Pointing Error And Mitigation Techniques Using Machine Learning Algorithms in Free Space Optical Communication

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Introduction: Free Space Optical Communication

- FSO communication uses light to transmit data between satellites or ground stations.
- **Applications** : Satellite networks (e.g., Starlink), deep-space missions (NASA), military and disaster recovery operations.
- **Advantages :** High Bandwidth, low power, quick deployment.

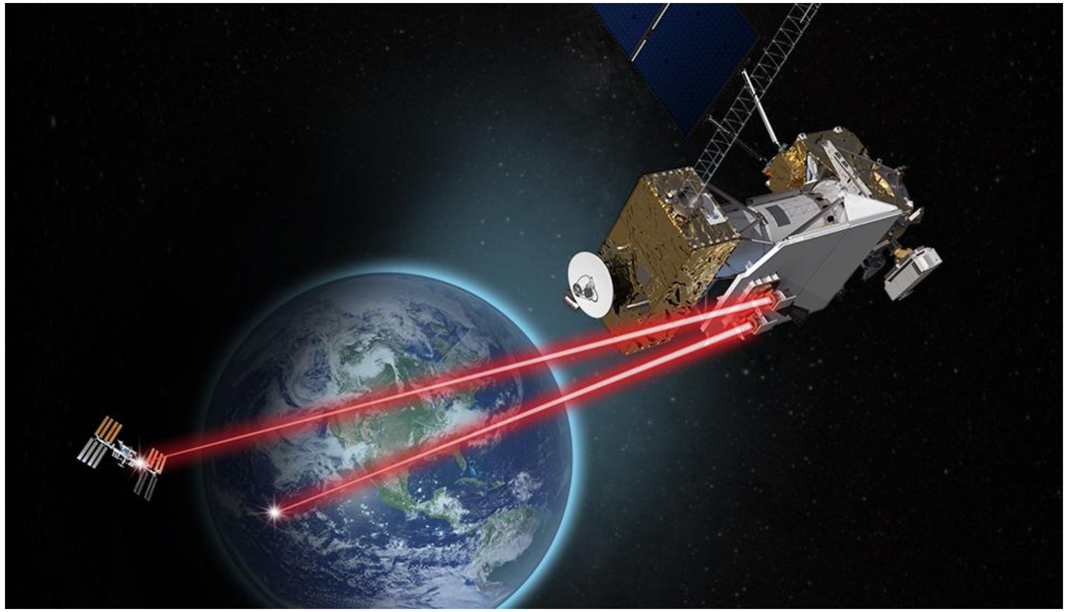


Image Source: https://www.nasa.gov/missions/tech-demonstration/whats-next-the-future-of-nasas-laser-communications

Introduction: Pointing Errors

- Misalignment between the transmitted beam and the receiver aperture.
- Signal power loss, increased bit error rates, potential link failure
- Mechanical vibrations, Point-Ahead Angle (PAA) misalignment, Acquisition, Pointing, and Tracking (APT) errors, Beam divergence over long distances.

