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Automated Guided Vehicle Controlled by Li-Fi: A Study Case

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Abstract: Some Automated Guided Vehicles (AGVs) currently use bidirectional infrared (IR) laser communication to control their tasks in industrial facilities. Laser technology's disadvantage is the need for tight alignment between the transmitter's narrow beam and the receiver's small surface, imposing mobility constraints. The present work tackles this challenge by proposing a replacement for laser communication, using Light Emitting Diodes (LEDs) and Light Fidelity (Li-Fi). It uses the visible and near-infrared spectral bands of the electromagnetic spectrum to send data. A small-scale solution to an existing industrial scenario where laser communication is used to send data to moving AGVs is presented. A white LED is used as an emitter to simultaneously enlighten and send data to the AGV, while a photodiode is used as a receiver to decode the variations of light into electric control signals. So that the vehicle can send information back, infrared LED communication is used. Since the beam of an LED is wider than a laser beam, the AGV under this beam has more freedom of movement. This gives more flexibility and robustness to the industrial facility. The small-scale prototype presented in this work reports freedom of movement gain factor of 157 compared to the previous solution.

Keywords: Industry 4.0, AGV, Autonomous Vehicle, Li-Fi, Visible Light Communication, LED

1. INTRODUCTION

The automation and optimisation of industrial processes encouraged the implementation of Automated Guided Vehicles (AGVs) in all sectors [1]. The diversity of these AGVs is important. To cite few examples, there are autonomous parcels sorting trolleys that follow a path thanks to QR (Quick Response) codes and anti-collision algorithms [2], autonomous vehicles using 5G to move in storage sheds without privileged direction [3] or, AGVs that go only in one direction to collect and distribute pallets [4]. More examples can be found in [5]. In this work, the focus is on industrial AGVs that browse straight paths to collect pallets. These self-driven vehicles receive orders from a central Programmable Logic Controller (PLC) which is an autonomous unit that controls, automates and regulates various industrial processes and all the elements that go into these processes, and return data to it using IR laser technology in both ways. The AGV is usually guided by a ground rail to keep it on a linear course. The disadvantage of IR laser technology is the need for a tight alignment between the transmitter and the receiver. This is why it imposes specific constraints in scenarios where the transmitter or receiver has a degree of mobility. Even if the AGV is guided by a rail on the ground, the vibrations of the engine at start-up may induce a local misalignment of the laser communication and thus an additional waiting time to recover the communication. An illustration, taken from a practical example developed by the company MAF RODA AGROBOTIC, which specialises in the fruit industry, can be found in Figure 1 [6]. The IR Communication (IRC) using lasers can be observed. The AGV is controlled by IR laser thanks to equipment such as an optical data transmission ISD400 developed by Sick - Sensor Intelligence company. The role of these autonomous vehicles is to repeat a sequence of actions at different stations, typically collecting filled or empty pallets and bringing them to another station. The commands are sent from a PLC via IR laser to the AGV. Once the action is completed, the vehicle informs the central PLC of its state. In addition, the AGV also has a safety sensor which verifies that the area including the trolley's movement is free to ensure the safety of the staff. Thus, if there is an object or a person present in a nearby area, the vehicle speed decreases. If the object or person is too close, an emergency stop is activated. Although each IR equipment has a transmitter and a receiver (transceiver), in order to facilitate the understanding of the paper, the transceiver, denoted as "Tx", will refer to the IR equipment that is connected to the PLC, and the transceiver, denoted as "Rx", will refer to the equipment connected to the AGV. In Figure 1, an illustration of such system is presented (more details can be found at [4]).

