High-speed Communications Enabling Real-time Video for Battlefield Commanders Using Tracked FSO

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ABSTRACT

Free Space Optics (FSO) technology is currently in use to solve the last-mile problem in telecommunication systems by offering higher bandwidth than wired or wireless connections when optical fiber is not available. Incorporating mobility into FSO technology can contribute to growth in its utility. Tracking and alignment are two big challenges for mobile FSO communications. In this paper, we present a theoretical approach for mobile FSO networks between Unmanned Aerial Vehicles (UAVs), manned aerial vehicles, and ground vehicles. We introduce tracking algorithms for achieving Line of Sight (LOS) connectivity and present analytical results. Two scenarios are studied in this paper: 1 - An unmanned aerial surveillance vehicle, the Global Hawk, with a stationary ground vehicle, an M1 Abrams Main Battle Tank, and 2 - a manned aerial surveillance vehicle, the E-3A Airborne Warning and Control System (AWACS), with an unmanned combat aerial vehicle, the Joint Unmanned Combat Air System (J-UCAS). After initial vehicle locations have been coordinated, the tracking algorithm will steer the gimbals to maintain connectivity between the two vehicles and allow high-speed communications to occur. Using this algorithm, data, voice, and video can be sent via the FSO connection from one vehicle to the other vehicle.

Keywords: Free space optics, high-speed communications, and real-time video.

1. INTRODUCTION

Free Space Optics (FSO) communications, or Optical Wireless, refers to the transmission of modulated visible or infrared (IR) beams through the atmosphere to achieve optical communications. Like traditional fiber optic communications, FSO uses lasers to transmit data, but instead of enclosing the data stream in a glass fiber, it is transmitted through the air. Today, this technology is mainly used in a campus environment where network infrastructure is lacking between buildings or as a last-mile hop to connect segmented networks. FSO is a technology capable of offering full-duplex gigabit Ethernet. In some applications, FSO is capable of over 2.5 gigabits of bandwidth once a link is established and both the transmitter and the receiver are aligned with a clear line of sight. The potential of FSO technology decreases when mobility is required; nevertheless, many studies have been done to bring its strength to mobile environments [1, 2, 9].

Communications are a very important aspect of the battlefield. Currently, radio frequency (RF) technology is used for communications between ground troops and their commanders, between airborne surveillance vehicles and ground troops, and between airborne surveillance vehicles and other aircraft. But with RF, the bit rates achieved are low and unreliable. High quality real-time video is difficult at best with bandwidths less that one megabit per second. A 2005 Associated Press report noted “Unmanned warplanes still face difficulties”[4] referring to a Government Accounting Office report citing problems that delay commanders from receiving critical information for hours due to frequency congestion. Additional concerns about interoperability and lacking data that prevents time-critical targeting were also cited.

The RF bit rates are modest compared to those offered by an FSO link. While studies are still continuing, mobile optical wireless has considerable advantages over RF. By solving the mobile problem, FSO provides the solution: low bandwidth and frequency congestion are no longer the limiting factors in battlefield situation awareness for the military.

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FSO combined with RF provides robust, high bandwidth battlefield communications enabling real-time video, situational awareness, and command and control communications.

There are two basic methods for mobile FSO communications: one is to use multiple lasers and receivers in a fixed pattern while catching the target as it passes through the field of one of the laser/receiver pairs and burst data through the communications channel. The second is to steer a single laser/receiver pair toward the target to maintain communications. The use of spherical antennas covered with transmitter and receiver modules [9] was demonstrated using low power LEDs and a small train moving in a circular path of 30cm radius. The two nodes were not aligned all the time, but whenever connectivity was lost, a new connection initialization algorithm was executed to promote alignment and establish communication.

In this paper, a tracking algorithm for mobile FSO communication is introduced in two- and three-dimensional (2D and 3D) systems while one or both ends of the link are moving. Then, the two scenarios specified in the abstract are set up and illustrated in the suggested environments. The results from calculations made on the established equations are then analyzed and a conclusion is drawn from them.

