Bi-Directional Communication Between Infra-Structure and Mobile Device Based on Visible Light Communication

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***Abstract*—A visible light bi-directional data transmission system based on visible light communication using white tri-chromatic LEDs is presented. The proposed communication system allows indoor navigation for a mobile autonomous picking robot moving in a warehouse. Downlink communication from the infrastructure to the mobile device allows positioning, navigation services and data transmission. White LEDs are used at the lamps infra-structure to illuminate the space and to transmit data and provide positioning. An a-SiC:H/a-Si:H pin-pin photodiode is used at the receiver unit to decode the transmitted data and infer location. Different coding schemes are proposed, considering the need to prevent flickering effects in downlink communication.**

Keywords- visible light communication; white LED; on-off keying, indoor navigation; bidirectional communication.

I. INTRODUCTION

The connection of people and physical objects with the Internet gave rise to new demands on the performance of communication networks, regarding essentially, transmission data rates. This created new challenges to develop communication networks operating at higher data rates and reduced latency, ensuring simultaneously energy saving and cost reduction solutions. The combination of these features is thus the key for higher system capacity and massive device connectivity. In order to accomplish this goal, it is expected that the next-generation of communication networks will integrate several different complementary access technologies, addressing thus the challenge to explore other ranges of the electromagnetic spectrum, also suitable for communication.

Non-guided optical communications are currently a competitive technology, that in a few application areas can be considered as alternative to radio transmission systems or guided optical communication systems. It operates in the near infrared or visible range, using lasers or Light emitting Diodes (LED) as optical sources. Wireless Optical Communication (WOC) technology can be used indoor or outdoor, using four generic system configurations, i.e., directed Line-Of-Sight (LOS), non-directed LOS, diffused, and quasi diffused. Outdoor wireless optical communication operating in the infrared range are also named as Free-Space Optical (FSO) communication. Optical communication operating in the visible range, either indoor or outdoor, are labelled as Visible Light Communication (VLC) and use white LEDs or single-color LEDs [1], to code and transmit the information data [2].

In VLC, data are basically transmitted by switching on and off the LEDs at a higher rate that the human eye can discern [3]. This technology is nested on the ubiquitous use of LEDs for lighting solutions. LEDs provide high energy efficiency when compared to conventional, almost obsolete, incandescent and fluorescent lamps, and at the same time are much more reliable and environmentally friendly, as they are mercury free. Thus, VLC is a precursor optical communication technology for large scale integration with other conventional widespread communication technologies, either indoor or outdoor [4][5].

Main advantages when compared to radio technology are free licensed spectrum, immunity from electromagnetic interference and, less power and weight/volume requirements [6]. Therefore, VLC finds application in many fields ranging from smart systems (transportation, targeted advertisement, health care monitoring), safe communication at RF hazardous places (petrochemical industries, mining) or RF undesirable locations (hospitals, aircrafts), indoor navigation and localization services [7], specific networks (underwater, near field, high speed data communication, Internet of Things network) to energy efficient systems as home automation and domotics [8].

Indoor navigation based on VLC are attractive solutions for Indoor Positioning Systems (IPS), as Global Positioning Systems (GPS) signals are strongly absorbed by the buildings and other wireless solutions need to be used. IPS based on VLC can be used for multiple purposes. Main applications include accessibility aids for visually impaired, navigation in large indoors areas (such as museum guided tours, shopping malls, airports, bus or train stations, parking lots), targeted advertising, augmented reality, indoor robotics, asset tracking and warehouses, among others.

Nowadays, retail market has several online and offline channels of sales and services like same day delivery or store pickups. Costumers preferences have evolved forcing companies to reduce the order-to-delivery time which demands an increased logistics and new enterprise models based very often on technological innovation [9].

Warehousing is designed to provide value and service quality to clients and customers, which corresponds simply to deliver in the shortest possible time [10]. In this field,

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flexible automation is the best solution for warehouses to gain a competitive advantage. Order picking is one of the most labor intensive and expensive activity in every warehouse, where high efficiency is a demand to improve the delivery process. Any underperformance of the order-picking process can affect the whole supply chain and lead to unsatisfactory service and high operational cost for the warehouse. Thus, under the dual goal of efficiency and save labor costs, modern warehouses are evolving to new levels of automation using a diverse type of driverless vehicles, such as, mobile picking robots, self-driving forklifts, autonomous inventory robots or unmanned aerial vehicles [11].

