Indoor multi-robot intelligent coordination based on omni-directional visible light communication

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Multi-robot coordination (MRC) is a key challenge for complex artificial intelligence systems, and conventional wireless-communication-based MRC mechanisms that cannot be deployed in radio-frequency-limited environments. In this Letter, we present a promising solution that utilizes indoor omni-directional visible light communication (VLC) technology to realize efficient multi-robot intelligent coordination (MRIC). The specific design is presented along with the implemental details of a practical MRIC experimental platform. The experimental results show that a 50 Mb/s on-off-keying-based omni-directional VLC can be realized with an effective distance of 2.3 m and a bit error rate of $<10^{-6}$ in the proposed MRIC platform.

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Robots along with artificial intelligence technologies play an important role in the modern information society. Recently, a series of related national strategies was launched successively throughout the world, such as the German “INDUSTRIE 4.0” plan, the American “Industry Internet” plan, and the “Made in China 2025” plan. With the wide deployment of robots in various fields, multi-robot coordination (MRC) becomes a key challenge[1]. Efficient coordination depends on real-time signaling interaction, rapid data convergence, and accurate command operation, so the communication for signaling and data transmission is a basic factor for multi-robot system design. Currently, such transmission typically relies on radio-frequency (RF)-based wireless communication[2]. However, robots are preferably deployed in dangerous working situations such as underwater, in an epidemic area, in an infectious ward, in deep mines, and inside fires, but the conventional RF-based wireless devices are not efficient in these scenarios considering the great attenuation of the RF wave underwater, the spectrum conflict with biochemical detection instruments, and the security risks of RF propagation in mines or fires, respectively.

Visible light communication (VLC), a novel technology which utilizes visible light radiation from a light-emitting diode (LED) to transfer information in free space, has attracted much attention nowadays in both academic and industrial fields[3–7]. Actually, the great popularity of VLC is not merely because it inherently combines the advantages of both optical and wireless communication, but more importantly, because that the LED has been widely deployed as the next-generation green lighting device. The VLC can be introduced into RF-limited indoor environments as a promising solution for MRC because of the technical advantages and safety of the visible light spectrum[8,9].

In this Letter, we present a multi-robot intelligent coordination (MRIC) system for indoor RF-limited environments, which is based on omni-directional VLC technology. The design principles and implementation schemes are described in detail, along with the experimental results and performance analysis. A prototype for an omni-directional VLC transceiver is presented in Ref. [10] with the discussion of possible applications. A special design of a hexagonal-pyramid-structure transceiver is provided in Ref. [11] and is used for communication of underwater sensors. These Letters have discussed the possible usage of VLC for a robot system, but, to the best of our knowledge, this Letter is the first to present a specific solution for MRC in general indoor RF-limited situations based on omni-directional VLC technology, and also the first to build a corresponding experimental platform for performance analysis.

For a typical application scenario of the proposed MRIC system, multiple robots are deployed in an RF-limited indoor environment to accomplish the tasks such as object searching, information acquisition, and performance evaluation. Two VLC channels are required to guarantee efficient MRC. One is the top-down communication between the management server and the robots, realized by the VLC transceivers embedded at the ceiling and at the top of the robots, respectively. The other is the communication among the robots themselves realized by the circumferential VLC transceivers embedded on the bodies of the robots. Traditional MRC is always accomplished by passively operating the commands from the management system, but, in our presented system, MRIC can be actively realized based on signaling interactions on the circumferential channels.

The indoor MRIC system contains two sub-systems: the management sub-system and the robot communication sub-system, which is shown in Fig. 1. To realize the top-down and circumferential communication channels simultaneously, an omni-directional optical transceiver should be designed on each robot which contains a top-down communication module with the backstage management server and a circumferential module with other robots.

Since the coverage of a single LED and photodiode (PD) chip is limited, an LED transmitting array and a PD receiving array is required to realize the omni-directional communication. The spatial intensity distribution of the LED theoretically obeys the Lambertian pattern, and practical measurements show that the available half divergence angle (DA) of a typical commercial LED chip, which is defined as the illumination angle scaling from the maximum intensity position to the half intensity position, is less than 60° (shown in Fig. 2). Therefore, at least four LED chips are required to realize the circumferential coverage. Similarly, the field-of-views (FOVs) of PD chips with different packages are different, scaling from 70° to 120°[12]. Therefore, a different number of PD chips is required to realize the circumferential coverage (shown in Fig. 3).

