Maintaining A Free-Space-Optical Communication Link Between Two Autonomous Mobiles

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***Abstract*—Free-Space-Optical (FSO) communication has the potential to not only deliver wireless communication links at optical-level speeds but also solve the wireless capacity problem that the traditional RF based technologies are confronting. Despite its advantages, FSO communication is prone to mobility. The highly directional FSO transceivers require establishment and maintenance of line-of-sight (LOS) between them. Facilitating continuous alignment requirements has been a major concentration of mobile FSO research to date. We consider two autonomous mobile nodes, each with one FSO transceiver mounted on a movable head capable of rotating 360 degrees. We propose a novel scheme that deals with the problem of automatic detection, establishment and maintenance of LOS alignment between the two nodes with mechanical steering of the FSO transceivers. The proposed method shows that using such mechanically steerable transceivers and a simple autoalignment mechanism, it is possible to maintain optical wireless links in a mobile setting with nominal disruption.**

***Index Terms*—Free Space Optical Communication, Line of Sight, Autonomous Mobiles.**

I. Introduction

As a wireless technology, free-space-optical (FSO), a.k.a. optical wireless, communication has recently attracted significant interest from telecommunication research and industry, mainly due to the increasing capacity crunch faced by the RF wireless technologies [1]. The RF bandwidth is already heavily saturated and becoming more scarce as cellular capacity has mostly hit its limits. FSO communication (FSOC) has the potential to complement the traditional radio frequency (RF) networks. It uses the unlicensed optical spectrum and mostly uses the same technology as the fiber optic communications. FSOC can provide a higher bandwidth channel for transferring large volumes of data. It has shown the ability to reach modulation speeds up to 10 Gbps [2] easily. It can also provide connectivity in conditions that are unfavorable for RF communication and has low probability of interception and detection [3]. Furthermore, FSOC is advantageous in terms of cost efficiency as its propagation medium is free space and does not necessitate costly fiber cable deployments.

While FSOC has been mainly useful for stationary nodes in a fixed network, there are also several scenarios involving mobile nodes that can benefit from the various advantages offered by FSOC. Secure command and control of mobile units in combat, sharing of high-resolution imagery and guidance data in next-generation air-traffic control, airborne internet, and rapid communication deployment in disaster recovery are a few examples of these scenarios [4]. Application of FSOC in mobile settings has been considered for indoor environments, within a single room, using diffuse optics technology [5], including multi-element transmitter and receiver based antennas. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances only. For outdoors, fixed FSOC techniques have been studied to remedy small vibrations [6], swaying of the buildings using mechanical auto-tracking [7] or beam steering [8], and interference [9] and noise. Line-of-sight (LOS) scanning, tracking and alignment have also been studied for years in satellite FSOCs [10]. Again, these works considered long-range links that utilize very narrow beam widths (typically in the microradian range) and typically use slow, bulky beam-scanning devices such as gimbaled telescopes driven by servo motors.

In order to serve as a complementary medium for mobile wireless networking, the major challenge for FSOC is its vulnerability against mobility [2]. Mobile FSOC requires effective maintenance of LOS. Since the optical beam is highly focused, the existence of LOS is not enough. The transmitter and the receiver must be aligned; and the alignment must be maintained to compensate for any sway or mobility in the nodes. In this paper, we propose a novel scheme showing the feasibility of maintaining optical wireless communication in a mobile setting using mechanically steered transceivers and a simple auto-alignment mechanism. We consider two autonomous nodes/robots moving in random directions, each initially unaware of the location of the other. We focus on the case where the mobiles have an FSO transceiver each, mounted on a mechanically steerable head (which could as well be a simple arm) capable of rotating 360 degrees. We show that using such mechanical steering capability to control the rotation of the transceivers, the problem of LOS detection, establishment and maintenance can be dealt with effectively *without a global positioning system but merely a compass*.

