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Visible light communication based vehicle positioning using LED street light and rolling shutter CMOS sensors

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ABSTRACT

This paper proposes a vehicle positioning system using LED street lights and two rolling shutter CMOS sensor cameras. In this system, identification codes for the LED street lights are transmitted to camera-equipped vehicles through a visible light communication (VLC) channel. Given that the camera parameters are known, the positions of the vehicles are determined based on the geometric relationship between the coordinates of the LEDs in the images and their real world coordinates, which are obtained through the LED identification codes. The main contributions of the paper are twofold. First, the collinear arrangement of the LED street lights makes traditional camera-based positioning algorithms fail to determine the position of the vehicles. In this paper, an algorithm is proposed to fuse data received from the two cameras attached to the vehicles in order to solve the collinearity problem of the LEDs. Second, the rolling shutter mechanism of the CMOS sensors combined with the movement of the vehicles creates image artifacts that may severely degrade the positioning accuracy. This paper also proposes a method to compensate for the rolling shutter artifact, and a high positioning accuracy can be achieved even when the vehicle is moving at high speeds. The performance of the proposed positioning system corresponding to different system parameters is examined by conducting Matlab simulations. Small-scale experiments are also conducted to study the performance of the proposed algorithm in real applications.

1. Introduction

In the imaging industry, two types of sensors are available: CCD and CMOS. CCD has long been considered to yield superior image quality, and in the early days of the digital age, most cameras were equipped with CCD sensors. However, there has been a dramatic evolution in CMOS sensors in recent years, which has resulted in CMOS sensors performing better than CCD sensors in various aspects, including image quality, frame rate, and production costs. Consequently, CMOS sensors are now used as building blocks for most imaging devices, and their widespread adoption makes them suitable for use as receiving devices in visible light communication (VLC) [1–3] and VLC based positioning [4–6].

This paper examines the vehicle positioning problem, which currently has three popular approaches. The most popular approach is using Global Positioning System (GPS) thanks to its low cost. However, GPS might be unavailable in tunnels or streets in urban areas where the GPS signals are hindered by high building. Another approach is using 4G/LTE, which can overcome the limitation related to the availability of GPS. Nevertheless, this approach only provides tens of meters of positioning accuracy [7,8], which is insufficient for applications that require a high level of accuracy such as autonomous vehicle. The most successful approach for vehicle positioning is using Light Detection and Ranging (LIDAR), which can provide very high accuracy. However, LIDAR demands extra equipment which is generally very expensive. Because of these reasons, it is still necessary to find new techniques for vehicle positioning.

In recent years, a new kind of technique based on visible light communication has been proposed for vehicle positioning. In [9], taillights or headlights of the vehicle were used to transmit positioning signals that were received by two photodiodes installed in another vehicle. Then, a type of time difference of arrival (TDOA) algorithm was used to determine the relative position between the vehicles. This method is very difficult to achieve high accuracy in practice since with TDOA, a small error in time measurement leads to large positioning error. In [10], LED traffic lights and photodiode were used to determine the position of the vehicle. However, since photodiode cannot distinguish different light sources, this systems would be greatly vulnerable to ambient light, especially the sunlight. In [11], a neural network was used for the

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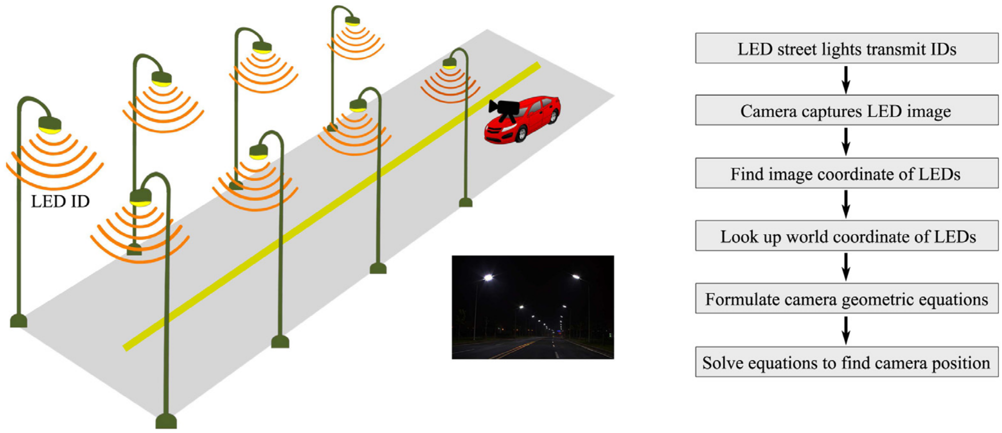

Fig. 1. System architecture.

vehicle to estimate the position of a target vehicle which sends the VLC positioning signal through its rear LED lights. The estimating vehicle used two cameras to receive the positioning signal. It is well known that in camera based positioning, the accuracy greatly depends on the distance between reference points, which are LEDs in this case. Since the rear LEDs of the target vehicle is relatively close to each other compared to the distance between the two vehicles, the positioning accuracy achieved through the simulation was not high.