Mobile robotic picking solutions that provide the transport of goods to the packaging station operated by a human worker can add a new level of efficiency to the process. These autonomous machines typically carry carts or racks following a previously defined route in the warehouse to move products to the packaging stations. These autonomous vehicles take advantage of sensing technology development and advanced algorithms to infer optimized routes. The vehicle movement inside the warehouse lays on indoor localization and indoor navigation techniques based on WiFi communication technology [12][13].

In this paper, we propose an indoor localization system [14][15] designed with white RGB LEDs and a pinpin photodiode based on a-SiC:H/a-Si:H with a simple On-Off modulation scheme [16][17]. The system is designed to establish bidirectional communication between a static infrastructure and the mobile picking robot. The LED luminaires at the warehouse ceiling are used to lighten the warehouse space, and to transmit information about positioning and available racks. The picking robots communicate with the ceiling luminaires to send information about the rack that is being removed and carried to the packaging station. The system uses bi-directional communication which demands different codification schemes to establish both uplink and downlink communication between LED luminaires and mobile robots. This communication uses three different communication channels ensured by 3 different wavelength emitters of white tri-chromatic LEDs.

During the past decades, channel coding has been used extensively in most digital transmission systems. It is now widely used also in optical communication, which, however, brings in several challenges to the code design and implementation. In the specific case of optical links based on VLC, the use of on-off keying intensity modulation (OOK IM) to carry digital information into LED light signal may affect the light brightness. This is due to the distribution of information bits 1's and 0's in the transmitted data frames, as LEDs are turned on or off whether the data bits are 1 or 0. This procedure is prone to produce unbalanced light intensity as long runs of 1's and 0's may cause light intensity fluctuation over a short period, which may exceed the persistence of the human eye and cause noticeable brightness change, i.e., flicker.

To ensure a stable and dimmable illumination, modulation and coding technologies of VLC systems must be able to provide flicker mitigation and dimming support [18] to avoid perceivable brightness fluctuation, as suggested in IEEE Standard 802.15.7 [19].

Different approaches to overcome this undesirable effect make use of Forward Error Correction (FEC) codes followed by DC-balanced Run-Length Limiting (RLL) line codes (e.g., Manchester codes), which break long runs of the same symbols in the code word (i.e., 1 s or 0 s). However, as RLL line codes have code rates less than 1, the transmission efficiency of VLC systems can be decreased, which in certain applications will affect the system performance. Other solutions use auxiliary coding techniques, such as code puncturing, scrambling, RLL line codes or even advanced coding schemes such as Low-Fensity Parity Check (LDPC) codes and turbo codes [8]. In the proposed application, the transmission speed is not a critical issue, as the whole process is mainly dependent on the mobile robot speed along the warehouse. Thus, the use of run-length limiting line codes is adequate as far as the code word for downlink communication balances the distribution of symbols. In uplink communication these effects are negligible as the optical source from the mobile robot is used only for data communication and not for illumination.

The simultaneous use of three different wavelengths corresponds to wavelength multiplexing which demands demultiplexing of the generated photocurrent signal by the photodiode receiver. This task was accomplished using a photodetector based on a-SiC:H/a-Si:H with operation in the visible spectrum. Its sensitivity to different wavelengths can be tuned using steady state light illumination [20]. This feature is used in the decoding strategy to infer the optical signals received by the photodetector [21].

II. COMMUNICATION CHANNELS

The proposed VLC system includes an indoor scenario of bidirectional infrastructure-to-device communication. The LED luminaires at the warehouse ceiling are used to perform three tasks, namely, room illumination, position/navigation services and data transmission. The picking robots communicate with the ceiling luminaires to send information about the rack that is being removed and carried to the packaging station.

The proposed system is composed of the transmitter and the receiver modules, located at the infra-structure and at the picking robot. Downlink communication is established from the ceiling luminaires to the picking robots and uplink communication is from the picking robot to the correspondent ceiling lamp where the movable rack belongs. The optical source of the transmitter at the ceiling lamps is composed of four white RGB LEDs while at the robot it is a multicolor LED or three different single-color LEDs placed at the top of the robot. Coding and modulation of the transmitters allow the transmission of the encoded data signal using on-off modulation. Different coding schemes are proposed to establish uplink and downlink communication. The receiver modules are placed at the ceiling lamps and at the robot. It includes demodulation and decoding of the electrical signal generated at the photodiode. The transmission channel of the optical link is free space propagation. In Figure 1, it is displayed the communication channels established between the lamps and the mobile robots.

