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MouseVLC: Visible Light Communications using Mouse Sensors

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***Abstract*—This paper presents a novel Visible Light Communications (VLC) system that utilizes a low resolution LED panel as the transmitter and an image sensor that is used in a computer mouse as the receiver. The image sensor inside a mouse is a low resolution (15x15 to 30x30 pixels) and high frame rate (1K to 10K frame/s) sensor that is integrated with an image processing unit to track the movements of the surface under the mouse using an optical flow algorithm. It has very low cost and very low power consumption and thus is highly suitable for a variety of internet-of-things (IoT) applications. For example, the proposed system can be used as part of an intelligent transportation system to carry transmissions from digital signage to vehicles, or from an electronic vehicle license plate to a road-side communication unit. In our system, we encode the digital information to be transmitted in the form of a series of fast moving patterns presented on the LED panel, and the receiver can reconstruct the transmitted data from the output of the mouse sensor. Our evaluation shows that, without the use of a forward error correction code, our system can achieve a data rate of up to 74 bit/s.**

***Keywords*-Visible Light Communications, Camera Communications**

I. Introduction

Visible Light Communications (VLC) recently has become an active research topic due to its unique advantages compared to conventional RF communications, such as interference-free operation, the availability of a much larger, unregulated bandwidth in the optical spectrum, and minimal energy consumption. Most modern mobile devices have on-board cameras which can act as a receiver of a VLC system, resulting in a Camera Communications (CamCom) system. Utilizing the image sensor's high spatial resolution, a CamCom system has the additional advantages of allowing the receiver to simultaneously obtain signals from multiple transmitters, and low deployment cost due to pervasive installations of the transmitters, LED lighting and LED/LCD display panels, and the receivers, cameras.

This paper presents MouseVLC, a novel VLC system that utilizes a common *mouse sensor* as the receiving component. A mouse sensor combines a low resolution (10x10 to 15x15 pixels) and high frame rate (1K to 10K frame/s) image sensor with a built-in image processing unit that calculates the displacement of consecutive image frames using an optical flow algorithm. In normal operation, displacement of the image frames is due to the movement of the mouse.

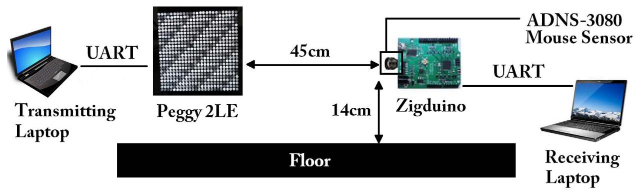

Figure 1. Scenario of mouse VLC design

The mouse sensor has been in use for decades, and is a very mature technology; it has very low cost (less than US$10 per chip) and very low power consumption (around 50 mA@3.3V), making this system suitable for a wide range of Internet of Things (IoT) applications - IoT devices, usually a form of embedded system, can easily incorporate a mouse sensor to receive transmissions. In our system, instead of capturing the appearance of the surface under the mouse, with the help of a proper lens, the mouse sensor captures images of a transmitting LED panel. The digital information is encoded into the movements of the patterns displayed on the LED panel, and these movements "trick" the mouse sensor into thinking that it is looking at a moving surface under the mouse. The transmitted digital information can then be reconstructed from the output of the mouse sensor in the form of a series of X and Y displacement values.

MouseVLC can serve as an alternative form of short-range wireless communications that supports a similar set of applications of QR code or near field communications (NFC). A common application of this type of low-speed and short-range communication link is to convey the configuration parameters to establish a high-speed communication link that will be used for subsequent data transmission, such as the service set identifier (SSID) and the encryption parameters of a WiFi network. Another common application is to utilize the fact that the probability of eavesdropping is minimized for short-range communications, and treat this communication link as the initial secure channel to bootstrap a subsequent high-speed secure communication link. For example, a shared key used for a particular communication session can be transmitted over this channel. MouseVLC can easily serve these purposes. In addition, compared to QR code, MouseVLC can utilize a low resolution LED panel