The rest of the paper is organized as follows: In Section II, we review the literature for wireless link maintenance between multiple mobiles or in robot teams. Then, in Section III, we describe our proposed method for maintaining communication link between two autonomous mobiles using FSOC. Section IV presents an initial simulation-based evaluation of our approach. Finally, we conclude in Section V.

978-1-4799-3083-8/14/$31.00

II. Related Work

Maintaining communication link between two or more mobiles has been an attractive problem due to its desirability in many application areas, ranging from robotics to vehicular systems. In [11], a framework is developed for controlling a team of robots to maintain and improve a communication bridge between a stationary robot and an independently exploring robot in a walled environment using point-to-point radio communication. Similarly, [12] illustrated an experiment which is representative of various prominent stages in a group-formation task such as formation-achievement, maintenance, and response of formation movement to the presence of obstacles among multiple robots.

In terms of localizing and tracking, [13] presented experimental studies of strategies for maintaining end-to-end communication links for search-and-rescue and surveillance to a base station. The multi-robot team used in the experiment consisted of four unmanned ground vehicles (UGVs) built from radio-controlled scale model trucks each equipped with a laptop computer, odometry, stereo camera, GPS receiver, and a small embedded computer with 802.11b wireless connectivity, called the Junction Box (JBox). Likewise, Parker et al. [14] deployed a team of mobiles to form an indoor sensor network. In this approach the mobile sensors use different techniques such as acoustic sensing, laser scanning and a vision system like camera for localization. Shoval et al. [15] measured the relative position and orientation between two mobile robots using a dual binaural ultrasonic sensor system. In [16], a laser-based pedestrian tracking system in outdoors is presented using GPS-enabled mobile robots. Our approach assumes FSOC between two mobiles, *no availability of GPS*, and *only uses point-to-point distance measurement*. It also assumes autonomy for the mobiles and works in a completely distributed manner.

III. Technical Approach

A. Problem Statement and Assumptions

For the problem of maintaining an FSO link between two mobiles, we make the assumptions that the two nodes:

- are in a GPS-free environment with no medium of communication available other than FSO;
- are mobile and completely autonomous;
- move on straight lines only, but in either direction;
- are equipped with a compass giving them the sense of direction; and
- are also equipped with a mechanically steerable head (with which they can scan complete 360 degrees) that is mounted with an FSO transceiver.

Our algorithm has two main stages: (i) Detection of line-of-sight (LOS) and establishment of an FSO link, and (ii) Maintaining the FSO link. The essence of our LOS alignment protocol is to exchange small frames between the mobile FSO nodes through the transceivers mounted on rotating heads and identify the transceivers that are in each others LOS. A simple three-way handshake method is used for full assurance of the LOS detection and establishment of a full-duplex optical communication link. There are four different types of frames: SYN, SYN_ACK, ACK and DATA. We consider that the frames contain the following information: Sender ID, receiver ID, frame type, direction and velocity of the node, orientation of its steerable head and the actual data to be transferred. The node's direction of movement and the orientation of its head are determined with respect to the compass it is provided with.

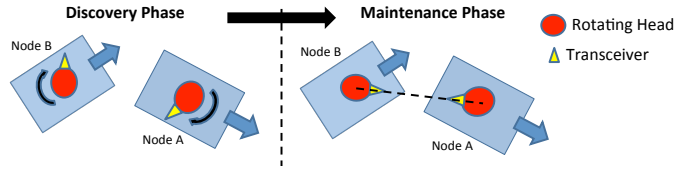

Fig. 1. Establishment of an FSO Link Between A and B

B. Discovery

Let us consider the case where the two mobile nodes (**A** and **B**) as shown in Fig. 1, are moving in random directions but within the transmission range of each other. The steerable heads of both the nodes rotate continuously in the same direction (both clockwise/ both counter clockwise) but with different angular velocities. While rotating, both the nodes periodically send SYN frames through their respective transceivers. A node stops sending this signal when it receives either a SYN_ACK frame as a reply to its own SYN frame or a SYN frame from the other node. As an answer to the SYN_ACK the sender again sends ACK ensuring detection and establishment of LOS.