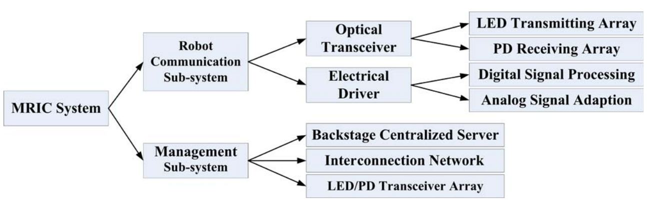

Fig. 1. Architecture of the indoor MRIC system.

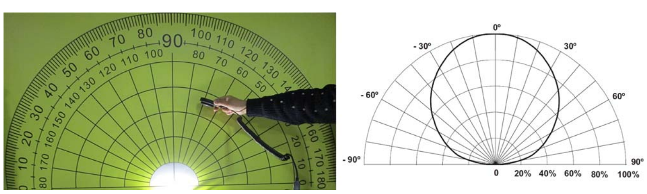

Fig. 2. Measurement on the DA of the LED chip.

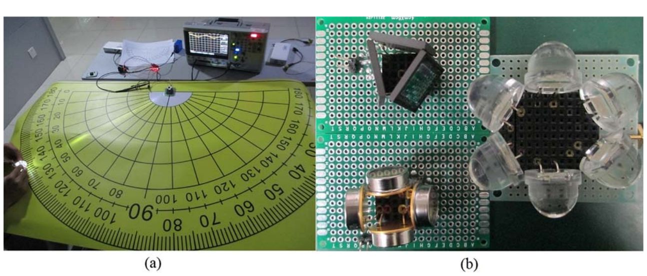

Fig. 3. (a) Measurement on the FOV of PD chips. (b) PD arrays for circumferential receiving: triangle-arranged S1337 array, square-arranged S1226 array, and hexagon-arranged S6968 array (Hamamatsu).

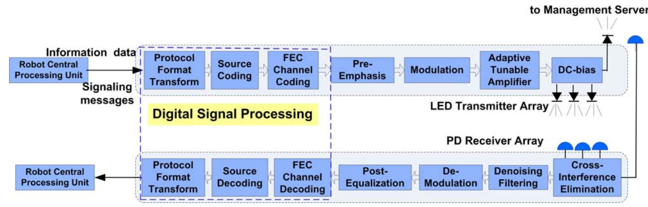

Fig. 4. Schematic diagram of the electrical adaption circuit modules.

Besides the optical transceivers, electrical driver modules are required to realize the format adaption between the signals from the omni-directional optical transceiver and the data operated by the robot central processing units: Fig. 4 presents the schematic diagram. At the transmitter end, the original information data and signaling messages are generated by the robot central processing unit. A protocol format transform module realizes the signal format conversion, and the encoding procedure is then implemented which contains a source coding module and a forward-error-correction (FEC) channel coding module. Since the modulation bandwidth of the LED chip is quite limited, a pre-emphasis circuit is utilized to enhance the system available bandwidth[13,14], and the signal is then sent to the modulation module where it will be modulated on a certain carrier. An adaptive tunable amplifier circuit is inserted to dynamically adjust the signal amplitude according to the channel conditions and receiver distances. At the receiver end, the top-down channel and the circumferential channel are two separate VLC channels, which should be guaranteed simultaneously. To avoid the signal self-interference within each channel itself, the time-division multiplexing mechanism is implemented, whereas to avoid the signal cross-interference between these two channels, a cross-interference-elimination (CIE) module is designed in which a feedback circuit is adopted to eliminate the signal influence from the other channel. A conventional de-noising and filtering circuit is operated to extract the valuable information from the noise-added signal, which is then sent to the demodulation module. The post-equalization circuit is utilized to enhance the system bandwidth along with the pre-emphasis circuit[14], and the signal is then amplified to the standard transistor–transistor logic (TTL) level for the following FEC and source decoding module. The protocol format transformation and encoding/decoding functions are implemented by the digital signal processing (DSP) units.

On the other hand, the management sub-system can be further divided into three parts: the LED/PD transceiver array deployed at the ceiling, the backstage-centralized management server, and the interconnection network between these two parts, shown in Fig. 5. In practical application cases, the indoor surveillance scope of one management server probably scales from several tens to several thousands of square meters, which will be covered by various LED/PD transceivers. The direct interconnection between all transceivers and the server