Figure 1 emphasises the crucial need of an alignment between Tx and Rx to have a functional system. One could also think about other wireless classical Radio Frequency (RF) to perform the previously described communication link, but some would presumably not behave well in industrial warehouses where many metallic walls induce multipath effects and environments are possibly electromagnetic sensitive [7]. To alleviate this problem of alignment, Light Fidelity (Li-Fi) is a good candidate to replace such infrared laser systems. The advantages of Li-Fi are the union of lighting and communicating, combined to the LED's wide beam aperture. As the radiation

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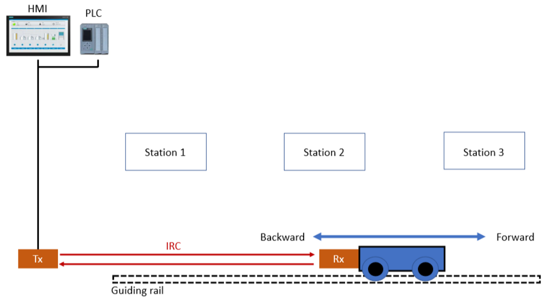

Fig. 1. Illustration of the system deployed nowadays at MAF RODA AGROBOTIC

pattern of the optical power of LEDs is much broader than a laser, it enhances mobility flexibility under the beam of light. It should be noted that replacing the infrared lasers by LEDs would solve the alignment constraint but will not solve the problem of loss of communication when an obstacle is located between Tx and Rx and far enough away from the AGV not to engage its emergency stop mechanism. Using the LED lamps that illuminates the stations from the ceiling of the infrastructure allows to avoid this kind of blockage while taking advantage of the LED's light coverage. Furthermore, a preliminary research paper has studied the potentials of commercialising the idea of this paper and has caught the attention of industry experts [8].

The rest of the paper presents first a scientific literature review focused in particular on how to geolocate AGVs and give it orders using Li-Fi. It is followed by the current state of standardisation of this technology. Then, the general structure of the solution is presented as well as its small scale practical implementation. Finally, the results and a discussion conclude the paper.

2. RELATED WORKS

2.1 Scientific literature

The fast-going adoption of LEDs on a global scale in indoor and outdoor environments has increased the interest in studying Li-Fi in all areas of applications. In the industrial sector particularly, studies highlight its use in e.g. robotic arm control [9], mobile assembly lines [10] and in hospitals [11]. In the case studied in this paper, the Li-Fi system takes advantage of the existing LED infrastructure for illumination and complements it to send the different commands to the AGV. The latter should be equipped with an infrared LED in order to acknowledge the reception of the commands and to inform of its position at any time. The choice of having infrared instead of white light for the uplink communication is for eye comfort for the operators and to avoid interference between both communication paths. The scientific literature has been explored in the search for a method/algorithm for locating autonomous vehicles in an industrial environment using light. A method for an AGV to know where it is located in a room is to use frequency identifier (ID). The principle of this localisation is to have a room completely illuminated with a collection of LED lamps that flicker each at a defined frequency. This frequency is higher than the human retinal persistence and the epilepsy limit, thus abstracting from potential health problems. At the receiving robot side, the analysis of the light signals coupled with the signal's strength allows the AGV to locate itself spatially in the room and to execute a task accordingly. A small-scale demonstrator based on this principle can be found in [12]. Further investigation needs to be carried out to have a bidirectional communication. This technique, with some changes, can also be used as a marketing tool to trigger location-based content in interesting areas. For example, Li-Fi-enabled receivers located on shopping carts can receive short beacons to know where they are in the shop and trigger the right advertisement on the end device [13]. Nevertheless, these systems are limited to sending short data to enable location based actions. In the problematic of this paper, a bidirectional communication is needed to initiate a communication between the central PLC and the moving AGV. The work in [7] proposes a review on the different positioning methods as well as a Li-Fi positioning system prototype based on the G.9991 standard. The proposed system can achieve positioning accuracy in the centimetre range in three dimensions. The difference in value of the present paper is that it solves an existing problem using an AGV that does not need to be precisely located by light. Above all, it is essential to have a wireless means of communication that allows for mobility, handover and coverage.

