
				Normal operation	Precipitation = 0 Visibility ≥ 10 km
				Energy saving mode	Traffic density < 4
2	Summer	Clear, dry	Moderate	Short night	Lighting duration < 10h
				Normal operation	Precipitation = 0 Visibility ≥ 10 km
				Mid illumination requirements	4 $\leq$ Traffic density < 8
3	Transitional (spring/autumn)	Clear, dry	Severe	Balanced day-night periods	Lighting duration ~ 12 h
				Benchmark lighting, normal operation	Precipitation = 0, Visibility ≥ 10 km
				High illumination requirements	8 $\leq$ Traffic density < 10

(continued)

e				Local Conditions	
	Year period	Weather conditions	Traffic	Characteristics	Variables and Thresholds
4	Transitional (spring/ autumn)	Rain	Moderate	Balanced day-night periods	Lighting duration ~12h
				Increased glare, sudden changes	Precipitation > 0, Humidity > 90% Visibility ≤ 10 km
				Mid illumination requirements	4 ≤ Traffic density < 8
5	Winter	Rain	Moderate	Long night	Lighting duration >14h
				Increased glare, sudden changes	Precipitation > 0, Humidity > 90% Visibility ≤ 10 km
				Mid illumination requirements	4 ≤ Traffic density < 8
6	Winter	Snow and ice	Light	Long night	Lighting duration >14h
				Increased glare, critical safety	Temperature ≤ 0°C, Precipitation > 0 Humidity > 90% Visibility ≤ 10 km
				Energy saving mode	Traffic density < 4
7	Winter	Fog	Moderate	Long night	Lighting duration >14h
				Reduced visibility, increased reflection	Precipitation = 0 Humidity > 90% Visibility < 10 km
				Mid illumination requirements	4 ≤ Traffic density < 8

[0029] Generally, the local scenario conditions are depending on a year period lighting duration, weather, traffic and pedestrian conditions, wherein the year period lighting duration and each of said conditions has an assigned variable and threshold used for selecting dynamic reference values. The assigned variables and thresholds include precipitation level, visibility data, traffic density, diversity and density of pedestrians.

[0030] Therefore, each local scenario condition is determined by a specific local traffic, pedestrian and weather conditions and as a result provides a unique local predetermined streetlight dimming scenario. The list of examples of the local predetermined streetlight dimming scenarios is given in a Table II below.

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Local Scenario conditions				Local Dimming profile or local predetermined streetlight dimming scenario	
	Weather conditions	Traffic conditions Pedestrian conditions	Dynamic reference Variables and Thresholds		
5	1	Clear, dry	Light or no traffic and Small pedestrian percentage	precipitation = 0 visibility $\geq 10\ 000$ traffic density < 4 pedestrians_total < 10.0	D1 0.5@90% 0.5@40%
10					
15	2	Clear, dry	Moderate traffic or Moderate pedestrian percentage	precipitation = 0 visibility $\geq 10\ 000$ traffic density ≥ 4 traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	D2 0.5@95% 0.5@55%
20					
25	3	Clear, dry	Severe traffic or Severe pedestrian percentage	precipitation = 0 visibility $\geq 10\ 000$ traffic density > 8 pedestrians_total > 50.0	D3 0.7@100% 0.3@75%
30					
35	4	Rain	Moderate traffic or Moderate pedestrian percentage	precipitation > 0 humidity ≥ 90 visibility $\leq 10\ 000$ traffic density ≥ 4 traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	D4 0.5@100% 0.5@75%
40					
45	5	Snow	Moderate traffic or Moderate pedestrian percentage	precipitation > 0 humidity ≥ 90 temperature < 0 visibility $\leq 10\ 000$ traffic density ≥ 4 traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	D5 0.5@80% 0.5@50%
50					
55	e	Fog	Moderate traffic or Moderate pedestrian percentage	precipitation > 0 humidity ≥ 90 temperature ≤ 4 visibility $\leq 10\ 000$ traffic density ≥ 4	D6 0.5@90% 0.5@50%

	traffic density < 8 pedestrian_total ≥ 10.0 pedestrian_total ≤ 50.0	
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Table II. PREDETERMINED STREETLIGHT DIMMING SCENARIOS

[0031] For instance, the local predetermined streetlight dimming scenario (i.e., Dimming profile) provides the information on luminaire power consumption during operation. The local dimming profile of e.g., 0.3@100% and 0.7@75% means that the luminaire is using 100% of rated power for 30% of the operation time, and for the remaining 70% operation time it is operating on 75% rated power. Duration of operation of 100% depends on the day duration for the considered location. It is adjustable over year and is defined by the lighting norms or city users.

[0032] In the following, the objective function of the Model Predictive Control (MPC) algorithm is described.

[0033] Lighting lamps provide a necessary lighting and are dimensioned according to clear weather conditions, and according to the given international lighting standards. Lamp design, LED quality and their configuration (network) and lens / diffuser, as well as power electronics, diversify manufacturers, quality and efficiency. The norms define a required quality of lighting, mainly depending on the class of the road and not more precisely than that. Recently, the notion of a level of vertical lighting is often mentioned, i.e., the perception of lighting from the perspective of people (drivers, pedestrians and cyclists), but this part is not yet included in the norms but represents the future path.

[0034] Light propagates according to a well-known physical law and it is possible to express the dependence of a point in space depending on the angle and distance from the light source. As there are more lamps, reflection from the substrate and surrounding objects, i.e., more light sources, the light intensity of a particular point in space is the sum of all these sources and can be described by an exact mathematical law.

[0035] The total illumination at an arbitrary point in space where n different sources contribute can be described by:

$$E(x, y, z) = \sum_{i=1}^n E_i(x_i, y_i, z_i) = \sum_{i=1}^n f_i(I_i, l, \gamma), \quad (1)$$

where x, y, z are the coordinates in space, and where the contribution of each individual component is defined by the strength of source I , distance l and spatial variables (column height, lamp inclination, spatial angles of the observed point relative to the source, etc.) that are combined represented by the parameter γ .

$$E(x, y, z) = f(I, l, \gamma). \quad (2)$$

[0036] In different weather conditions, primarily rain and fog, additional phenomena occur. In fog, the intensity of illumination decreases further due to the distance from the source and the density of fog, but there is a pronounced vertical component of illumination, i.e., glare caused by light scattering on fog particles, where each particle can be physically described as a new separate light source. An additional significant phenomenon in road traffic is the headlights of vehicles coming from the opposite direction and their behavior in foggy conditions. To get an impression, the fog is made up of small drops of water whose radius is usually less than 100 μm . The mean radius of the droplet is usually 2-5 μm , while the density ρ of the mist is from 10^6 to 10^9 droplets per cubic meter. The liquid water content varies between 0.003 g/m^3 , for light fog, to 2 g/m^3 , for thick fog.

[0037] In the case of rain, the size of the droplets is significantly larger and their density in space is significantly lower than in the case of fog particles, and due to the rainfall, no significant vertical component is created. On the other hand, in this case, the reflection from the horizontal surface (road) is very pronounced, which significantly affects the subjective perception of the driver. In the case of snow, a slower fall causes a more pronounced scattering of light or a vertical component, and a longer fall creates a very pronounced reflection from the ground (white road).

[0038] Weather conditions can be represented through the visibility parameter, which is also available as a component of weather conditions, either current measurement or weather forecast (parameter prediction). The spatial coordination-based model refers to a weather-dependent spatial physical model of light propagation in a space at the predetermined set of points of interest p , where the propagation of light regardless of weather conditions (vu) can be uniformly generalized

and very simply represented as:

$$E_{vu}(x, y, z) = E(x, y, z)e^{-3/V^\tau} = f(I, l, \gamma, V), \quad (3a)$$

where V is visibility in meters, and the parameter τ denotes the thickness of the fog and can also be related to the visibility variable. Snow is additionally related to the temperature parameter.

[0039] Glare or blinding is a temporary (or permanent) disturbance in the observer's field of vision and, depending on the intensity, causes a feeling of discomfort to the point of complete visual incapacity. Glare is empirically modelled as:

$$E_g(x, y, z) = 10 E(x, y, z)(\theta_g^2 + 1.5\theta_g)^{-1} = f(I, l, \gamma), \quad (3b)$$

where E_g is the intensity of the point source of reflection, and θ_g is the angle of incidence. For $\theta_g = 0$, the source directly aimed at the observer's eyes, according to (3b), an infinite amount of reflection is actually obtained, which can be saturated to arbitrary selected maximum value. Variable z is also often set to a constant value, typically for eye height at 1.45 m.

[0040] From all the above, it follows that each point of space can be described by exact physical relations that take into account weather and glare conditions - as the sum of all different influences of sources, reflections, scattering, etc. Furthermore, any number of the predetermined set of points of interest p where we want to regulate lighting intensity can be chosen, and potentially the angle of incidence. These points can be declared as points of special interest and defined in space to correspond to the following coordinates: eye level of the average driver (left and right side of the road), eye level of the average pedestrian (left and right side of the road), ground lighting (middle of the road), visibility of the left edge of the road, visibility of the right edge of the road, and even a step further, the height of the eyes of children or adults in wheelchairs, etc. and thus, make for each lamp individually with, for example, known coordinates of one dimension (maximum illumination, i.e. just below the lamp), and further expand to one street separately, the entire city section (neighborhood, square, etc.) with individual or combined consideration.

[0041] An example of the predetermined set of points of interest p is shown in Fig. 2 where the points are marked with the letters A-K. For each of these points, the exact desired light intensity can be determined, either for all the same values corresponding to a precisely defined norm, or further corrected according to the subjective impression while the norm (e.g., ground / road illuminance) is simultaneously satisfied. Furthermore, for each point, its priority over other points (local weighting factor w) can be determined, thus giving different importance to the optimization problem that aims to simultaneously satisfy all desired levels at all points, but in a way that gives priority to the more important ones.

[0042] The local dimming profile is transformed to a light consumption demand for each chosen point of interest, individually or in groups, determined by the desired light intensity (i.e., Reference or Setpoint) and local weighting factor that determines significance of the point, with an exemplary Table III given below:

Scenario conditions				Points of interests references	Points of interests local weighting factors
	Weather conditions	Traffic conditions Pedestrian conditions	Dimming profile		
1	Clear, dry	Light or no traffic and Small pedestrian percentage	D1		
2	Clear, dry	Moderate traffic or Moderate pedestrian percentage	D2	A, B, C: D2; D, E, F: 0.8 D2 G, H, I: 0.6 D2 J: 0.5 D2; K: 0.8 D2	A, B, C: 1.0; D, E, F: 0.7 G, H: 0.5 I: 0.3; J: 0.2; K: 0.6
3	Clear, dry	Severe traffic or Severe pedestrian percentage	D3	A, B, C: D3; D, E, F: 0.8 D3 G, H, I: 0.6 D3 J: 0.5 D3; K: 0.8 D3	A, B, C: 1.0; D, E, F: 0.8 G, H: 0.5 I: 0.4; J: 0.3; K: 0.6
4	Rain	Moderate traffic or Moderate pedestrian percentage	D4	A, B, C: D4; D, E, F: 0.8 D4 G, H, I: 0.6 D4 J: 0.5 D4; K: 0.8 D4	A, B, C: 1.0; D, E, F: 0.8 G, H: 0.6 I: 0.4; J: 0.4; K: 0.7
5	Snow	Moderate traffic or Moderate pedestrian percentage	D5	A, B, C: D5; D, E, F: 0.8 D5 G, H, I: 0.6 D5 J: 0.5 D5; K: 0.8 D5	A, B, C: 0.8; D, E, F: 0.7 G, H: 0.5 I: 0.3; J: 0.3; K: 0.5
6	Fog	Moderate traffic or Moderate pedestrian percentage	D6	A, B, C: D6; D, E, F: 0.8 D6 G, H, I: 0.6 D6 J: 0.5 D6; K: 0.8 D6	A, B, C: 0.9; D, E, F: 0.8 G, H: 0.6 I: 0.3; J: 0.3; K: 0.6

Table III. DESIRED LIGHT INTENSITY CALCULATION FOR POINTS OF INTEREST

[0043] For instance, scenario condition 1 defines that points of interest A, B, and C follow the same reference of D1 (e.g., 0.5@90%, 0.5@40%) while D, E, F follow the reduced value of 0.8·D1. Scenario condition 1 also defines that weight for points of interest A, B, C is 0.9 and for D, E, F is 0.7, which means that A, B, C is given a priority of delivering

the desired light intensity.