A key issue with LOS discovery among two autonomous nodes is the time it will take for the two nodes to finally get their transceivers in LOS and hence make the above SYN-ACK exchange. If the nodes are rotating their heads in similar speeds, it may take longer time to discover each other. Increasing the rotation speed will not work after a point. A more detailed study of the issue of how fast and which direction the nodes should turn their heads needs to be done. In this paper, we focus on the next stage of the problem, i.e., preserving an existing LOS link between two mobiles.

C. Maintaining The Link

In this stage, we assume that an FSO link has been established between the two mobiles, but the goal is to maintain this link. While establishing the link, a node conveys the information about its velocity, the direction in which it is moving and the orientation of its head to the other node. This information is used by the other node to set the angular velocity and the direction of rotation (clockwise/counterclockwise) of its head to maintain the link.

After establishing the FSO link, the nodes maintain the link with the aid of mechanical steering. Using the determined angular velocity and finding which way to rotate (clockwise/counterclockwise), the head is steered accordingly to maintain the FSO link. If one or both of the nodes change velocity or direction or both, then they need to recalculate their heads' angular velocity and direction of rotation, which

we detail in the next two sections. Also, the nodes periodically run the three-way handshake to assure if the link exists. If not, then the nodes go back to the discovery phase.

1) Setting Up The Angular Velocity: Assuming that two nodes A and B have already detected the LOS and established an FSO link between them, there are three cases according to the relative directions and positions the nodes. We detail these cases for autonomously calculating the angular velocity of the nodes' heads so that the link can be maintained.

Case I: One Moving, One Stationary. As depicted in Fig. 2, let's consider the case when A is stationary and B is mobile. B continues to move in the direction it was already moving. Let us assume that B moves a distance of x in some given time t (very small amount of time in tens of milliseconds). To sustain the link, both A and B will need to rotate their heads. If the angle of rotation for the head of A is X_1 and for the head of B is X_2. From Fig. 2 it can be seen that:

$$\angle X_1 + \angle Y + \angle Z = 180\,^\circ \tag{1}$$

and that the path traversed by B is a straight line:

$$\angle Z + \angle X_2 + \angle Y = 180\,^\circ. \tag{2}$$

(1) and (2) show that $\angle X_1 = \angle X_2$. Let this angle of rotation be X, where $\angle X = \angle X_1 = \angle X_2$. Then, the angle of rotation $\angle X$ can be determined using the following formula:

$$\frac{x}{\sin X} = \frac{y}{\sin Y} = \frac{z}{\sin Z} \tag{3}$$

where x, y and z are the edges of the triangle in Fig. 2. Since we know B's velocity, $\vec{v_b}$, from the discovery phase, we can calculate x by measuring the time difference between the two positions of B and applying

$$Distance = Velocity \times Time. \tag{4}$$

That is, $x = v_b \times t$. Next, we can also calculate $\angle Y$ as it is the angle between the direction of B's motion and the orientation of its head. To find y, we look at Fig. 2. Let us consider the position of B at the moment of LOS discovery as the origin $(0, 0)$ of the reference frame. After time t, B's position is (a_1, b_1) and let A's position be (a_2, b_2). Then, we can write $a_1 = x \sin\theta$, $b_1 = x \cos\theta$, $a_2 = z \sin\phi$, and $b_2 = z \cos\phi$, where θ is the angle between the compass and the direction of B's motion, ϕ is the angle between the compass and the orientation of the head. We can now calculate $y = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2)}$, which means everything needed to calculate X in (3) is complete. Finally, the angular velocity for A's head will be $\angle X/t$. We will describe how to find z later in Section III-C2.