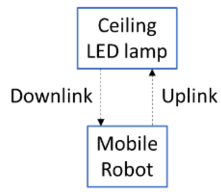

Figure 1. Communication channels established between the lamps at the ceiling and the mobile robots.

A. Transmitters and receivers

The transmitter proposed in this VLC system uses ceiling lamps based on commercial white LEDs with red, green and blue emitters (w-RGB LEDs). Each LED luminaire at the ceiling is composed of four white LEDs placed at the corners of a square. The w-RGB LEDs are designed for general illumination providing therefore, high output power (550 mcd, 850 mcd and 320 mcd, for the red, green and blue emitters, respectively) and wide viewing angle. Analysis of the output light spectrum demonstrates the presence of three distinct gaussian peaks located in the blue (460 nm – 480 nm), green (520 nm – 540 nm) and red (619 nm – 624 nm) regions.

The receiver module includes a photodetector to transform the light signal into an electric signal that is later demodulated and decoded to extract the transmitted information. The photodetector used for the transduction of the optical signal is a monolithic heterojunction composed of two pin structures based on a-Si:H and a-SiC:H and built on a glass substrate between two transparent electrical contacts. The device operates in the visible spectrum and exhibits two different absorption regions due to the presence of the two absorber layers in each pin structure. Selective absorption of long and short wavelengths can be achieved by adding steady state illumination of short wavelength (400 nm) to the photodetector. When this background light soaks the device, from the side of the a-SiC:H pin structure (front illumination), long wavelengths (red and green) provide amplification of the photocurrent, while short wavelengths (blue) attenuate the signal. Under background illumination, from the side of the a-Si:H pin structure (back illumination), the behavior is reversed. Signal amplification is obtained for shorter wavelengths and attenuation for longer wavelengths. The quantification of the signal amplification under front and back optical bias is evaluated by the optical gain, defined at each wavelength as the ratio between the signal magnitude measured with and without optical bias. For the red, green and blue light the front optical gain under 400 nm background light is, respectively, 5, 3.5 and 1.3, while the back optical gains, is, for the same wavelengths, 0.6, 0.6 and 1.7.

In Figure 2, it is displayed the configuration of the luminaire with the four tri-chromatic white LEDs. With this configuration all emitters (red, green and blue) are switched on to provide uniform white lighting in the indoor area. However, only specific emitters are modulated at a frequency imperceptible to the human eye.

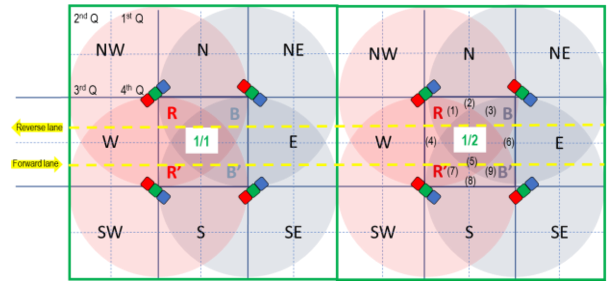

Figure 2. Configuration of the RGB white LEDs of the ceiling lamp showing the optical patterns generated by the red and blue modulated emitters (red emitters at each left side: R and R', and blue emitters at each right side: B and B').

Each of these lamps illuminates an area as shown Figure 2. All green emitters of the lamp are modulated with the same coding scheme to transmit the unique identification of the lamp. Red emitters at the left corners of the square are also modulated, using different frequencies, while the blue emitters remain on in a steady state. The top emitter is pulsed at half frequency of the bottom one. At the right side, a similar modulation scheme is used for the blue emitters, and here the red emitters stay on in steady state. Under this configuration the illumination pattern in the area covered by the light supplied by the lamps allows the definition of the unit navigation cell. Inside this area any receiver will be able to receive the identification of the emission luminaire (supplied by the green emitters) and make the correspondence to the spatial position. Increased position accuracy within each navigation cell is obtained through the optical pattern established by the red and blue modulated emitters of each lamp. Top emitters are assigned to the north cardinal direction inside the navigation cell, while bottom emitters to the south, and left and fight emitters, respectively, to the west and east directions. The illumination of the indoor space is done using different luminaires placed contiguously at the ceiling, which enables successive identification of each luminaire. In Figure 3, it is displayed the spatial organization of adjacent navigation cells with the illustration of the different nine cardinal sub-sections. Each of these regions can contain 4 racks, which spatial position is assigned by the correspondent quadrant (first, second, third and fourth).