[0044] The general common optimization problem would be defined as:

$$J_{uk} = J_{en} + J_z + J_{A...K}, \quad (4)$$

with the following components of the criterion function:

- J_{en} Light intensity (lamp consumption)
- J_z Light pollution
- $J_{A...K}$ Deviation from the desired lighting at points A-K (with assigned priorities)

and may comprise one or more lamps (individually or comprehensively).

15 Steady-state illuminance intensity distribution

[0045] The central component of the streetlamp controller device is the streetlamp illuminance distribution model which provides the information on how the level of the light intensity is distributed over the prediction horizon N . This model is essential for setting the optimal decision in the current time step as well. The illuminance intensity distribution at any point p on the street surface considering steady-state operation case (without considering weather and glare effects) as shown in Fig.1. is calculated by:

$$E_j(x, y, z) = \sum_{i=1}^{n_u} \frac{I_i(C_i, \gamma_i) h_i}{[x_i^2 + (y_i - d_i)^2 + (h_i - z_i)^2]^{\frac{3}{2}}}, \quad (5)$$

where:

- $I_i(C_i, \gamma_i)$: the angular luminous flux of each contributing light source (luminaire) i in cd;
- C_i : the photo-metric azimuth of light path to point p in degree of arc from light source i ;
- γ_i : the vertical photo-metric angle of light path to point p in degree of arc from light source i ;
- h_i : the mounting height of the i^{th} luminaire in m ;
- d_i : the boom length of the i^{th} luminaire in m ;
- n_u : number of luminaires affecting point of interest j .

[0046] The Photo metric azimuthal angle C can be calculated using:

$$C = 90^\circ + \arcsin \left\{ \frac{x}{\{[(y - d) \cos \beta - h \sin \beta]^2 + x^2\}^{\frac{1}{2}}} \right\}, \quad (6)$$

and the vertical photo metric angle γ can be calculated using:

$$\gamma = \arccos \left\{ \frac{h \cos \beta + (y - d) \sin \beta}{[x^2 + (y - d)^2 + h^2]^{\frac{1}{2}}} \right\}, \quad (7)$$

where:

β : the boom inclination in degrees.

[0047] According to this model, the illuminance intensity distribution is based on the angular luminous flux of each contributing luminaire and the coordination of the points of interest. To adjust this intensity distribution at the points of interest, the vehicle and pedestrian motion must be considered. Controlling the streetlight illuminance intensity will improve the energy efficiency (optimal utilization) of this system while maintaining comfortable level of brightness for

safety and security reasons. The most significant feature of this model is that the intensity level of illuminance is completely and accurately determinable based on the coordinates of the points of interest. Which makes this model very efficient to design a smart control system for streetlighting.

[0048] Once obtained, the model from (5) is extended to include weather or glare components from (3).

Dynamic lighting

[0049] Dynamic lighting as a term refers to a change in a light intensity over time. This implies a predictive component and adaptation of a lighting to different variables - currently and on the prediction horizon N (e.g., 4h in advance), where variables indicate local road conditions that can be predicted: number (density) of vehicles, cyclists, pedestrians, weather conditions (precipitation, visibility, temperature), etc. The variables are related to a micro location, i.e., a considering an individual lamp M .

[0050] A sample time, or time resolution T_s , means a time window in which the system observes the variable or how often it gets a new information. In the below example, the time resolution T_s is 1 minute and for the whole duration of the next minute the system will not get the new information. Hence, the information can be current state of the traffic at the given point and the system would behave as given above (lot of unregistered cars may pass between minutes 3 and 4) or can be summed or averaged for the whole last minute on the number of cars. This time resolution T_s may be chosen on available data and every technical system obtains relevant data in an intelligently chosen way - meaning that if there are lot of unregistered cars between minutes 3 and 4, the sample time may be reduced to e.g., half minute or ten seconds etc. to capture the relevant information.

[0051] The prediction horizon N is number of future sample times, also called future time steps or time resolution T_s . For a e.g., 1 minute time resolution T_s and the prediction horizon of 120 steps, that means the system is observing 120 minutes or 2 hours ahead. The prediction of the data can be calculated based on mathematical models and historical data (e.g., number of cars that will pass in next 1 minute, next 2 minutes... next 120 minutes), and obtain optimal system behavior with this prediction horizon N . As the observed variables now imply time profile of discrete steps (vectors instead of single values), they are given index k while index $k + 1$ implies next time step of T_s in the future. Consistently, variables span until the index $k + N$, which implies N number of time steps T_s in the future.

[0052] In the present control method, both prediction horizon N and the time resolution T_s are arbitrary parameters, and the algorithms will work with any of the chosen.

[0053] The system imposes a continuous, gradual transition between two levels of illumination over two-time intervals. This can be an arbitrary function for intervals of arbitrary duration. In a specific exemplary case, the function is a ramp and a time interval is 1 minute which means that the change in an intensity level from 100% to 85% will change over 15 minutes by 1%. This transition can also be defined by street / city users or persons in charge of managing and maintaining city lighting. In another specific (edge) scenario, the optimization problem can be adapted to the individual lamp and a speed of the pedestrian or vehicle, so as to maintain the same illumination during passage, i.e., reduce when the pedestrian or vehicle is away from the lamp, and amplify when closer. In other words, the lighting system monitors a position and movement of pedestrians or vehicles. These functions can be described as an arbitrary nonlinear law between the states x_k and x_{k+1} :

$$x_{k+1} = f(x_k, u_k) \quad (8)$$

respectively, in a specific linear variant as a common state-space system representation model within the optimization problem and thus model predictive control.

[0054] In discrete time state-space model, the streetlamp MPC controller is represented as follows:

$$x_{k+1} = Ax_k + Bu_k \quad (9)$$

$$y_k = Cx_k$$

Where:

$k \in \mathbb{Z}$ is the sampling time index.

$x_k \in \mathbb{R}^{n_x}$ is the system state vector (the illuminance intensity level at each point of interest, $x_k = [E_1, E_2, \dots, E_{n_x}]$)

T_j with n_x as the number of the states.

$u_k \in \mathbb{R}^{n_u}$ is the system input vector i.e., vector of luminous intensity level of each contributing streetlight luminaire, $u_k = [I_1, I_2, \dots, I_{n_u}]^T$ with n_u as the number of the luminaires.

$y_k \in \mathbb{R}^{n_y}$ is the system output vector with n_y as the number of outputs.

[0055] The system matrices, A , B and C represent the system dynamics, the illuminance level at the points of interest, and the input-output relationship. For a city street consisting of 150 luminaires, as an example, the illuminance intensity dynamics are presented with $n_x = 74 * 9 = 666$ states, where 74 is the number of simulation street areas and 9 is the number of points of interests in each area as shown in figure 1. Now, if we consider the prediction horizon of 6 hours with a sampling time of 5 minutes, the final dimension is $n_x = 666 * 72 = 47952$ states. It is evident that the dimension of the problem increases significantly which is the main drawback of the centralized model. However, in the distributed form of a Model Predictive Control algorithm (MPC), the problem can be decomposed into several smaller problems rather than a single large problem. This means that if the street is decomposed into 3 street zones of 50 luminaires in each street zone, the number of states will decrease to $n_x = 24 * 9 * 72 = 15552$ states. The luminaires in one street zone only send the required amount of energy to a central system such as a central cloud.

[0056] The criterion function from (4) now takes on a predictive character and is observed on the prediction horizon N with the time resolution of T_s :

$$\sum_k^N J_{u_k}, \quad (10)$$

with an arbitrarily chosen time step between two-time intervals k and $k + 1$ (e.g., 1 minute) on the prediction horizon N (e.g., 1h, which means that k is in the interval $(k=1, \dots, 60)$).

[0057] A and B are constants for linear systems and in the present invention for the constant weather. If the weather changes from clear to foggy, that means less light gets to the points of interest p from city lamps, which results in lower values in B matrix.

$$x_{k+1} = A(V_k)x_k + B(V_k)u_k. \quad (11)$$

[0058] The system additionally includes gradual adaptation to weather-changing micro-location conditions, which can be concluded by the fusion of a publicly available historical data and latest measurements from real locations: Weather conditions may include humidity, precipitation, visibility, temperature, and potential additional mathematical variables such as the assessment of precipitation retention on the road, etc. The source of information is meteorological services, and with them the actual measurements and their historical data; Road traffic density may include number and type of vehicles, average speed, congestion factor, etc., and potential additional mathematical variables, obtained from navigation services, the nearest traffic counters and actual micro location measurements and their historical data; and Pedestrian traffic density may include number of pedestrians and demographic data, and potential additional mathematical variables obtained from city data, public information, and actual micro location measurements and their historical data.

[0059] Predictions of this dynamic component are implemented by one of the groups consisting of physical models, machine learning methods, neural networks, etc., and then finally converted into requirements for the desired lighting at selected points of interest for a lighting optimization.

[0060] Simultaneous steady-state illuminance intensity distribution and dynamic component is combined into one optimization problem with mutually contradictory components considering the propagation of variables and external conditions on the prediction horizon N and with the selected time resolution T_s of consideration reads:

minimize energy consumption, light pollution, and deviation from the desired lighting at selected points of interest (with priorities) considering: norms for the road category (depending on the time of night), meeting the minimum defined conditions, lighting components at points of interest, the influence of weather conditions at points of interest, lighting transition dynamics, and limitations of light sources (power characteristics, etc.).