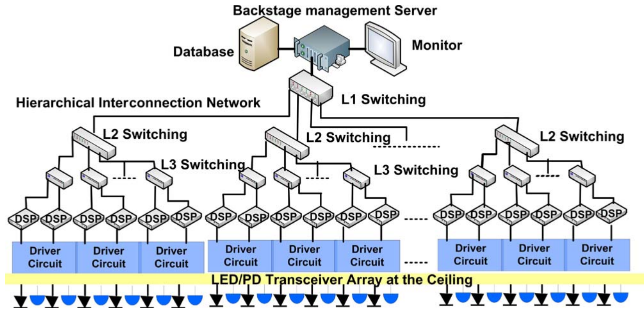

Fig. 5. Structure of the management sub-system.

using bus-topology or star-topology is not efficient, so a scalable hierarchical tree-topology structure should be introduced in which different layers of switching devices are deployed to realize the information distribution and aggregation. Figure 5 presents a typical three-layer interconnection network. The DSP units and the driver circuits for the LED/PD transceiver are similar to the modules defined in Fig. 4.

In practical applications, if there are more than two robots communicating simultaneously, the receiver cannot identify the super-positioned signals, so other multiplexing mechanisms are required in the electrical domain, such as time-division multiplexing or sub-carrier division multiplexing, which will be implemented with the assistance of the upper-layer control and signaling protocols. Furthermore, the circumferential channel may be blocked due to the random moving of the robot, and the top-down channels can be used to transfer the information, which is implemented by the signal interaction between the two robots involved and the backstage server[15].

An experimental platform of the MRIC system is built according to the above design principles. In the management sub-system shown in Fig. 6, a management server (Lenovo M3300-N000) is connected with four VLC access-point (AP) modules using a router, which is adopted as the single-layer interconnection network for information distribution and aggregation. The VLC AP module contains four parts: a DSP unit (Xilinx, Virtex-5 FPGA board), which realizes the format transforming and encoding/decoding; a driver circuit for electrical signal adaption; a LED chip (XPEBWT-L1-0000-00D51, Cree Inc.) for signal transmitting; an avalanched PD (ADP) chip (c12702-12, Hamamatsu Inc.) for signal receiving. The signaling messages are defined based on the user datagram protocol (UDP) to realize the command interaction between the server and the robots.

On the other hand, the robot sub-system, shown in Fig. 7, contains three parts: a mobile platform at the bottom for robot movement, a processing module in the middle for data transmission and operation, and a camera at the top for image acquisition. To enhance the distance of communication, the focusing lenses are embedded on the optical transceivers which narrow the DA/FOV of the LED (XPEBWT-L1-0000-00D51, Cree Inc.)/PD chips (Hamamatsu, S6967), and, therefore, at least four VLC transceivers are required to realize the circumferential communication, along with another VLC transceiver for the top-down communication. The information-processing unit includes a DSP unit (Xilinx, Virtex-5 FPGA board), an image processing unit, and seven driver circuits for electrical signal adaption.

The intelligent coordination efficiency depends on the signaling and data transmission, so we design two experiments to evaluate the communication performance and measure the bit error rate (BER) on the omni-directional VLC channels. In the experiments, we use an arbitrary waveform generator (AWG, Tektronix AWG5012) to generate baseband signals, and we use an oscilloscope (OSC, Lecroy 735Zi, 50 Ω) to analyze the received signal.

The first experiment evaluates the performance on the circumferential channel. Utilizing pre-emphasis and post-equalization circuits[14], the −3 dB bandwidth of the circumferential VLC channel is extended to 104 MHz. A 6 Mb/s pseudo-random sequence is generated by the AWG and sent to the DSP (Xilinx, Virtex-5 FPGA board) for 2/3 FEC encoding. The signal is then modulated by a 50 Mb/s NRZ-OOK carrier and added to the LED chip. Six LED/PD transceivers are deployed on each robot for the circumferential communication, so each transceiver is responsible for 60° of sectorial coverage. Since the spatial intensity distribution of the LED theoretically obeys the

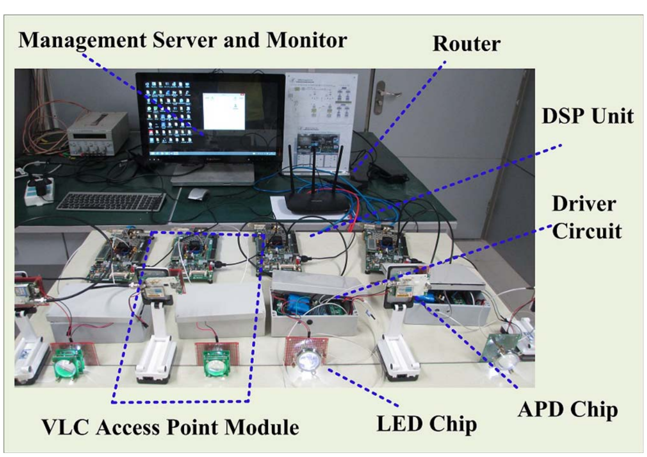

Fig. 6. Experimental platform of the management sub-system.

