Integrating Optical Wireless Communication Into an Optical Bifocal Metrology for Aerospace

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***Abstract*—Recently an innovative bifocal optical metrology method was proposed for space applications (e.g., rendez-vous and docking), based on unmodulated white LEDs. Here we design, realize, and test a solution that upgrades the metrology to include a digital communication feature, with no modification of the optical elements of the original system: indeed, the scheme exploits the same optical sources that are needed for metrology, which are now also working as optical antennas as their intensity is now modulated. At the receiver side, the conventional camera is now sided by a common photodiode. The system provides unidirectional data communication at 10 kbit/s speed. It is designed to support manoeuvres up to 400 m distance. The lab tests confirm the effectiveness of the proposed solutions, showing correct data transfer without any noticeable degradation of the metrology system.**

***Index Terms*—Metrology, optical communications, visible light communications.**

I. Introduction

TODAY, metrology systems are widely used to determine the flight attitude and/or position of a satellite. As a key example, given a pair of satellites, the metrology allows to find the mutual position (see e.g., [1], [2]) and is thus of paramount importance in *rendez-vous* and docking operations [3].

To this aim, a new approach was recently proposed, based on optical means, and indicated as Bifocal Metrology (BM): BM was introduced as an optical metrology applicable to any spacecraft (S/C) that must track or point another S/C [4]. It can also be used when a S/C (chaser) should control the relative position and flight attitude in six degrees of freedom in respect of a second S/C (target) in either a short, medium, and far range. By using only one image sensor and proper image processing, BM is able to perform this measurement in both fine and coarse accuracies.

The BM solution exploits an innovative optical projective system embedded on the target S/C and an imaging system on the chaser. On the target, the system is simply composed by three LED sources, placed on a fixed plane, exactly at the vertexes of an isosceles triangle. On the chaser S/C, the light from the LEDs is collected by a bifocal imagining system and sent to a CCD camera, mounted on the chaser S/C. On this camera, the light from the two paths forms an image that is made by six points (three for each triangle resulting from the two different focal length paths). The output image is post-processed to precisely determine the 3D relative position of the target respect to the chaser. This solution has been experimentally demonstrated [4].

However, in many applications, it would be very beneficial to upgrade the BM by adding digital data transmission. A key example would be the manoeuvres of *rendez-vous* and docking [3]: here, even the unidirectional transmission of mission-critical data would provide a significant upgrade of the system features [5]. To this aim, BM system provides indeed only the data related to the attitude and position of the target satellite. This notwithstanding, the difficulty of the *rendez-vous* and docking operation is still very high, since the orbital speed and the orbit of the two satellites must coincide exactly. Thus, if the chaser does not know the data of the target satellite, communicating these data would be dramatically important because it can directly provide to the chaser all the relevant data of the target. These data (e.g., weight, volume, speed, on-board payload) are dramatically helpful for a successful *rendez-vous* and docking accomplishment.

For that purpose, we propose here, for the first time, a system that combines both metrology and communication capabilities. In our scheme, the last is realized by sending digital data by means of the very same white-LEDs of the BM, without even changing the type of devices: these would be then used both as light sources for the BM and as transmitters (TXs) of digital data. Indeed, it has been recently demonstrated that visible LEDs can act as optical antennas [6], [7], allowing transmission of digital data. Although LEDs emit incoherent light, they were successfully used to transmit high-speed data [6]–[8]. This technology, indicated as Visible Light Communication (VLC) can find many different applications both in indoor and outdoor environments, as well as underwater. To realize VLC, no special transmitters are needed; indeed, commercial LEDs can be used, so that we can expect to use the same devices that are embedded in the BM triangle.

We note that, although VLC could provide Gbit/s rates [6], [7], our implementation is targeting much lower speed values. This is related to modest bandwidth requirements of our application. Mostly, it is due to the engineering constraint of keeping the details of BM system untouched: this fixes the emitted power and emission angle: these two figures, coupled with the typical operating distance, limits the bit rate to tens of kbit/s. However,

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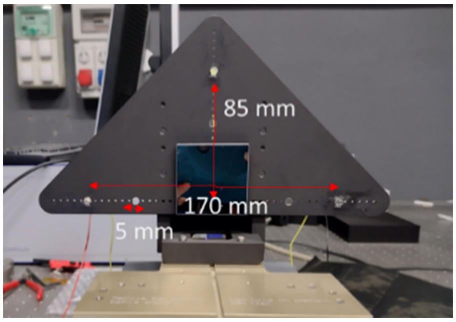
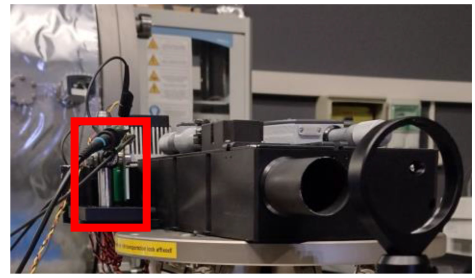