2.2 Standardisation effort

At present, there is no single standard for Li-Fi. The most popular standard, IEEE 802.15.7 (2011), is mainly concerned with low-speed applications and uses simple modulation techniques such as On-Off Keying (OOK) [14]. The last update of this standard was provided in 2018. Next, is the ITU (International Telecommunication Union) G.9991 standard which focuses on merging the ITU G.9960 standard and the Li-Fi optical interface and including more complex modulation schemes [15]. Over the years, the interest of using Li-Fi in the industrial sector grew and the new standard IEEE 802.15.13 is being written targeting solely this sector [16]. The industrial standard mainly targets high data rate optical wireless communication systems (up to 10 Gbit/s), with communication distances up to 200 m. It has been foreseen to be compatible with difficult or sensitive environments such as industrial warehouses or hospitals where conventional wireless system can not be easily deployed. Furthermore, Li-Fi is immune to RF interference and do not spike through walls which ensures privacy and thus security for the industry owner. The wavelength range used by the standard is from 190 nm to 10000 nm containing the visible spectrum that lies between 380 nm to about 750 nm. The standard also defines a physical (PHY) and a Medium Access (MAC) layers to provide handover protocols between cells of light. The most robust modulation scheme devised for the industry is OOK. Finally, even though a single standard does not target Li-Fi, there are already tailored proprietary market products that are available [17][18][19][20].

3. ARCHITECTURE OF THE LI-FI COMMUNICATION SOLUTION FOR AGVS

Three stations lighting the moving AGV are shown on Figure 2. Where one IR laser per direction was used in the initial scenario described in the introduction of this paper (cfr Fig. 1), these narrow laser beams are replaced by several LEDs located on the ceiling of the facility, all linked to the central PLC. It is important to mention here that a laser beam with a long range is replaced by a set of LEDs, keeping the same range of communication as the former solution and addresses the restricted alignment of the laser. On Figure 2, HMI (Human Machine Interface) represents the screen the technician uses to send and control the data to and from the AGV. In order to send data through light, the current of each LED is shaped at the pace of the digital data. In this paper, a proof of concept is described to encourage the use of Li-Fi in industrial environments, especially when laser-based communication link is currently in use.

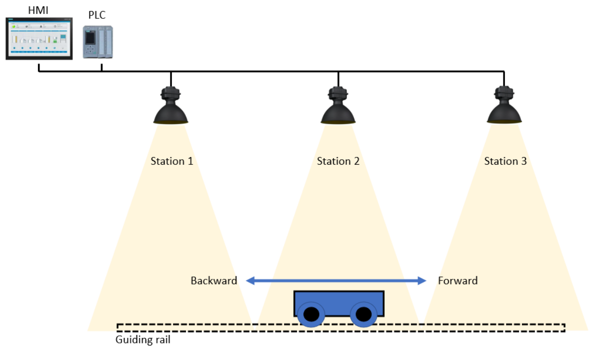

Fig. 2. General architecture of the system

The AGV needs to receive instructions and to send back some information about its state. These commands and information can be seen on Figure 3. The commands go from the ceiling white LED to the AGV. Each command mentions the station of destination as well as the action (give or receive pallets) that must be done. The vehicle always needs to check its safety state and acknowledge that it has done what it was required of it. The key point of this setup is that the light beams must cover enough ground surface to ensure that the AGV is always in line-of-sight (LoS) compared to the emitting LED and thus, receiving the instructions when under the light beam. For the LED infrared communication, the condition to reach is that the beam of the LED is sufficiently broad enough to cover one to two stations. The safety feature of the AGV operates in three modes. The safest one is when no obstacles are in the farthest zone up to the "Safety Warning" threshold distance. Below this critical distance, the speed of the vehicle is decreased until either the obstacle disappears or gets closer. If it gets closer and reaches the "Safety Alarm" threshold distance, the AGV stops immediately.

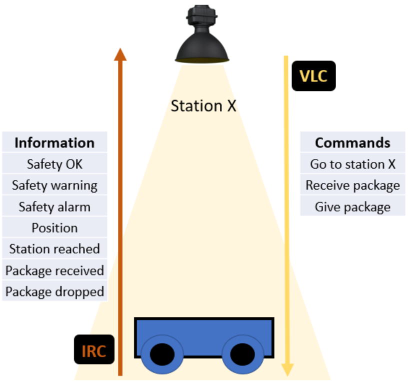

Fig. 3. Bidirectionnal communication needs of the AGV

4. IMPLEMENTATION

To demonstrate the feasibility of the Li-Fi solution, this section presents the small scale AGV system guided thanks to visible and infrared light. The AGV is emulated using a SunFounder PiCar-S connected to a Raspberry Pi 4. The VLC (Visible Light Communication) part is first presented followed by the AGV setup and finally the IRC.