[0061] In the selected specific case, the objective function of the above problem is:

$$\min_{u_{i,k}} \sum_{k=1}^N \sum_{j=1}^m u_k^T W_u u_k + r_{j,k}^T W_r r_{j,k} + (x_{j,k} - x_{j,k}^{ref})^T W_j (x_{j,k} - x_{j,k}^{ref}), \quad (12a)$$

$$x_{\min} \leq x_{j,k}, \quad j \in \mathcal{M}, \quad (12b)$$

subject to

$$x_{j,k}^{ref} = f(j, k, V_k), \quad (12c)$$

$$x_j = f_{stat}(u_i, l, \gamma_j, V_k), \quad (12d)$$

$$x_{j,k+1} = f_{din}(x_{j,k}, u_k), \quad (12e)$$

$$u_{\min} \leq u_k \leq u_{\max}, \quad (12f)$$

with notation explained in below table:

Variable	Description
m	Total number of points of interest p
j	Individual point of interest index
N	Prediction horizon
k	Discrete time step index
u	Control variable - light intensity (0-100%)
x	State variable - the light intensity at the point of interest p
$x_{j,k}^{ref}$	dynamic desired light intensities (dynamic reference values) at points of interest p
r	Light pollution
W	Weighting coefficients (priorities)
$\mathcal{M}$	Set of points of interest to which the quality of lighting (norms) strictly refers
f	Prediction and estimation of the desired lighting level at points of interest
f_{dyn}	Dynamic function of light intensity transition over time
f_{stat}	Static function of illuminance intensity at the point of interest in relation to all considered sources
$x_{\min}$	Minimum allowed lighting intensity stemming from the street lighting norms
$u_{\min}$	Minimum permissible light source intensity
$u_{\max}$	Maximum permissible light source intensity

[0062] Following from (4) and (12), objective function elements are:

$$J_{en} = \sum_{k=1}^N u_k^T W_u u_k, \quad \text{Light intensity (lamp consumption)}$$

(continued)

$$J_z = \sum_{k=1}^N \sum_{j=1}^m r_{j,k}^T W_r r_{j,k}, \quad \text{Light pollution}$$

$$J_{A...K} = \sum_{k=1}^N \sum_{j=1}^m (x_{j,k} - x_{j,k}^{ref})^T W_j (x_{j,k} - x_{j,k}^{ref}), \quad \text{Deviation from the desired lighting at points of interest}$$

Light pollution is chosen as an additional set $r_{j,k}$ of a single or multiple points of interest in the same way as for $x_{j,k}$, with the distinction that desired value to follow is set to zero.

[0063] Constraints from (12) are calculated as:

Constraint:

Obtained from:

- (12b) Street lighting norms requiring the least amount of light on specifically defined point(s) on the road
- (12c) Predetermined streetlight dimming scenarios from tables I and II
- (12d) Spatial coordination-based model of light propagation from (9) and (11)
- (12e) Lighting transition dynamics limitations of the streetlamps, such as (13) or (14)
- (12f) Technical specifications of the luminaire regarding physical limitations, e.g., 0% and 100%

[0064] Some of the exemplary conditions to impose gradual lighting transition dynamics:

$$|x_{k+1} - x_k| \leq \Delta x_{\min} \quad (13a)$$

$$|u_{k+1} - u_k| \leq \Delta u_{\min} \quad (13b)$$

where $\Delta x_{\min}$ and $\Delta u_{\min}$ are allowed rate of change, or more elaborate function to ensure smoother transition:

$$x_k \leq \frac{2}{\pi} \operatorname{atan}((k - k_0)T_s) - x_{k_0}, \quad (13c)$$

where k_0 and x_{k_0} are starting time step and value of transient. In one embodiment, for applying a Model Predictive Control (MPC) algorithm, the proposed objective function is given in (12). Figure 2 shows the proposed points of interest for illuminance intensity calculation. The main objective of the algorithm is to control the illuminance intensity at the selected points of interest i.e., to control light consumption demand of each streetlamp M illuminating these points.

[0065] Table IV. shows x, y and z coordinates of the points of interest A, B, C, D, E, and G that have been chosen in this illustrative case study of the street zone with respect to four contributing lamps.

Table IV - COORDINATES OF THE INTERESTING POINTS FOR THE THREE SELECTED CONTRIBUTING LUMINAIRES

(x,y)	A	B	C	D	E	G
l_1	(0, 3.5)	(0, 0.583)	(0, 6.417)	(4.5.5, 1.75)	(4.5, 6.417)	(0, 9)
l_2	(-30, 3.5)	(-30, 0.583)	(-30, 6.417)	(-25.5, 1.75)	(-25.5, 6.417)	(-30, 9)
l_3	(30, 3.5)	(30, 0.583)	(30, 6.417)	(34.5, 1.75)	(34.5, 6.417)	(30, 9)
l_4	(-60, 3.5)	(-60, 0.583)	(-60, 6.417)	(-55.5, 1.75)	(-55.5, 6.417)	(-60, 9)

[0066] Table V. shows the illuminance intensities of the chosen points of interest in this case study.

Table V - ILLUMINANCE INTENSITIES OF INTERESTING POINTS (A, B, C, D, E, AND G)

Points of interests	A	B	C	D	E	G
Illuminance intensities E_x	32	36	26	33	25	20

[0067] After determining the points of interest p according to the available illuminance intensity measurements, the illuminance intensities are calculated at these points in terms of the lamp luminous flux $I(C, \gamma)$.

[0068] The illuminance intensity at e.g., point A can be calculated from (5):

$$E_A(x_A, y_A, z_A) = \frac{I_1(C_1, \gamma_1) \times 11}{\left[(0)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} + \frac{I_2(C_2, \gamma_2) \times 11}{\left[(-30)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} + \frac{I_3(C_3, \gamma_3) \times 11}{\left[(30)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} + \frac{I_4(C_4, \gamma_4) \times 11}{\left[(-60)^2 + (3.5 - 0.1)^2 + (11 - 0)^2 \right]^{\frac{3}{2}}} \quad (15)$$

where the point A is affected by four lamps. Substituting with the available values of the variables in the above equations gives:

$$E_A(x_A, y_A, z_A) = 0.0072I_1 + 0.0003I_2 + 0.0003I_3 + 0.0000I_4$$

[0069] And for the other remaining points, put in matrix form:

$$\begin{bmatrix} E_1(k+1) \\ E_2(k+1) \\ E_3(k+1) \\ E_4(k+1) \\ E_5(k+1) \\ E_6(k+1) \end{bmatrix} = \begin{bmatrix} E_1(k) \\ E_2(k) \\ E_3(k) \\ E_4(k) \\ E_5(k) \\ E_6(k) \end{bmatrix} + \begin{bmatrix} 0.0072 & 0.0003 & 0.0003 & 0.0000 \\ 0.0082 & 0.0003 & 0.0003 & 0.0000 \\ 0.0054 & 0.0003 & 0.0003 & 0.0000 \\ 0.0085 & 0.0005 & 0.0002 & 0.0001 \\ 0.0060 & 0.0005 & 0.0002 & 0.0001 \\ 0.0039 & 0.0003 & 0.0003 & 0.0000 \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (16)$$

$$\begin{bmatrix} y_1(k+1) \\ y_2(k+1) \\ y_3(k+1) \\ y_4(k+1) \\ y_5(k+1) \\ y_6(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ x_3(k+1) \\ x_4(k+1) \\ x_5(k+1) \\ x_6(k+1) \end{bmatrix} \quad (17)$$

DISTRIBUTED MODEL PREDICTIVE CONTROL FOR STREETLIGHTING SYSTEM

A- Prediction of variables

[0070] In addition to the mathematical model, predictive feature of the MPC is accomplished by exploiting the knowledge of future evolution of the references and the disturbances over the prediction horizon N . Disturbances are related to weather forecast, mainly clear and dry, rain, and snow weather conditions. The MPC is formulated as a reference tracking problem. Slack variables are also introduced, and they include:

S : is the season, $S \in \{1, \dots, 4\}$. For Summer, Short night (lighting duration ~ 12 hours). For winter, long night (lighting duration > 14). For Spring and Autumn, balance day-night periods (lighting duration < 10 hours). From diming profile,

different peak hours for different seasons are existed.

JF : is the Jam Factor (traffic volume). For low traffic volume, $JF < 0.5$. For medium traffic volume $0.5 \leq JF \leq 1.5$. For high traffic volume, $JF > 1.5$.

PD : is the Pedestrian diversity factor.

W : is the weather condition. Clear and dry weather (precipitation = 0), rainy weather (precipitation > 0), snowy weather (precipitation > 0, Humidity > 40%, Temperature < -5°).

VL : is the visibility level. For high fog density, $VL < 100$ m. For medium fog density $100 \text{ m} \leq VL \leq 500$ m. For light fog density, $VL > 500$ m.

B- Distributed Model Predictive Control Algorithm:

[0071] The optimization problem is formulated as an MPC reference tracking quadratic problem, where equations (11)-(14) are local optimization problems for each streetlamp M individually.

[0072] Distributed optimization for street zones separates a single problem in two parts: a street zone controller device (central operator) and streetlamps (local agents). This way, every street zone takes care of its own light intensity level corresponding to its own reference, model and local constraints, which inherently implies capability of considering heterogeneous street zone topologies. The street zones are coordinated through the street zone controller device, as a simply intermediary entity that collects the overall energy demand, without a deeper insight on the time-profile of the applied energy or any other local information. Each street zone bases its decision on the own information and the required level of light intensity from the street zone controller device and adjusts its own lighting strategy. The behavior of the street zones that interact in the described configuration is coinciding with Nash equilibrium from the game theory area, as the overall optimal strategy for each participating streetlamp. The street zone and plurality of streetlamps M in the street zone of a distributed predictive street lighting system is presented in Fig. 2, and Fig. 4 illustrates a distributed predictive control streetlighting system.

[0073] The distributed model predictive control algorithm is based on iterative convergence of control actions and constraints, along their individual gradients, until an equilibrium point is reached, i.e., a global optimum. Such an equilibrium point is aligned with game theory premises of minimizing the risk of a negative joint decision outcome for all the streetlamps M , leading to a common best interest strategy, which is called the Nash equilibrium. Global joint constraints of the street zone, if required, are formulated as:

$$Gu \leq w \quad (18)$$

where u is a vector of requested streetlamp consumption (current, power, etc.) extended on the prediction horizon N . Constraint matrices w and G assure that total consumption of the street zone does not exceed defined limits. Local constraints keep the power supply of each streetlamp M within allowed levels. Local constraints for each streetlamp M are set independently, depending on current local condition or each streetlamp M position, defined through (12b) and (12f).

[0074] The distributed model predictive control algorithm consists of 3 steps:

Initialization: set $k = 0$ and $\tau > 0$. Each streetlamp i has initial input $u_{(0)}^i$, the street zone controller device sets $\lambda_{(0)} \in \mathbb{R}_{\geq 0}^m$

Iterate to convergence

[0075] Step 1: Street zone controller device receives light consumption demands from each streetlamp M and calculates an average light consumption demand σ - average update:

$$\sigma_{(n)} \leftarrow \frac{1}{n_u} \sum_{i=1}^{n_u} u_{(n)}^i \quad (19)$$

wherein the average light consumption demand σ is being sent to each streetlight controller device.

[0076] Step 2: Local individual strategy update-each streetlamp controller device performs calculating and updating light consumption demand by a step τ along a gradient $\mathcal{F}$ of cost function respecting global constraints and a multiplier vector λ , and sends updated light consumption demand to the street zone controller device:

$$u_{(n+1)}^i \leftarrow \prod_{\chi^i} \left[u_{(n)}^i - \tau \left(\mathcal{F}^i \left(u_{(n)}^i, \sigma(n) \right) \right) + G_{(:,i)}^{F^T} \lambda_{(n)} \right], \quad (20)$$

where the double dot index in $G_{(:,i)}^{F^T}$ refers to all the indices of the corresponding dimension.