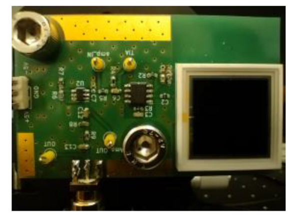
Fig. 1. Detail of the target triangle, with the three LED sources.

the result is far beyond the expectations for transmission of mission-critical data (64 bit/s) [5].

Here, we illustrate the experimental demonstration of the concept. First, we present how we combine the BM and the VLC, in a single setup. We then report the performance characterization of both schemes, when operated alone and when operated together: this allows to demonstrate that the coexistence of the two functionalities has no impact on either of them.



(a)



(b)

Fig. 2. (a) Picture of the BM chaser equipment (main part), integrated with the small external VLC RX (red square). (b) PCB of the RX with PD and the electronics, corresponding to red square in (a).

II. The VLC-Metrology System

The communication system is based on IM/DD (Intensity Modulation/Direct Detection) with a RS232 OOK-NRZ signal at 9.6 kb/s. The RS-232 is among the most common communication protocols. It was chosen because it is frequently used in serial transmission between digital devices in avionics, thanks to its low complexity and high robustness. The selected data rate is high enough to transmit the relevant telemetry information.

The LEDs on the BM system are LEDWE-15, white-light sources commercially available from Thorlabs. They are made by a hetero-structure of InGaN with phosphor, which produces a wide emission spectrum between 430 and 660 nm. To maximize the optical signal power at the receiver, we chose to exploit all the 3 LEDs, which were thus connected in series and driven by the same electrical signal; therefore, they all work simultaneously both as point sources for the BM (target) and as TXs of VLC. At the receiver this produces a final signal current that is around the triple of the signal current obtained when using only one LED. We directly modulate the LEDs by a single RS-232 electrical binary signal with voltage of $\pm$ 7 V at 9.6 kb/s. They are driven by 23 mA bias current by the driver PCB, with an emitted optical power of around 15 mW. Each of the three white LEDs is placed just behind a hole.

In Fig. 1, we show the picture of the planar support of the target. We see a triangular-shaped steel mask that is perfectly planar and where holes were created with laser numerical control. On the back, attached to the three holes at the vertexes of a triangular shape, we placed the triangle of LEDs mounted with very high precision (the distances among the holes are indicated by the red arrows in Fig. 1). Each LED clearly corresponds to one hole on a target (diameter: 0.5 mm).

We then modified the chaser. As the only relevant difference from the original BM setup on the chaser S/C, here we have inserted in a dummy output after the last beam-splitter an additional photo-detector (PD) that collects a fraction of the light from the other arm and works as VLC RX (see later in Fig. 3 the scheme).

As we expected a quite low illumination level at the chaser position, we carefully selected the PD in terms of active area, responsivity, electrical bandwidth, and opto-electrical noise [9]. Moreover, we decided to adopt a wide-area PD, so that all the 6 spots (14×14 mm^2), generated by the BM fall onto the sensitive surface. Therefore, we used a 18×18 mm^2 PD by Hamamatsu (cut-off frequency of 43 kHz, Noise Equivalent Power of 2.5×10^{-14} W/H$^{1/2}$ and dark current of 500 pA). The PD was followed by a trans-impedance amplifier (TIA) and a rail-to-rail amplifier in saturation regime to restore an amplitude compliant with the RS232 standard. Finally, the signal is filtered with a first-order low-pass electric filter at 10 kHz to remove high-frequency noise and increase the signal-to-noise ratio of the signal.

In Fig. 2(a), we show the BM equipment integrated with the VLC RX. As can be seen, a minimal addition of complexity is introduced by the VLC RX. A detail of the PCB hosting the VLC RX is reported in Fig. 2(b).