Case II: One Node Eastbound, One Node Westbound. Fig. 3 portrays another case where A is going westbound and B eastbound. Let θ_1 be the angle between the compass axis and the direction of motion of the first node, A and θ_2 be the angle between the compass axis and the direction of motion of the second node, B. Then, eastbound represents $\theta_2 = [0\,^\circ, 179\,^\circ]$ and westbound represents $\theta_1 = [180\,^\circ, 359\,^\circ]$. Assume that B moves x_1 and A moves x_2 after discovering

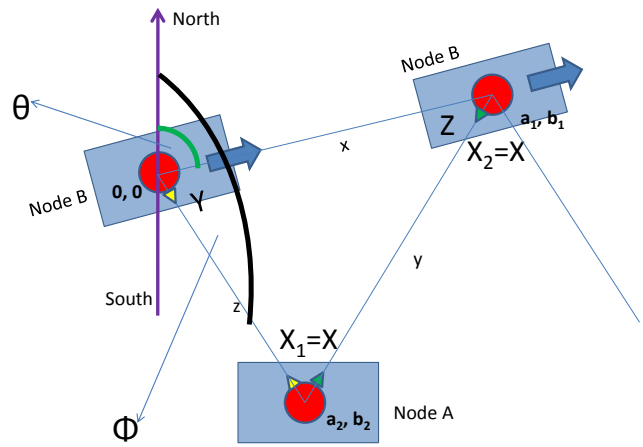

Fig. 2. Case I: Node A stationary and Node B moving

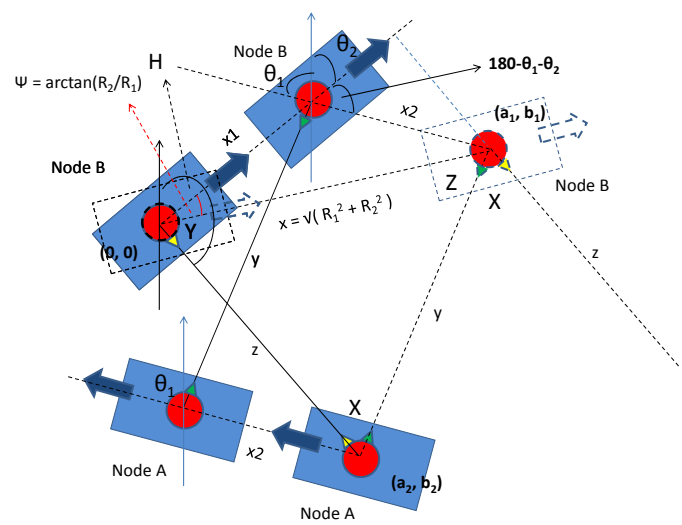

Fig. 3. Case II: Node B is westbound and Node A is eastbound

LOS between each other. Similar to Case I, we can assume A as stationary and B as moving with relative velocity $\vec{v_a} + \vec{v_b}$ which gives B's relative displacement, x, as $\vec{x} = \vec{x_1} + (-\vec{x_2})$. Here, $x = \sqrt{R_1^2 + R_2^2}$ and $\psi = \arctan(R_2/R_1)$, where $R_1 = x_1 + x_2 \cos(180\,^\circ - \theta_1 - \theta_2)$, $R_2 = x_2 \sin(180\,^\circ - \theta_1 - \theta_2)$, and ψ is the angle between the original direction and the relative direction of B's motion. Similar to Case I, considering B's position at the moment of LOS discovery as the origin $(0, 0)$ of the global reference frame, we can calculate A's position (a_2, b_2) at the moment of LOS detection and B's apparent position (a_1, b_1) at distance x. This would give us $y = \sqrt{(a_1 - a_2)^2 + (b_1 - b_2)^2}$. And $\angle Y = \angle H - \theta_2 - \psi$. Here, $\angle H$ represents the orientation of the head of Node B with respect to the compass axis. Finally, we then again use (3) and (4) to determine the angular velocity, $\angle X/t$.