[0077] Step 3: Local individual strategy update- the street zone controller device performs calculating and updating the multiplier vector A:

$$\lambda_{(n+1)} \leftarrow \prod_{\mathbb{R}_{\geq 0}^m} \left[\lambda_{(n)} - \tau (w^F - 2G^F u_{(n+1)} + G^F u_{(n)}) \right] \quad (21)$$

[0078] A cost function from (12a) for one streetlamp i , is re-formulated as:

$$J^i = u^{iT} \mathcal{H}^i u^i + c^i u^i + f^i, \quad (22)$$

with:

$$\begin{aligned} \mathcal{H}^i &= B^{iT} C^{iT} W_x^i C^i B^i + W_u^i, \\ c^i &= 2x_0^T A^{iT} C^{iT} W_x^i C^i B^i + 2x^{ref,iT} W_x^i C^i B^i, \end{aligned} \quad (23)$$

with weighting factors W_u for points of interest p and W_r for light pollution combined to:

$$W_x^i = \begin{bmatrix} W_j^i & 0 \\ 0 & W_r^i \end{bmatrix}, \quad (24)$$

and notation explained below:

Variable	Description
i	Streetlamp index in the segment
n	Number of iterations
f	Constant cost element not related to control variables
σ	Average consumption of the segment
n_u	Number of streetlamps M in the street zone
χ	Feasible set of states, defined with (12b)
τ	Step size, set arbitrarily
$\mathcal{F}$	Gradient of the cost function
λ	Lagrange multiplier, zero if global constraints are triggered, positive if not
T	Transpose operator

[0079] The solution is obtained by iterating the steps from the distributed model predictive control algorithm to convergence. In every iteration, denoted with index n , first the street zone controller device calculates an average light consumption demand σ and sends it back as feedback to each streetlight controller device. Second and third steps shift the solution towards constrained gradient descent, where $\tau > 0$ is a gradient step, and Π is a projection on the feasible solutions hyperplane. Projection to a set of constraints finds a point x best approximating the initial point y in the local street zone domain x corresponding to street zone model and individual constraints. This expressed as a quadratic problem minimizing the Euclidean norm:

$$\prod_{\chi} y = \operatorname{argmin}_{x \in \chi} \|y - x\|_2, \quad (27)$$

[0080] Function $\mathcal{F}^i(u_{(n)}^i, \sigma(n))$ is the gradient of the cost function calculated as:

$$\mathcal{F}^i(u_{(n)}^i, \sigma(n)) = \nabla_{u^i} J^i(u^i) = \frac{\partial J^i}{\partial u^i} = (\mathcal{H}^i n_u \sigma + c^{iT}). \quad (28)$$

[0081] The cost segment $G_{(:,i)}^T \lambda_{(n)}$ represents an influence of streetlamp i in the coupling constraint and on the multiplier vector λ . The street zone controller ensures respecting the global joint constraints (18) regardless of the starting point for iteration.

[0082] First, algorithm initialization is performed where starting value of number of iterations n is set up to be zero. Larger value of τ means that step rate is also higher, but it can potentially lead to the algorithm divergence. Setting up τ as a very small number secures the convergence but gives needlessly long calculations. Therefore, it is set arbitrarily somewhere in between these two extremes. Multiplier vector λ is a non-negative parameter that secures adherence to the global constraints. If λ is equal to the zero, global constraints are satisfied and if λ is larger than the zero, the constraints are not triggered. In the beginning of the algorithm execution λ is filled with small positive numbers.

[0083] In the first step, the street zone controller accepts all the requested current demands from every streetlamp in the street zone and calculates the average consumption demand σ . Then in Step 2, the street zone controller device sends the average consumption demand σ to each streetlamp controller device, so streetlamps can adjust their initial light consumption demands using within gradient of cost function. Also, factor that includes the multiplier vector λ is added so the global joint constraints will be respected. Newly obtained light consumption demand, i.e., the input variable, is potentially placed outside of the allowed hyperspace due to arbitrary selection of the initial conditions. That means that local constraints are no more satisfied. Therefore, a projection is made to find a new light consumption demand within the allowed hyperspace as the closest point to the original one, defined by the Euclidean norm.

[0084] In the third step of the distributed model predictive control algorithm, street zone controller device receives new light consumption demands from all the streetlamp controller devices and obtains the multiplier vector λ to assure the respecting of the global joint constraints. It is possible that the multiplier vector λ is outside the feasible hyperspace and therefore the projection is performed here again to avoid negative values of the multiplier vector λ .

[0085] With the iterative execution of the algorithm steps, the light intensity (control variable) is moving toward the Nash equilibrium and a difference in light consumption demands between two iterations becomes smaller. The algorithm is therefore executed until the convergence is satisfied, defined as the e.g., end condition:

$$\|u_{(n+1)} - u_{(n)}\| \leq \varepsilon_{\text{toll}},$$

where $\varepsilon_{\text{toll}}$ is a small arbitrary number defining the allowed suboptimality of the solution, i.e., with $\varepsilon_{\text{toll}} \rightarrow 0$, the solution is optimal and coinciding with the result of the centralized MPC. The choice of $\varepsilon_{\text{toll}}$ is also a trade-off between the suboptimality and the execution time.

[0086] The proposed DMPC algorithm is applied to the streetlighting system of the J. J. Strossmayera street in the city of Sisak, Croatia. As a case study, 10 luminaires (lamps) were considered as 1 zone and controlled by 10 local MPC controllers. The reference for each local controller is changing dynamically to represents different scenarios considering traffic volume, pedestrian's diversity, and weather conditions. The schematic diagram of the of the PrecisionLUX3 120W-D3T luminaire from LED Elektronika d.o.o. mounted on the poles of a one single-sided streetlighting system is shown in Fig. 3. Table VI shows the main characteristics of this luminaire type. All the luminaires are identical and have the same power rating and other technical specifications as shown in table VII.

[0087] Table VI shows luminaire characteristics and Table VII technical specifications of a considered industrial lamp.

Table VI LUMINAIRE CHARACTERISTICS

Characteristics	Luminaire values
Pole distance	30.000 m
h -Light spot height	11.000 m

(continued)

	Characteristics	Luminaire values
5	s-Light spot overhang	0.100 m
	β -Boom inclination	0.0
	d -Boom length	0.000 m
10	Annual operating hours	4000 h: 100%, 120W
	Consumption	3960.0 W/km
	ULR/ULOR	0.00/0.00
15	Max. luminous intensities Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.	≥ 70 : 528 cd/klm ≥ 80 : 49.4 cd/klm ≥ 90 : 0.00 cd/klm
20	Luminous intensities The luminous intensity values in [cd/klm] for calculations of the luminous intensity class refer to the luminaire luminous flux according to EN 13201:2015	$G * 3$
	Glare index class	D.6

[0088] The prediction horizon of 6 hours ahead is selected as a relevant to capture long-term dynamics of the system. The parameters W_x and W_u of the local MPC controllers' cost function are chosen as 100 and 0.01, respectively, with a large difference to co-measure the illuminance intensity level and the required luminous intensity. The distributed control algorithm parameters τ and ε_{tol} are set to 0.1 and 10, respectively. The illuminance intensity level of the 10 luminaires (lamps) with the proposed DMPC algorithm are shown in Fig. 10. Figure 8 shows the successful reference tracking of the 10 luminaires together with the corresponding lighting powers. Figure 9 shows a comparison between local MPC controllers for each streetlamp where the local optimum is achieved and the distributed MPCs that are jointly coordinated through the iterations such that the global conditions are satisfied. The local optimum achieved with local MPCs without specified joint constraints or efforts towards the reduction of the overall control action (global energy efficient operation).

Table VII TECHNICAL SPECIFICATIONS OF A LUMINAIRE

35	Technical Specifications	luminaire values
	P	120 W
	ϕ_{Lamp}	15600 lm
40	$\phi_{Luminaire}$	14337 lm
	μ	92%
	Luminous efficacy	119.5 lm/W
45	CCT	3000 K
	CRI	81 W

[0089] From Fig. 9, it can be observed that although local controllers achieved better performance regarding reference tracking, distributed MPC improves the overall energy savings of the street which ultimately leads to the joint energy efficiency goal. A better tuning of the cost function weighting parameters W_x and W_u may lead to more emphasis on the reference tracking over the overall energy savings. Joint global constraints are satisfied through the coordination of the DMPC and distributed control algorithm. Such joint constraints may be imposed by the system operator due to limitation in the energy supply and the required level of illuminance. The joint global power constraint is set to k in our case, while the maximum requested power is kW. From Fig. 4, it can be seen clearly that this joint constraint is never exceeded with the proposed DMPC. This is because the lamp powers are adjusted by the central supervisor of the distributed MPC. The overall cost functions are decreased through the iteration of the distributed control algorithm as it can be observed from Fig. 7. Figure 10 shows the luminous intensity level of the contributed luminaires.

[0090] The presented results indicate that the proposed DMPC strategy ensures the optimal lighting level at the points of interest along the whole street zone while minimizing the overall energy consumption. The dynamic reference tracking strategy enables the adjustment of the lighting level according to difference scenarios to achieve the optimal lighting profile. While the minimization of the required energy ensures the lowest energy consumption of the whole system.

[0091] The present invention further relates to a distributed prediction-based controllable lighting system illustrated in Figs. 11-13. The system comprises connectivity and telemetry exchange means to and between a plurality of streetlamp controller devices each being incorporated in a streetlamp M and a street zone controller device. Said connectivity and telemetry exchange means may be aided by suitable protocols which act as distributed control means, standards, frameworks, and mechanisms for self-regulating large volumes of distributed entities to achieve a collective objective or benefit. Said connectivity means typically include standard communication technologies such as fixed and wireless telephony and mobile networks (GPRS, 1-5G, LTE), local communication technologies such as WiFi, Z-Wave, Zigbee, mesh networks, Powerline or signals carried over an electrical circuit, together with leverage of the Internet and remote servers, and cloud hosted components and technologies, and on end customer devices. A street zone includes the street zone controller device controlling light intensities of a plurality of streetlamps M distributed in the street zone, each streetlamp M is controllable to vary a light intensity. Each streetlamp controller device comprises a streetlamp data processing module for executing a Model Predictive Control (MPC) algorithm configured to calculate a light consumption demand of each streetlamp M over the prediction horizon N with the time resolution of T_s and a memory storing programming instructions for executing the Model Predictive Control (MPC) algorithm, a streetlamp mesh network communication processing module for communicating and receiving light consumption demands to and between each streetlamp controller device and the street zone controller device and a streetlamp mesh network communication interface configured for processing and formatting the control actions of the Model Predictive Control (MPC) algorithm between the plurality of streetlamp devices each incorporated into one streetlamp M and the street zone controller device, and a streetlamp module for collecting, storing and updating generated local prediction data and local predetermined streetlight dimming scenarios. Each streetlamp controller device further comprises a streetlamp sensor module for measuring air quality, weather and traffic conditions and a streetlamp mesh communication module connected with streetlamp mesh network communication interface and the streetlamp data processing module.

[0092] The street zone controller device comprises a zone data processing module configured for executing a distributed model predictive control algorithm that iteratively calculates light consumption demands for each streetlamp M in the street zone and a memory storing programming instructions for executing the distributed model predictive control algorithm, a zone mesh network communication processing module for communicating and receiving light consumption demands to and between each streetlamp M streetlamp controller device and the street zone controller device, a zone data processing module for exchanging local and cloud data, a zone mesh network communication interface configured for processing and formatting the control actions of the distributed model predictive control algorithm, and a zone module for collecting, storing and updating generated local prediction data and local predetermined streetlight dimming scenarios. Further, the street zone controller device comprises data processing module for exchanging local and cloud data and a wide area network communication interface for configured for processing, formatting and exchanging local and central street cloud data.

