Reduction of Beam Pointing Error on Free Space Optical Communication links using Tree Based Machine Learning Multi-Output Regression Model

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Abstract-- **Free space optical (FSO) communications have the potential to be one of the most essential technologies for solving the high-bandwidth demands of communications between satellites and ground stations. However, a line-of-sight link is required between the transmitter and the receiver for effective establishment of communication link. In this paper, we examine the FSO beam pointing error systems under controlled weak turbulence using a robust $\mathcal{H}_\infty$ control law. The goal is to maintain the transmitter-receiver line, which refers to keeping the optical beam's center as close as possible to the receiving aperture's center while staying within the boundaries of the permitted disturbance attenuation level. Based on this, we use a tree-based machine learning technique to predict gain value of $\mathcal{H}_\infty$ norm optimization problem guaranteeing a stable closed loop pointing error.**

Keywords— Free-space optical (FSO) communications, $\mathcal{H}_\infty$problem, Lognormal distribution, Machine Learning

I. INTRODUCTION

The demand for high-speed internet, video conferencing and other services has increased recently. This has led to an increase in the need for bandwidth and capacity [1]. Since there is a constant need for data and multimedia services, the radio frequency (RF) spectrum is congested [1]. The usage of RF spectrum is constrained. Free-space optical communications (FSO) enable wireless communication between transmit-and-receive optical terminals. Furthermore, it is a line-of-sight (LOS) communication system that utilizes the atmosphere or free space as the communication channel. The channel might be subjected to turbulence, absorption, and dispersion of the optical signal due to various environmental factors [2].

Atmospheric turbulence is a random phenomenon caused by temperature and pressure fluctuations in the atmosphere along the propagation path [3]. This turbulence can cause a beam of light to become misaligned from diffraction from the channel's obstructions, leading to an increase in beam size and a decrease in beam intensity, which in turn results in pointing errors that shift the optical beam both horizontally and vertically [4]. Accurate pointing is required in FSO communication links to lessen the loss caused by these factors. The influence of pointing errors on optical link performance is of tremendous relevance for many prospective applications. For this, several strategies have been put forth to meet the LOS requirement in optical communication systems to reduce the pointing error.

A study by Rust et al. [5] utilizes numerous photodiodes and light emitting diodes (LEDs) to eliminate the requirement of actively pointing the light at the receiver to transmit information. In Pontbriand et al. [6], the receiver's field of vision is expanded using large-area photomultiplier tubes in Furthermore, the possibility of accurately predicting the point-ahead angle in advance using the two-line element sets for orbiting satellites has been proposed in [7]. In another study by Lazzaro et al. [8], it utilizes a satellite's attitude control system for coarse relative pointing and a fine pointing system within the payload to mitigate residual pointing error and maintain the link under environmental and spacecraft induced disturbances. Other research by Arnon et al [9] and Komaee et. al [10] involves adjusting the transmitted beam width and transmitted power to optimize link performance of FSO system. However, these methods did not consider the vibration levels of the transmitter and receiver utilized in FSO communication link and the impact of atmospheric turbulence. In addition to this, FSO links mainly use existing components such as optical telescopes, position-sensitive photodetectors, optical filters to mitigate pointing errors, without considering the controller design aspect, which involves development of algorithms and methods that can accurately maintain the optical alignment between the transmitting and receiving stations.

To address these problems, we propose a tree-based machine learning technique for predicting the FSO system model's gain. Using a closed loop feedback control system based on FSO satellite to ground scenario, the expected gain value helps to maintain the optical link between free space stations using a laser communication channel. For this, several system model parameters, including the transmitter and receiver's system and control matrix, are considered. Additionally, elements imapcting the status of optical channels including irradiance, noise, and scintillation index are taken into account. Based on our experiment, irradiance, scintillation index and stimulated optical channel state are the most important factors, which contribute to the design of the controller that helps in minimizing the pointing error.

The following contributions are made on this study to minimize pointing error for FSO systems

- We develop a machine learning model based on the $\mathcal{H}_\infty$ *norm* optimization problem to predict the gain of the closed loop system which guarantees the closed loop pointing error is stable.
- We measure the effectiveness of tree-based machine learning algorithms on closed loop pointing error control and demonstrate that the gain predicted assists in keeping the optical beam's center at the receiving aperture.
- We assess the significance of the features impacting the closed loop feedback system's controller design.