2. DESIGN CONSIDERATIONS

2.1 Equipment Used

The aim of this study is to have two objects moving and have laser communications established between the two. To have the optical nodes directed towards one another, gimbals are used. These gimbals are steered using certain applications that input different parameters. The parameters needed for such an event are: speed, heading, altitude, longitude, latitude, pitch, roll and yaw of the two vehicles. There are a variety of internal systems that determine such parameters as will be suggested in the tracking algorithm.

In laser communications, the two main wavelengths of 850 nm and 1550 nm are typically used. A 1550 nm beam exhibits more divergence at high altitudes and thus will acquire fewer updates than the 850 nm wavelength. Common gimbals used in similar applications have a slew rate that ranges between 60 and 120 degrees/second. These gimbals are used to steer the mounted transceivers in such a way as to have them both aligned. The 2D and 3D systems presented in the next sections explain how angular positions and velocities can be determined when two vehicles are moving in opposite directions.

2.2 Two-dimensional System

In a 2D system, a simple study of two objects in motion can be examined. Having in mind that both the transmitter and the receiver are mounted on gimbals, the goal is to always to have a clear line of sight and ensure alignment on both ends, as shown in Figure 1.

![Figure 1 - A 2D plot of two objects moving in different directions while maintaining connectivity.](http://proceedings.spiedigitallibrary.org/ on 10/09/2013 Terms of Use: http://spiedl.org/terms)
The first and simplest case to consider would be when one object is moving and the second is not. The second case would be when both objects are moving. Since the first case can be treated similar to the second, in terms of calculating the angular positions and velocities, only the second will be considered. The difference between the two cases is that in the second, the distance between the two vehicles would change faster than that of the first case where only one car is in motion, increasing the angular velocity as they approach each other. On the contrary, if the vehicles were going away from each other, the angular velocities would be smaller.

To accurately compute a gimbal steering command, the exact orientation of the gimbal relative to the vehicle must be known. Additionally, the vehicles’ attitudes must also be considered. In Figure 2, an illustration of the effect of pitch, roll and yaw on a vehicle’s attitude is shown. As will be explained later on in this paper, if the moving object rotates on any of these axes, the gimbal’s steering commands must compensate for the change caused by this rotation to prevent over or under steering of the gimbal.

![Diagram of a vehicle with axes labeled](image)

Figure – 2 Effect of pitch, yaw and roll on the gimbal’s movement.

Using classical mechanics, the following equations that will specify the angular positions and velocities of the gimbals on both ends of the link are formulated. Time, X (Latitude) and Y (Longitude) coordinates; angular velocity and angular position are the basic components of the following equations:

\[
\alpha = \arctan \left( \frac{y}{x} \right)
\]

where \( \alpha \) is the angular position of the gimbals in the \( x-y \) plane, or in other words yaw, \( x \) and \( y \) are the distances between the two vehicles on the \( x \)-axis and \( y \)-axis, respectively, at a certain time. Since we are considering a 2D system, the gimbals can move only in the \( x, y \) plane and thus only have one angular dimension (yaw).

\[
\alpha' = \frac{\alpha_t - \alpha_{t_0}}{t} = \frac{\arctan \left( \frac{y_t}{x_t} \right) - \arctan \left( \frac{y_{t_0}}{x_{t_0}} \right)}{t}
\]
where $\alpha'$ is the angular velocities of the gimbals, $\alpha_{t_1}$ and $\alpha_{t_0}$ are the angular position of the gimbals at time $t_1$ and $t_0$, respectively, $y_{t_1}$ and $y_{t_0}$ are the differences in y coordinates between the two vehicles at time $t_1$ and $t_0$, respectively, $x_{t_1}$ and $x_{t_0}$ are the differences in x coordinates between the two vehicles at time $t_1$ and $t_0$, respectively, and $t$ is the time difference between $t_1$ and $t_0$. Using these equations as applied to two automobiles passing on a highway 100 m apart at 50 km/h along parallel paths, we get the results shown in Figure 3.

![Figure 3](image-url)  
Figure 3 - Angular velocities of the gimbals as two cars are passing one another.

As the two cars pass, the angular velocities of the gimbals increase until both cars meet at the line perpendicular to their path. The angular velocity increases as the vehicles get closer to one another and then starts decreasing as the cars move away again.