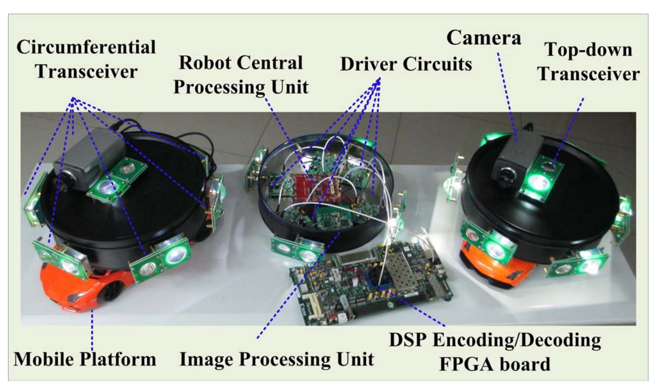

Fig. 7. Experimental platform of the robot sub-systems.

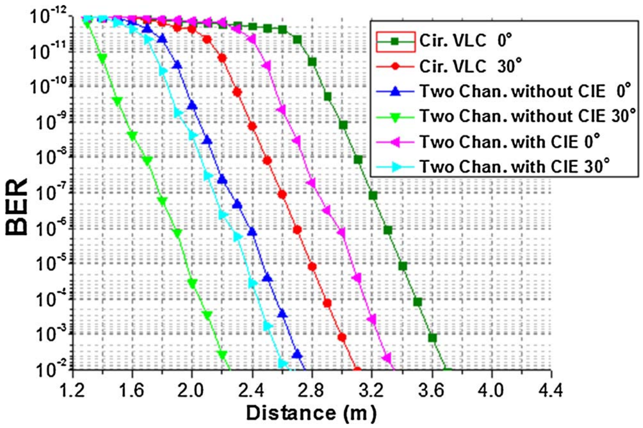

Fig. 8. Performance of the circumferential VLC channel. (Cir. = circumferential channel only; Two Chan. = circumferential and top-down channels).

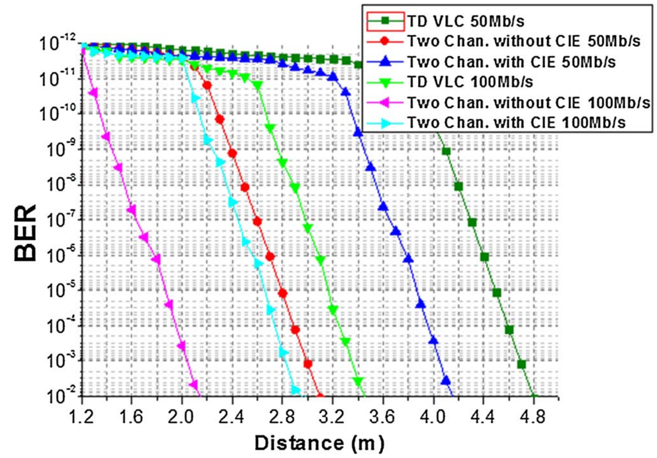

Fig. 9. Performance of the top-down VLC channel. (TD = top-down channel only; Two Chan. = circumferential and top-down channels).

Lambertian pattern, the maximum BER differences theoretically occur at the 30° direction. Therefore, we measure the receiving BER on the central 0° direction (stands for 0°, 60°, 120°, 180°, 240°, and 300° directions) and the 30° direction (stands for 30°, 90°, 120°, 150°, 210°, 270°, and 330° directions) at different distances. Figure 8 presents the experimental results after average calculations, which shows that when there is only a circumferential channel (Cir. VLC in Fig. 8) working, the effective communication distances (BER $<10^{-6}$) at the 0° and 30° directions are 3.3 and 2.7 m, respectively. The transmitting signal intensity is not uniform-distributed, so a feedback circuit can be added after the demodulation circuit, which is responsible for dynamically adjusting the receiving signal strength. Since the robot may not moving in a certain circle in practical situations, the signal-to-noise ratio of the received signal rather than the intensity uniform is more important for correct receiving. In practical applications, the top-down channel and the circumferential channel may transmit different signals simultaneously, while the transmitting signal on the top-down channel of the receiving robot will interfere with the receiving signal on its circumferential channel, and we design the CIE circuit to reduce the interference. Figure 8 presents the experimental results, which show that the effective distances without the CIE module at the 0° and 30° directions are degraded to 2.4 and 1.9 m, respectively, and the effective distances with the CIE module are improved to 3.0 and 2.3 m, respectively.