Finally, we recall that, for this type of LEDs, the equivalent electrical bandwidth can be strongly increased if detecting only the emitted light in the blue region, which is achieved by filtering out the blue light by the phosphor [8]. We measured the equivalent bandwidth of around 3 MHz for the unfiltered white light; this increases to around 8 MHz when filtering the blue light, but at the expense of around 4.5 dB lower optical power. Considering the data rate of 10 kb/s, we do not need to filter out the blue light in transmission, and we can thus benefit from a higher received optical power. Finally, we recall that the wide bandwidth (>200 nm) of incoherent modulated) light of

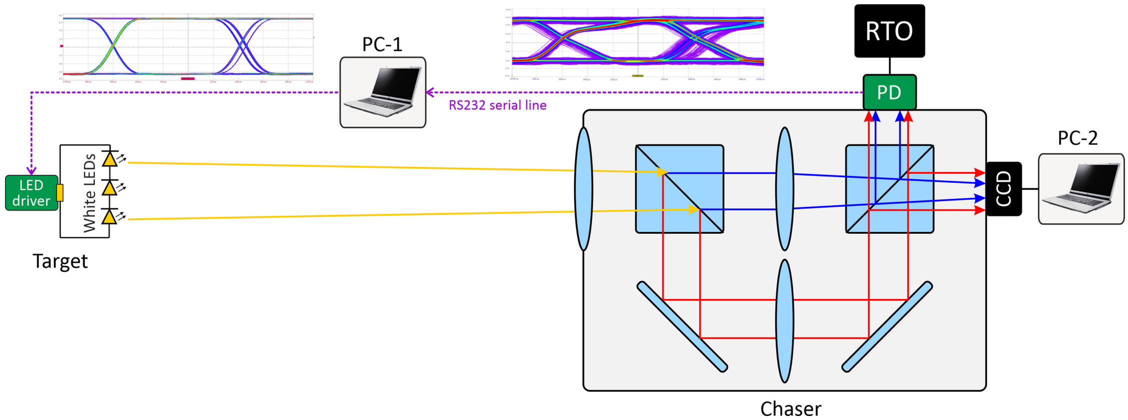


Fig. 3. Experimental setup. On the left the grey square includes the bifocal metrology optics (where signal is split in two paths, with red and blue lights). The final splitter sends part of the light to the CCD for BM and part to the RX for VLC. Insets refer to the eye diagram of the electrical signal (left) and of the VLC receiver (right).

the LED, combined with a low bandwidth of the RX (around 10 kHz), produces a fully negligible intensity noise.

III. BM-VLC Experiment

In Fig. 3, we present the schematics of the experimental setup. The target is mounted on a base that is fixed to the PI F-206S precision base. At 3.72 m distance from the target, we have the equipment for BM and for VLC detection, which should be hosted on the chaser. This is shown on the right in Fig. 3, where the grey square includes all the BM optics: here the light is split in two paths, indicated by red and blue lines, which have different focal planes.

At the chaser, the illumination is around 5 lux (at the input of the BM system), which corresponds to optical intensity of around -46.4 dBm/cm^2. Because of practical limitations in the setup, the BM and VLC RX are controlled and monitored separately by two common PCs (in a real case, one PC or FPGA could be enough).

Noteworthy, VLC modulation can be turned on/off to work separately or together with BM. When VLC is off, the LEDs are driven with the same average current. Clearly, the BM cannot be turned off because it requires the LEDs to be active. To test the impact of VLC on BM, we turned off the modulation.

We first measured the VLC communication performance. To reproduce the space conditions, the entire experiment is performed in a dark environment. We characterize the link by modulating the three LEDs with the same sequence. There is no relevant delay among the TX sources, so that they produce the same signal. This travels through the free space and then passes through the BM optics. Finally, it is received by the VLC RX.

We present in Fig. 4 a typical eye diagram obtained when BM and VLC are both active. This shows clear eye opening. Note that minor distortions on the right side of the eye are due to the suboptimal device (USB-to-serial), which is generating the signal with a non-negligible drift of the clock frequency (same distortions can be noticed on the back-to-back electrical eye diagram, see left inset in Fig. 3).

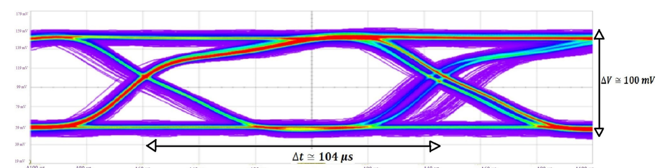


Fig. 4. Eye diagram for the VLC signal at TIA output (DC-coupled).

We then measure the bit error rate (BER) as a function of the received optical power P_{RX} to measure the receiver sensitivity [9]. We vary P_{RX} by means of various fixed optical attenuator made of glass plates.