2.3 Three-dimensional System

In a 3D system, we consider a tank as a ground vehicle and a Global Hawk as an unmanned aerial vehicle (UAV) to show how results change with adding the z-axis (Altitude). As shown in Figure 4, the two ends have a clear line of sight and connection is already established.

Most of the equations in the 2D system are changed in the 3D system due to the existence of the z-coordinate. The equations for the angular position of the gimbals on both sides become as follows:

\[
\theta = \arctan \left( \frac{z}{y} \right)
\]

and

\[
\alpha = \arctan \left( \frac{y}{x} \right)
\]
where \( \theta \) is the angular position of the gimbals in the \( z-y \) plane, or in other words the pitch, \( z \) is the position of the vehicles on the \( z \)-axis, \( z_p \) is the \( z \)-axis position of the vehicle affected by the change in pitch of the vehicle itself and \( z_R \) is the \( z \)-axis position of the vehicle affected by the change in roll of the vehicle itself.

![Figure 4 - A snapshot of scenario 1 and a display of how the algorithm is used in a 3D system.](image)

The two moving objects should be able to determine the position of one another and accordingly the gimbals mounted on them will track each other [2]. If the two vehicles are moving towards each other and the airplane is changing its altitude, the following values of angular velocities on pitch and yaw of the gimbals are obtained, as shown in Figures 5 & 6.

![Figure 5 - Angular velocities on yaw of the gimbals.](image)

In Figure 5, we assume that the two vehicles are moving in the \( x-y \) plane with a constant altitude difference (\( z \)) of 13,716 m. The vehicles start 3000 m apart on the \( x \)-axis and 500 m on the \( y \)-axis. In Figure 6, we assume that the two vehicles are 0 m apart on the \( x \)-axis and the motion is only in the \( z-y \) plane. The vehicles start at 13,716 m apart on the \( z \)-axis and 5000 m on the \( y \)-axis.
3. TRACKING ALGORITHM

3.1 Algorithm Overview

As discussed in the previous section, the angular positions and velocities can be determined using the suggested equations. But that does not stand alone as a complete system for tracking; we must know information about the vehicles themselves. In order to form our algorithm, we will use other systems to achieve the desired goal. In the two scenarios, advanced ground and aerial vehicles are used which contain a variety of devices that will simplify many tasks. Among those are the Global Positioning Systems (GPS) which are used to determine the $x$, $y$, and $z$ coordinates that define the vehicles’ positions. Other types of equipment found in these vehicles are the Inter-Vehicular Information System (IVIS) and the Inertial Navigation System (INS) that provide our system with the vehicles’ position, heading, and velocity.

We assume that the two vehicles receive all the information needed to determine the precise positions of both vehicles. An application is used to obtain this information that is transferred to the gimbals. The application translates the positions of the vehicles at different time intervals into angular positions and velocities of the gimbals. These angular positions and velocities are used to ensure that the two optical transceivers mounted on the gimbals are pointing at one another as the two vehicles move.

As will be illustrated in the next two sub-sections, this algorithm is used in a battlefield environment. We assume that the weather conditions are suitable for FSO communications and a line of sight can be established when the proposed algorithm is initialized. Also, that initial connection is established using another technology such as RF to transfer the vehicles’ information between them.

3.2 Scenario 1

On the battlefield, communications are essential in order to keep forces organized and updated. Lack of communications or even poor communications can lead to a weakening of the whole combat system and result in added casualties. The first scenario addresses the Global Hawk UAV communicating with a stationary ground vehicle, an M1 Abrams Main Battle Tank. The use of high speed communications is critical; also the existence of real-time video surveillance for battle commanders will simplify a lot of tasks. Both functions are achievable with the use of FSO technology.
Gimbals are fixed on the bottom of the UAV and on the top of the tank. Optical transceivers are then mounted on the gimbals. As both vehicles move in different directions and variable speeds, the gimbals will adjust in a way to keep track of the other vehicle. We will use the equations mentioned in 2.2 with slight changes in both scenarios according to the scenario setup.

