

Design of holographic tracking module for long range retroreflector free space systems

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Weight reduction and low power consumption are key requirements in the next generation of unmanned aerial vehicles (UAVs). To communicate with an operator, a secured link between the UAV and a ground base station is desirable. To realise these links, retro-reflecting free space optics is potentially attractive as it offers light-weight and low complexity at the UAV. However, the base station requires a high performance tracking module to enable a steady illumination of the UAV retroreflector. In this paper, we present the design and implementation of a tracking system, which consists of coarse tracking and holographic fine tracking modules working cooperatively. Using this system, experimental field trials were carried out by mounting a multiple quantum well (MQW) based modulated retro-reflector (MRR) on a commercial UAV. A 2 Mbps optical link was achieved with a bit error rate of $\sim 2 \times 10^{-4}$ at a link range of 300m.

OCIS codes: (060.2605) Free-space optical communication, (090.1970) Diffractive optics, (090.1995) Digital holography, (120.4880) Optomechanics

1. Introduction

Unmanned aerial vehicles (UAVs) have recently emerged as a promising solution in different scenarios ranging from surveillance, water treatment assessment, vegetation monitoring and emergency response [1]. These devices are typically equipped with sensors (e.g. visible, infrared or hyperspectral camera) that generate large volumes of data. This information would ideally be transmitted to a ground base station in real time. Traditionally, this task is performed using radio frequency (RF) communications.

The growing congestion of the electromagnetic spectrum has led to free space optics (FSO) becoming an alternative to RF systems to implement long range point to point high speed data links [2] [3]. Additionally, FSO increases data transmission security offering low probability of interception (LPI) and low probability of detection (LPD) capabilities against unauthorized eavesdroppers.

Conventional FSO links require a laser source and an acquisition, pointing and tracking (ATP) subsystem at both ends of the link. This approach is challenging in UAV applications, where both weight and power consumption of the communications payload should be minimized. Retroreflective free space optics (RFSO) addresses this problem by transferring much of the system complexity to the base station (BS). Such a link uses a high power continuous wave (CW) laser beam launched from the BS towards a

modulating retroreflector (MRR) located at the UAV. This device reflects back the light and encodes the data using either liquid crystal (LC), micro-electro-mechanical systems (MEMs) or Multiple Quantum Well (MQW) optical shutter. Data rates up to 70Mbps have been reported by Naval Research Laboratory (NRL) using MQW modulators [4-5]. Data can also be transmitted to the UAV modulating the interrogating beam [6].

In an RFSO configuration, a high performance fine tracking module is essential to allow steady illumination of the MRR. Fast steering mirrors (FSM) are widely used to perform fine beam steering because of their high efficiency and quick response [7]. In this work we have used a spatial light modulator (SLM) to perform this task. This solution significantly increases the system flexibility, by introducing the potential capability to also perform beam divergence control, aberration correction and multi-spot generation [8-9]. Holographic beam steering has already been explored for tracking purposes in short range applications [10]. However, it has never been used in medium-long range application to track a flying UAV in a real scenario. Here we present the design and implementation of a full tracking system (including both coarse and fine modules) for medium-long range communications. This system was used to track a UAV with a built-in MQW based MRR. A reliable data link of 2Mbps was established at a range of 300m. This paper is structured as follows: in section 2 the system design is presented, explaining

both the BS and the UAV terminal. Section 3 describes the optical design. System operation, BER test performance in outdoor trials and tracking loop time optimization results are shown in section 4. Finally, conclusions are given in section 5.

2. System design

Figure 1 shows a schematic diagram of the system. A BS directs a CW laser interrogator beam towards an UAV (Cinestar 8's Mikrokopter model) equipped with an MRR. The MRR modulates and reflects the incoming beam back to the BS.

A 1550 nm system is presented here as it makes use of mature C-band technology and relaxed eye-safety constraints ((maximum permitted exposure (MPE) at 1550nm is 50 times higher than at 850nm). The use of a lower wavelength like 850nm requires a more complex optical system to face the safety limitation. However, SLMs operating at that wavelength are lightly quicker than those at 1550nm as described in section 4.3, and GaAs and AlGaAs MQWs modulators used at 850nm offer a better contrast ratio [11]. The following sections focus on the base station design as well as the MRR link.

