A Low-Cost and Noninvasive System for the Measurement and Detection of Faulty Streetlights

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Abstract—Badly lit roads lead to vehicle accidents and encourage crime. Therefore, it is important to rapidly detect and report faulty streetlights (FSLs) to the relevant authorities to keep roads safe. Currently, communities primarily depend on electrical inspectors to check streetlights regularly, which may result in long and unnecessary delays prior to repair. Recent studies have focused on adding a networking capability (i.e., a wireless sensor network) into street light poles to enable real-time status reports. However, a smart system that would incorporate sensors and network modules into every streetlight would be expensive; therefore, it would be nearly impossible to realize this system quickly. In this paper, we propose a noninvasive method for detecting faulty lights that involves designing special equipment, called the Hitchhiker, which could be installed on vehicles and would collect information about streetlights’ intensity. This system would not require the modification of conventional streetlights. The collected data would be used to create illumination maps (IMaps), the analysis of which could help identify changes in lighting intensity in specific regions. As far as we know, this is an unprecedented approach; no other approaches use IMaps to find FSLs and consider cost and invasiveness. The proposed system could be extended to a citywide scale with minimal cost, and could be used as a complementary system for electrical inspectors possibly identifying FSLs sooner and shortening the duration of poor lighting on streets.

Index Terms—Detect, fault, intelligent, management, mobile, sensor, streetlights.

I. INTRODUCTION

BEYER AND KER [1] showed that street lighting might prevent vehicle accidents and injuries. However, maintaining streetlights and ensuring that they work correctly is labor intensive. Communities primarily depend on electrical inspectors from local government or residents to report faulty streetlights (FSLs). Some studies have focused on the addition of sensing and networking capabilities to streetlights that enables remote monitoring and automatic reporting of a streetlight’s condition via Wi-Fi, ZigBee, power line communication (PLC), or GPRS [3]–[6]. However, these approaches require the addition of sensing components and networking modules to every streetlight that significantly increases costs and prohibits this system from being quickly realized. A practical solution is needed to detect FSLs at a low cost and with minimal human labor.

We propose a novel method for detecting FSLs: the use of illumination maps (IMaps). This paper is based on our previous work [2]. An IMap describes the illumination intensity in several 2-D locations. Fig. 2 shows two IMaps, IMap1 and IMap2, describe changes in illumination intensity along the same path, P.

Fig. 1. FSLs may cause vehicle accidents and encourage crime.

Fig. 2. Two IMaps, IMap1 and IMap2, describe changes in illumination intensity along the same path, P.
The proposed system has the following salient features.

1) No need to install additional devices (i.e., wireless sensors) on each conventional light. Our method significantly reduces cost and labor; therefore, our system is practical, can be used in the short term, and can be used as a complementary system for electrical inspectors identifying possibly FSLs sooner.

2) Existing vehicles (e.g., shuttle buses and taxis), could carry the Hitchhiker to collect illumination data without additional effort.

3) The Hitchhiker is designed to be automatic and require little to no maintenance. No human intervention is required for data collection or uploading. The proposed system is expected to find the location of FSLs and relay this information to enable faster remediation.

The remainder of this paper is organized as follows. Section II briefly describes related research. Section III describes the proof-of-concept experiment. Section IV describes the details of design requirements. Section V discusses the evaluation of the system. Section VII provides the discussions. Finally, the conclusion is drawn in Section VIII.

II. RELATED RESEARCH

Utilizing intelligent wire/wireless streetlights for automatic road lighting management has been difficult. Wireless sensor networks (WSNs) are a promising and widely studied [3]–[6] technology that would achieve this goal. The WSN approach dictates that each streetlight must be equipped with a special microcontroller used to measure its working condition (i.e., current/voltage, lighting intensity, and temperature of the light). All data are collected and transferred via an RF transceiver to the central data server for managing.

The communication method for a streetlight is comprised of two parts: 1) short-range wireless communication for data exchange between streetlights and 2) long-range communication for data exchange from streetlights to the remote data center. Since the distance between streetlights varies from 25 to 50 m, ZigBee, a short-range radio, is normally used with a multihop networking protocol to relay data between poles. Some studies [7] have also suggested adopting PLC as a replacement for wireless communication, enabling more reliable data transmissions. For long-range data communication, GPRS/3G is commonly used to transfer the collected data from the streetlights to the remote data center.

The WSN-enabled streetlights have unprecedented applications. Since WSN can transfer data from streetlights to the central server by equipping it with the corresponding sensors, it can be used to determine road traffic and adjust the lighting intensity to save energy if traffic decreases. In addition, a panic button could be installed on the streetlights that would enable people to report traffic accidents or emergencies without having to report their locations, as the location of the streetlight is known by the central server.