We highlight that the BER measurements cannot be performed using the exact RS232 signal, because it can allow measuring BER values in a very limited range. Therefore, to perform this measurement, the signal at the TX is a NRZ signal at 10 kbit/s produced by an arbitrary waveform generator (AWG), which also produces a signal with a high-quality clock, suitable for the following processing. At the RX, the electrical output signal is stored by a real time oscilloscope (RTO) and then sent to a PC. The sampled signal is processed by a home-made custom routine in MATLAB, which measures the input optical power, extracts the clock, reconstructs the bit sequence, and finally compares it with the original one, computing the BER value (also as a function of the decision threshold).

It is known that to consistently measure a BER value of 10^{-6} you must send and receive at least 10^7 bits, which, at our data rate, requires a measurement time of about 20 minutes in real-time transmission. Whilst this might even be done, lower BER values ask for correspondingly longer times (e.g., 2000 minutes for BER $= 10^{-8}$), which would make the measurement times too long. Therefore, in order to have a reliable BER estimation, we applied a well-known technique that can be used to get a reliable estimation of the low BER values, which is taken from fiber communications [10]. In that context, it was introduced to estimate BER values up to 10^{-20} in 10 Gbps systems and it exploits the measurements of BER as a function of the decision threshold. Namely the BER is estimated from

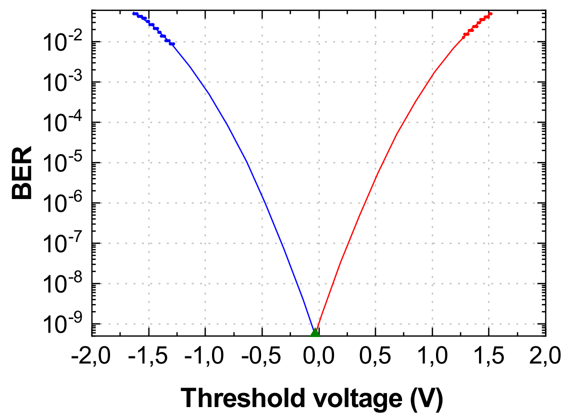


Fig. 5. Example of the BER measurement method, at −54.5 dBm received. The blue and red points (curves) refer to the data (pdf) of spaces and marks, respectively.

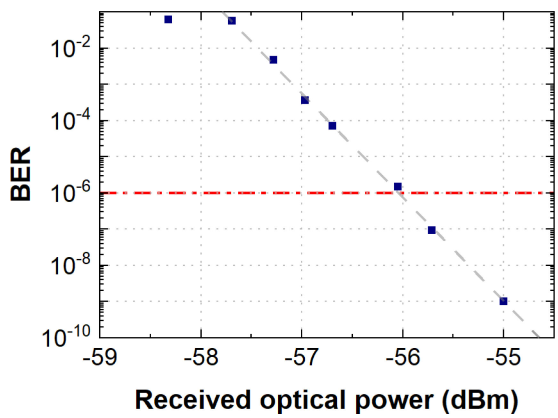


Fig. 6. Measured BER curve vs. optical power.

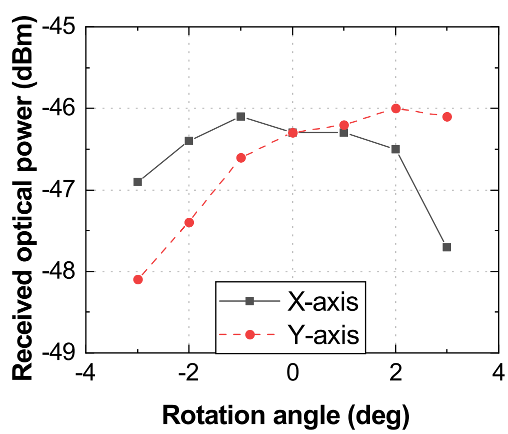
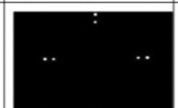
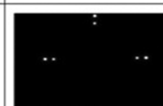
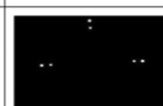


Fig. 7. Measured power at VLC RX vs rotation angle (in respect of X and Y axes).

the extrapolation of the two measured trends for bits 1 and 0, assuming the Gaussian probability density function (pdf) for both [10]. We used this technique to obtain the data reported in Figs. 5 and 6.

Namely, in Fig. 5 we report the BER curve as a function of the threshold voltage at the received power of −54.5 dBm. In the graph, we observe the marks (red dots) and spaces (blue dots).