A. Base station

To meet the system requirements we designed a tracking system based on coarse and fine tracking modules working cooperatively. The latter offers a high pointing accuracy within a limited narrow field of view (FOV). It is supported by the coarse tracking subsystem, which locates and mechanically points the BS towards the UAV position. The coarse module is also responsible for tracking the UAV; keeping it in the fine tracking's FOV. Both subsystems are managed by a common control module as shown in figure 1.

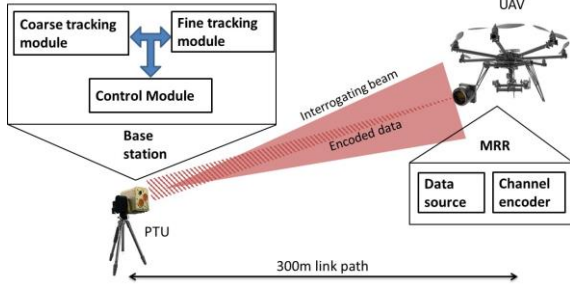


Fig. 1. System schematic. PTU refers to Pan and Tilt Unit, UAV to Unmanned Aerial Vehicle and MRR to Modulating Retroreflector.

1. Coarse tracking

This subsystem is based on a video tracker board and a mechanical head that holds the fine tracking module. The video tracker (FLIRVilga board) uses video signals captured by a visible CCD camera to calculate the UAV coordinates. The camera is provided with an adjustable zoom lens to allow the operator to find and then zoom into the region of the UAV. Optical system details will be provided in the next section. AFlirD300 pan and tilt unit (PTU) was used to perform the mechanical motion. This device offers a motion range of 336 and 120° in pan and tilt axis respectively. Its angular resolution is 0.006°, which is enough to meet the system requirements.

2. Fine tracking

The fine tracking subsystem uses a beam steering unit and a position sensing device. Figure 2 shows a block diagram of the fine tracking system. This is a bi-static design where transmitter and receiver do not share the aperture. For the transmitter, a collimated 1550nm laser beam illuminates the SLM (Meadowlark HSP512-1550) in an off-axis configuration. The device works in phase-only mode offering an analogue steering angle up to $\pm 2.96^\circ$ and beam divergence control of the interrogator beam. The phase levels are set on the device using 8-bit 512x512 images, hereafter referred to as holograms. After the SLM, the beam is expanded by a factor of ten. This magnification reduces the fine tracking FOV to $\pm 0.296^\circ$. Further detail about the corresponding optical design is provided in section 3.

The light reflected off the MRR is collected at the BS by an 8cm aperture and $\pm 0.296^\circ$ FOV optical system. It is detected by both an InGaAs PIN photodetector and a high frame rate InGaAs camera (Xenics Bobcat 640) acting as a data receiver and a position sensing device. As opposed to quad-detectors, InGaAs cameras offer higher sensitivity and constant performance regardless of the spot position. The captured images are transferred to a frame grabber and then processed in an NVidia Tesla K10 graphical processing unit (GPU). The calculated pair of coordinates is used to generate the new hologram to be sent to the SLM. Errors below 8cms of position determination at a range of 1.2km were obtained using centroid squared methods [12]. This variance in the centroid calculation is dominated by atmospheric turbulence. A phase ramp function was written to the SLM to perform the steering.

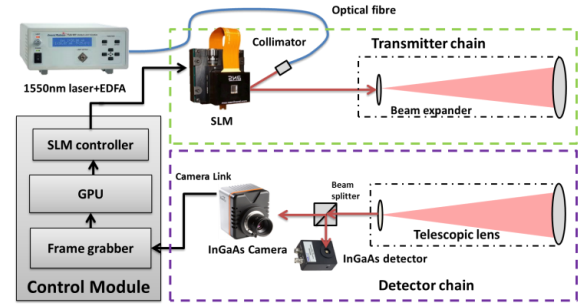


Fig. 2. Fine tracking module block diagram.