Claims

1. A distributed model predictive lighting control method for a street zone including a plurality of streetlamps M , the method is **characterized by** the following steps:

- providing a distributed prediction-based controllable lighting system for the plurality of streetlamps M of the street zone, the system comprising connectivity and telemetry exchange means to and between each streetlamp controller device of streetlamp M and a street zone controller device, wherein each streetlamp M light intensity is activated by a control action communicated by the street zone controller device; wherein each streetlamp controller device executes the following steps:

- a) obtaining of local historical weather, traffic, pedestrian and road condition data for each streetlamp M ;
- b) obtaining a local latest weather, pedestrian, traffic, and road condition data for each streetlamp M ;
- c) implementing a modelling method and generating local prediction data for a prediction horizon N with a time resolution of T_s of weather conditions, traffic conditions, pedestrian conditions and road conditions for each streetlamp M , the local prediction data are generated comparing a respective historical weather, traffic, pedestrian and road data and the latest weather, pedestrian, traffic, and road condition data, each generated prediction data is implemented by the modelling method by one of the group consisting of physical models, machine learning methods, or neural networks;

d) calculating a local spatial coordination-based model of light propagation at the predetermined set of points of interest p for each streetlamp M ;
 e) generating a local predetermined streetlight dimming scenario at the predetermined set of points of interest p for each streetlamp M for delivering a desired amount of light intensity over the prediction horizon N with the time resolution of T_s , the predetermined streetlight dimming scenario is based on the generated prediction data;
 f) selecting local dynamic reference values for the predetermined set of points of interest p for each streetlamp M , the dynamic reference values are selected according to the generated local predetermined streetlight dimming scenario;
 g) implementing a Model Predictive Control (MPC) algorithm configured to calculate a light consumption demand of each streetlamp M considering local dynamic reference values, assigned local weighting coefficients and calculated spatial coordination-based model at the predetermined set of points of interest p for each streetlamp M , the Model Predictive Control (MPC) algorithm performs calculating a sequence of the control actions comprising light consumption demands over the prediction horizon N with the time resolution of T_s for each streetlamp M ; and wherein the method further comprises:

- executing a distributed model predictive control algorithm, by the street zone controller device, the distributed model predictive algorithm comprising a plurality of iterations n , wherein in each iteration n

- the street zone controller device receives light consumption demands from each streetlamp M and calculates an average light consumption demand σ , wherein the average light consumption demand σ is being sent to each streetlight controller device;
 - each streetlamp controller device performs calculating and updating light consumption by step of τ along a gradient $\mathcal{F}$ of cost function respecting global constraints and a multiplier vector λ and sends updated light consumption demand to the street zone controller device; and
 - the street zone controller device performs calculating and updating the multiplier vector λ , wherein the distributed model predictive control algorithm is executed until a convergence is satisfied defined as an end condition:

$$\|u_{(n+1)} - u_{(n)}\| \leq \varepsilon_{tol}$$

where ε_{tol} is a number defining a trade-off between a suboptimality or an allowed execution time.

2. The method according to claim 1, wherein the multiplier vector λ is a non-negative parameter that secures adherence to global joint constraints $Gu \leq w$ of the street zone where u is a vector of streetlamps consumption extended on the prediction horizon N .
3. The method according to claim 1, wherein the method further comprising setting of the prediction horizon N , time resolution T_s , street zone and number of the predetermined set points of interest p for each streetlamp M in the street zone, weighting coefficients determining a significance of each point of interest p , parameter τ representing a size of a step taken in the direction of a gradient, and allowed execution time.
4. The method according to claim 1, wherein the step of generating the local predetermined streetlight dimming scenario is based on local scenario conditions, the local scenario conditions are depending on a day light duration, weather, traffic and pedestrian conditions, wherein the each of said conditions has an assigned variable and threshold used for selecting the local dynamic reference values, the assigned variables and thresholds include precipitation level, visibility data, traffic density, diversity and density of pedestrians.
5. The method according to claim 4, wherein the local predetermined streetlight dimming scenario is continuously and real-time updated over the prediction horizon N with the time resolution of T_s .
6. The method according to claim 1, wherein performing a prediction of the light intensities at the predetermined set of points of interest p is based on the local dynamic reference values and the local spatial coordination-based model, the local spatial coordination-based model is a function of light intensities at predetermined set of points of interest p in relation to all considered sources providing a distribution of the light intensities in a space in different weather conditions taking into account reflections from all light sources.

7. The method according to claim 6, wherein the local spatial coordination-based model includes calculated light intensities in the predetermined set of points of interest p based on a steady-state light intensity distribution and a continuous, gradual transition between two levels of light intensities over two-time intervals with an allowed arbitrary rate of change.
8. The method according to any of the preceding claims, wherein the Model Predictive Control (MPC) algorithm performs minimizing an objective function over the prediction horizon N with the time resolution of T_s , the objective function comprising calculating a light intensity J_{en} , light pollution J_z , and a deviation $J_{A...K}$ from the desired lighting at the predetermined set of points of interest p considering:
- a) calculated local constraints for street lighting norms requiring the least amount of light at the predetermined set of points of interest p at a street surface;
 - b) generated local predetermined streetlight dimming scenario at the predetermined set of points of interest p ;
 - c) calculated local spatial coordination-based model of light propagation at the predetermined set of points of interest p ;
 - d) calculated local constraint for lighting transition dynamics limitations of each streetlamp M ; and
 - e) technical specifications of each streetlamp M .
9. The method according to claim 1, wherein further comprising saving the latest local weather, pedestrian, traffic, and road condition data and updating the local historical weather, traffic, pedestrian and road data.
10. The method according to claim 1, wherein the latest local weather and road condition data are obtained from onsite measurements of meteorological sensors or remote sources on meteorological information and combinations thereof; pedestrian data are obtained from pedestrian mobile phones, wearable devices, traffic counters, video and acoustic sensors, or from remote sources on traffic information and combinations thereof; and the latest traffic data are obtained from onsite measurements of traffic counters, video and acoustic sensors, and from remote sources on traffic information, and combinations thereof.
11. A distributed prediction-based controllable street lighting system comprising connectivity and telemetry exchange means to and between a plurality of streetlamp controller devices each being incorporated in a streetlamp M and a street zone controller device, including
- a street zone including the street zone controller device controlling light intensities of a plurality of streetlamps M distributed in the street zone, each streetlamp M is controllable to vary a light intensity;
 - a plurality of streetlamp controller devices, each associated with each streetlamp M to control a streetlamp light intensity, where each streetlamp controller device comprises a streetlamp data processing module for executing a Model Predictive Control (MPC) algorithm configured to calculate a light consumption demand of each streetlamp M over the prediction horizon N with the time resolution of T_s and a memory storing programing instructions for executing the Model Predictive Control (MPC) algorithm, a streetlamp mesh network communication processing module for communicating and receiving light consumption demands to and between each streetlamp controller device and the street zone controller device and a streetlamp mesh network communication interface configured for processing and formatting the control actions of the Model Predictive Control (MPC) algorithm between the plurality of intelligent devices each incorporated into one streetlamp M and the street zone controller device, and a streetlamp module for collecting, storing and updating generated local prediction data and local predetermined streetlight dimming scenarios; wherein
 - the street zone controller device comprises a zone data processing module configured for executing a distributed model predictive control algorithm that iteratively calculates light consumption demands for each streetlamp M in the street zone and a memory storing programing instructions for executing the distributed model predictive control algorithm, a zone mesh network communication processing module for communicating and receiving light consumption demands to and between each streetlamp M streetlamp controller device and the street zone controller device, a zone data processing module for exchanging local and cloud data, a zone mesh network communication interface configured for processing and formatting the control actions of the distributed model predictive control algorithm, and a zone module for collecting, storing and updating generated local prediction data and local predetermined streetlight dimming scenarios.
12. The system according to claim 11, wherein a streetlamp mesh network communication interface configured for processing and formatting the control actions of the Model Predictive Control (MPC) algorithm between the plurality of streetlamp controller devices incorporated into each streetlamp M and the street zone controller device.

13. The system according to claim 11, wherein each of the plurality of streetlamp controller devices comprises a sensor module for measuring local air quality and a latest local weather, pedestrian, traffic, and road condition data.
- 5 14. The system according to claim 11, wherein the street zone controller device comprises data processing module for exchanging local and cloud data and a wide area network communication interface for configured for processing, formatting and exchanging local and central street cloud data.
- 10 15. A computer programs comprising program code that, when executed by processors, enables the processors to carry out a method according to any of the claims 1 to 10.

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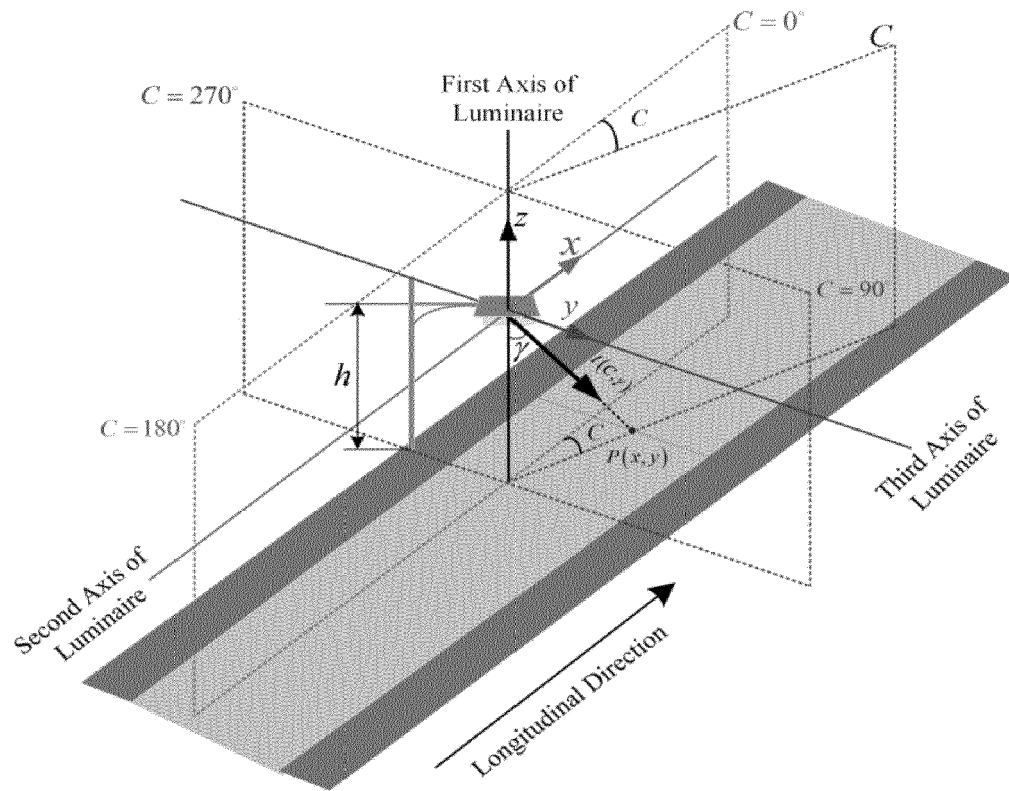