TABLE I
MEASURED PERFORMANCE OF BM WHEN VLC WAS ON OR OFF, IN THREE DIFFERENT CONDITIONS

Real Position of the Target	BM Spot Image	Estimated Position of the Target	VLC	Error Introduced by VLC
D: 3.723 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg RZ: 1 deg.		D: 3.723 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg RZ: 1 deg.	OFF	
D: 3.723 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg RZ: 1 deg.		D: 3.723 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg RZ: 1 deg.	ON	Not detectable
D: 3.723 m X: 0.006 m Y: 0.008 m RX: 0 deg. RY: 0 deg. RZ: 1 deg.		D: 3.721 m X: 0.006 m Y: 0.008 m RX: 0 deg. RY: 0 deg. RZ: 1 deg.	OFF	
D: 3.723 m X: 0.006 m Y: 0.008 m RX: 0 deg. RY: 0 deg. RZ: 1 deg.		D: 3.724 m X: 0.006 m Y: 0.008 m RX: 0 deg. RY: 0 deg. RZ: 1 deg.	ON	0.1% on D (within measurement accuracy)
D: 3.723 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg. RZ: 3 deg.		D: 3.721 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg. RZ: 3 deg.	OFF	
D: 3.723 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg. RZ: 3 deg.		D: 3.725 m X: 0 m Y: 0.004 m RX: 0 deg. RY: 0 deg. RZ: 3 deg.	ON	0.1% on D (within measurement accuracy)

The blue and the red curves show the parabolic extrapolation whose intersection indicates the optimal threshold (green dot), and the intercept indicates the corresponding BER. In this example, the estimation gives a BER value of 5×10^{-10}, at the optimal threshold voltage (0 V).

Following this procedure at different received power values, we obtained the BER curve as a function of P_{RX}. The results are shown in Fig. 6. As can be seen, the sensitivity value is around −56 dBm, considering a BER target of 10^{-6}.

In our case the received power is much higher (around 10 dB), so that we can expect the VLC system to work over quite longer distances (up to around 13 m), with the present configuration. Longer distances can be achieved by using VLC signals with higher optical power (e.g., by increasing the driving current or using more powerful LEDs).

After the VLC characterization, we then tested the VLC performance, for different rotations of the available target. We report in Fig. 7 the results taken by varying the target rotation along X- or Y-axis. We can see that, in the achievable range of angles, the received power is by far higher than the sensitivity. We note that the variation is asymmetric when varying the Y-angle: this is because the initial alignment had likely some initial misalignment (around 2 deg.).

Finally, we measured the impact of VLC on the BM performance; in Table I, we show a summary of measurements of BM in 3 realistic conditions, where VLC was initially off (odd lines) and then turned on (even lines). The tested positions are the ones typically observed during the *rendez-vous* and docking phase [3], [4]. Noteworthy, we expect data exchange to come into play only after the chaser and target become close, i.e., after a good preliminary alignment between the two spacecrafts is performed.

In Table I, we report the target position set by means of the hexapod, the picture by the CCD camera used for BM, the measured target position and comment on the error in the measurement introduced by the VLC. We highlight that in this case the VLC transmission is realized by transmitting RS232 signals. As can be seen, in the first case, the VLC does not introduce a noticeable change. In the second and third cases, the results with VLC on differ by around 0.1% from the results where VLC is off. This is within the measurement error. Therefore, we can conclude that using modulated LEDs has no impact on the performance of BM, so that the upgrade of functionality comes at no price, in terms of accuracy.

IV. Conclusion

We have proposed and demonstrated that a recently proposed bifocal metrology system can be upgraded by means of VLC, to include also a channel for digital data transmission. There are only two minor modifications of the original BM scheme: the LEDs that are used for the imaging are now modulated by digital electrical data, whilst on the other side a part of the collected light is split and sent to a VLC receiver.

In our experiment, we have demonstrated that these small modifications are enough to transmit a conventional RS-232 signal together with BM lights, by using the same LEDs of the BM setup. This is indeed obtained by minimal increase of complexity in the BM system and has negligible impact on its accuracy. We have experimentally proven that the communication and BM can work simultaneously without any noticeable effect. This approach can find relevant applications in the space industry. Namely, it can be possible to retrofit this communication system for a satellite that is currently under design, including all hardware that we used to demonstrate VLC-BM, because hardware cannot be added after the design is finalized. Furthermore, in order to add our new hardware, we must first test all devices to be sure that they are space graded (in terms of robustness to mechanical stress, temperature variations, radiation etc.).

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