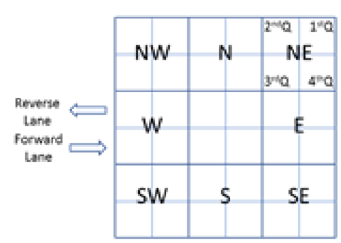

Figure 3. Spatial organization of the navigation cell and respective cardinal sub-sections.

B. Network topology

The network established between the luminaires and the mobile robots demands the definition of specific coding schemes to enable the accurate identification of signal transmitters and receivers. The downlink channel from the ceiling lamps to the mobile robot provides positioning information which enables navigation services and information about the available racks in each area. The uplink channel from the mobile robot to ceiling lamps provides information about the removed rack by each robot. Ceiling lamps provide information about location and about the presence of racks in the area covered by the unit navigation. As these luminaires use slow and fast modulated red/blue emitters and green emitters, the data frame structure is defined differently, depending on the type of emitter. In the downlink coding scheme, each frame in each channel is a word of 32 bits, divided into four blocks. An on-off keying modulation scheme was used with a 32-bit codification (logical state 1: light on and logical state 0: light off). The first and the last blocks ensure synchronism between the emitter and the receptor for correct demodulation of the transmitted signal. The first block (4 bits) is composed of two idle bits (logical value 1) and two start bits (logical value 0) and the fourth block by two stop bits (logical value 0) and two idle bits (logical value 1). The second block is a word of 12 bits. In the fast and slow red and/or blue emitters, this word contains the information on the position within the navigation cell, which is assigned to the frequency. Slow emitters have a frequency half of the fast emitters. The green emitter is used to carry the identification of the unit cell. Its format was designed to ensure safe decode of the signals and prevent errors. It is a 12 bits word where the logic state of each bit never changes simultaneously with the other fast and slow red and blue emitters. The format of the word code is 0XXXX00YYYY0, where XXXX addresses the line and YYYY the column of the unit navigation cell. The third block of every emitter is a 12 bits word, reserved for the transmission of the information related to the available racks inside each navigation area. As the area covered by the navigation unit comprises nine cardinal sub-sections containing four quadrants each, it is necessary 9 x 4 = 36 bits to infer which of these spatial positions, i.e. racks, are available. Each of the channels (12 bits available) transmits information about 3 sub-sections, using 4 bits for each. The first bit is assigned to the first quadrant, the second to the second quadrant and so on. Slow emitters of each navigation cell transmit information about northwest, north and northeast directions, fast emitters at the bottom about southwest, south and southeast, and the green emitters about west, center and east positions.

When the picking robot reaches the desired position defined by the route, it will remove the rack and carry it to the packaging station. It will be necessary for the robot to inform the ceiling lamp which rack will be removed from the correspondent navigation cell. Thus, a dedicated channel establishing communication from the picking robots to the ceiling lamps is needed to register which rack will be temporarily out of the corresponding position inside the navigation unit. This communication will be enabled by VLC using a multicolor LED or three different single-color LEDs placed at the top of the robot. The establishment of communication demands the identification of both partners (lamp and robot). The uplink channel uses three wavelengths and the info is coded in a 3x32 bits word with a simple structure of four blocks: two synchronization blocks (2x4 bits) located at the beginning and at the end of the word and two informative blocks (2x12 bits) in the middle. The first 12 bits block contains the identification of the ceiling luminaire that is illuminating the robot (red emitter) and the identification of the robot responsible for picking the rack (green emitter). Bits of the blue emitter identification block are all assigned to zero. This will demonstrate that the origin of the communication comes from the robot, as in the words from the ceiling luminaires this block is sequentially fulfilled of ones and zeros codes. Flickering effects are negligible, as these LEDs are used only to transmit information and not for lighting.