While WSN-based streetlights have been designed and tested for several years, since every streetlight must integrate a special device for sensing and transmitting data, the cost of modifying conventional streetlights is so high that it is nearly impossible in the short-term. Replacing conventional streetlights with new, intelligent streetlights would cost even more. Therefore, neither is a practical solution in the near future.

Recently, Zanjani [9] used computer vision technology to determine whether streetlights were working properly. 

Fig. 3. Procedure of the proposed method.
This approach uses stationary surveillance cameras installed along roads to capture images of streetlights, and it compares images of the same location taken over several days to determine whether the lighting differs over time. This method does not require the installation of special devices on streetlights. Instead, it involves installing many stationary surveillance cameras that can be very costly if widespread installations are required.

Table I compares various methods of monitoring FSLs. We defined the number of streetlights as 20,000 and the number of electrical inspectors as two, according to statistical data from Minsyong Township, Chiayi County, Taiwan, where we conducted the proof-of-concept experiment. According to Table I, the electrical inspectors can help find FSLs but may cause long and unnecessary delays in repair since two full-time inspectors are responsible for 20,000 streetlights.

Both the WSN/PLC sensor network and surveillance cameras can provide real-time reports and identify the exact location of FSLs. However, the cost of hardware, installation, and modification of conventional streetlights, and laying of cables for data and power transmission are very high. In addition, there would be maintenance costs related to the equipment and cables, as their lifetimes are limited. In contrast to these methods, the Hitchhiker can operate without modifying existing streetlights. Therefore, the cost is significantly lower than that of other methods, despite some limitations (it cannot determine the exact location of the FSL or report it in real time, and it can only monitor the streetlights on the path it follows).

In summary, the proposed method has a low cost and does not require streetlight modification. Accordingly, it is practical and can be applied immediately. It can assist electrical inspectors by helping them to find FSLs sooner and with little extra cost. In Section III, we describe the details of our method and test its performance with a proof-of-concept experiment.

### III. Proof-of-Concept Experiment

To verify our method, we executed a proof-of-concept experiment to create an IMap. We modified a laptop computer to integrate a GPS module and light meters to collect illumination intensity data and GPS locations at a frequency of 10 Hz. The light meters and GPS module were installed on the roof of a car, as shown in Fig. 4. This enabled us to collect illumination intensity data as we drove along the road several times, as shown in Fig. 5. Note that in the first experiment, we installed three light meters on the car's roof to determine whether the installation location would affect the measured light intensity.
This experiment was executed from 7:33:46 PM to 7:42:58 PM on December 13, 2011 on the campus of National Chung Cheng University. All the streetlights along the road were working when we executed the experiment. Therefore, we were able to use this IMap as a control group for later comparisons. If the light intensity in a specific location \( q \) changed significantly, we could infer that the streetlight near \( q \) was possibly out and might need repair soon.

To transform the data collected by the Hitchhiker into an IMap, first enclose the area to be examined with a rectangular area, denoted by \( S_t \), and partition it into \( m \) by \( n \) cells. Then, denote each cell by \( C_{x,y} \), where \( 1 \leq x \leq m \) and \( 1 \leq y \leq n \), as presented in (1). In this example, the cell size is set to 0.001° longitude and 0.001° latitude, respectively (1.852 m × 1.852 m). Since the data collected are a sequence of GPS locations and their corresponding light intensities, the data can be organized into a trajectory \( t \) that consists of a series of points, \( p_1, p_2, p_3, \ldots \), as presented in (2).

Algorithm 1 Transform IMap

1. Load trajectory \( t \)
2. Define rectangle map area \( S_t \)
3. Divide \( S_t \) into \( m \times n \) cells, each cell denoted as \( C_{x,y} \) (where \( 1 \leq x \leq m \) and \( 1 \leq y \leq n \))
4. \( \textbf{while}(t \neq \emptyset) \)
5. \( pt = \text{remove the first point} \ p \ \text{from} \ t \)
6. \( C_{x,y} = \text{find_corresponding_cell}(pt) \)
7. \( F_{x,y} \ add(pt) \)
8. \( \textbf{end while} \)
9. Define illumination map \( IMap_1 \)
10. Divide \( IMap_1 \) into \( m \times n \) cells, each cell denoted as \( L_{x,y} \) (where \( 1 \leq x \leq m \) and \( 1 \leq y \leq n \))
11. \( \textbf{for} (\forall x,y \ | \ 1 \leq x \leq m \ \text{and} \ 1 \leq y \leq n) \)
12. \( L_{x,y} = \text{mean(light}(p_1) \ \text{light}(p_2) \ldots) \) for \( (\forall p \in P_{x,y}) \)
13. \( \textbf{end for} \)
14. \( \textbf{output} \ IMap_1 \)