4.1 Visible Light Communication

The research institute IMDEA develops open source VLC shields that can be connected to a BeagleBone Black (BBB) board called OpenVLC1.3. The system allows the transfer of up to 400 kbit/s through light using the UDP (User Datagram Protocol) transport protocol. The BBBs use a Debian Linux operating system. The capes use OOK modulation scheme, meaning that the light is turned ON when a digital 1 is sent and turns OFF when a digital 0 must be sent. Even though the BBB controlling the VLC shield is connected through USB to the central computer (which in practice will be the PLC in a large scale implementation), a Secure Shell (SSH) communication is used to communicate securely to the VLC. On the car's side (mimicking the AGV), the Ethernet interface is used to connect the VLC BBB to the Raspberry Pi.

4.2 Automated Guided Vehicle

The SunFounder PiCar-S Smart Car Kit is a smart car that works with a Raspberry Pi and rechargeable batteries. To mimic the AGV of the example taken from MAF RODA AGROBOTIC, an ultrasonic obstacle avoidance sensor is implemented as the safety sensor. Moreover, the developed Python algorithm running on the car mimics the different states of the AGV. Figure 4 shows the final VLC assembly result with the VLC receiver only. The OpenVLC shield, the Raspberry Pi and the Safety sensor can be seen. The algorithm running on the Raspberry Pi of the car, diagrammed on Figure 5, uses the

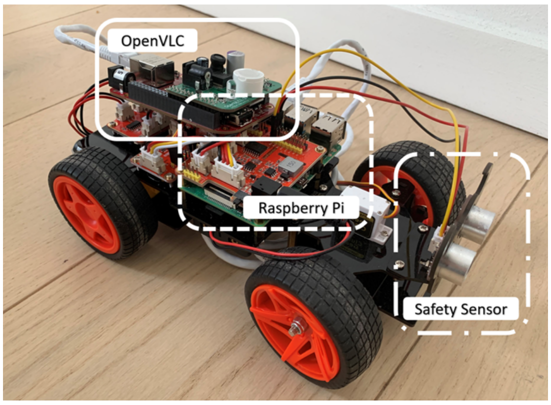

Fig. 4. AGV emulator with OpenVLC1.3 shield

library developed for the PiCar-S as well as a network socket to receive the commands from the Tx light. Once the command is received, the car quits the IDLE mode to go to the required station. Once at the station, it informs the central PLC (here a laptop) of its position then do the task of receiving or giving the package.

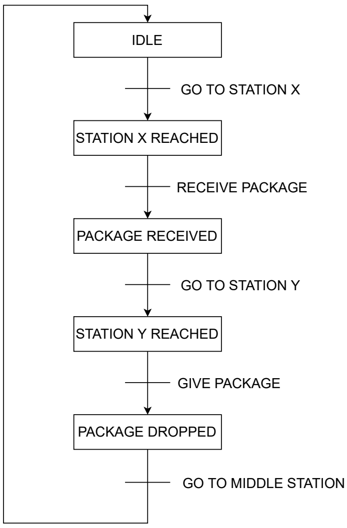

Fig. 5. Algorithm running on the AGV - SunFounder PiCar S

4.3 Infrared Communication

As the openVLC 1.3 capes do not have an infrared communication channel, one is implemented thanks to an OSLUX® 1 PowerStar IR LED with a peak wavelength of 810 nm as the emitter and a S1223 HANAMATSU photodiode with a mean responsivity of 0.56 A/W. An OOK scheme is used to send the AGV's state to the central PLC through infrared as recommended for industrial facilities. Ideally, the AGV's safety check loop should run on a parallel routine but for testing purposes this is checked at a pre-defined periodicity only. A data rate of about 200 kbit/s is reached.