The remainder of the paper is organized as follows: In Section 2, we examine the lognormal weak turbulence model, discrete-time lognormal optical channel state, receiver aperture model, the FSO communication scenario and tree-based machine leaning algorithms to predict gain maintaining the centroid of optical beam as close as possible to center of receiver aperture. In section 3, we evaluate the quality of the pointing error control. Finally, in section 4, conclusions are drawn from our study.

II. FSO channel characterization

FSO links include a transmitter and receiver linked through an atmospheric channel. The intensity of the signal fluctuates across this channel due to atmospheric turbulence, and numerous statistical models for various turbulence environments have been proposed. The most popular model for weak turbulence conditions is the log-normal distribution. It has been proven through research [11]. Weak turbulence was incorporated into computations for the FSO channel, which led to its use as a well-known modeling methodology. The lognormal model will be utilized throughout this paper since it focuses on weak turbulence.

A. Lognormal weak turbulence model

The probability density function (PDF) of the log-normal model is given by [12]. Fig. 1 depicts the curve graphs of various received intensity signals with turbulence. At lower values of σ^2 ,the PDF distribution is almost Gaussian. Additionally, experimental research has revealed that the statistics of irradiance variations follow the log-normal distribution in the region of weak fluctuations, with scintillation index σ^2 falling within the range of [0,1] characterized by weak turbulence [14].

B. Discrete-time lognormal optical channel state

The PDF of the optical beam is crucial to its structure, so we take a modeling approach to determine its position. Our strategy is based on samples distributed in lognormal space and have matching correlation functions. The first step is to imitate the effects of atmospheric turbulence using theoretical results from lognormal processes with predefined autocorrelation function (ACF) and Milstein scheme for the channel states, that converges to a simple discrete-time differential equation [15].

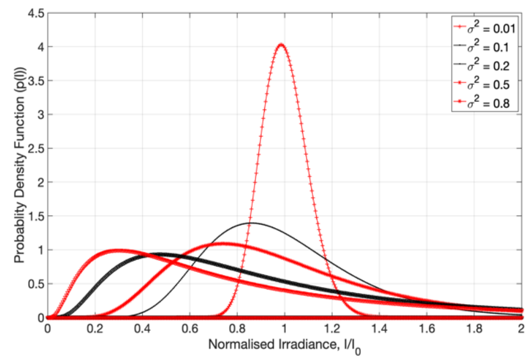

Fig. 1. PDF of various received intensity signals

C. Receiver aperture model

The photodetector's receiver aperture may be fixed, but random physical vibrations caused by thermal expansion, voltage jitter, etc. still influence it [17]. It is expected that the motion of the receiving aperture is analogous to the Brownian motion of a particle that has been stimulated, whose equation is provided by [18] [19].

D. FSO communication scenario generation

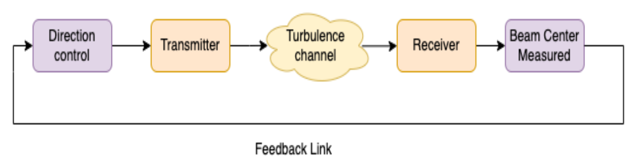

Fig. 2. Block diagram of pointing error control strategy

An optical transmitter and receiver are subject to relative motion in an optical link. The optical beam emitted has a non-uniform intensity profile [20], which can be viewed as a moving object. In this scenario, the objective is to regulate how the location of the optical beam changes over time. Moreover, it is assumed that the receiver's aperture is smaller than the optical beam being received, meaning only a portion of the beam is collected by the receiver [10]. This captured fraction can be increased by using active pointing, which aims to keep the center of the laser's output in its receiving aperture. Figure 2 demonstrates how this process works using lognormal conditions: at the receiver side it uses a photodetector to determine intensity profiles of incoming light beams; output is then sent over an optical link as feedback [10] to adjust position of transmitter.

The discrete-time model that is generated from the stochastic state-space model [15] is introduced. It is approximated by a general and effective discrete-time model, which largely explains the influence of the transmitter and receiver's relative positions on signal strength. We designate the vector for the position of the transmitted optical beam in each coordinate system and for the location of the stations' receiving aperture in the same system. The optical beam center's relative displacement to the receiving aperture center in which the receiving aperture is held perpendicular to line-of-sight of optical beam is given by $y_k = d(\theta_k - \alpha_k)$. Here, d is distance between transmitter and receiver. Optical beam in receiving aperture's plane and displacement vector y_k is shown in figure 3.