where each point \( p_k \) has a longitudinal and latitudinal location and a specific light intensity, as presented in (3). The set of points that geographically fall into a cell, \( C_{x,y} \), is denoted by \( P_{x,y} \), and \( N_{x,y} = |P_{x,y}| \), indicating the number of points in the cell, as presented in (4)

\[
\begin{align*}
S_t &= \{C_{1,1}, C_{1,2}, \ldots, C_{1,n-1}, C_{1,n}, C_{2,1}, \\
&\quad C_{2,2}, \ldots, C_{m,n-1}, C_{m,n}\} \quad (1) \\
t &= \{p_1, p_2, p_3, \ldots\} \quad (2) \\
p_k &= \text{longitude}(p_k), \text{latitude}(p_k), \text{light}(p_k). \quad (3)
\end{align*}
\]

For a cell \( C_{x,y} \in S_t \)
\[
\begin{align*}
P_{x,y} &= \{\forall p \in C_{x,y}\} \\
N_{x,y} &= |P_{x,y}| \\
L_{x,y} &= \text{mean(light}(p_1) \ \text{light}(p_2) \ldots) \ (\forall p \in P_{x,y}) \\
IMap_1 &= \{L_{1,1}, L_{1,2}, \ldots, L_{1,n-1}, L_{1,n}, L_{2,1}, \\
&\quad L_{2,2}, \ldots, L_{m,n-1}, L_{m,n}\}. \quad (4)
\end{align*}
\]

Algorithm 1 describes how trajectory \( t \) transforms into an IMap. The while loop from lines 04 to 08 retrieves the point as \( pt \) from trajectory \( t \), then finds its corresponding cell, \( C_{x,y} \) (that is, \( pt \) geographically falls into the area of \( C_{x,y} \)), and adds \( pt \) to the list of \( F_{x,y} \) (line 07).

The for loop from lines 11 to 13 iteratively calculates the average light intensity, \( L_{x,y} \), from its corresponding \( P_{x,y} \). After calculating \( L_{x,y} \), the IMap for \( S_t \) is built. The IMap in Fig. 6 shows that the average illumination intensity has a 0.001-min resolution (~1.852 m) for both longitude and latitude. Due to positioning errors of the GPS receivers, the collected GPS traces did not overlap perfectly, even though we drove the same loop several times. However, Fig. 6 shows that illumination intensity was highly geographically correlated. In addition, we found that the three light meters evidenced nearly the same readings for light intensity. Consequently, we used only one light meter in later experiments.

Through this experiment, we demonstrated that creating an IMap was feasible, and that we could use it to measure the light intensity of streetlights over a large area. In Section IV, we discuss the device’s design, the aim of which was to create IMaps automatically.
IV. DESIGN REQUIREMENTS

To increase the adoption of Hitchhikers on shuttle buses or taxis, we kept the following requirements in mind when designing the Hitchhiker.

1) It must be a noninvasive device for the vehicle on which it will be installed. No modification of the vehicle is allowed.
2) The Hitchhiker must be able to run autonomously without human intervention or manual control, and it must not require any effort from the driver of the vehicle.
3) Errors of or damage to the Hitchhiker must not hinder the original service of the vehicle. All maintenance work must be done by us, and not the drivers (or their companies).
4) The operation and hardware cost of the Hitchhiker must be low to allow for numerous installations without exceeding our limited budget and labor resources.

V. SYSTEM ARCHITECTURE AND DESIGN

In the following, we present our system architecture and discuss the design considerations. An overview of the proposed system is shown in Fig. 7. It is composed of three types of devices: 1) Hitchhiker; 2) check point (CP); and 3) Hitchhiker access point (HAP). The Hitchhiker is an embedded system that is installed on the roofs of vehicles, such as shuttle buses or taxis, to collect illumination readings along the route the vehicles traverse. All data from the Hitchhiker is uploaded to the HAP for data storage, analysis, and user query, which allows for the identification of possible locations of FSLs. We designed and implemented a prototype Hitchhiker to demonstrate the practicability of this system.

A. Hitchhiker

The key idea of the Hitchhiker is to take advantage of existing vehicles to carry our specially designed embedded system to collect illumination data along its route. As shown in Fig. 7, the Hitchhiker is installed on the roof of a shuttle bus, and it collects readings of the street lighting, as well as the location and acceleration of the bus. The large amount of data generated by the Hitchhiker is saved on its SD card. The Hitchhiker’s power is supplied by a 12/24 V plug inside the vehicle.