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as the transmitter, and supports continuous transmission of a data stream, while QR code requires a high resolution media and can only convey a fixed amount of data per image. Compared to NFC, MouseVLC can be implemented at much lower cost. On the receiver side, only a low-cost mouse sensor and a lens component is required, which can be easily integrated as an onboard component or packaged as an external add-on module for a mobile device. On the transmitter side, both high resolution LCD display (such as the display of computers/laptops/smartphones) and a low-resolution LED panel can serve as the transmitter and they are already widely used in our daily life; it requires only software modifications to become a MouseVLC transmitter and thus the cost is also minimized. MouseVLC is also more secure than NFC as optical transmission is highly directional and unwanted leakage of transmitted energy can be easily eliminated by putting a visual barrier to block the light; on the other hand, NFC is known to be vulnerable to eavesdropping and data modifications.

In this paper, we address a few challenges that arise from this new form of CamCom:

- *Noisy displacement output from the mouse sensor.* The output of the optical flow algorithm executed in the mouse sensor, in the form of X and Y displacements, is very noisy. A surface movement does not necessarily appear in the output and the amplitude of the displacement, i.e., the distance that the mouse moves, is also not very accurate. This creates difficulty in designing a robust and low-error communication system.
- *Low resolution transmitter.* This creates difficulty in designing a transmitting pattern that can emulate the movements of the surface under the mouse. Note that this difficulty would be eliminated if a high-resolution display is used; however, we intentionally choose to use a low-resolution LED display as the transmitter since it has a lower cost and can be used in a wider range of scenarios.

The rest of the paper is structured as follows. Section II describes related works. Section III presents the design of MouseVLC. Section IV shows the evaluation results, and finally we conclude the paper and discuss our future works in Section V.

II. Related Works

CamCom. Several existing research works [1], [2] have explored ways to implement an one-way LCD-to-camera wireless link. [1] used OFDM and complex computer vision algorithm to implement a 10-meter wireless link that can achieve 12 Mb/s with black and white checkboard patterns displayed on a high-resolution LCD screen as the transmitter and a high-end camera as the receiver. [2] instead utilized the small LCD display and the low-speed camera on a smartphone to implement the LCD-to-camera wireless link; utilizing a 2D color barcode streaming system, the system can achieve tens of Kb/s throughput at a distance of 5 inches. Our MouseVLC system implements CamCom with a lower cost and lower energy consumption with a mouse sensor receiver, making it suitable for a different set of applications, especially for IoT.

Mouse sensor related research. Mouse sensors have been used for a range of different applications in research in the past. A number of past works have used mouse sensor in a robot to determine its own location [3]–[5]. The mouse sensors have also been used as a counterfeit coin detector [6] as well as a rotary encoder [7]. In this work, we take advantage of the low-resolution and high-speed image sensor and the optical flow algorithm executed in the mouse sensor to implement a communication system.

III. System Implementation

Transmitter. Peggy 2LE board [8] is used as our transmitting LED panel. The board contains a 25x25 LED array, where each of the LEDs is a 5mm white LED with a diffused-lens. The LEDs are controlled by a ATmega328P microcontroller, and is compatible with Arduino's development framework. The board also has a Universal Asynchronous Receiver/Transmitter (UART) port that we can utilize as an input to specify the digital information to be transmitted. The firmware of the board converts the digital information taken from the input into a series of moving patterns presented on the LED array.

Receiver. Our receiver is an optical flow sensor board that incorporates an ADNS-3080 mouse sensor [9] and a replaceable 8mm lens. With the default lens, the field-of-view is about 11 degree. The mouse sensor is capable of taking images at a rate ranging from 2000 to 6469 frame/s with a resolution of 30x30 pixels. The sensor outputs X and Y displacements since the last report, in unit of pixel and with values ranging from -128 to +127. A Zigduino board [10] with an on-board ATmega1281rfa1 microcontroller is used to initialize and control the mouse sensor and interface with a laptop via a UART port, as well as to perform the demodulation process with its firmware, i.e., converting the output of the mouse sensor to the original transmitted digital information.

