Performance of a Wavelength-Diversified FSO Tracking Algorithm for Real-Time Battlefield Communications

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ABSTRACT

Free-space optical (FSO) communications links are envisioned as a viable option for the provision of temporary high-bandwidth communication links between moving platforms, especially for deployment in battlefield situations. For successful deployment in such real-time environments, fast and accurate alignment and tracking of the FSO equipment is essential. In this paper, a two-wavelength diversity scheme using 1.55 \( \mu m \) and 10 \( \mu m \) is investigated in conjunction with a previously described tracking algorithm to maintain line-of-sight connectivity battlefield scenarios. An analytical model of a mobile FSO communications link is described. Following the analytical model, simulation results are presented for an FSO link between an unmanned aerial surveillance vehicle, the Global Hawk, with a mobile ground vehicle, an M1 Abrams Main Battle Tank. The scenario is analyzed under varying weather conditions to verify continuous connectivity is available through the tracking algorithm. Simulation results are generated to describe the performance of the tracking algorithm with respect to both received optical power levels and variations in beam divergence. Advances to any proposed tracking algorithm due to these power and divergence variations are described for future tracking algorithm development.

Keywords: Free-space optics, laser communications, mobile platforms, wavelength diversity, battlefield communications.

1. INTRODUCTION

One of the most appealing problems in communications is the last-mile problem in which methods for the provision of high-bandwidth communications links are being widely investigated. Free-space optical (FSO) technology has been seen as a proposed solution for bridging the last-mile gap by high-bandwidth communications links. FSO technology utilizes lasers or LEDs as a signal source to transmit data on modulated infrared (IR) beams through the atmosphere. The basic operation principle of FSO is similar to that of infrared television remote controls, wireless keyboards or wireless Palm devices. However, FSO has advantages over the technologies mentioned; it can provide higher data rates and much longer transmission ranges. FSO communications links operating at bandwidths up to 10 Gb/s have been reported in literature. FSO is seen as being further advantages due to several factors: FSO communications links are immune to electromagnetic interference; FSO technology does not require licensing from the Federal Communications Commission (FCC); Once established, FSO links are highly immune to interference and interception. The implementation of a wavelength diversity scheme is advantageous for use in adverse weather conditions as well as for certain alignment improvement methods.

The deployment of FSO technology in battlefield environments is not a new concept. Several approaches have been suggested for military applications. Battlefield, communications are an essential component for successful military
operations. An FSO link can be established between air-to-ground or air-to-air vehicles. These vehicles are supported with GPS devices to determine their location with a certain percentage of accuracy. GPS has been used to direct mobile and fixed FSO links, as many studies showed moderate levels of pointing\(^7\). The key factor for mobilizing FSO is to have gimbals on both sides of the communications link. These mechanical devices are used to rotate their load in the pitch, roll, and yaw directions. Gimbals are capable of achieving rotating speeds of 120 degrees/s, which is sufficient for directing FSO transceivers in mobile communications links. Direction and speed of the gimbals can be determined by simple mathematical calculations. These would help to establish, maintain, and end a transmission link between communicating entities. A combination of gimbals and GPS devices were proposed to the Air Force Research Laboratory’s EO Sensor Technology & Evaluation Research (ESTER) program in an approach to use FSO in battlefield scenarios\(^9\). The proposal suggested using beacon signals to switch between narrow and wide divergence angles after achieving signal lock.

Currently, the common telecommunications technology used in military applications is RF (Radio Frequency) technology. The bit rates of RF are low compared to those offered by an FSO link. If the mobile problem in FSO is solved, low bandwidth and frequency congestion will no longer be limitations to military communications in the battlefield.