The system components of the Hitchhiker and its photograph are shown in Fig. 8. The illumination readings from the precise light sensor (TSL2561 [15]) and the GPS (FMP04-TLP [17]) locations are collected at 10 Hz. All data are stored on the SD card and wait to be uploaded by the NRF24L01P [14] low-power RF transceiver, while communicating with the HAP at the bus depot. The accelerometer detects the acceleration of the vehicle to avoid saving redundant illumination data on the SD, while the vehicle is stopped.

Fig. 9 shows a working flowchart of the Hitchhiker. When it is turned ON, it begins to collect data in its data collect mode (DC mode). It continuously collects GPS locations and illumination intensities at 10 Hz. All data are stored on the local SD card. Meanwhile, the Hitchhiker continuously listens for radio messages from the CP and HAP. If it receives a message from the CP, it simply saves the message (with the CP’s GPS location and illumination intensity) on its SD card. This data may be used for later verification and ensures consistency of the illumination intensity of the CP and Hitchhiker. When the Hitchhiker is close to the bus depot, it might receive a message from the HAP and switch to data upload mode (DU mode). The HAP might schedule the upload of several Hitchhikers (on different vehicles). Afterward, the
Hitchhiker returns to DC mode and waits for the next data collection trip.

B. Check Point

Since the Hitchhiker uses one light sensor and one GPS module to collect the light intensities along the route, if the light sensor or GPS module reports inaccurate data, then erroneous IMaps will be generated that wrongly report FSLs. The Hitchhiker must deal with the following reliability issues.

1) The illumination reading from the light sensor may be incorrect due to different weather conditions (such as rain or fog) or dirt on the light sensor.

2) The GPS location may be incorrect due to defective GPS modules, bad weather conditions, or radio interferences.

To detect these errors, as was indicated in Fig. 7, CP is designed to provide the ground-truth of the illumination reading at a specific location. The CPs design goals are as follows.

1) To provide ground-truth illumination readings in a fixed location so the Hitchhiker can check its light sensor.

2) To provide the GPS location of the CP to verify the Hitchhiker’s location.

The CP, shown in Fig. 10, is a special device equipped with a TSL2561 light sensor, a GPS module and an NRF24L01P low-power RF transceiver that broadcasts its illumination readings at 1 Hz. The CP is attached to a streetlight at 2 m above the ground. The data provided by the CP is assumed to be accurate since: 1) it is stationary, so the GPS location is fixed, making it easy to verify its location and 2) the light sensor on the CP is designed to measure the light intensity at its location, and its readings will be validated periodically to ensure their accuracy. Therefore, in this application, the data provided by the CP is used as a ground-truth for the Hitchhiker’s data to avoid generating inaccurate IMaps.

Fig. 11 shows an example of how CPs can help verify the data the Hitchhiker collects. As the bus moves into the range of wireless communication with the CP (15 m in this design, according to the intentional adjustment of the output power level of the CPs RF transceiver), indicated by the red dotted circle in the figure, it receives the messages CP(GPS_x, light_x). With this, the Hitchhiker can verify its own data by Algorithm 2.

Algorithm 2 CP_verification

01 Receive CP(GPS_x, light_x) from CP
02 If Distance(GPS_x, My_location) > k
03 return (GPS_ERROR)
04 If Distance(GPS_x, My_GPS_location) < k AND
05 If Absolute_Difference(light_x, My_light_intensity) > j
06 return (Light_Sensor_ERROR)
07 return (NO_ERROR)
are not positive, indicating that the Hitchhiker’s GPS locations and light readings are acceptable.

It should be noted that in this design, the Hitchhiker simply discards problematic data without trying to calibrate it. This is because the next Hitchhiker-equipped shuttle bus may travel the same route soon. It makes more sense to use an IMap from a working Hitchhiker than to try to calibrate an inaccurate IMap from a faulty Hitchhiker.

Since the radio range of the CP is intentionally adjusted to 15 m (therefore, ensuring that the Hitchhiker is close to the CP when verifying the Hitchhiker’s GPS location), a CP can only serve a 15-m radius. However, deciding how many CPs to install is a tradeoff between cost and performance; if high reliability is required, installing as many CPs as possible would help to detect any errors causing the generation of faulty IMaps, but would increase the cost of this system, contradicting the original goal of cost efficiency. Nevertheless, the Hitchhiker and CP strike a good balance between cost and performance, and they serve as a complementary solution for electrical inspectors reporting the working condition of streetlights sooner without an expensive WSN infrastructure.

VI. SYSTEM EVALUATION

In this section, we evaluated the Hitchhiker to verify the correctness of this design and the idea of IMaps.