III. RESULTS AND DISCUSSION

The test case used to validate the proposed communication scheme is displayed in Figure 4, that shows the specific blocks of the 32 bits word of each emitter assigned to the lamps and to the mobile robot.

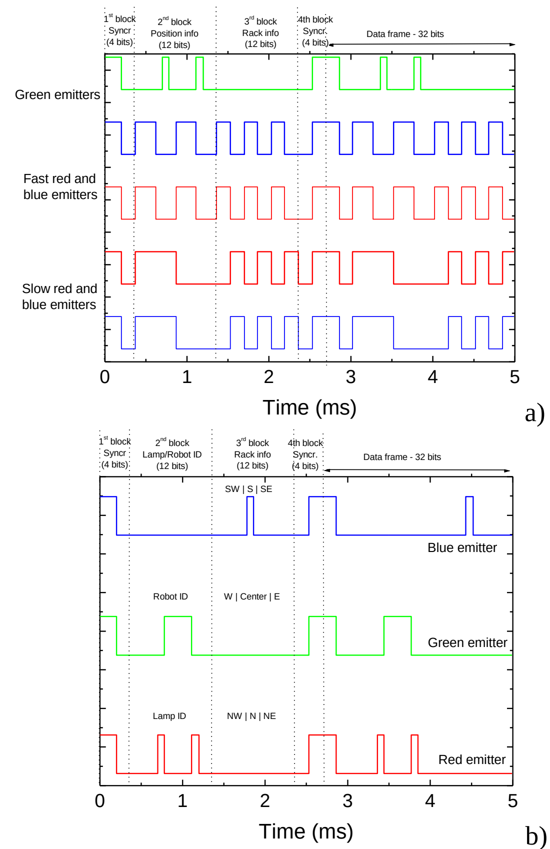

Figure 4 Codification of the optical signals transmitted by the: a) ceiling lamp; b) mobile picking robot.

In the code transmitted by the ceiling lamp (Figure 4a), the green transmitters send the code 1100 | 000010000100 | 0000 0000 0000 | 0011, which corresponds to the navigation cell with identification 1-2 (line 1: 0001, column 2: 0010) and to the information that there is no rack placed in the position west, center and east of the same cell. Slow emitters transmit the 1100 | 111111000000 | 0011 0011 0011 | 0011 code which identifies them as top emitters inside the navigation unit cell and states that in northwest, north and northeast sub-sections the third and fourth quadrants contain available racks that can be picked by the robot. In these quadrants, the 1st and 2nd quadrants are empty of available racks. Fast emitters transmit the code 1100 | 111000111000 | 1100 1100 1100 | 0011 which represents their position as bottom emitters in the navigation unit cell and informs that in the southwest, south and southeast sub-sections the 1st and 2nd quadrants contain available racks to be moved while the 3rd and 4th racks are not accessible as they are empty

In Figure 5, it is displayed the photocurrent signal measured by the mobile robot under variable conditions of optical bias (without and with front/back steady state background light). The signal was acquired in position (9) of the navigation cell 1-2, when the picking robot moves in the forward lane to remove a rack of the first quadrant of sub-section southwest (SE).

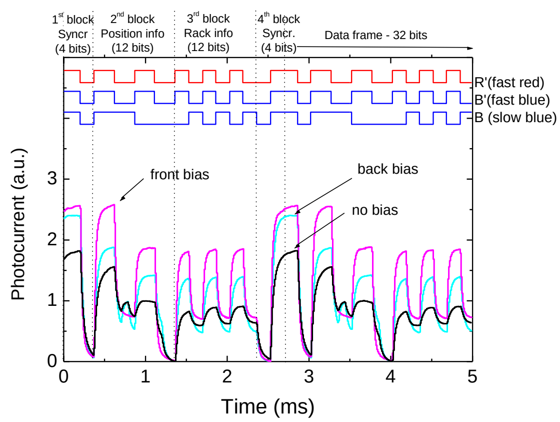

Figure 5 Photocurrent signal (measured without and with front/back steady state light) measured at position (9) of the navigation cell 1-2 after removing the contribution from the green emitters At the top it is displayed the optical signal of each emitter.