The pointing error $y_k = d(\theta_k - \alpha_k)$ can be written as the following augmented system [21]

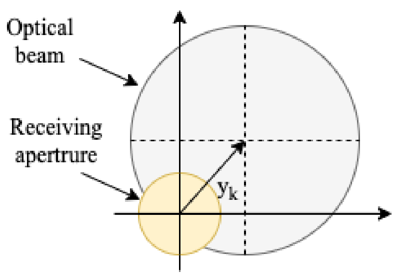

Fig. 3. Optical beam, receiving aperture and the displacement vector y_k

$$\begin{cases} x_{k+1} = \mathbb{A}x_k + \varphi(x_k) + \mathbb{B}u_k + \mathbb{R}w_k, \\ \epsilon_k = \mathbb{C}x_k, \end{cases} \quad (1)$$

where

$$\mathbb{A} = \begin{bmatrix} a^p & \mathbf{0} \\ \mathbf{0} & a^l \end{bmatrix}, \mathbb{B} = \begin{bmatrix} b^p \\ \mathbf{0} \end{bmatrix}, \mathbb{R} = \begin{bmatrix} r^p \\ r^l \end{bmatrix}, \mathbb{C} = [c^p \quad -c^l],$$

and $x_k = \begin{bmatrix} x_k^p \\ x_k^l \end{bmatrix} \in \mathbb{R}^2$ is the augmented state vector, $w_k = [w_k^p \quad w_k^l]$ is the augmented disturbance vector, $y_k = d\epsilon_k$ is the pointing error and $\epsilon_k = \theta_k - \alpha_k$.

The goal of the robust control problem investigated in this study is to minimize closed loop poitning error while maintaining desired amounts of disturbance attenuation. The goal is to keep the optical beam's centroid as near as feasible to the photodetector's center by finding a set point $u_k = -\mathbb{K}x_k$ that satisfies the following $\mathcal{H}_\infty$ norm of pointing error y_k with respect to disturbance w_k i.e.

$$\|y_k\| \leqslant \varepsilon \|w_k\|,$$

with ε being the smallest positive real to be minimized.

E. Dataset generation

Equations 1 creates a dataset consisting of parameters including transmitter (TX), receiver (RX), and optical channel state (SC). Table 1 below shows the list of parameters utilized for a dataset generation. The first columns show the 17 factors influencing system dynamics that result in four output values which is equivalent to a K gain. First, input and output data to be used in machine learning are determined and predictive performance of three tree-based machine learning models are analyzed.

TABLE I: Input parameters and symbols

Input Parameters	**Symbol**	**Input Parameters**	**Symbols**
System matrix (Transmitter)	a^p	Noise matrix (Receiver)	r^l
Control matrix (Transmitter)	b^p	Source Initial Position (Receiver)	x_k^l
Output matrix (Transmitter)	c^p	Friction coefficient	γ_1
Noise matrix (Transmitter)	r^p	Trap stiffness	k_1
Irradiance	I	Boltzmann constant	k_B
Scintillation Index	σ^2	White Gaussian noise (Transmitter)	w_k^p
Stimulated optical channel state	x_k^p	White Gaussian noise (Receiver)	w_k^l
System matrix (Receiver)	a^l	Attenuation	ε
Output matrix (Receiver)	c^l		

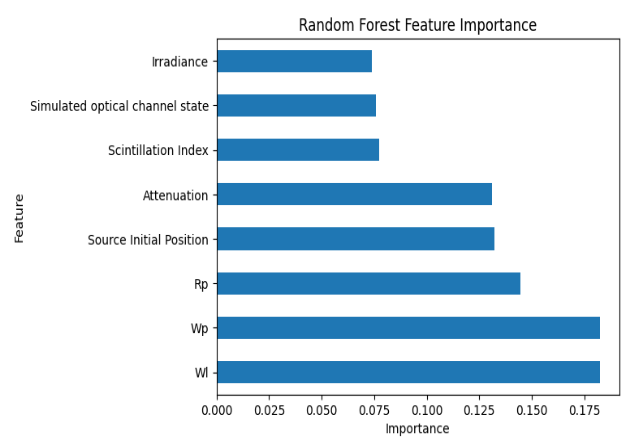

Fig. 4. Feature importance

To predict the gain value of a closed-loop system, various influencing factors need to be studied. Since these influencing factors can vary widely depending on the characteristics of the FSO channel, it is necessary to define them individually according to the channel scenario. The following feature importance in figure 4 for the gain prediction was analyzed using Random Forest analysis. The results shows that white noise present at both the transmitter and receiver greatly influences gain values. Figure 4 demonstrates the eight most important features when predicting gain values of closed loop systems. Considering these points, this study attempts to show general characteristics of system dynamics that can easily be identified while setting up an FSO system.