In this scenario, the tank is moving at ground level and is far in distance from the UAV which can be flying at altitude of 18,000 m and up to 2 km away from the tank. The tank will also be moving in different directions and at variable speeds.

As shown in Figure 7, a clear line of sight exists between the tank and the UAV at all times. The tank contains an intervehicular information system (IVIS) that can provide the position, heading, and velocity of the tank. An inertial navigation system (INS) and a global positioning system (GPS) provide the position, velocity, orientation, and angular velocity of the UAV by measuring the linear and angular accelerations applied to the system in an inertial reference frame [6]. Commercial GPS devices can achieve accuracies of 1-3 m which is sufficient in our study, as will be explained later [3]. Some of these parameters are used as inputs to several equations to get the direction and angular velocity of the gimbals to keep track of each other.

\[
\theta = \arctan \left( \frac{z + z_P + z_R + z_Y}{y + y_Y} \right)
\]

and

\[
\alpha = \arctan \left( \frac{y + y_Y}{x + x_Y} \right)
\]

where \( z_Y \) is the z-axis position of the vehicle affected by the change in yaw of the vehicle itself, \( y_Y \) is the y-axis position of the vehicle affected by the change in yaw of the vehicle itself and \( x_Y \) is the x-axis position of the vehicle affected by the change in yaw of the vehicle itself.

Both vehicles are subject to not only changing position (latitude and longitude) and direction (heading), but also rotating along the three axes: pitch, roll and yaw, as illustrated in Figure 2. When the vehicle rotates along any of these axes a change in \( x, y \) or \( z \) coordinates is detected and a value is added to \( x, y \) or \( z \) component accordingly. This addition compensates for the gimbals sitting off axis (not flying straight and level). Each vehicle contains a system that determines these variables and can be given as inputs to our equations to determine the angular positions and velocities. In addition to the effects of pitch, roll and yaw, we have the heading effect on the result of our equations. Heading is
defined as where the vehicle is directed; this aspect becomes crucial in cases where vehicles stop and change their heading. A connection might be lost in such cases and a new connection is initiated.

Accordingly, the required angular velocities of the two gimbals to get to those angular positions are:

\[
\theta' = \frac{\theta_2 - \theta_1}{t} = \frac{\arctan \left( \frac{z_{t_1} + z_{p_{t_1}} + z_{G_{t_1}} + z_{R_{t_1}}}{y_{t_1} + y_{P_{t_1}}} \right) - \arctan \left( \frac{z_{t_0} + z_{p_{t_0}} + z_{G_{t_0}} + z_{R_{t_0}}}{y_{t_0} + y_{P_{t_0}}} \right)}{t}
\]

and

\[
\alpha' = \frac{\alpha_2 - \alpha_1}{t} = \frac{\arctan \left( \frac{y_{t_1} + y_{P_{t_1}}}{x_{t_1} + x_{G_{t_1}}} \right) - \arctan \left( \frac{y_{t_0} + y_{P_{t_0}}}{x_{t_0} + x_{G_{t_0}}} \right)}{t}
\]

Thus, for any position the tank or the UAV chooses to be in, a connection will always be established; even when the tank is going uphill or downhill, rolled a bit sideways or turning right or left, the gimbals will get the necessary information to steer towards one another and maintain alignment of the FSO transceivers.

3.3 Scenario 2

In this scenario, the E-3A Airborne Warning and Control System (AWACS) is communicating with the Joint Unmanned Combat Air System (J-UCAS) using the proposed algorithm, as shown in Figure 8. In this scenario, a line of sight is considered to be of greater importance than in scenario 1.

Taking into consideration the fact that a J-UCAS is capable of changing its direction dramatically in few seconds, communications might not be achievable at all times between a J-UCAS and an AWACS. A solution for such a setback would be having an RF mesh network connecting these two with a base station or a tank.