B. MRR module

A MQW based MRR was used to establish a data link between the UAV and the BS. The modulator offers a contrast ratio of 1.1:1 at 1550nm. The MRR optical system is based on a 10mm aperture cat's eye design [13].

The modulating data was generated using a field programmable gate array (FPGA). This device not only implements a pseudo random number generator (PRNG), but also a channel encoder.

3. Optical design

In this section we present the optical design of both the coarse and fine tracking modules. The fine tracking module at the BS is a bi-static design with different optical paths for the transmitter and the receiver chains. A precise alignment between both chains is required to obtain a good system performance. Software calibration using an steady retroreflector was employed to face this requirement.

1. Coarse tracking

The coarse tracking optical system is required to have a zoom lens and match the fine tracking optics FOV ($\pm 0.296^\circ$) at maximum zoom. Using a standard $\frac{1}{2}$ inch CCD camera, this requires an optical system with a focal length lens of 0.62m. A commercial off the shelf (COTS) solution met these requirements, consisting of a Computar H30Z1015 lens, which has a 10-300mm zoom capability. Using a 2X magnifier with this lens gives the required 20-600mm focal length. The system FOV is then $\pm 9.1^\circ \pm 0.297^\circ$.

2. Fine tracking transmitter optics

The key requirement for the transmitter optics was to ensure the output beam at the exit aperture was eye-safe (class 1M). From BS EN 60825-1:2007 for continuous laser light of wavelength 1550nm, the MPE is 1000 W m^{-2} . As the maximum power through the system is 4W (limited by the damage threshold of the SLM), the beam needs to be at least 79.8mm diameter at the exit aperture. The SLM has dimensions of 7.68mm by 7.68mm, therefore an optical system with factor of ten demagnification of the SLM onto the exit aperture would be suitable. As the beam is being expanded by a factor of ten, the steering angle is reduced by a factor of ten, therefore the maximum steering angle of the system will be $\alpha = 0.296^\circ$.

Figure 3 shows the final transmitter optical design. It consists of the fibre-fed laser, feed into a collimating lens (L1). The light is reflected off the SLM, and then a 10X beam expander (L4 and L5) is used to output a beam of correct diameter. To minimise aberrations in the system, an aspheric lens was used as the final output (L5). L2 and L3 are a 1:1 relay which places the SLM plane on the lens L4 minimising the beam movement across the final lens as the beam is steered. The design was generated and optimised using Zemax.

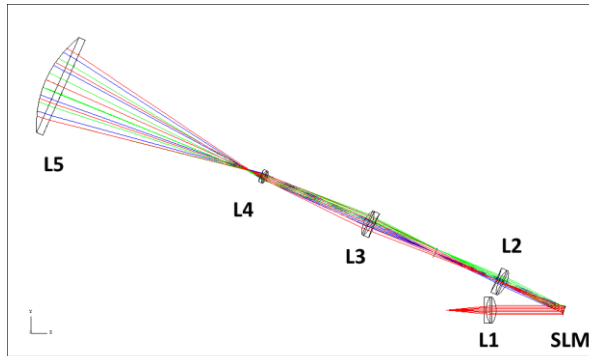


Fig. 3. Transmitter optical design

3. Fine tracking receiver and data photodetector optics

The receiver fine tracking system optics has several functions: to match the transmitter FOV; to have a fine focal adjustment for the IR camera; and finally to split most of the light from the imaging path to use as a data channel. With these specifications, an optical layout for the receiver system was designed, and is shown in figure 4. Light is collected by the front 100.2mm diameter lens (L1) (80mm effective aperture), and then collimated by the second smaller lens (L2), forming a beam compressor. L2 is mounted on a motorised linear translation stage to allow focussing of the system. An optical bandpass filter is also introduced to reduce the background light reaching the detectors. The light is then split into two, with a 90/10 beam splitter (as only a small fraction of the light is required for the position sensing). The reflected arm is then

focussed onto the photodetector with a high NA (Numerical Aperture) lens, whereas the straight through path has a much longer focal length lens system to focus onto the IR camera. A two lens design (L3 and L4) is used to achieve this. The equivalent focal length of this arm is 0.9862m. As the sensor side is 10.2mm a FOV of $\pm 0.2975^\circ$ was obtained meeting one of the system requirements.