The signal was acquired in position (9) of the navigation cell 1-2, when the picking robot moves in the forward lane to remove a rack of the first quadrant of sub-section southwest (SE). At this position the optical excitation comes from the fast red and blue emitters and from the slow blue emitter. The displayed output signal has already been removed of the contribution due to the green optical excitation. In the graph, the trigger event allows easy synchronization and identification of each transmitted frame. This is noticeable by the highest peaks of the front photocurrent signal (represented in the graphs by the magenta line), as well as by the idle bits (all emitters are set to 1). This combination results in photocurrent amplification when the device is soaked by front steady state illumination. By opposition, the same signal under back background light is decreased.

Then, it is necessary to decode the next blocks of the data frame. It is assumed that in the front photocurrent the highest levels correspond to the presence of the red light, while the lowest ones to its absence, which allows the immediate recognition of the ON-OFF states for the red channel. The same reasoning can be used to analyze the back-photocurrent signal. Here the highest levels are assigned to the presence of the blue input signal and the lowest levels to its nonexistence, which allows the decoding of the blue channel. However, at the regions where there are two different signals transmitted by the same wavelength, this approach is not feasible, as it is necessary to infer which of these is channels is on or off. The approach used to decode each optical state was based on the use of a calibration curve. This was obtained by scaling all the possible signal output levels (Figure 6, solid black line) and measuring the photocurrent signal under front optical bias using two red and two blue optical signals. The driving current of each LED emitter was adjusted to provide different levels of photo excitation. On the right side of the picture in Figure 6, it is shown the label of the modulated emitters that correspond to each photocurrent level.

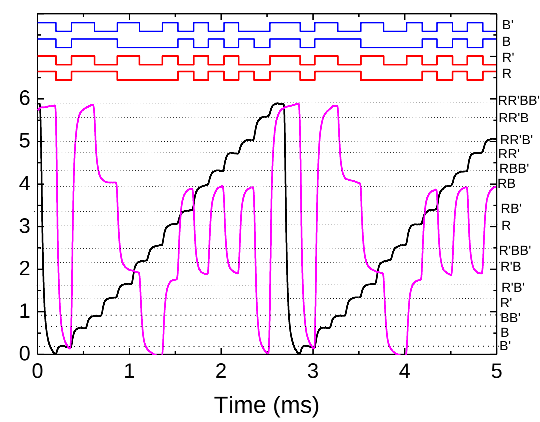

Figure 6 Front photocurrent signal acquired along the forward path at position (9). In superposition it is displayed the calibration grid. Contribution from the green emitters has been removed.

In Figure 7, it is displayed the front photocurrent signal due to the optical signal transmitted by the robot after removing a specific rack at the third quadrant of the south sector inside the navigation cell 1-2.

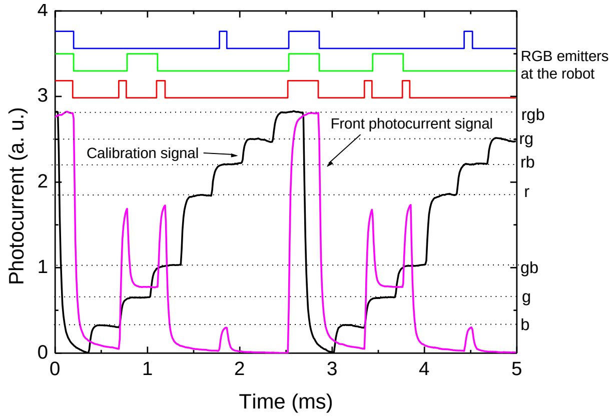

Figure 7 Front photocurrent signal transmitted by the robot when removing a rack. In superposition it is placed the calibration curve with 8 levels.

The calibration curve obtained with the 8 possible combinations is also displayed for decoding purposes.

IV. CONCLUSION

Simultaneous navigation and data transmission based on visible light communication was presented and discussed using bidirectional communication between infrastructure and autonomous vehicle in an indoors scenario. The infrastructure is the ceiling luminaire and the autonomous vehicle a mobile warehouse picking robot. The transmitted data is encoded in a 32 bits word, defined using specific data frames in each direction of the communication to ensure information transmission. Codification of the optical signals ensured synchronization between frames and was also designed to shield the decoding process from errors that might provide wrong identification of the correspondent spatial position and to minimize flickering effects.

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