![Figure 8 - A sketch of an AWACS and J-UCAS using FSO to transmit and receive battlefield information.](http://example.com/figure8.png)
Equations used to determine both the angular positions and velocities of the two gimbals are approximately the same as in scenario 1. The equations appear as follows:

$$\theta = \arctan\left(\frac{z + z_p + z_r + z_y}{y + y_y}\right)$$

and

$$\alpha = \arctan\left(\frac{y + y_y}{x + x_y}\right)$$

also,

$$\theta' = \left(\frac{\theta_2 - \theta_1}{t}\right) \equiv \theta' = \left(\frac{\arctan\left(\frac{z_{t_2} + z_{p_{t_2}} + z_{r_{t_2}} + z_{y_{t_2}}}{y_{t_2} + y_{y_{t_2}}}\right) - \arctan\left(\frac{z_{t_1} + z_{p_{t_1}} + z_{r_{t_1}} + z_{y_{t_1}}}{y_{t_1} + y_{y_{t_1}}}\right)}{t}\right)$$

and

$$\alpha' = \left(\frac{\alpha_2 - \alpha_1}{t}\right) \equiv \alpha' = \left(\frac{\arctan\left(\frac{y_{t_2} + y_{y_{t_2}}}{x_{t_2} + x_{y_{t_2}}}\right) - \arctan\left(\frac{y_{t_1} + y_{y_{t_1}}}{x_{t_1} + x_{y_{t_1}}}\right)}{t}\right)$$

5. RESULTS

Using the equations in the previous sections, an update rate can be calculated to determine how long it takes for the gimbals to be steered. This factor is directly affected by the divergence angle of the laser beam [10]. The laser power and wavelength, turbulence and other parameters can change the divergence angle of the beam and thus the update rate.

To plot the graph of divergence angle versus update rate, one first calculates the speeds of both vehicles and then estimates, in the worst case scenario, how long connectivity is still established. Assume that the divergence angle will be the same for all angular positions the gimbals attain. The case studied is when the UAV is directly over the tank and connectivity has already been established.

The ALTM (Atmospheric Laser Turbulence Module) software application, commonly used in FSO, was used to determine an approximation of the divergence angle for two different wavelengths [2]. Under normal turbulence conditions, with a separation height of 13,716 m and using a 1550 nm laser source with 1 mW of optical power, the approximate divergence angle is 0.0565 degrees [1]. With the same setup, but now with the added effect of turbulence, the divergence angle increases to 0.0567 degrees [8]. In Figure 9, a plot of the mean intensity profile versus the radical distance is shown using such a laser source.

The update rate varies according to the width of the beam at the receiver caused by the divergence of the laser beam from the source. For scenario 1, the case studied was when the two vehicles were moving at top speed toward each other. The maximum speed of the Global Hawk is approximately 640 km/h [7], whereas the M1 tank reaches a maximum speed of 72 km/h [5].
Assume that both vehicles just updated their location information and sent the commands to steer the gimbals. The next update, if the Global Hawk is at an altitude of 13,716 m and both vehicles are going in maximum speeds toward each other, should be in less than 34 ms or connectivity is lost and another connection initialization is issued.

The update rate is even less in scenario 2 where the J-UCAS is capable of reaching speeds of 1040 km/h and the AWACS of 855 km/h. The time needed to update both systems should be less than 12.8 ms if the divergence distance at the receivers is 13.5 m, as in the above example. Figures 10 & 11 illustrate the update rate versus divergence angle caused by dispersion in the two scenarios.

Figure 9 - ALTM plot of Mean Intensity Profile vs. Radical Distance for a 1550 nm laser source

Figure 10 - Graph of Divergence Angle vs. Update Rate in scenario 1.
Scenario 2

Figure 11 - Graph of Divergence Angle vs. Update Rate in scenario 2.

6. Conclusion

FSO technology will grow beyond its applications in the last-mile problem and become a more versatile technology. As shown herein, tracking and alignment can be achieved for mobile end points. For the two scenarios examined in this study, connectivity can be maintained by using various positioning systems that are found in the moving vehicles and gimbals. Data, voice, and video can be sent via the FSO connection where data rates of up to 2.5 Gbps are currently possible. More specifically, real-time video can be sent from aerial vehicles to other aerial or ground vehicles to maintain battlefield situational awareness for command and control. Future plans call for this algorithm to be tested with a transceiver mounted on a mobile platform. Further studies are required with scenarios exhibiting greater complexity to validate the viability of this proposed approach.

References