A. GPS Positioning Accuracy

Choosing an appropriate GPS module for the Hitchhiker helps generate accurate moving trajectories and enables us to compare the IMaps at a high resolution to position FSLs more accurately. We found that the moving trajectories of the Hitchhiker with a SiRF Star IV chipset [16] in the same loop almost overlapped, as shown in Fig. 12.

B. Test of the Hitchhiker in a Real Environment

We tested this system within a 600 m × 400 m area in Minsyong Township, Chiayi County, Taiwan, on July 22, July 29, August 8, and August 15, 2013, as listed in Table II.

![Fig. 12. Moving trajectory generated by a SiRF Star IV chipset GPS module with a resolution of 0.001 min.](image-url)

![Fig. 13. Working flowchart of the design of experiment.](image-url)

The route traversed when collecting the IMap is shown in Fig. 14(a); each route began at S. This is also where the picture in Fig. 1 was taken. We created two IMaps each day, resulting in eight IMaps, as listed in Table II. These IMaps were denoted by IMap\textsubscript{before} and IMap\textsubscript{after} to indicate when the maps were collected, in relation to the repair work on August 7, 2013.

As shown in Table II, four IMaps were collected before the FSL was repaired (i.e., IMap\textsubscript{before1}, IMap\textsubscript{before2}, IMap\textsubscript{before3}, and IMap\textsubscript{before4}). The remaining four (IMap\textsubscript{after1}, IMap\textsubscript{after2}, IMap\textsubscript{after3}, and IMap\textsubscript{after4}) were collected after the FSL was repaired.

The repair of FSLs was completed by the local government on August 7, 2013. We organized the IMaps into two groups (IMap\textsubscript{before} and IMap\textsubscript{after}), as shown in Table II.

![Table II](image-url)

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\[
\text{IMap}_{\text{before}} = \{\text{IMap}_{\text{before1}} \cup \text{IMap}_{\text{before2}} \cup \text{IMap}_{\text{before3}} \cup \text{IMap}_{\text{before4}}\},
\]

\[
\text{IMap}_{\text{after}} = \{\text{IMap}_{\text{after1}} \cup \text{IMap}_{\text{after2}} \cup \text{IMap}_{\text{after3}} \cup \text{IMap}_{\text{after4}}\}.
\]
1) Evaluation of IMaps When the Lighting Conditions Have Not Changed: Fig. 14(b) and (c) shows two IMaps with a resolution of 0.001 min that were collected on July 22, 2013. As expected, they are highly consistent regarding illumination intensity. Fig. 14(d) shows the difference in illumination by overlapping the locations of the IMaps in Fig. 14(b) and (c), which were generated using Algorithm 3. In lines 01 and 02, it loads two input IMaps and defines a new IMap_diff. The for loop in lines 06–08 loads every cell from the two input IMaps and calculates the absolute value of the difference of the average illumination intensity, then outputs the corresponding cell in the IMap_diff. As shown in Fig. 14(d), all the differences in illumination are insignificant. Even though Fig. 14(b) and (c) includes data collected from the same route on the same night, the moving trajectories do not completely overlap because: 1) the vehicle may not drive in the same lane and 2) there may be GPS positioning errors. We will deal with this issue later in this section.

Next, we verify another illumination consistency in the IMaps by comparing it to the data from July 29, as shown in Fig. 14(e). It is shown that the lighting conditions are the same for both July 22 and 29. The differences in illumination are shown in Fig. 14(f). All the differences are <24 lux in Fig. 14(f) as well as in Fig. 14(d).

Algorithm 3 Generate_IMap_diff From IMap1 and IMap2

01 Load IMap1, IMap2 in the same cell size and cell number (m x n)
02 Define a new IMap_diff with the same cell size and cell number (m x n)
03 Define L1x,y as average of illumination from Lx,y in IMap1
04 Define L2x,y as average of illumination from Lx,y in IMap2
05 Define Ldiffx,y as average of illumination from Lx,y in IMap_diff
06 for (∀x,y | 1 ≤ x ≤ m and 1 ≤ y ≤ n)
07 Ldiffx,y = |L1x,y - L2x,y |
08 end for
09 output IMap_diff

As expected, two IMaps collected under the same lighting conditions are highly similar and have insignificant differences in illumination. This supports the initial idea of our method: If the lighting conditions do not change, IMaps made of data collected from the same path on different nights should have no significant differences.