The common optical wavelength used in FSO is the 1.55 \(\mu\)m; although sometimes the 0.85 \(\mu\)m can be used for certain applications. In this paper, we investigate the 10 \(\mu\)m wavelength as well and show results of using such wavelength in a tracking algorithm designed for mobile FSO\(^6\). The 10 \(\mu\)m wavelength is introduced due to transmission advantages that can be achieved, especially when transmitting through certain types of fog\(^4\). Using different wavelengths, results in different divergence angles, power consumption, and data rates. This paper uses analytical and simulation tools to investigate several transmission scenarios between mobile FSO platforms. The remainder of this paper is organized as follows: Section 2 describes an analytical model of three-dimensional mobile FSO links, Section 3 introduces the mobile FSO scenario that is simulated in this paper, the simulation results are presented in Section 4 and finally concluding remarks are made in Section 5.

2. THREE-DIMENSIONAL MOBILE FSO LINKS

In order to implement different scenarios in which FSO technology is used between mobile platforms, it is first necessary to analyze a three-dimensional scenario between two mobile platforms. The platforms are moving in opposite directions toward each other having variable velocities and altitudes. On each platform, a gimbal is mounted to control the movement of the FSO transceivers on the pitch, roll, and yaw axes. Figure 1, shows both the xyz and the pitch, roll, and yaw axes. GPS devices are used to determine the positions of the platforms at time \(t\). The GPS system is used in order to provide a course alignment and tracking algorithm for the transmitter-receiver pair. A fine alignment mechanism will also be necessary to successfully track and align the FSO system. Inertial Navigation Systems (INS) are used to determine the velocity the object is moving in which will specify the angular velocity of the gimbal as it steers.

![Figure 1 – xyz and pitch, roll and yaw systems](image-url)
Figure 2, shows the setup of two mobile platforms in a 3-dimensional plane. The two platforms can move on x, y or z axes at any time. In the figure, only x and y directions are shown; the z direction is toward the viewer. As vehicles A and B move closer, the angular speed of the gimbals increases until it reach a maximum at the point of intersection.

After the two vehicles meet, the value of the angular speed decreases as the distance $D(t)$ between the two increases. Using the propagation of the lowest order transverse electromagnetic Gaussian-beam wave, we can calculate the beam divergence $W(t)$ at the receiver plane, this is expressed by the following:

$$U_0(\vec{r}, 0) = A_0 e^{-\left(\frac{r^2}{W_0^2} + \frac{kr^2}{2F_0}\right)}$$  \hspace{1cm} (1)

where $A_0$ is the amplitude of the wave, $r$ is the distance from the center line in the transverse direction. $r_x, r_y, \text{and } r_z$ are the x, y and z components of vector $r$. $j^2 = -1$, $W_0$ is the effective beam radius at the transmitter, $F_0$ is the parabolic radius of curvature of the phase distribution and $k$ is the optical wave number$^{10,11}$. Setting:

$$\alpha_0 = \frac{2}{kW_0^2} + j \frac{1}{F_0},$$ \hspace{1cm} (2)

Equation (1) becomes:

$$U_0(\vec{r}, D(t)) = A_0 e^{-\left(\frac{1}{2\alpha_0 r^2}\right)}. $$ \hspace{1cm} (3)

The optical field of the Gaussian-beam wave at a distance $D(t)$ is given by the Huygens-Fresnel integral:

$$U_0(\vec{r}, D(t)) = -2jk \int_{-\infty}^{\infty} G(\vec{s},\vec{r};D(t))U_0(\vec{s}, 0)d^2s,$$ \hspace{1cm} (4)

where $U_0(\vec{s},0)$ is the optical field at the ground station transmitter plane and $G(\vec{s},\vec{r};D(t))$ is Green’s function which is defined by$^{10}$:
\[ G(\vec{s}, \vec{r}; D(t)) = \frac{1}{4\pi D(t)} e^{\left[ \frac{jL \gamma - jk}{2D(t)} \right] A}. \] (5)