F. Regression methods

a) Multi-output Decision Tree Regressor: A decision tree is a structured method for analyzing data. It uses a top-down, greedy approach that begins with splitting the data into groups based on certain decisions. Once these points are chosen, the process repeats itself, with each new split creating more groups from which to choose features that best fit our input data. The goal of this approach is to create a tree of decisions which accurately predicts the gain value based on our input data.

b) Multi-output Random Forest Regressor: The idea behind random forest is to build many decision trees, each trained on a random subset of data. These trees are then averaged to make a final prediction. Once the decision trees have been trained, the random forest model makes a prediction and then averages their predictions to make a final prediction.

c) Multi-output Gradient Boosting Regressor: The process of gradient boosting involves training a series of decision trees, with each tree built to correct the mistakes made by the previous tree. This process is repeated until a satisfactory level of accuracy is achieved, or until a pre-determined number of trees have been trained. One key feature of gradient boosting is that it uses a loss function to measure the error made by the model on each iteration. The loss function is used to update the model in a way that reduces the overall error with the goal of minimizing it.

III. RESULTS

We compare three regression models with the artificial dataset generated to predict the overall gain of a system. This assist in evaluating the quality of our pointing-error-control strategy. After tuning hyperparameters of the model, the models are evaluated on independent data sets. When evaluating the performance of a multioutput regression model, it is important to consider multiple evaluation metrics to get a comprehensive understanding of the model's performance. Table II shows evaluation metrics of all three-regression algorithm based on Mean Absolute Error (MAE), Mean Squared Error (MSE) and Root Mean Squared Error (RMSE). Decision tree regressor algorithm is chosen as the algorithm to predict the gain value of the system model.

TABLE II: Evaluation metrics of tree-based machine learning regression algorithms

Regressor	MAE	MSE	RMSE
Decision Tree	0.84043	0.98627	0.99311
Random Forest	0.84030	0.98703	0.99349
Gradient Boosting	0.83227	0.98694	0.993451

TABLE III: Scintillation index of the FSO signal at different times.

Parameter	Value
Scintillation Index	1.01×10^{-2}

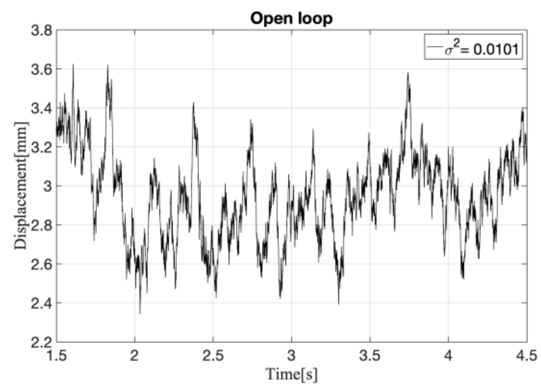

Fig. 5. Open loop pointing error versus time

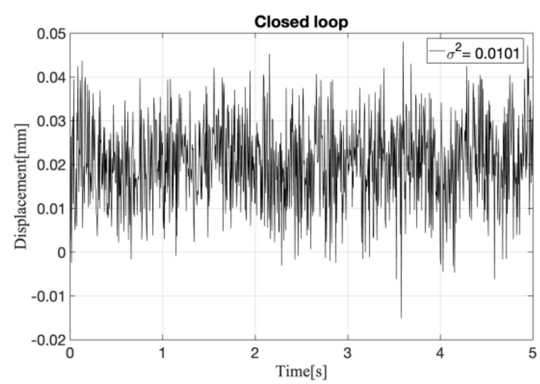

Fig. 6. Closed loop pointing error versus time

Table III lists the scintillation index of the FSO signal in morning, afternoon, and night. Figures 5-6 show the pointing error at for an open loop and closed loop system. We clearly observe that gain value applied to the system maintains relatively smaller alignment errors in closed loop system than in open loop systems, thus guaranteeing a stable closed loop pointing error.

IV. CONCLUSION

In this paper, the link performance of the presented FSO link under the influence of weak atmospheric turbulence has been investigated. A deterministic nonlinear discrete-time model for pointing error was analyzed. We then investigated tree-based machine learning algorithms to predict the gain value of the system model. The gain value predicted was then provided as feedback on the model which ensured stable closed loop pointing error. Stimulated results showed that center of optical beam being close enough to aperture center, verifying propose tree based multi output regression model for FSO communication systems.

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