Fig. 1

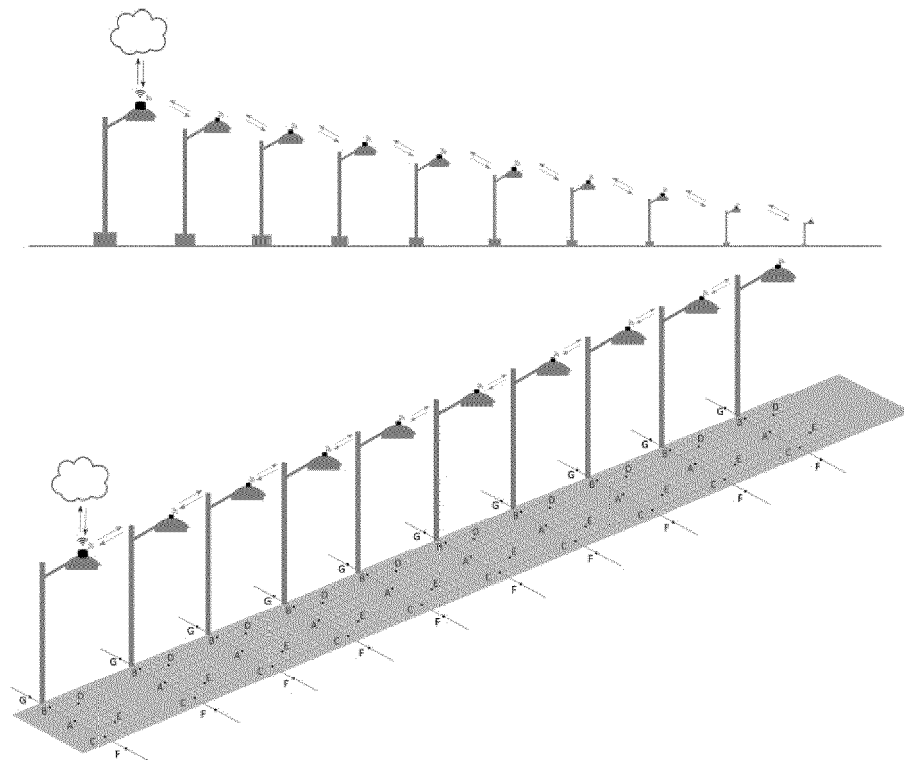


Fig. 2

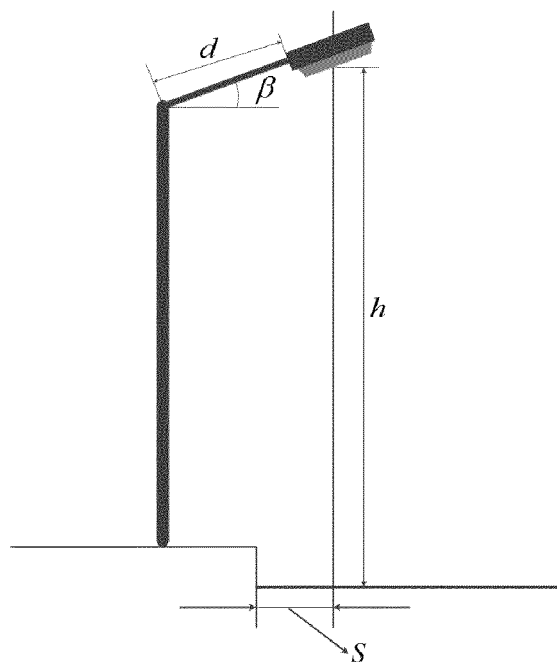


Fig. 3

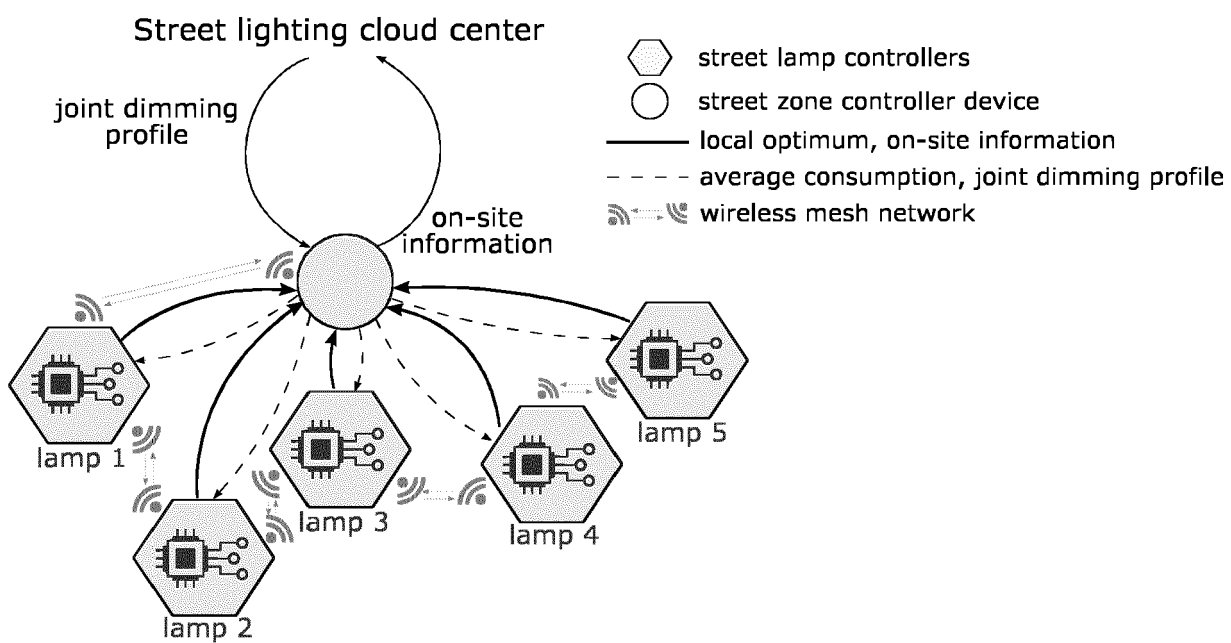


Fig. 4

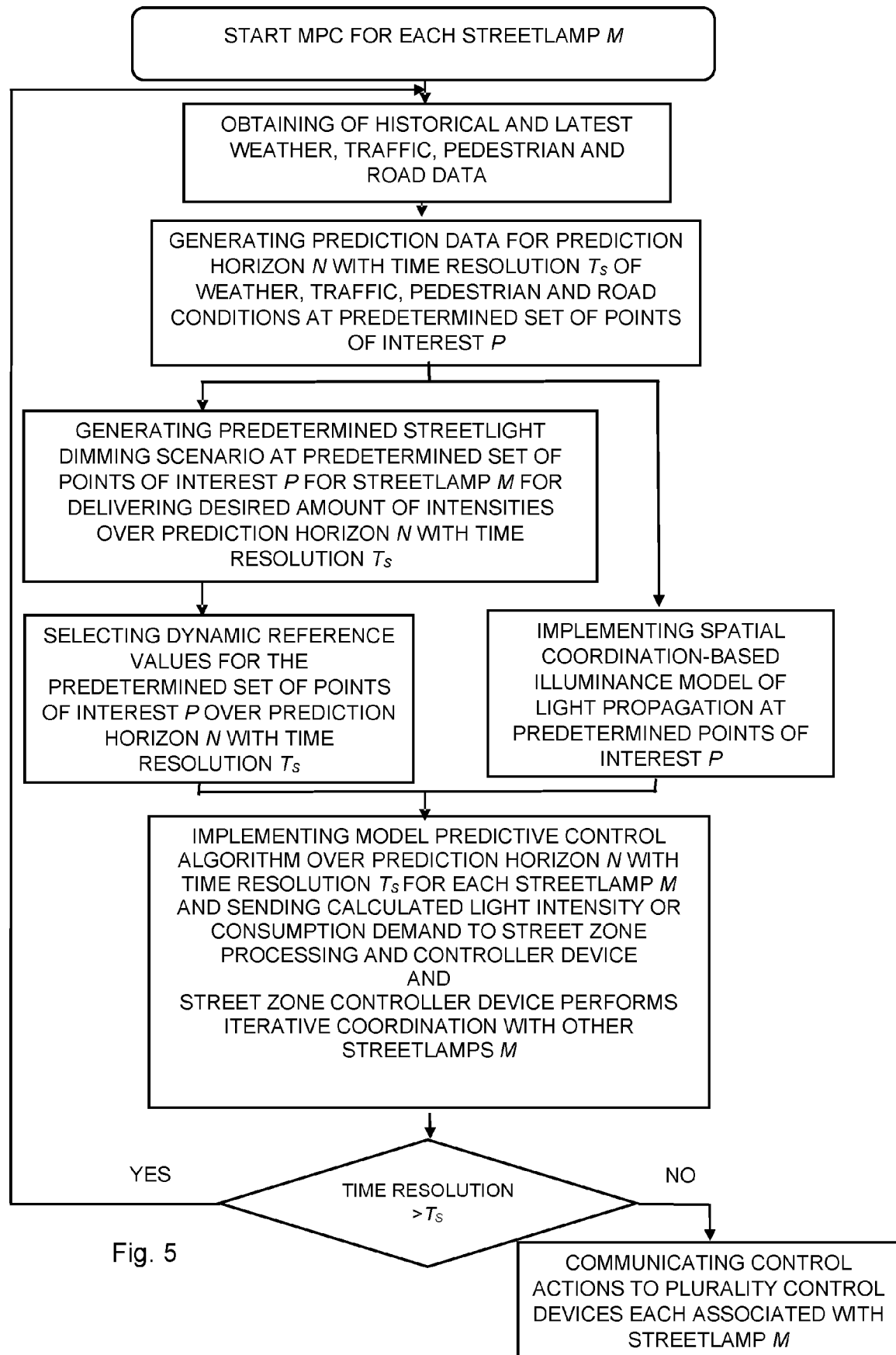


Fig. 5

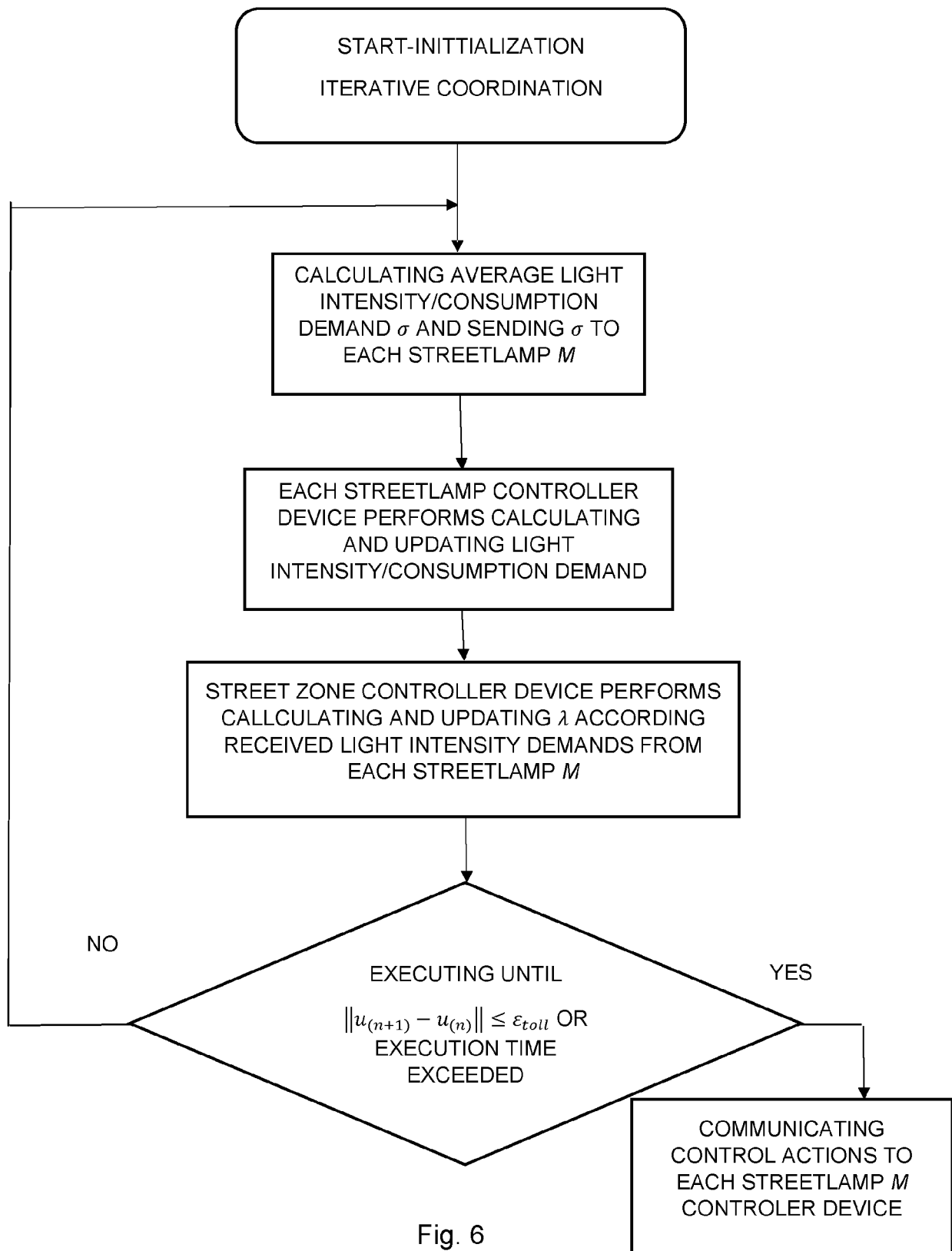


Fig. 6

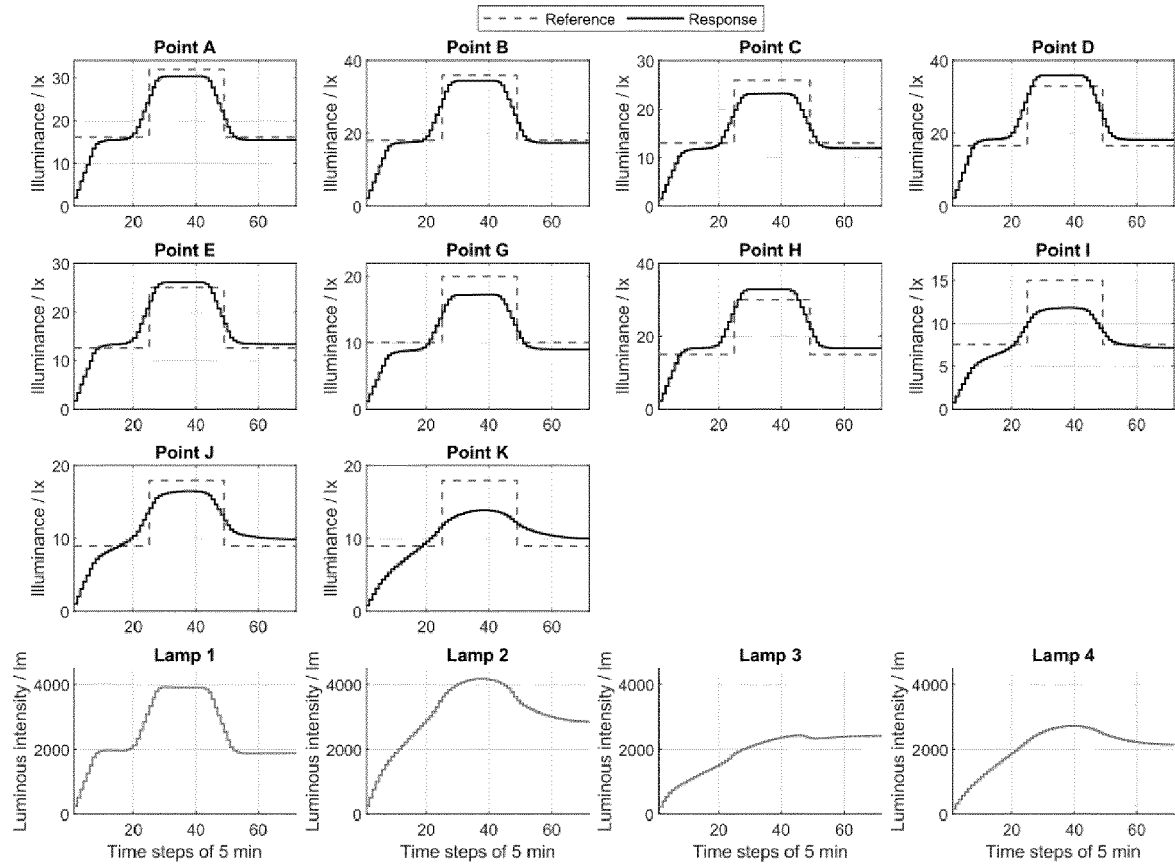


Fig. 7

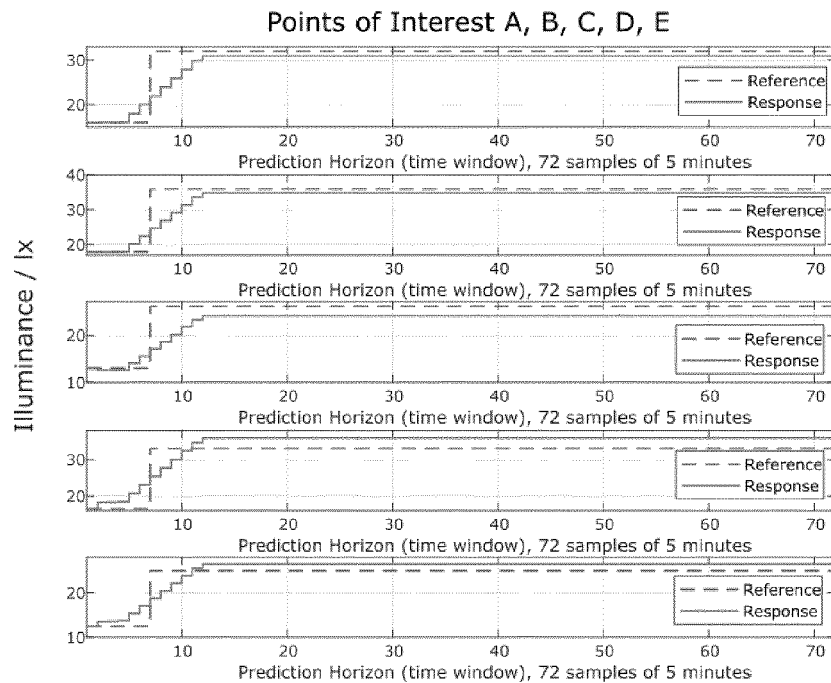


Fig. 8

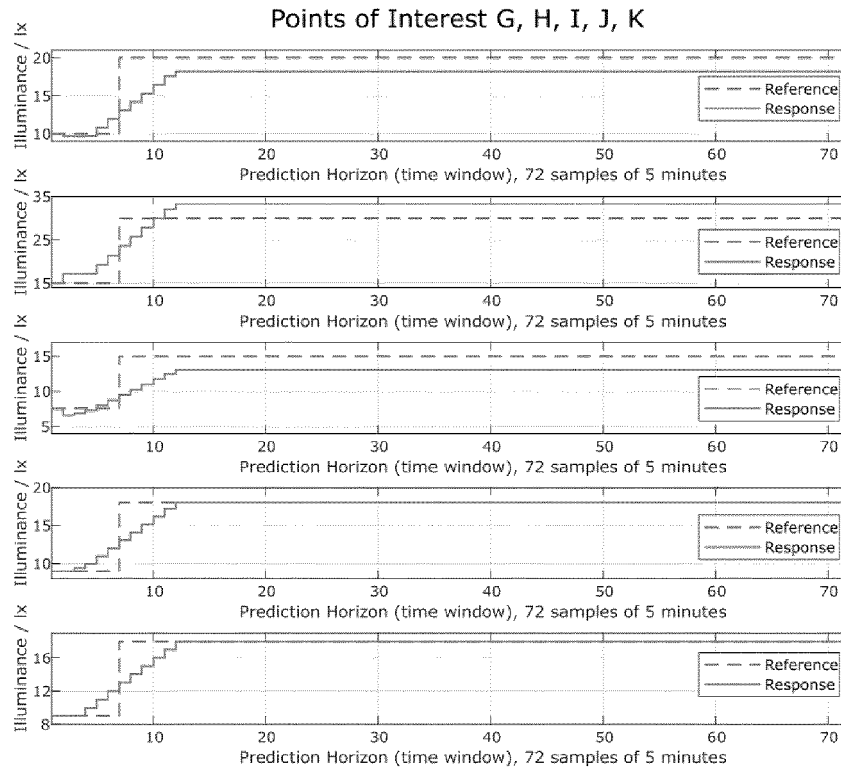


Fig. 9

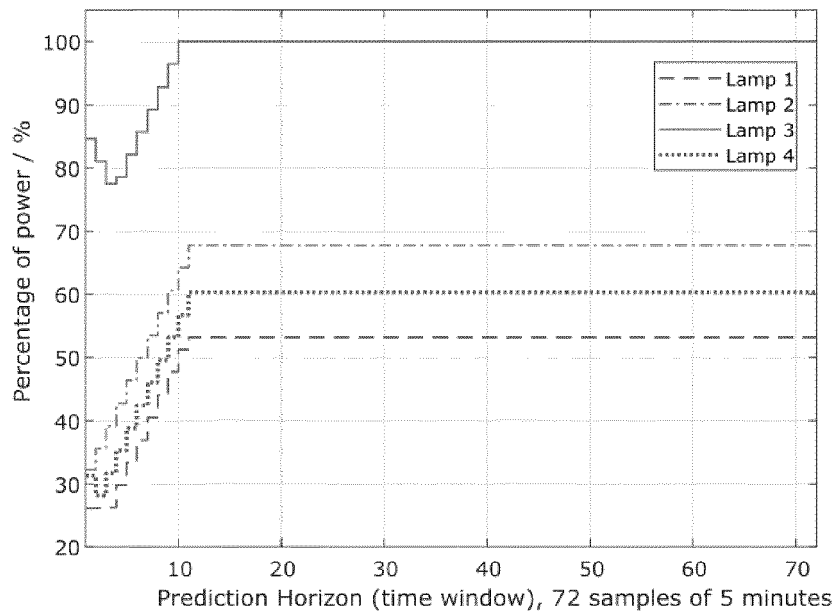


Fig. 10