2) Evaluation of IMaps When the Lighting Conditions Have Changed:

a) Design of the experiment: We investigated whether IMaps could help identify the location of a FSL. A major difficulty of this experiment is that, in order to avoid affecting working streetlights and local residents, we could not turn the
streetlights on or off via the Parks and Streetlight Office. In order to respond to this limitation, we designed a test procedure, shown in Fig. 13, to verify the system's ability to catch significant illumination changes as follows.

1) Through human labor, we found and recorded the location of FSLs on FSL_MAP before, and we collected data for IMap before to save the current illumination states.

2) Then, we asked the local Parks and Streetlight Office to repair the FSLs according to FSL_MAP before.

3) After the FSLs were repaired, we physically checked the previously marked FSLs according to FSL_MAP before and incorporated the repaired FSLs into FSL_MAP repaired. Even though most of the FSLs on the FSL_MAP before were repaired, some could not be due to repair errors, or an inability to effect the repair quickly (i.e., the power cable of the streetlight was stolen). Thus, the IMap after was collected to determine the current illumination states.

4) Next, we determined the differences between IMap before and IMap after in IMap diff.

5) We checked whether IMap diff could point out the location of significant illumination changes by comparing it with FSL_MAP repaired.

If this experiment could help us to locate where FSLs had been repaired by determining the difference in illumination using IMaps, it must be possible to determine, which FSLs were functioning properly previously. Therefore, we executed this procedure in a real environment, as described in Section VI-B2b.

b) Execution of the design experiment: We executed this experiment on July 28, 2013. We physically checked the FSLs and created FSL_MAP before, as shown in Fig. 15. The 20 red circles on the map indicate the locations of FSLs, which were numbered for easy identification. We also attached a number to each FSL for easy reference. All the IMaps were collected according to the times listed in Table II.

After FSL_MAP before was created, we sent it to the local Parks and Streetlight Office, and we asked them to check and repair the FSLs on the map. The local administration reported that the repairs were completed on August 7, 2013.

We physically checked whether the lights were fixed and created a new map, FSL_MAP repaired, to indicate the correctly repaired FSLs, as shown in Fig. 16. This map indicates that some of the previously marked FSLs in FSL_MAP before were still malfunctioning (i.e., FSLs 5, 11, 12, 13, 16, and 20). However, if FSL f was malfunctioning prior to August 7 and had been repaired after August 7 the illumination intensity near f should have evidenced a significant illumination change. Its location may be determined by comparing several IMaps.

c) Analysis and evaluation of experiment:

i) Difference in illumination between two IMaps: Fig. 17 shows the difference in illumination between IMaps by comparing the IMaps collected before the repair and one of the IMaps collected after the repair. The repaired FSLs are given the group notation G1, G2, . . . , G6 to easily reference the location, as shown in Fig. 17(f). Fig. 17(a) presents the difference in illumination between IMap before1 and IMap after1. According to the group notation in Fig. 17(f), Fig. 17(a) identifies the locations of G1, G3, and G4, which demonstrate a significant change in the illumination intensity (i.e., the illumination change is >25 lux). Both Fig. 17(b) and (c) identifies G3 and G4. Fig. 17(d) identifies G1, G4, and G5. Fig. 17(e) identifies G2 and G4.

However, none of the above IMaps highlights G6. This might be because only FSL No. 1 was not working and many streetlights near FSL No. 1 (indicated by G6) remain in good condition. This results in an insignificant change in the illumination intensity near FSL No. 1. This is acceptable.
Fig. 17. Illumination difference among IMaps with a resolution of 0.001 min. (a) Difference in illumination between IMap \textit{before} 1 and IMap \textit{after} 1. (b) Difference in illumination between IMap \textit{before} 2 and IMap \textit{after} 1. (c) Difference in illumination between IMap \textit{before} 3 and IMap \textit{after} 1. (d) Difference in illumination between IMap \textit{before} 3 and IMap \textit{after} 2. (e) Difference in illumination between IMap \textit{before} 4 and IMap \textit{after} 3. (f) Notation of the repaired FSL group.

because in most conditions, a single FSL among many working streetlights does not affect safety or require immediate remediation.

Fig. 17 shows the possibility of identifying the locations of FSLs and repairing them. However, the overlapping portion of the route is small (as shown in both Figs. 14 and 17), while the IMap resolution is high (0.001 min). To increase the portion of the route that overlaps, we can create groups of IMaps. The IMaps collected before and after FSL repairs can be organized into two groups, IMap \textit{before} and IMap \textit{after}, as shown in (5).