Case III: Both Nodes Eastbound or Westbound. The last case is portrayed in Fig. 4, where A and B are both going eastbound, with velocities $\vec{v_a}$ and $\vec{v_b}$, respectively. Again, similarly to Case II, we can assume A as stationary and B

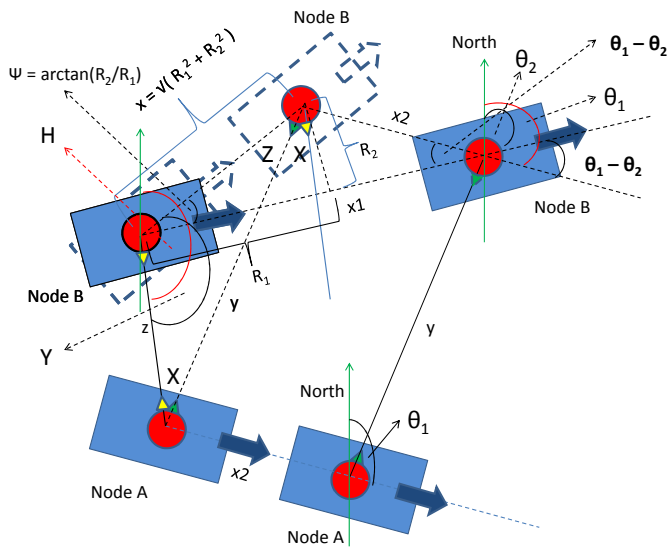

Fig. 4. Case III: Both A and B moving eastbound

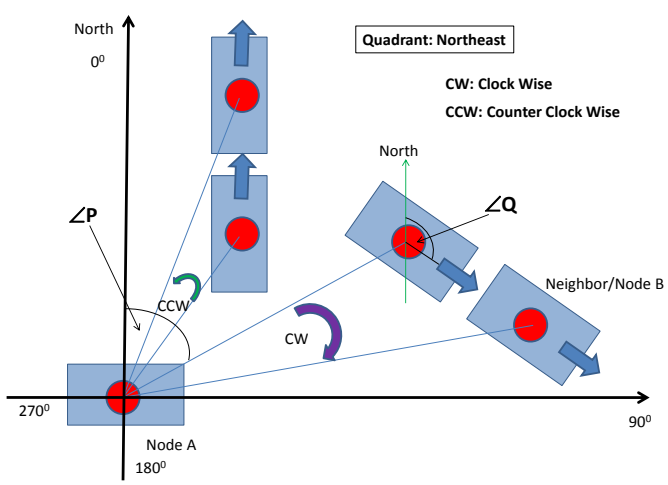

Fig. 5. Rotation direction: Neighbor in Northeast Quadrant

as moving with velocity $\vec{v_b} - \vec{v_a}$. Here $\vec{x} = \vec{x_1} + (-\vec{x_2})$, where $x = \sqrt{R_1^2 + R_2^2}$ and $\psi = \arctan(R_2/R_1)$. Here, $R_1 = x_1 - x_2\cos(\theta_1 - \theta_2)$ and $R_2 = x_2\sin(\theta_1 - \theta_2)$. Here, θ_1 = angle between the compass axis and the direction of motion of Node A. And θ_2 = angle between the compass axis and the direction of motion of Node B. Similar calculations as in Cases I and II give us y. We then calculate $\angle Y = \angle H - \theta_2 + \psi$. Finally, we apply (3) and (4) to find the angular velocity, $\angle X/t$.

2) Determination of z: We represent the distance between the two mobile nodes at the moment they discover the LOS as z. To find z, we assume availability of an optical distance measurement device, which are available in three categories: interferometry, time-of-flight (TOF) and triangulation methods [17]. The FSO transceivers can use the TOF technique to measure z. TOF refers to the time it takes for a pulse of energy to travel from its transmitter to an observed object and then back to the receiver. If light is used as energy source, the relevant parameter involved in range counting is the speed of light, i.e., roughly 30 cm/ns. A TOF system measures the round trip time (RTT) between a light pulse emission and the return of the pulse echo resulting from its reflectance off an object. When LOS is established between the two nodes, this technique is perfectly applicable. Since RTT is representative of traveling twice the distance and must, therefore, be halved to find the actual range to the target [17]. In our case, RTT is: <time when response is received from the receiver (Node B)> − <time when initial signal was sent by sender (Node A)> − <the time it takes for receiver (Node B) to respond>.