The photodetector chosen for the system was a Thorlabs DET10C/M. This device has an active area of 1mm diameter. In spite of its large junction capacitance (80pF), it is possible to achieve a receiver bandwidth of 2MHz when combined with a trans-impedance amplifier (TIA).

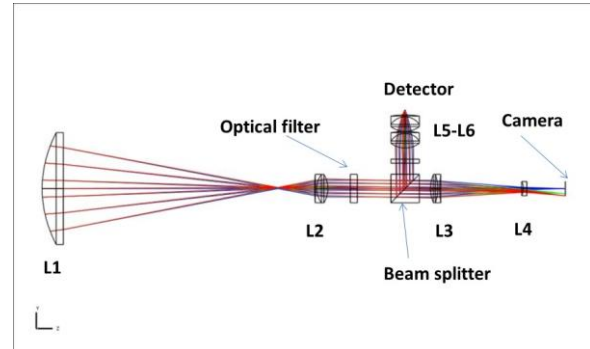


Fig. 4. Fine tracking receiver optical design

4. Results

We describe here the tracking system operation and the interaction between coarse and fine tracking modules. Then link budget calculation and BER measurements performed in a field trials whilst tracking the UAV are reported. Finally, we show how the tracking loop time can be reduced.

1. Operation

Figure 5 shows a flow chart detailing the operation of the tracking system. The system operates as follows: initially (idle state), the operator has control on the PTU and the visible camera lens. The operator is responsible to manually set the UAV into the coarse tracking FOV. A ring of green LED can be set up on the UAV to operate the system during night time. For this, the fine tracking module is off. Once the UAV is selected by the operator, the coarse tracking system takes the control of the PTU and centres the UAV on the image. Subsequently, the fine tracking module is triggered. At this point, the UAV is located in a random position within the fine tracking FOV. An acquisition stage is first required by the fine tracking module to locate the MRR position. The SLM is used to increase the divergence of the beam and perform a raster scanning search with the interrogator beam. Using the diverged beam, a speed up factor of 15 compared to a scanning carried out with a collimated beam was achieved. This scanning process finishes when a return signal is detected on the InGaAs camera. In this case, the beam divergence is reduced to its minimum value and the tracking stage is enabled. For each iteration of the system, a snapshot captured by the InGaAs camera is processed to obtain the new UAV pair of coordinates. These are used to generate a steering hologram, which is transferred to the SLM and displayed. The time required since the snapshot is captured until the hologram is finally displayed on the SLM is defined as the tracking loop time.

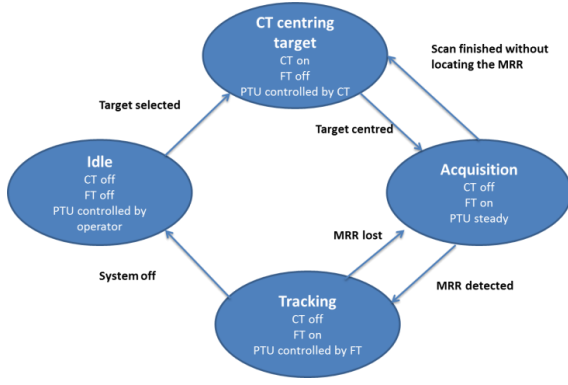


Fig. 5. Tracking system operation. CT and FT refers to coarse and fine tracking respectively.

2. Link budget

The system's link budget was studied for a free space distance from 100 to 1000 m. Table 1 shows the system parameters. A beam divergence of $35\mu\text{rad}$ has been considered to include the beam spreading introduced by the atmosphere. Figure 6 shows the received optical power as a function of the distance for different MRR apertures. At 300m there is a link margin of 12dB when 10mm aperture is used. Figure 6 also includes the calculated received power for a MRR aperture of 20mm diameter. For this configuration, a link range of 1km is achievable by lightly enhancing the receiver sensitivity.