These two IMap groups included more overlapping routes, potentially helping identify the location of FSLs and repaired FSLs. Fig. 18 provides the difference in illumination between IMap \textit{before} and IMap \textit{after}. In Fig. 18(a), the overlapping portion of the IMaps is much larger than that in the IMaps in Fig. 17, and it denotes five locations with significant changes in illumination in G1, G2, G3, G4, and G5. Table III shows the hit rate, comparing different IMaps to indicate the best hit rate (83.3%) and miss rate (16.7%) achieved in this experiment. However, G6 remains undetected. We changed the color bar so it was discrete and set all values <24 lux. The threshold value changes to dark green to emphasize locations with significant light change, as shown in Fig. 18(b).

### Table III: Hit Rate of FSL

<table>
<thead>
<tr>
<th>Compared between</th>
<th>Figure</th>
<th>FSL regions</th>
<th>Hit rate</th>
<th>Miss rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMap \textit{before} \textit{before}</td>
<td>Fig. 17(a)</td>
<td>G1, G3, G4</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>IMap \textit{before} \textit{after}</td>
<td>Fig. 17(b)</td>
<td>G3, G4</td>
<td>33.3%</td>
<td>66.7%</td>
</tr>
<tr>
<td>IMap \textit{after} \textit{before}</td>
<td>Fig. 17(c)</td>
<td>G3, G4</td>
<td>33.3%</td>
<td>66.7%</td>
</tr>
<tr>
<td>IMap \textit{after} \textit{after}</td>
<td>Fig. 17(d)</td>
<td>G1, G4, G5</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>IMap \textit{before} \textit{after}</td>
<td>Fig. 17(e)</td>
<td>G2, G4</td>
<td>33.3%</td>
<td>66.7%</td>
</tr>
<tr>
<td>IMap \textit{after} \textit{before}</td>
<td>Fig. 18</td>
<td>G1, G2, G3, G4, G5</td>
<td>83.3%</td>
<td>16.7%</td>
</tr>
</tbody>
</table>

The discrete color bar enhanced the difference in illumination, we can see that the locations of the repaired FSLs are highly consistent with those in Fig. 17(f). The results further indicate that the proposed method can be used to identify the locations of FSLs and repaired FSLs.

ii) Difference in illumination between grouped IMaps IMap \textit{before} and IMap \textit{after}: Fig. 19 scales the resolutions of IMap \textit{before} and IMap \textit{after} down; each pixel represents a larger geographical area. This shows the increasing overlapped routes and enhanced visibility of the locations of changes in illumination. Fig. 19(a)–(c) all clearly indicate significant changes in illumination in G1, G2, G3, G4, and G5, but not in G6.

Fig. 19(a) shows some noise signals, indicated by a red dotted triangle [G1 in Fig. 17(f)], where the illumination...
difference is inaccurate due to insufficient overlap of illumination data in the IMaps. This issue can be alleviated in several ways, including: 1) collecting more illumination data from this area or 2) scaling down the resolution of the IMap, as this issue is invisible in Fig. 19(c).

d) Evaluation of the CP: During the evaluation, we installed two CPs. Their GPS locations are 23°33′23.3″N 120°28′11.9″E and 23°33′21.0″N 120°28′24.1″E, as shown in Fig. 20. In the following, we evaluate how the CP can help detect faulty light sensors and faulty GPS of the Hitchhiker.

i) Detecting the Hitchhiker’s faulty light sensor: During the experiment, the Hitchhiker experienced a problem: its light sensor connector was loosened intermittently, resulting in readings of zero. The raw data is shown in Fig. 21.

As shown in Fig. 21, the light sensor readings are indicated by the string $1:0$, for which all readings are zero lux. However, this Hitchhiker received the message $SC$, 2333.3879, 12028.1986, 27 from the CP, indicating that the CPs light sensor measured the light intensity as 27 lux (highlighted by red dotted rectangle in Fig. 20). Therefore, by executing the Algorithm 2 in Section IV, the Hitchhiker can determine that their readings are inconsistent and decide to discard the collected data to avoid generating incorrect IMaps.

ii) Detecting the Hitchhiker’s faulty GPS: In this paragraph, we verify the function of the CP to check the Hitchhiker’s GPS location. Because we cannot force the Hitchhiker’s GPS to report incorrect locations, we chose raw data collected by the Hitchhiker with CPs message, and modify the Hitchhiker’s GPS location to offset its original trajectory. The modified raw data is shown in Fig. 22.

Fig. 22 shows that the Hitchhiker’s GPS module reported its location as 2333.3141 120°28′23.3″E. Meanwhile, it received a message from the CP, indicating that the distance between the CP and Hitchhiker...
Fig. 20. Two CPs were installed during the experiment.

Fig. 21. Raw data of a Hitchhiker, the light sensor connector of which was loosened intermittently.