TABLE I
NEIGHBOR IN NORTHEAST QUADRANT

∠P(In Degrees)	0-45		46-89	
∠Q(In Degrees)	0-44	CCW	0-45	CCW
	45-224	CW	46-225	CW
	225-359	CCW	226-359	CCW

TABLE II
NEIGHBOR IN SOUTHEAST QUADRANT

∠P(In Degrees)	90-135		136-179	
∠Q(In Degrees)	0-134	CCW	0-135	CCW
	135-314	CW	136-315	CW
	315-359	CCW	316-359	CCW

TABLE III
NEIGHBOR IN SOUTHWEST QUADRANT

∠P(In Degrees)	180-225		226-269	
∠Q(In Degrees)	0-44	CW	0-45	CW
	45-224	CCW	46-225	CCW
	225-359	CW	226-359	CW

TABLE IV
NEIGHBOR IN NORTHWEST QUADRANT

∠P(In Degrees)	270-315		316-359	
∠Q(In Degrees)	0-135	CW	0-134	CW
	136-315	CCW	135-314	CCW
	316-359	CW	315-359	CW

3) Rotation: Clockwise (CW) or Counterclockwise (CCW): Another important decision to make for the nodes is, which way to rotate, clockwise/counterclockwise. Considering two nodes A and B again, the decision depends on two parameters: orientation of the head of Node A and the direction of motion of Node B. Fig. 5 shows one of the cases with regard to the way of rotation. Tables I-IV shows all the possible cases which aids in deciding whether the rotation should be clockwise or counterclockwise. Here $\angle P$ is the orientation of the head of node A with respect to the compass axis. $\angle Q$ is the angle between the direction Node B is moving and the compass axis. Assume that the head of Node A is facing Node B at $0° - 45°$, and Node B is moving at $45° - 224°$ with respect to the compass axis. In this case, the heads of both the nodes should rotate clockwise for maintaining the FSO link.

IV. PERFORMANCE EVALUATION

To gain insight into effectiveness of our approach, we performed simulations using MATLAB [18]. We considered walking speeds and reasonably capable robots for our nodes, e.g. Packbots [19]. We detail our simulation setup and assumptions, followed by results below.

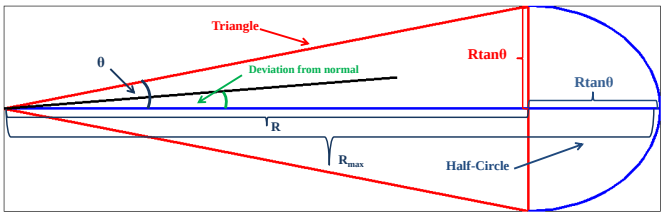

Fig. 6. Coverage Area of an FSO Transceiver as "Triangle+Half Circle"