Experimental setup and system operation. Figure 1 shows the system block diagram of our MouseVLC implementation. A laptop sends the digital information to the Peggy board, which is then converted into moving patterns shown on the LED array. The transmitting Peggy 2LE board is placed vertically on the floor, and the receiving mouse sensor is 45 cm from the transmitter and at a height of 14 cm from the ground. Experiments are performed in an indoor environment with normal ambient lighting level. The mouse sensor outputs the X and Y displacement values, and they are processed and demodulated with Zigduino firmware. Finally, the demodulated digital information is relayed via UART to the receiving laptop for display.

Table I
PATTERN ERROR RATE EVALUATION RESULT

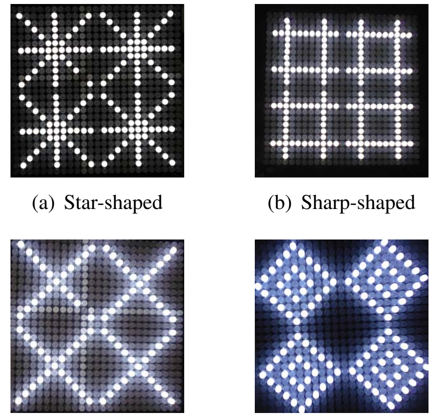
	Number of movement detection	Number of errors	Error rate
Cross	16679	18	0.108%
Double Diamond (1px spc)	18843	35	0.186%
Double Diamond (2px spc)	16264	501	3.080%
Single Diamond	11246	13	0.116%
Star	21771	33	0.152%
Sharp	21044	266	1.264%

IV. EVALUATION

Moving Pattern Design. The optical flow algorithm utilized by the mouse sensor is proprietary and unknown to us. To determine a transmitting pattern that could produce accurate displacement information, both in the sense of less losses, i.e., undetected movements, and less errors, i.e., accurate reports of moving distance, a small experiment was performed. 6 patterns, including cross-shaped, double-diamond-shaped with 1 pixel spacing and 2 pixel spacing, single-diamond-shaped, star-shaped, and sharp-shaped patterns, were used in this evaluation. Figure 2 shows the 4 of these 6 patterns, and Figure 3 shows the 30x30 images captured by the mouse sensor when these 4 patterns are used. Note that the mouse sensor does not capture the entire pattern shown on the transmitting LED array. In the experiment, the LED array would shift the pattern to the right by 1 pixel for 13 times, and then repeat the same operation but instead shifting the pattern to the left. Each pattern is displayed for approximately 1.352 ms before it is shifted, resulting in a transmission frame rate of 740 Hz. Since there are only horizontal movements displayed by the LED array, the output of the mouse sensor should report non-zero X displacement and zero Y displacement.

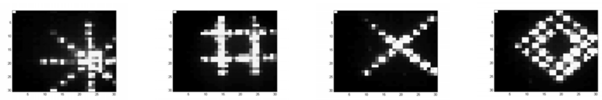
Table I shows the evaluation results, which help us to select a well-detected shape. Observed non-zero Y displacement values are treated as errors. One can observe that the star-shaped pattern has the best performance; the number of movement detection is higher and the error rate is lower. Although the cause of the errors is hard to determine, it is apparent that patterns including slashes lead to lower error rates. On the other hand, patterns with higher density of ‘ON’ pixels, such as double diamond with 2 pixel spacing, could result in a larger number of errors. Due to space limit, the accuracy in the amplitude of the displacement values is not evaluated in this paper.

Modulation design. The modulation used in MouseVLC is a form of *“binary movement shift keying”*. The movements of the pattern to the right and to the left represent bit 1 and bit 0, respectively (see Figure 4). The transmission frame rate is kept at 740 Hz, the same as the previous experiment. To improve robustness of our system, we have the following design choices: (1) the movements to the top and to the bottom are not used to represent data; this ensures that a



(a) Star-shaped
(b) Sharp-shaped
(c) Cross-shaped
(d) Double-diamond-shaped with 2 pixel spacing

Figure 2. Four of the patterns used in the evaluation, shown by the transmitting LED array



(a) (b) (c) (d)