Fig. 22. Raw data in which a Hitchhiker's GPS location is significant flawed. was <15 m. The Hitchhiker then executed Algorithm 2 to calculate the distance between its own GPS location and the CPs GPS location, 23°33′23.3"N 120°28′11.9"E, with a result of 81 m. Since 81 m is significantly >15 m, the Hitchhiker detected that its GPS data was not correct and decided to discard its collected data. In this case, the readings of light intensity collected by the CP (19 lux, highlighted by the red dotted rectangle in Fig. 22) and the Hitchhiker are similar since they are geographically close. This shows that the CP can help verify the Hitchhiker’s light sensors.

VII. Discussion

Based on the experimental results, the proposed method can identify changes in illumination and indicate the locations of possible FSLs. To improve the accuracy of the positioning of FSLs, the following issues must be addressed.

A. GPS Positioning Errors and Mitigation

Positioning errors due to the GPS were nearly unavoidable, as we used a consumer-grade GPS module, despite the fact that the GPS modules we used were enabled differential GPS (DGPS) units, as described in [11]. We could upgrade the GPS antenna to have a higher radio sensitivity. However, positioning errors would still be likely due to external factors, such as weather conditions (i.e., heavy rain or ionospheric distortion) or obstacles (i.e., tall buildings). Since the positioning accuracy with DGPS is ~2.5 m, according to the datasheets [16], an expedient approach would be to downscale the resolution of IMaps to 0.003 min (=5.556 m), as shown in Fig. 19(a). This would also increase the portion of overlap among several IMaps, therefore helping to identify more regions with significant illumination changes. This also alleviates the issue of data obtained from driving in different lanes because the illuminations are averaged into a larger cell.

Another approach to dealing with GPS positioning errors is to apply a map-matching technique [12] (like a car navigation system) or a trajectory estimation [13] to correct the GPS position. This would avoid unwanted trajectory drifting. However, it requires a precise geographical information system that could provide accurate road maps to correct trajectories. This approach could solve the problem, but might not be available in rural areas, where road maps are usually out-of-date and unverified, which presents more challenges to realizing this system.

B. Accuracy of Detecting FSLs

Regarding the accuracy of detecting FSLs, WSN would offer near 100% accuracy because it installs a sensor on every streetlight to measure the light intensity. However, the proposed approach still achieves 80% accuracy and costs thousands of dollars less, according to the results in Section VI-B2c-ii and Table I. From this point of view, the proposed solution is valuable and can be deployed soon.

C. System Reliability

In this system, the CP offers a ground-truth for the Hitchhikers to check their own data, including their current locations and light sensors. If the error of a GPS or light sensor is significant, the Hitchhiker will discard the data it collected and call for hardware service. Therefore, the system’s reliability is maintained at a level proportional to the number of CPs installed. If high reliability is necessary, more CPs can be installed, but the cost will increase. The proposed approach considers performance, hardware, and deployment costs in the design stage, and can be used as a complementary system for electrical inspectors identifies possible FSLs sooner and shortens the duration of badly lit streets. In addition, it can be extended to a citywide scale at a low cost.
D. Self Diagnosis

It is worth mentioning that we can add a self-diagnostic feature to verify the function of the Hitchhiker and CP. If the Hitchhiker and CP collect light intensity data on sunny days, then regardless of whether the streetlights are working or not, the CP can detect the sunlight and then broadcast this message to the passing Hitchhiker. The Hitchhiker can then use this message to ensure that its reading is consistent with that of the CP, and that the GPS module is working correctly.

E. Other Data Sources for IMap Generation

To generate more accurate IMaps, we can extend the function of the CP to log long-term data, which can serve as a reliable data source when generating IMaps. We can configure the CP to log the long-term history of light intensity in a fixed location, and then wirelessly download the data from the CP to generate an IMap for the specific location. If certain locations (i.e., street crossings) must monitor lighting conditions very carefully, this approach can provide significant benefits while maintaining the CPs original function.

VIII. CONCLUSION

We proposed a new method that, through the Hitchhiker, created IMaps and used them to detect possible FSLs. As far as we know, the proposed method is unprecedented in its use of IMaps to find FSLs and in its consideration of cost-effectiveness and noninvasiveness. The proposed method has significant advantages as follows.

1) Additional sensors and networking modules do not need to be installed on every streetlight, so the cost is low, meaning that this method could be realized in the near future.

2) The Hitchhiker can be used on fixed bus routes to collect illumination intensity and create IMaps regularly without extra effort or cost.

3) The differences in illumination between IMaps can help determine and report FSLs, reducing the time between streetlight repairs. We plan to install this system on a local fixed bus route to create town-sized IMaps. This system should help detect FSLs and keep roads safer.

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REFERENCES