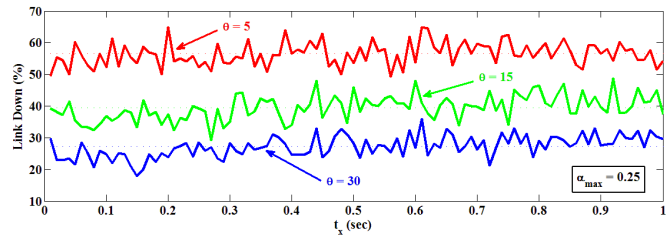

Fig. 7. Effect of Divergence Angle, θ

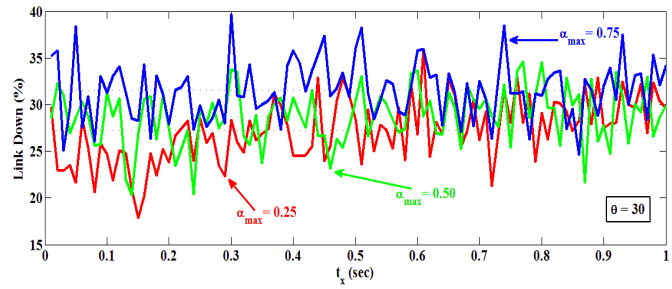

Fig. 8. Effect of α_{max}

A. Model for Transceiver Coverage

A key part of the simulation is to model transmission and field-of-view areas of an FSO transceiver, which follow the Lambertian law. To ease the computations, we approximated an FSO transceiver's coverage area L as the combination of a triangle and a half circle, which was shown to cause negligible error in [20]. Fig. 6 illustrates the key parameters: R, the height of the triangle; θ, the divergence angle and R_{max}, the maximum reachable range. The radius of the half circle is $R\tan\theta$, and R can be found by $R_{max} = R + R\tan\theta$. Then, the coverage area of the transceiver, L, can be derived as:

$$L = R^2 \tan\theta + \frac{1}{2}\pi R(\tan\theta)^2 \tag{5}$$

B. Simulation Scenario and Assumptions

We considered the nodes having length and width of 75cm and 40cm respectively, with maximum speed of 2.5 m/s (or 9 km/h) [19]. We assumed R_{max} to be 25m. We concentrated on the "Maintaining the Link" phase, and assumed that the nodes had discovered each other. We randomly chose the initial positions of the nodes. We also randomly picked the velocities and the direction of movement of the FSO nodes for each run of the simulation.

A crucial part of simulating the nodes' autonomy is to let the nodes decide how fast to turn their heads autonomously. We assumed that the nodes will exchange their velocity and signal quality values periodically. These periodic exchanges will allow the nodes to recalculate how fast they should turn their heads so that the FSO link stays up. We considered a simplistic protocol for this: Every time the nodes exchange their information with each other, the receiver node will see if it has deviated greater than a preset threshold. If so, the receiver node will recalculate the angular speed of its head. We assume that the nodes can turn their heads as fast as needed, which is realistic since we only consider walking speeds.

Let t_x be the time period of information exchanges between the two nodes. Further let α be the ratio between the Angle of Deviation of the receiver from the height of the triangle in L and the Divergence Angle(θ), and α_{max} be the maximum allowed α before recalculation of rotational speed is performed. At every t_x, α is checked, and if $\alpha > \alpha_{max}$ then the angle of rotation for the mobile FSO nodes were recalculated. A value of $\alpha > 1$ meant that the link was down. We compared the percentage of time the link was down for different values of the divergence angle θ (5°, 15° and 30°), α_{max} (0.25, 0.5 and 0.75), and t_x (10ms to 1s). For each t_x, we calculated average percentage of link down time over 100 simulation runs.

C. Results

Fig. 7 depicts the performance of the algorithm for maintaining the FSO link for various divergence angles when $\alpha_{max} = 0.25$. It is clear that the lower the divergence angle, the longer the link is down. An encouraging result is that the performance is not dependent to t_x even if it reaches to 1s. So, it is possible to increase t_x to seconds without harming the link's performance. However, for higher node speeds (e.g., driving or flying), a fine tuning of t_x may be necessary.

