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Spaander, Joshua; Guo, J.

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A Space Multi-Beam Multi-Link Capable Laser Communications Terminal for Satellites

Joshua Spaander[1], **Jian Guo**[1*]
[1]Delft University of Technology, Kluyverweg 1, Delft, 2629HS, The Netherlands
[*] j.guo@tudelft.nl

Abstract

Free-space optical communication has proven to have many advantages over traditional radio communications. For instance, the hardware power efficiency and limited beam spread increase data rates for lower power consumption. Furthermore, the technology does not suffer from decreased bandwidth due to crowding. Free-space optical communication is usually done using laser communication terminals. In the past the focus has been on increasing the data rates for a single link and this has led to an exponential rise in the data rate performance. However, these modules have been limited to single beams and are hence capable of only one link. This decreases the number of users, networking, and relay capabilities of optical communication satellites. The advent of MEMS Micro-Mirror Arrays (MMA) and Spatial Light Modulators (SLM) have allowed for compact and lightweight control of wavefronts. These applications would also allow for scalable independent steering of multiple laser beams. The Delft University of Technology is conducting a study of a compact and scalable multi-beam terminal using these beam steering methods[1]. The terminal consists of a MEMS MMA for high frequency response in the aperture with a high resolution SLM for the beam steering and shaping. This terminal is designed for spacecraft-to-ground and spacecraft-to-spacecraft duplex communications. It is expected to support up to 10 or more duplex links in one terminal and, therefore, suitable for usage in small satellites and mega-constellations. The high resolution can also be used for sub-aperture wavefront correction in future. This paper discusses the design of the multi-beam terminal.

Terminal Design

The multi-beam terminal was designed in such a way as to be widely applicable in many use cases. As a result, the system was designed to be able to handle most of the optical signal types by not being polarization or modulation sensitive. Furthermore, a wide Field Of View (FOV) would allow for applications at a wide range of orbiting altitudes and constellations. The targets should also be able to move around within the field of view randomly and with little to no interruption. The system was also designed to be duplex to support both up and down links for each target. To be competitive with other systems, the Size, Weight and Power (SWAP) as well as the performance of the system should be comparable to its single beam counterparts with respect to each link. The resulting design achieved this through the use of Commercial Off The Shelf Components (COTS).

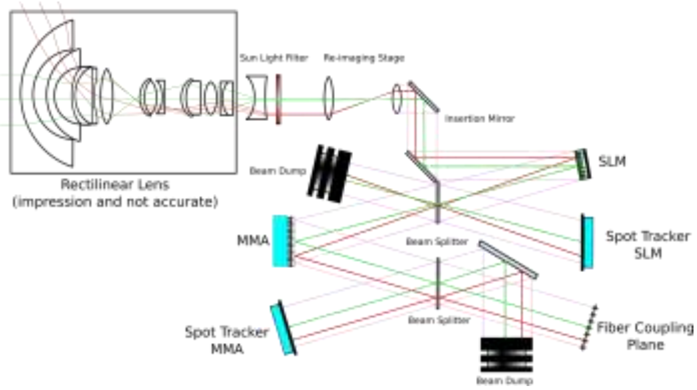

Fig. 1. The optical train containing the telescope and multibeam steering system.[1]

The optical train, in Fig. 1, contains 2 parts, the telescope and the multi-beam steering system. The system will be discussed from the perspective of incoming beams from the top left, entering the rectilinear lens. A transceiver was also designed but is not discussed here. The telescope accommodates a large FOV with low distortion to optimize fiber coupling by using a rectilinear lens. The output of the telescope is then filtered for sunlight to prevent damage. The beams are then inserted into the steering system.

Numerous practical hurdles were found when designing the steering system. The size and density of the steering surfaces is a limiting factor for the max number of beams and the uptime. Reason being the diffraction losses and proximity issues which occur when the beams cross between large steering surfaces. As a result, using high resolution SLMs to separate the beams and steer them to individual micro-mirrors on an MMA. The MMA mirrors act as a compact FSM array to correct for angular error and high frequency jitter above that of the SLM. The SLM can also be used to correct for wavefront errors, having the ability to correct sub-beam beam diameter. To track the beams spot trackers were chosen. Each steering mechanism utilized a spot tracker which is optically equidistant to their target plane giving direct feedback. A dedicated steering algorithm was developed to utilize the system's closed feedback control loop for each steering stage. The system is fully duplex. To accommodate the additional beams of the downlink, the same path concept was applied where up and downlink beams follow the same optical path in the terminal. This implies that when the incoming beams are steered to the transceiver, the outgoing beams are automatically steered towards the target. This saves the amount of space and beams to track by 50%. The system was designed to handle 10 beams and has comparable SWaP as well as performance compared to single beam design[2][3].

A model of the system was made to analyze the system, verify the steering performance, and validate the system. The model is shown in Fig. 2. The propagation through the optical train of the beam was performed using a custom propagation model derived from Fresnel propagation. The propagator was verified by performing diffraction experiments in real life and comparing the resulting intensity patterns to the model outputs.

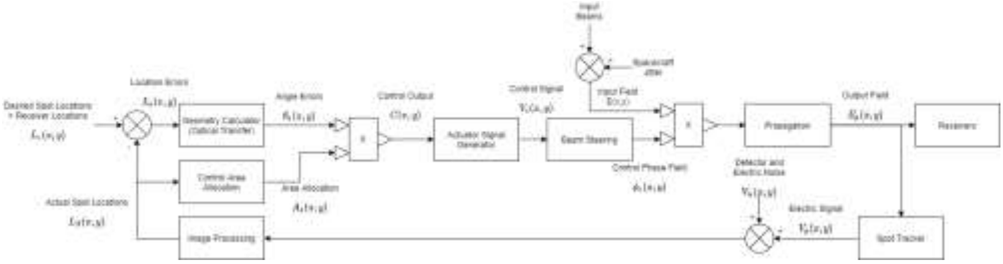

Fig. 2. Block diagram of the system model.[1]

Performing the simulation of the system, the resulting pointing error over time for a 3 beam-3 transceivers scenario is depicted in Fig. 3. The simulated system steering error was below required for about 90% of the time required for fiber coupling. This indicates the feedback loop works as intended. However, there are 3 periods of increased error. The first and last are when the beams enter and exit the aperture which are depicted at the start and at the end of the graph. Third region with increased error occurs when 2 beams cross. During the crossing, the 2 beams become unresolved and re-resolved. The transition period causes large errors due to diffraction caused by the algorithm and is a point of improvement. When unresolved, the system treats both beams as one, decreasing the error. The down time due to the system is around 10%. With a SLM resolution of 1080p on a 4x4 cm surface and beam diameters of 1.8 mm, it was found that the main factor limiting the number of beams as well as the up time were the beam diameters.

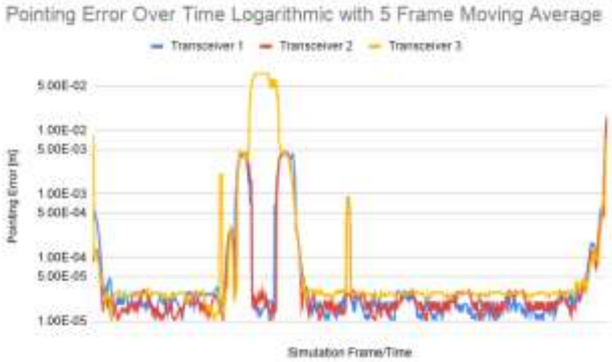

Fig. 3. Depicted is a time moving average of the pointing error over time.[1]

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