This paper proposes a VLC based vehicle positioning system using LED street lights and CMOS image sensors. With many advantages including their being environmentally friendly, long lifetime, energy efficiency, etc., LED street lights have been used more and more around the world. These high power and high density illuminating systems can be utilized for communication and positioning purposes. Furthermore, in principle, positioning using street lights has a lot of potential to provide high accuracy results thanks to the dense arrangement of street lights. In the proposed system, the LED street lights are used to send identification codes from which the real world coordinates of LEDs can be obtained. CMOS image sensors are used to capture the images of LEDs in which the VLC data is embedded. The geometric relationship between the real-world coordinates of LEDs and their coordinates on the images are used to determine the position of the vehicle. The problem of using camera for positioning has been studied in the field of computer vision for a long time. However, there are two limitations of traditional positioning algorithms in solving the vehicle positioning problem considered in this paper.

First, traditional algorithms require the objects used to determine the position of the camera to not be collinear. LED street lights, however, might be collinear in many cases, and thus traditional algorithms would fail to find the position of the vehicle.

Second, regardless of the arrangement of the LED, the positioning accuracy always suffers from the inherent disadvantages of using a CMOS sensor with the rolling shutter artifact. With the rolling shutter mechanism used in CMOS sensor, each row of pixels in the sensor is exposed at a different time. Therefore, a change in the position of the objects during the exposure period results in image artifacts as the distortions of the objects in the captured images. When objects move at a high speed, these distortions might give wrong information to the positioning algorithms and thus introduce errors to the results. Neither traditional positioning algorithms, which were originally designed for use with CCD sensors that do not use the rolling shutter mechanism, nor more recent algorithms, which were intentionally designed for use with smartphone CMOS sensors [4–6] address these artifacts.

In this paper, the two difficulties mentioned above are addressed. To deal with the problem of a collinear LED arrangement, this paper proposes an algorithm that uses two cameras placed at different positions in the vehicle to capture the images of the LED street lights. The data from both images is then fused, and the position of the camera can be found even for the case with collinear LEDs. The rolling shutter artifacts are also solved using a proposed compensation method. This method uses the speed of the vehicle and the readout time of the sensor to compensate for the artifacts in the LED images. Consequently, a high positioning accuracy can be achieved even when the vehicle moves at high speeds.

To examine the performance of the proposed positioning algorithm and the rolling shutter compensation, Matlab simulations are conducted with the speed of vehicle assumed to vary from 0 to 100 km/h. The results of the simulation show that the achieved accuracy remains stable when the speed of the vehicle increases. The simulations also show the impact of the different parameters, including vehicle speed, vehicle travel distance, sensor resolution, exposure time of the sensor, and focal length of the lens on the positioning accuracy. Small-scale experiments are also conducted to give the insight into the performance of the proposed algorithm in real applications.

2. System fundamentals

2.1. System architecture

The entire system architecture is shown in Fig. 1. LED street lights installed along both sides of the street transmit a visible light signal that contains their identification (ID) codes to the camera attached on the vehicle. After receiving the IDs of the LEDs, the real world coordinates of the LEDs are obtained by looking up the database stored in the camera. This technique is normally used in VLC-based positioning systems to shorten the time required for the mobile devices to obtain the world coordinates of the LEDs [4,5]. On the other hand, the coordinates of the LEDs in the image are obtained via image processing. Given that the intrinsic parameters of the cameras are known, including sensor size, sensor resolution, and focal length of the lens, the real-world coordinates of the camera (i.e., the position of the vehicle) can be determined through the geometric relationship between the real-world coordinates and the image coordinates of the LEDs. In addition, the information regarding the speed of the vehicle is obtained through a speedometer. This information is then used by the rolling shutter compensation, as explained in the following sections.

2.2. The problem of existing positioning algorithms using camera

2.2.1. Pinhole camera model

All positioning algorithms using a camera are based on a pinhole camera model [12], which is shown in Fig. 2. There are three types of coordinate systems in this model: 3D world coordinate system, 3D camera coordinate system, and 2D image coordinate system. The 3D