Substituting Equation (3) into Equation (4) and evaluating the integrals, a Gaussian-beam wave with complex amplitude \( A_0(1+j\alpha_0 D(t)) \) is obtained:

\[ U_0(\vec{r}, D(t)) = \frac{A_0}{1 + j\alpha_0 D(t)} \left[ e^{\left[ \frac{j\beta D(t) - \frac{1}{2} \beta \alpha_0^2}{1 + j\alpha_0 D(t)} \right]} \right], \] (6)

where \( 1+j\alpha_0 D(t) \) is referred to as the propagation parameter\(^10\). In order to express Equation (6) in terms of beam radius, the following notation is defined:

\[ \Theta_0 = \text{Re}(1+j\alpha_0 D(t)) = 1 - \frac{D(t)}{F_0}, \] \[ \Lambda_0 = \text{Im}(1+j\alpha_0 D(t)) = \frac{2D(t)}{kW_0^2}. \] (7)

The parameter \( \Theta_0 \) describes the amplitude change in the wave due to focusing and \( \Lambda_0 \) describes the corresponding change due to diffraction. Substituting this notation, Equation (6) becomes:

\[ U_0(\vec{r}, D(t)) = \frac{A_0 e^{-\frac{j\beta}{2}\Theta_0^2}}{(\Theta_0^2 + \Lambda_0^2)^{1/2}} \left[ e^{\left[ \frac{j\beta D(t) - \frac{1}{2} \beta \Theta_0^2}{\Theta_0^2 + \Lambda_0^2} \right]} \right], \] (8)

where the term \( A_0 \left( \Theta_0^2 + \Lambda_0^2 \right)^{1/2} \) represents the amplitude changes due to both focusing and diffraction and \( \tan^{-1}(\Lambda_0/\Theta_0) \) is the longitudinal phase shift. Performing a statistical analysis of a Gaussian-beam wave does not require the algebraic complexity of the beam parameters defined in Equation (7)\(^11\). It is therefore possible to use the transformation \( 1/(\Lambda_0/\Theta_0) = \Theta - j\Lambda \) where:

\[ \Theta = \frac{\Theta_0}{\Theta_0^2 + \Lambda_0^2}, \Lambda = \frac{\Lambda_0}{\Theta_0^2 + \Lambda_0^2}. \] (9)

where \( \Theta \) and \( \Lambda \) are the receiver beam parameters. The beam radius, \( W \) and the phase front curvature \( F \) at the receiver have been shown to be\(^10\):

\[ \Theta = 1 + \frac{D(t)}{F}, \Lambda = \frac{2D(t)}{kW^2(t)}. \] (10)

The beam radius at the receiver plane of the mobile platform B is:

\[ W(t) = W_0 \left( \Theta_0^2 + \Lambda_0^2 \right)^{1/2} = \frac{W_0}{\left( \Theta^2 + \Lambda^2 \right)^{1/2}}. \] (11)

The Gaussian-beam wave at the receiver can be expressed as:
\[
U_b(\hat{r}, L) = A_0 (\Theta - j \Lambda) e^{\left(\frac{\beta_0 r^2}{W^2 (r)} \frac{k_r^2}{2F}\right)}.
\]  

(12)

The profile of the Gaussian-beam wave in the receiver plane is of importance due to the change in beam profile introduced to the system due to mobility. As the transmitter and receiver move, the changing separation distance between them will result in an increase of decrease of the beam diameter. This constantly changing beam diameter introduces further complexity to any alignment and tracking algorithm that needs to be implemented in order to successfully establish the mobile FSO communications link.

3. SIMULATION CONFIGURATION

The simulation results obtained in this paper consider a three dimensional scenario in which a secure FSO communications link is established between an M-1 tank and a Global Hawk unmanned aerial vehicle (UAV). This scenario is analyzed using ALTM and PCModwin simulation software from Ontar Corporation in order to analyze both power levels and beam divergence variations present in the FSO link that need to be accounted for when developing a tracking algorithm. Figure 3, shows a schematic view of the simulation configuration.

![Figure 3 – 3D simulation configuration](image)

The simulation was run for both the 1.55 \( \mu m \) and 10 \( \mu m \) wavelengths of the diversity scheme. The output power of the source laser is set to 20 mW. The link is configured so that the UAV cannot fly below an altitude of 1,000 m or above an altitude of 5,000 m relative the ground-based tank. The effective beam radius at the transmitter was set at 2 cm with a half angle divergence of 100 \( \mu \text{rad} \).