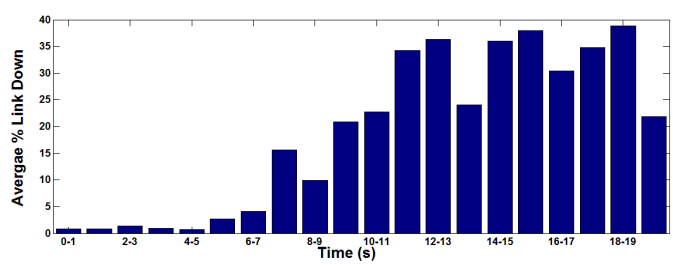

Fig. 9. Distribution down time percentage across link duration ($\alpha_{max} = 0.25, \theta = 30^0, t_x = 100ms$)

For a fixed divergence angle, $\theta = 30^0$, Fig. 8 shows the link maintenance performance for varying α_{max}. Although it is subtle, we observe that increasing α_{max} degrades the performance. This is also an expected result, because for a lower α_{max} the recalculation of rotational angle is done for lower deviation of the receiver from the sender node's area of coverage. So, lower α_{max} means more accurate calculation of angle of rotation and thus the link is up for longer.

A relevant issue is how the links' duration relates to the link down time. Fig. 9 shows the averages of the percentage

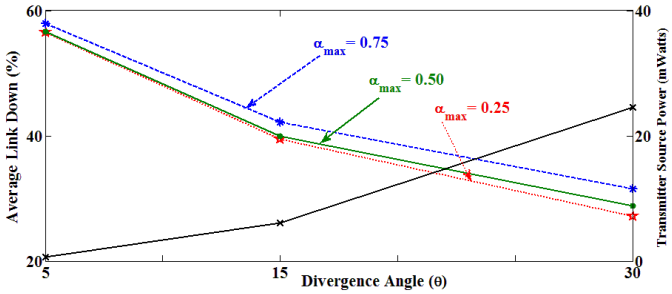

Fig. 10. Effect of α_{max} and θ

of link down time across link duration. The link duration is the time when the two nodes are both in communication ranges of each other. The distribution is skewed and the percentage of down time is larger for the links that had longer duration, e.g., $\approx 2\%$ down time for links ongoing up to 5s while $\approx 35\%$ for links ongoing longer than 11s. This is a motivating result since the percentage of link down time plateaus after for links longer than 11s, and the link down time stays under control.

Fig. 10 displays the combined effect of θ and α_{max}, averaged over all possible values of t_x. It can be seen that increasing divergence angle yields better link maintenance, but, increasing α_{max} deteriorates the performance. We also observe that, although the performance of the algorithm improves with larger divergence angles, this is achieved at the cost of higher transmitter source power (calculated from [20]). To maintain a particular R_{max}, the required transmitter source power increases (Black line) with increase in the divergence angle. Lastly, Fig. 11 shows that the communication and computation overhead (i.e., the average number of recalculations of rotational speed) decreases as α_{max} increases. It also shows that the overhead decreases with larger divergence angles.

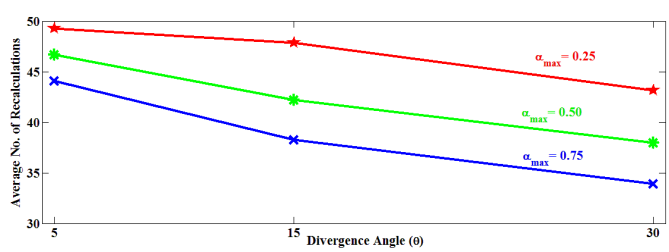

Fig. 11. Overhead for various α_{max} and θ

V. Summary and Future Work

We presented a novel approach to overcome the problem of LOS detection and maintenance for maintaining an FSO link between two autonomous mobile nodes. Each of the nodes is equipped with a mechanically steerable head (or arm) on which an FSO transceiver is mounted. Using the proposed algorithm to control the mechanically steered head, the FSO transceivers on the nodes can maintain a communication link successfully. We outlined all possible cases for calculating the angular velocity of the nodes' heads and the direction of the heads' rotation so as to maintain the FSO link. For our method, we assumed the height of the FSO transceivers to be same. Also, we considered the nodes to be traveling in straight lines only. A promising line of future work is to extend the capabilities of the algorithm by considering the nodes in positions with different heights and moving on curves.

Acknowledgement

This work was supported in part by NSF award 1321069.

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