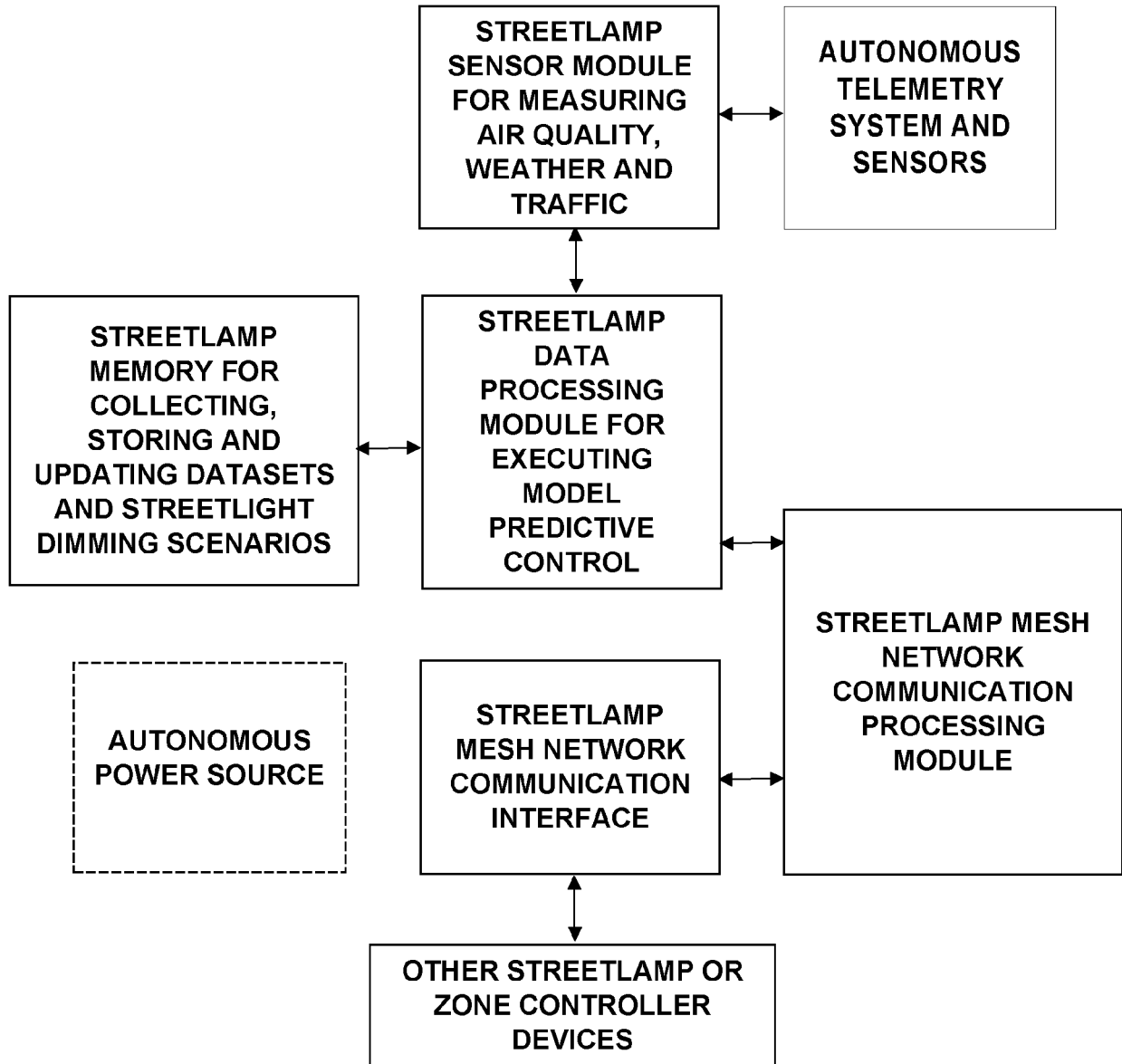


Fig. 11

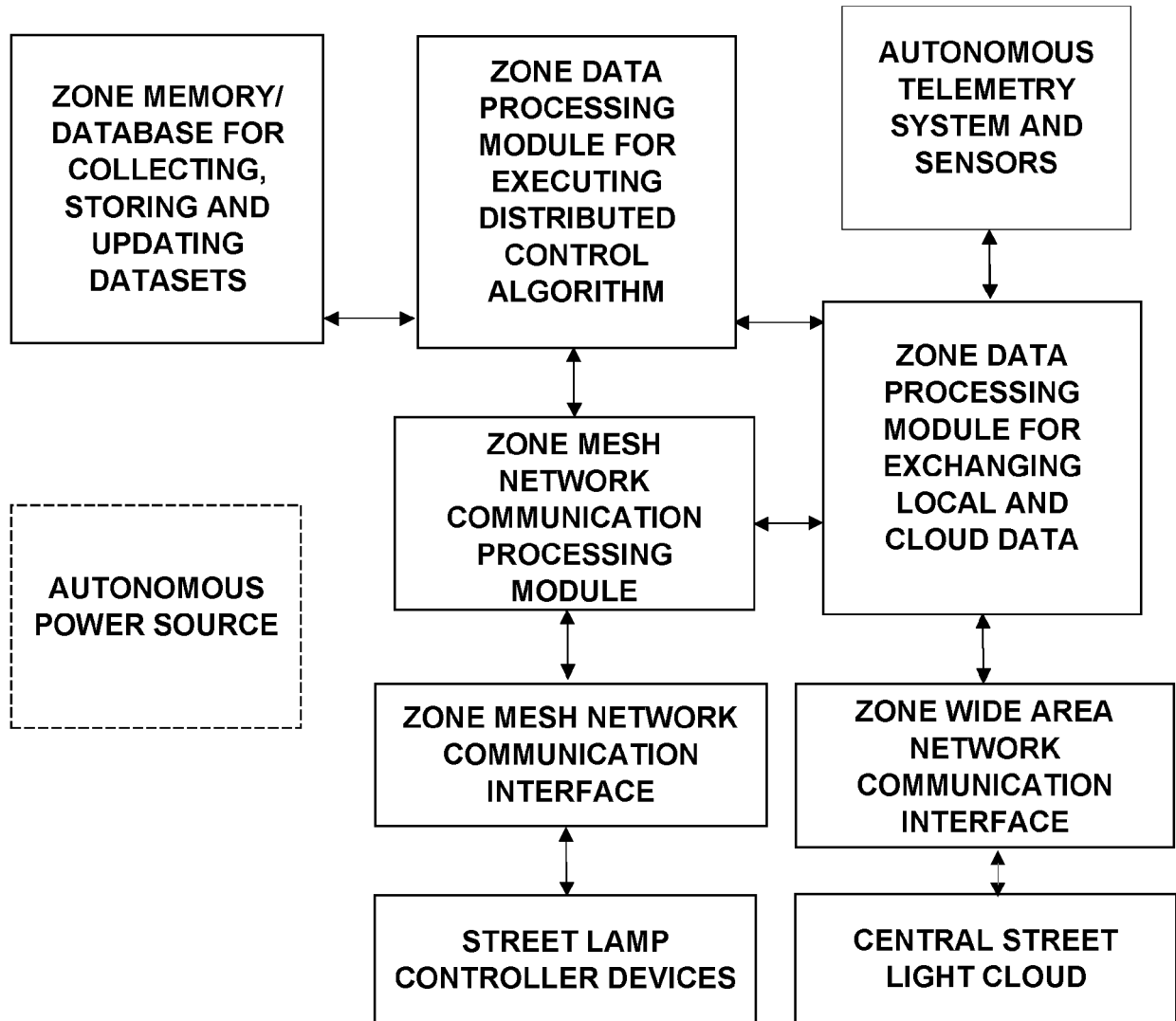


Fig. 12

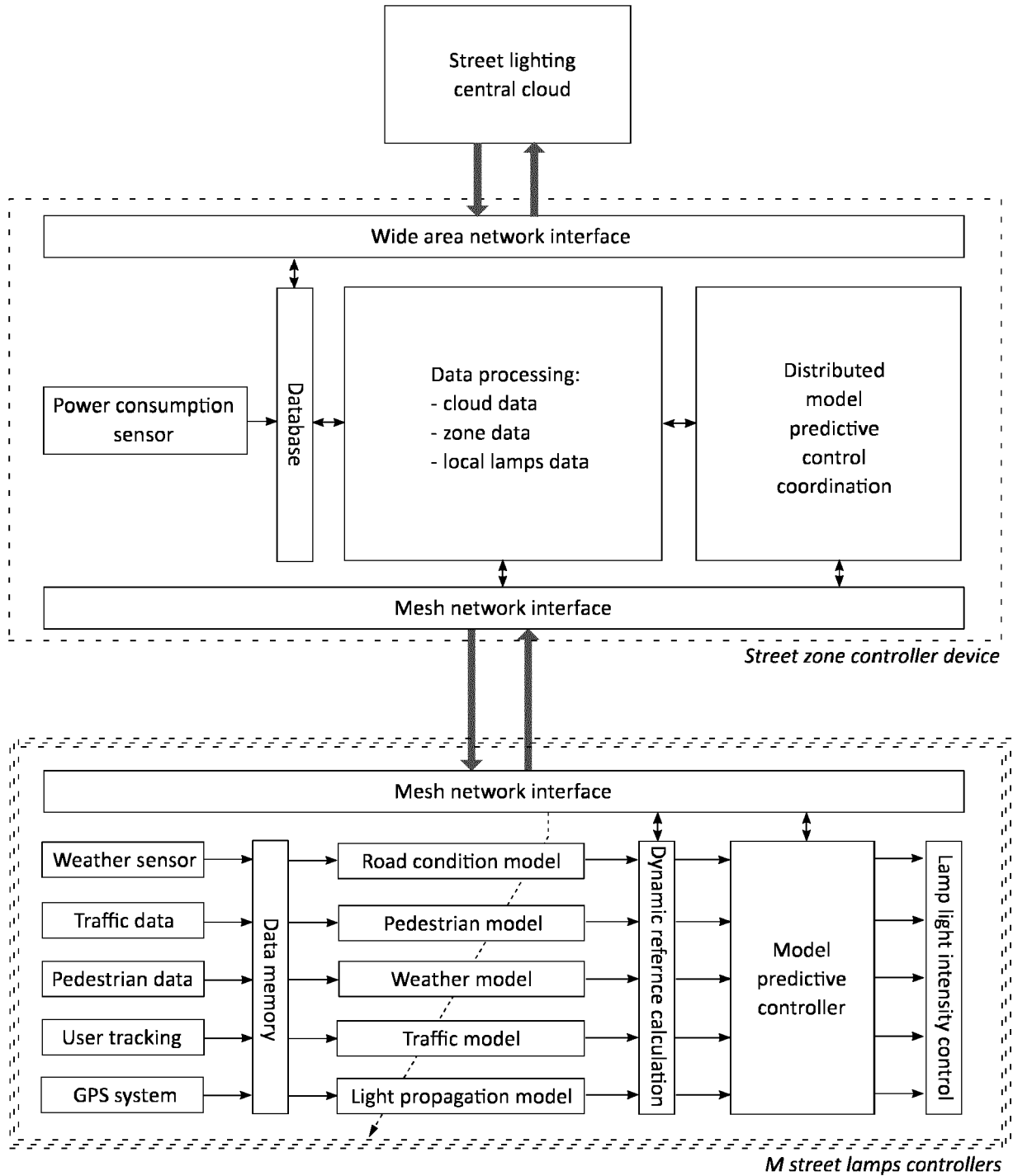


Fig. 13



EUROPEAN SEARCH REPORT

Application Number

EP 22 02 0554

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The present search report has been drawn up for all claims			TECHNICAL FIELDS SEARCHED (IPC) G05B H05B

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EPO FORM 1503 03:82 (P04C01)

Place of search

Munich

Date of completion of the search

10 May 2023

Examiner

Erskine, Andrew

CATEGORY OF CITED DOCUMENTS

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Application Number

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The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 10 May 2023	Examiner Erskine, Andrew
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**ANNEX TO THE EUROPEAN SEARCH REPORT
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