The second experiment evaluates the performance on the top-down channel. The APD in the top-down channel has a better performance than the common PD chip in the circumferential channel. Utilizing the pre-emphasis and post-equalization circuits[14], the −3 dB bandwidth of the top-down VLC channel is extended to 183 MHz. A 10 Mb/s pseudo-random sequence is generated by the AWG and sent to the DSP (Xilinx, Virtex-5 FPGA board) for 2/3 FEC encoding. The signal is then modulated by a non-return-to-zero (NRZ) on-off-keying (OOK) carrier and added to the LED chip. In the experiment, two different carriers, 50 and 100 Mb/s, are used, and Fig. 9 presents the experiment results after the average calculation, which shows that when there only a top-down channel (TD VLC, shown in Fig. 9) is working, the effective distances (BER $<10^{-6}$) of the 50 and 100 Mb/s systems are 4.4 and 3.1 m, respectively. Similarly, the transmitted signal on the circumferential channel of the receiving robot will interfere with the receiving signal on the top-down channel, and we designed the CIE circuit to reduce the interference. Figure 9 presents the experimental results, which shows that the effective distances of the 50 and 100 Mb/s systems without the CIE module are degraded to 2.7 and 1.8 m, respectively, and the effective distances of the 50 and 100 Mb/s systems with the CIE module are improved to 3.8 and 2.6 m, respectively.

The above experiment results are based on the basic NRZ-OOK modulation, and the system speed and effective communication distance can be further improved using advanced modulation mechanisms such as orthogonal frequency-division multiplexing (OFDM)[7,8]. On the other hand, the LED and PD chips are arranged in the same plane for circumferential communication, which suggests that only a two-dimensional omni-direction is realized in our platform, and the three-dimensional omni-direction communication can be realized using more advanced and complex LED/PD arrays[10,11]. With the signaling and data communication on the omni-directional VLC channels, the robots can not only passively follow the management operations, but also actively share the information among the robots themselves, and the intelligent coordination can be realized. The above experimental results and performance analysis show that the presented MRIC system is a promising solution for efficient MRC in RF-limited indoor environments.

In conclusion, an MRIC system is designed and experimentally demonstrated in this Letter to realize efficient MRC in indoor RF-limited environments. Our future work is to evaluate the OFDM modulation performance for an omni-directional VLC transceiver, and to extend such a

MRIC system to more general scenarios in which no pre-deployed indoor VLC transceiver is required.

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References

1. L. Sabattini, C. Secchi, M. Cocetti, A. Levratti, and C. Fantuzzi, IEEE Trans. Rob. **31**, 1018 (2015).
2. J. H. Jung, S. Park, and S. Kim, IEEE Commun. Mag. **48**, 126 (2010).
3. L. Kong, H. Shen, W. Xu, H. Zhang, C. Zhao, and X. You, Sci. China Inf. Sci. **58**, 82310 (2015).
4. H. Burchardt, N. Serafimovski, D. Tsonew, S. Videv, and H. Haas, IEEE Commun. Mag. **52**, 98 (2014).
5. Y. Wang, Y. Wang, and N. Chi, Photon. Res. **2**, 138 (2014).
6. Y. Ji, X. Wang, S. Zhang, R. Gu, T. Guo, and Z. Ge, Sci. China Inf. Sci. **59**, 1 (2016).
7. J. Li, Z. Huang, X. Liu, and Y. Ji, Opt. Express **23**, 611 (2015).
8. R. Zhang, J. Li, Z. Huang, X. Liu, and Y. Ji, Chin. Opt. Lett. **13**, 072302 (2015).
9. Z. Huang and Y. Ji, Chin. Opt. Lett. **11**, 060603 (2013).
10. A. Sevincer, M. Bilgi, and M. Yuksel, Ad. Hoc. Netw. **11**, 585 (2013).
11. J. A. Simpson, B. L. Hughes, and J. F. Muth, IEEE J. Sel. Areas Commun. **30**, 964 (2012).
12. HAMAMATSU Inc., http://www.hamamatsu.com.cn.
13. H. Li, Y. Zhang, X. Chen, C. Wu, J. Guo, Z. Gao, and H. Chen, Chin. Opt. Lett. **13**, 080605 (2015).
14. H. Li, X. Chen, J. Guo, and H. Chen, Opt. Express **22**, 27203 (2014).
15. Y. Liu, Z. Huang, W. Li, and Y. Ji, Opt. Eng. **55**, 030501 (2016).