5. RESULTS

The final setup studied in this paper consists in two stations comprising two OpenVLC1.3 shields that are hanged 1.95 meters above the ground and 1.5 meters apart from each other. For the uplink communication, an IR photodiode is connected to the ceiling BBB and one infrared LED emitter is located on the top of the PiCar. The AGV is asked to move from the first station to the second one or vice versa and to acknowledge its state every time. Figure 6 shows the schematic of the setup under study.

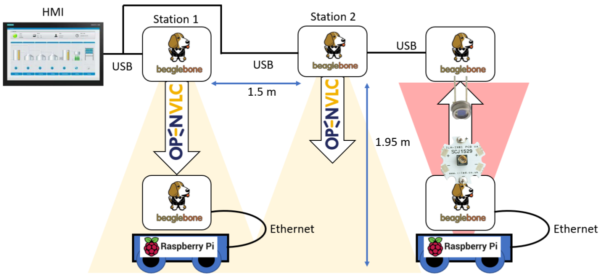

Fig. 6. Setup studied

5.1 Visible Light Communication

The estimation of the signal coverage depends on two main factors. The first one is the characteristics of the openVLC LED and the second one is the attenuation due to the medium between the emitter and the receiver. To assess the coverage and good reception of the signal, measurements of the optical power level as well as the packet loss rate have been conducted starting from the point just under the LED and moving outward. The measurements being made at uniformly distanced steps, it has been found that the LED covers a ground circle of 1.5 m of diameter in which the signal is well received. An LED's aperture angle of 42 degrees can therefore be deduced. Moreover, the light's strength is not sufficient enough to ensure a robust communication beyond the radius of 0.75 cm. The optical power received in that boundary is a level around 3.58 μW. It is measured thanks to an optical PM100D powermeter from Thorlabs. To determinate the operating range of the openVLC system, the optical power received at each increase of 10 centimetres of the radius of the circle is put in parallel with the percentage of packet loss of the system measured thanks to iPerf. The tool iPerf allows for the measurements of the maximum achievable throughput of an IP network, packet loss rates and includes many features and parameters like timing, buffers, throughput, protocols, etc. The bandwidth set for the test is a UDP communication of 400 kbit/s and the percentage of packet loss is also reported. Figure 7 displays the result. Depending on the application, a maximum loss rate and a maximum radius need to be adjusted. In this demonstrator, a radius of 75 cm and a loss rate of 6% are considered to be the boundaries of the AGV's surface of action. The zeros present on the graph after 0.75 m represent data not acquired. This system proposes a bigger surface of action for the AGV compared to the laser communication

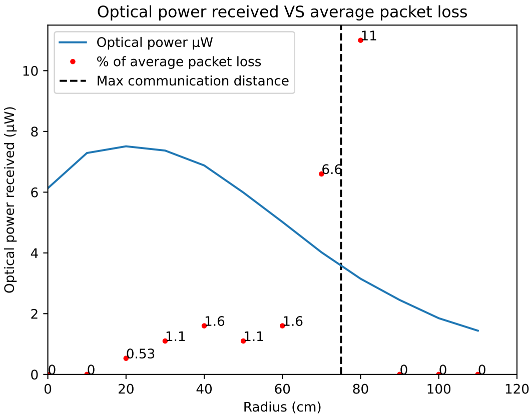

Fig. 7. Performance of the Li-Fi link

solution used by MAF RODA. If a radius of 0.75 m is considered for each station, the AGV can move freely on a surface of 4.71 m² for two stations 1.5m apart, thus on a horizontal distance of 3 meters. If we compute the movement freedom of the infrared laser solution, for a communication link of 3 meters, the alignment is sensitive to the centimetre, corresponding to a degree of freedom of only 0.03 m² for the AGV. If the ratio of available surface between the two scenarios is calculated, the result is called here the freedom of movement gain factor. The small scale prototype thus reports a freedom of movement gain factor of 157 compared to the previous solution. For the case we are solving, this factor is more than sufficient to avoid the parasitic vibrations of the AGV that cut off the laser communication during misalignment.