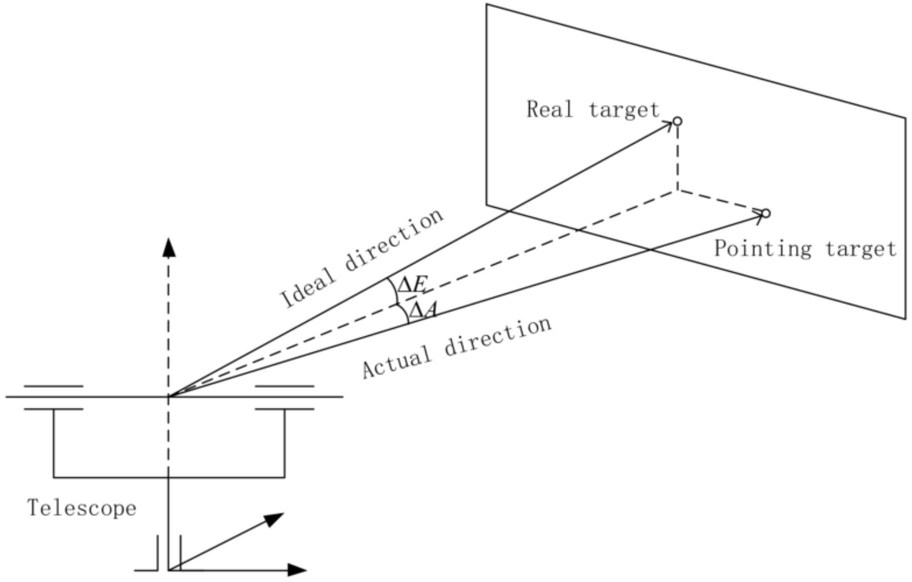


Image Source : Yan, Lingjie & Huang, Yongmei & Zhang, Yahui. (2018). Using Allan Variance Based Semi-Parameter Model to Calibrate Pointing Errors of Alt-az Telescopes. Applied Sciences. 8. 614. 10.3390/app8040614.

Mitigation Techniques: Traditional Methods

- **Mechanical Systems**:
  - **Fast-Steering Mirrors (FSMs):** Small, motor-driven mirrors that adjust rapidly to correct beam direction. FSMs help compensate for small, rapid disturbances (e.g., platform jitter).
  - **Gimbals:** Larger mechanical structures that rotate entire optical components to adjust beam alignment. Useful for larger corrections but slower than FSMs.
  - **Inertial Measurement Units (IMUs):** Sensors that detect angular velocity and accelerations to stabilize and correct the beam's pointing direction.

- **Adaptive optics:** Uses deformable mirrors that change shape to counteract the effects of atmospheric turbulence.

- **Feedback Control Systems:** Systems like Proportional-Integral-Derivative (PID) controllers adjust the beam alignment by continuously monitoring errors and applying corrective signals.

- **Wavelength Division Multiplexing (WDM):** A technique that splits the optical signal into multiple wavelengths (colors of light), allowing parallel transmission of data streams.

Mitigation Techniques: Machine Learning Approach

- **Why Machine Learning models?**
  - Real time correction capabilities
  - Ability to handle non linear dynamics
  - Availability of cheap computational resources.

- **ML Models**:
  - K-Nearest neighbor(KNN)
  - Tree-based Regression Model
  - Convolution Neural Networks(Conv1D)

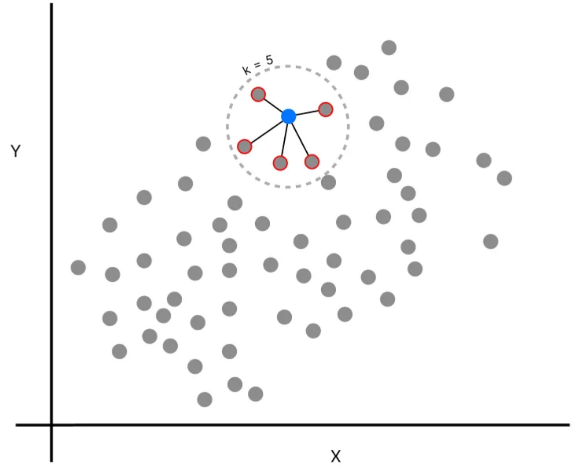
Image Source : https://cruzetechs.eu/steam-flow-prediction-of-a-paper-mill-using-machine-learning/

K-Nearest Neighbor (KNN) Approach

- KNN is a nonparametric machine learning algorithm that predicts a value based on nearby (or "neighboring") data points.

- The model helps reduce residual nonlinear errors that traditional mitigation techniques fail to address. It achieves this by learning from historical calibration data (e.g., known star positions and pointing errors).

- **Steps:**
  - *Distance Measurement*
  - *neighbor Selection using Generalized cross Validation*
  - *Gaussian Based Weight Calculation*
  - *Final Prediction*



- **Results:** After parameter model correction, the pointing error was reduced to 87.3 μrad. Finally, after KNN correction, the pointing error was further reduced to 69.0 μrad for calibration stars and 70.8 μrad for target stars.

Image Source : https://pub.towardsai.net/understanding-k-nearest-neighbors-a-simple-approach-to-classification-and-regression-e4b30b37f151

Tree-Based Regression Model Approach

- A multi-output regression model predicts and optimizes the **gain matrix K** (multi output) to minimize pointing error.