Table 1. System parameters for link budget calculation

Parameter	Value
Laser power	4W
Transmitter losses	1.67 dB
Interrogator beam divergence	$35\mu\text{rad}$
Atmospheric absorption	0.4dB/km
Link range	300m
MRR aperture	10mm
Receiver aperture diameter	8cm
MRR insertion losses	10.25dB
Receiver losses	3.915dB
Detector Sensitivity	-23dBm

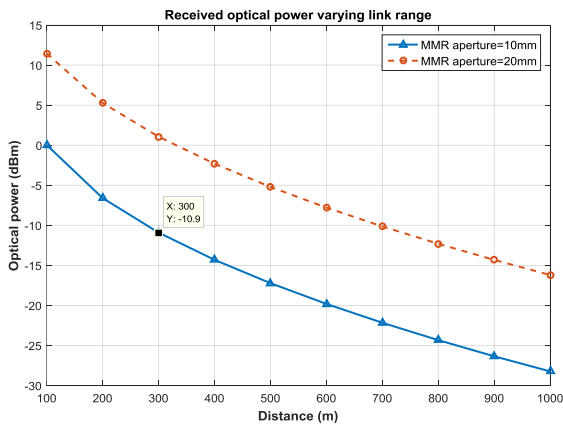


Fig. 6. Received optical power for different link range.

3. Field trials

To test the system performance we measured the BER of a data link established between a UAV and the BS. The UAV was tracked using both coarse and fine tracking modules whilst flying 300m away from the BS. A 4W 1550nm laser source was used as interrogating beam. This trial was performed in the UK on a partly cloudy day and a temperature of 22 °C. The system did not show any performance reduction on sunny conditions.

A pseudo-random data stream (2^8-1) was transmitted at 2Mbps using a non-return-to-zero on-off-keying (OOK) scheme. This data stream was generated using a Xilinx LX-9 board. This device also implements both an 8B10B encoder and a Golay correlator to perform the frame synchronization at the receiver. Figure 7 shows the 2Mbps transmitted signal (red dashed line) and that detected at the receiver (blue solid line). The detected signal was captured using a SignatecPX14400D2 board and later post processed. Adaptive thresholding techniques were used to remove the low frequency intensity variation introduced by the atmospheric turbulence. A BER of 1.9701×10^{-4} was measured on streams captured for 5 seconds.

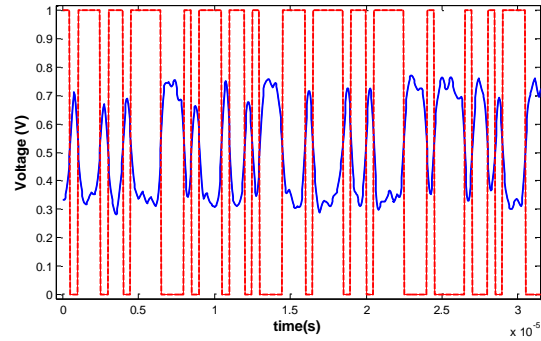


Fig. 7. 2Mbps data stream decoded on the ground station.

3. Tracking loop optimization

Minimizing the tracking loop time enhances the performance of the tracking system. Measurements performed by the control unit showed that the image acquisition takes 13ms, the image processing 2.965ms and the SLM update process 40ms. The viscosity of the Nematic LC used in the SLMs is the cause of this slow time response. To the best of our knowledge, HSP512-1550 SLM is the fastest commercial product working at this wavelength. However, its switching frequency is currently more than one order of magnitude slower than achieved by a FSM.

To improve this temporal response boosting techniques were used [14]. The time for the LC to change from its initial phase to that required in the subsequent frame is different for each pixel, and these transition times depend on initial and final phase values and also on the difference between them (the higher the difference the faster the transition). The boosting technique models the phase response as an exponential function, and initially applies a phase value higher than the final one. After a pre-determined delay, the final phase value is applied to stabilize the pixel phase value defined by the hologram. The same principle can be employed for both increases in phase and decreases in phase.

Figure 8 shows a simulation example of the boosting technique applied on a single pixel, which initial and final phase are $\pi/8$ and $3\pi/4$ respectively. The dashed line represents the LC temporal phase evolution applying a

normal transition, whereas the solid one shows the boosting method result. In the picture a phase value of 2π was set at $t=3.2\text{ms}$ and then stabilize to $3\pi/4$ at $t=8\text{ms}$.