4. SIMULATION RESULTS

The simulated results generated for the mobile FSO scenario described in Section 3 are divided into two sections: The first presents variations in received optical power based on transmitter-receiver separation variations, and the second presents variations in beam profile.
4.1 Received power

Two scenarios were run to generate received power versus UAV altitude plots for the two wavelengths. The first is that of a slant path using the standard 1976 US model atmosphere with a rural visibility of 23 km. Figure 4 shows the results of this simulation for both a 45° and 0° angle between the transmitter and receiver. The received power is shown from the perspective of the tank.

![Received Power versus UAV Altitude](image)

**Figure 4.** Received power for 3D FSO link in clear atmosphere

As can be seen from the plot, the received power for all scenarios is of sufficient magnitude to support data transmission between the UAV and tank. The second simulation run used the same parameters, but introduce radiation fog into the atmosphere surrounding the UAV and tank. This situation introduces the worst-case scenario for FSO communications. The results of this simulation are shown in Figure 5.
From the data obtained in the presence of fog, the advantage of introducing the 10 µm wavelength can be seen. While transmission with the more common 1.55 µm wavelength is not possible in foggy conditions, the longer 10 µm wavelength allows for the establishment of a usable FSO communications link between the transmitter and the receiver. The 10 µm link is, however, more expensive and difficult to establish due to the need of a cooling mechanism for the laser transmitters. For this reason, the wavelength diversity scheme is proposed in which the standard 1.55 µm wavelength is used under normal conditions, with an available 10 µm wavelength for transmission in adverse conditions.

4.2 Beam Divergence

In order to successfully align the mobile FSO transmitter and receiver, the use of controlled beam divergence is essential in order to provide the alignment and tracking algorithm with a beam profile of sufficient size to successfully lock onto the mobile target. To determine the range of beam profiles present simulations were run for both the slant and vertical path corresponding to the power simulations presented above.

Figure 6 shows a sample of the beam profile received for both (a) 1.55 µm and (b) 10 µm as a function of radial distance from the transmitter-receiver central plane for a UAV altitude of 5,000 m with a transmitter-receiver angle of 45°.
Figure 6. Beam profile for (a) 1.55 µm and (b) 10 µm wavelength

Figure 7 shows a plot of receiver plane beam profile radius for both wavelengths for the corresponding UAV altitudes used above.

![Receiver Profile as a Function of UAV Altitude](image)

From Figure 4 and Figure 5, it can be seen that for the 1.55 µm wavelength, the beam radius varies from a minimum of 0.54 m to a maximum of 2.09 m for the vertical case and a minimum of 0.6 m to a maximum of 2.96 m for the slant case. From this data, alignment of the transmitter and receiver will be significantly more complicated for situations when the UAV is flying at a lower altitude. To ensure successful alignment and tracking in this situation, an increase in beam divergence angle of the transmitter will improve link reliability. For the 10 µm case, the beam radius varies from a minimum of 0.76 m to a maximum of 3.77 m for the vertical case and a minimum of 1.07 m to a maximum of 5.34 m for the slant case.

The large variation in receiver-plane beam diameter present in the described FSO communications link introduces further complexity when designing a mobile FSO platform. Any implemented alignment and tracking algorithm requires the use of beam divergence to offset any alignment errors present in the gimbal equipment. Due to the continually varying beam...
profile in mobile links, the alignment and tracking algorithm will need to either continually adjust for the changing beam diameter, or a variable beam divergence will need to be implemented into the FSO transmitter.

5. CONCLUSIONS

This paper has presented an analytical model for a mobile three-dimensional FSO communications link. The results of the model are then used in order to simulate an FSO communications link between an unmanned aerial vehicle and a mobile battlefield tank. The simulation results reveal that in mobile FSO communications links, a significant variation in both received optical power and beam diameter in the receiver plane will be present. These power and beam profile variations will introduce further complexity to any alignment and tracking algorithm that is implemented between mobile platforms connected by FSO technology.

REFERENCES