Figure 3. The 30x30 images captured by the mouse sensor when different patterns are used (a) Star-shaped (b) Sharp-shaped (c) Cross-shaped (d) Double-diamond-shaped with 2 pixel spacing

rotation of the transmitter or the receiver do not introduce a large number of errors with the trade-off of reduced data rate; (2) the movement to the top is used as a delimiter between two consecutive symbols, so that the boundaries of the symbols can be recognized; (3) each symbol or delimiter is represented by K consecutive moves in the same direction, $K = \{5, 6\}$, with each move shifting the pattern by 1 pixel. This reduces the chance of a symbol error, but also reduces the symbol rate; (4) the star-shaped pattern is used as the transmitting pattern, since the evaluation in the previous subsection shows that it produces the least error.

Figure 5 shows an example of the demodulation process, starting from the sequence of X and Y displacement values (represented by dx and dy, respectively) obtained from the sensor (the first column of values from the left). The first step is to split the entries with non-zero X and Y displacement values into two separate entries, converting the first column into the second column. The second step is to either count the number of consecutive non-zero dx or dy entries (no. of detection method), or the total distance of movements in consecutive non-zero dx or dy entries (accumulated value method). If the calculated value is larger than the corresponding threshold, then these entries will be considered as a valid data symbol or a valid delimiter. Otherwise, they will be ignored. The thresholds for the no. of detection method are both 2 (for X and Y), and the

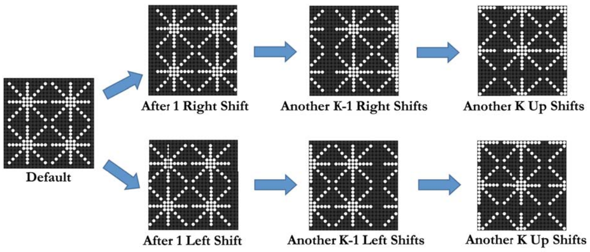


Figure 4. Simulation of the moving patterns of binary movement shift keying

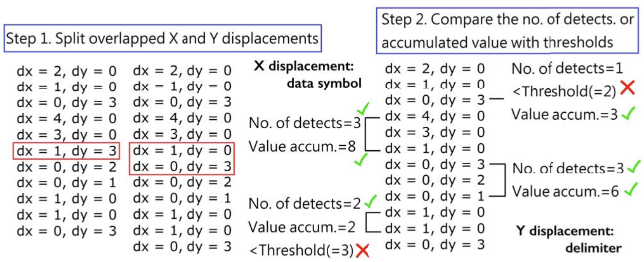


Figure 5. An example of the demodulation process

thresholds for the accumulated value method are 3 for X and 2 for Y, respectively.

Table II shows the final evaluation results. Two parameters are changed in 3 batches of experiments: the transmission frame rate (100% and 50%) and the number of shifts per symbol or delimiter (5 or 6). A random text is transmitted for a number of times and the demodulated text at the receiver is compared to the original transmitted text to calculate the byte success rate. One can observe that the accumulated value method is more robust to noises in the sensor output, resulting a higher byte success rate. One can also see that if the transmission frame rate is reduced or the number of shifts per symbol/delimiter is increased, the movements can be captured by the mouse sensor with less misses, and thus the byte success rate is increased. With our MouseVLC implementation, we can achieve a data rate of 74 bit/s (740 Hz transmission frame rate and 5 shifts per symbol/delimiter) with a byte error rate at 0.1%.

V. Conclusion and Future Work

In this paper, we present MouseVLC, a CamCom system that utilizes an ordinary mouse sensor as the receiver. The transmitter uses moving patterns shown on a LED array to represent digital information, and the receiver can reconstruct the transmitted digital information from the output of the mouse sensor in the form of a series of X and Y displacement values. Our system can achieve a data rate of 74 bit/s with less than 0.1% byte error. The future work will focus on improving the data rate by using less number of movements to represent a data symbol and introducing a FEC code in the system to improve robustness.

Table II
Byte success rate comparison

Scenario		Method	
TX frame rate	**No. of shift per symbol**	**No. of detection**	**Accumulated value**
740 Hz	5	95.5%	99.9%
740 Hz	6	97.1%	99.9%
370 Hz	6	98.0%	100%

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