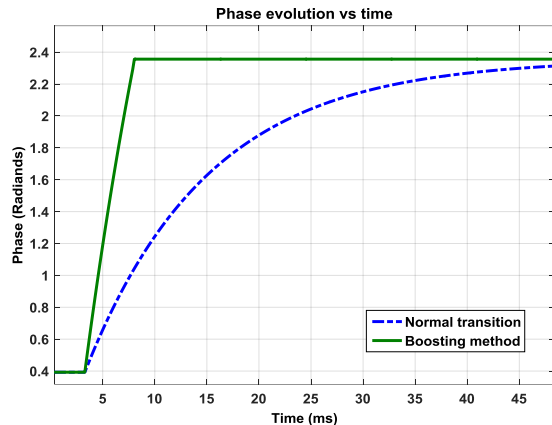


Fig. 8. Boosting method applied on the SLM to enhance the LC temporal response.

This method was implemented on each pixel of the hologram and measured the time taken by the SLM to steer the beam to a new position. A different overdrive and delay value was calculated for each pixel. To perform these measurements a detector was set up in front of the holographic beam steerer module. An initial hologram was written on the SLM to direct the light towards the detector. After 120ms a new hologram was updated to steer the light out of the detector collection area. The process is repeated so that a square signal should be obtained at the output of the detector. Figure 9 shows the rise and fall times employing a) simple transition and b) the boosting method. Comparing both pictures we can conclude that this technique halves the rise and fall times. This improvement allows a reduction of 60% in the fine tracking loop time.

Although further optimization might marginally enhance this time response, there is an intrinsic temporal limitation caused by the LC optical response. However, researchers have reported sub-microsecond LC optical response [15-16]. Future integration of these advances will make SLMs more attractive to perform not only high accuracy real time tracking but also turbulence correction at 1550nm. This temporal limitation can also be reduced using lower wavelengths like 850 or 1064nm. SLMs optimized for those wavelengths offer a response time 2-3 times quicker. However, the eye safety constrain would have a high impact on the link range and the optical design.

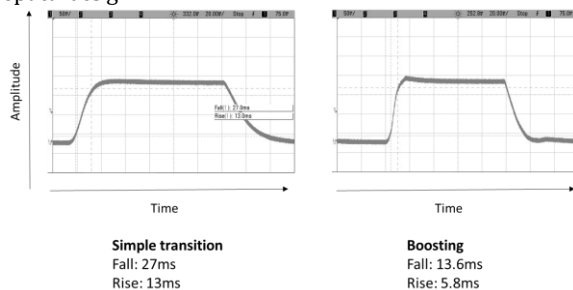


Fig 9. Rise and fall time measurement employing a) simple transitions and b) boosting method. Both images have been obtained with 50mV/division and 20ms time/division.

4. Conclusions

In this work we successfully demonstrated a real-time localization and tracking system for RFSO communications. We designed and implemented a base station with a video-based tracking module to coarsely locate an UAV equipped with an MRR. The coarse tracking worked cooperatively with a holographic fine tracking module based on SLM. This module implements beam steering and beam divergence controls. For the first time, an SLM has been integrated into a full tracking system to establish a data link between a UAV and a grounded BS.

The system was tested on a real environment offloading data from the UAV to the base station at 2Mbps at a range of 300m. OOK modulation schemes were used to transmit the data achieving a BER of 1.9701×10^{-4} . Additionally, the SLM optical response time was optimized using boosting methods. The enhancement gave a reduction of 60% in the fine tracking loop time.

Future work includes increasing the link throughput by using faster pixelated MQW modulators, as well as enhancing the receiver sensitivity to increase the link range. Data rates of hundreds of Mbps at a range of 1-2km are expected with these improvements. Additionally, multi-target tracking and aberration correction will be explored to tackle atmospheric turbulence and optimize the beam quality of the interrogator beam

Funding Information

Technology Strategy Board (TSB) UK (HYPERION (#101289)).

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