5.2 Infrared Communication

Figure 8 shows the results of the infrared communication with the LED, taken from a digital oscilloscope (PicoScope). The OOK modulation is observed when the photodiode is perfectly under the lamp (curve at the top of the figure) and when the limit of the communication is reached (curve at the bottom of the figure). The boundary was observed at a radial distance of 0.80 m, i.e. a coverage diameter of 1.60 m for the infrared LED and an aperture angle of 46 degrees. As both visible and infrared LEDs have similar aperture angles, the setup can be functional. Each AGV status to be communicated to the centre has been represented by a number and encoded on a byte. When the safety sensor is fine, the code “1” is sent and the rest of the codes mentioned in the table in Figure 3 follows the same logic. The reception on the ceiling is doing well and the codes are decoded correctly up to the border mentioned above. Indeed, it can be observed that at the boundary, it is difficult to have a clear threshold value to detect a “1” or a “0”. The mobility enhancement factor for the infrared communication is similar to the conclusions taken for the visible LED.

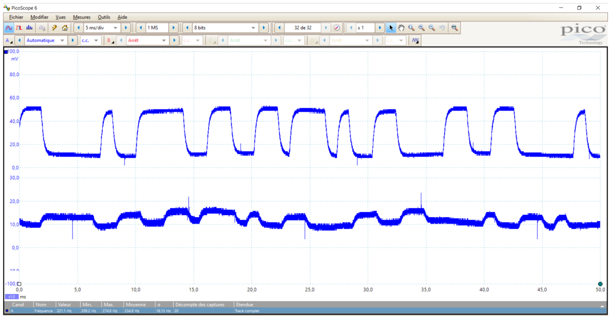

Fig. 8. IRC communication results

5.3 Upscaling

This small scale and low data rate prototype can be upscaled in an industrial facility thanks to Li-Fi companies such as, to cite a few, PureLiFi [18], OLEDCOMM [20], and Signify [19] that already produce ready to use bidirectional high data rate (up to 100 Mbit/s) communication systems. In order to implement an actual industrial setup, a study of the zone to cover must be realised. In order to increase the coverage area of the lamp, it is possible to increase the height between the lamp and the AGV or its aperture angle while taking into account its spatial distribution of optical power. Usually, industrial lamps are often hung several metres above the ground. This gives a wide optical coverage. A previous study showed for example the coverage of a industrial CoreLine Highbay Philips LED of 9 m² per light that can be adapted with the height of the lamp [10]. To study and design a Li-Fi system, the characteristics of the radiation patterns of any industrial LED must be studied as it represents how the LED’s lighting pattern covers the floor and thus the quality of the signal in relation to the sensitivity of the receiver.

6. CONCLUSION

Automated Guided Vehicles play undeniably a key role in the industry 4.0. They make most processes more efficient and rapid. This paper demonstrates the feasibility and relevance of Li-Fi solutions in the industry sector. The bidirectional system presented in this work is built in small scale thanks to equipment available in the academic field and on the market but it is important to mention that companies in the private sector are active in the domain of ready to use Li-Fi products. It has been shown in this work the advantages of Li-Fi in terms of lighting and mobility of the receiver. Such systems can also be deployed in electromagnetic sensitive environments and are robust to RF communications perturbations. Furthermore, as the pieces of equipment are on the top of the AGV and on the ceiling, communication blockages previously present in laser communication when an interfering obstacle is located within the laser beams are avoided. The main result of this paper is the demonstration of a small scale AGV system controlled thanks to Li-Fi. This system replies to the alignment constraint in infrared laser systems that are currently used in some industrial AGVs. The general architecture presented shows the advantage of having a broader LED light beam compared to a laser beam.

The small scale prototype presented in this work reports a freedom of movement gain factor of 157 compared to the previous solution. This offers more flexibility to the moving system while simultaneously lighting the premises.

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