- Models : *Decision Tree, Random Forest and Gradient Boosting Regression*

- **Steps:**
  - *Feature Extraction (System matrics, control matrix, Noise parameters)*
  - *Dataset trained by the three models*
  - *Performance matrics Evaluation(MSE, MAE, RMSE)*
  - *Gain matrix prediction*

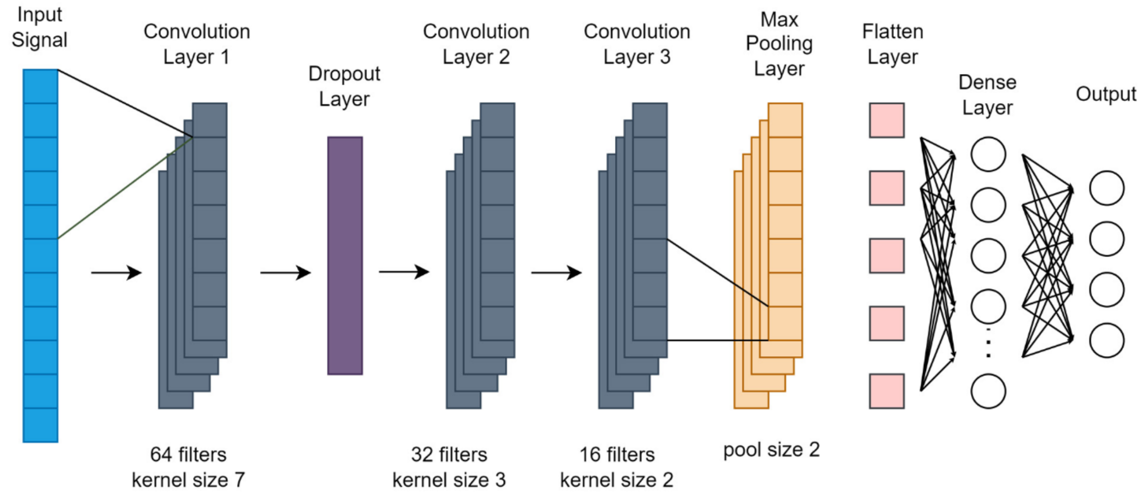
- **Result:** Across all the performance matrics *Decision Tree* performed well compared to Random Forest and Gradient Boosting Regression.

Convolutional Neural Network (Conv1D) Approach

- **Conv1D** is a 1-dimensional version of CNN that works well with time-series data by analyzing sequential relationships over time.

- The model's output is fed into a **closed-loop control system**, which continuously adjusts the transmitter's position to maintain beam alignment.

- **Steps:**
    - *Feature Extraction*
    - *Activation Function Selection (eg ReLU)*
    - *Pooling for Dimensionality Reduction*
    - *Regularization : dropout rate 0.5*
    - *Dense Layer creation*
    - *Gain Matrix prediction and closed-Loop feedback*



- **Result:** the Conv1D model achieved an **R-Squared score of 0.968**, which is higher than other tree-based regressors, indicating that Conv1D is more effective in predicting the gain matrix

Image Source : Maharjan, N., & Kim, B. W. (2024). Machine learning-based beam pointing error reduction for Satellite–Ground FSO links. Electronics, 13(17), 3466. doi:https://doi.org/10.3390/electronics13173466

Conclusion

- Each model has its unique advantages depending on the complexity of the system and the nature of the data.
- **K-Nearest neighbor (KNN):** This algorithm effectively corrects nonlinear pointing errors and improves pointing accuracy.
- **Tree-based regression models**: The models were tested on open-loop and closed-loop systems, and the results showed that the tree-based regression model effectively mitigates pointing errors in FSO systems.
- **Convolutional Neural Network:** By continuously feeding real-time pointing error measurements into the model, it dynamically adjusts the transmitter’s position to maintain beam alignment with the receiver.

References

- [1] H. Kaushal and G. Kaddoum, “Optical communicationin space: Challenges and mitigation techniques,” IEEECommunications Surveys & Tutorials, vol. 19, no. 1,pp. 57–96, 2017, Conference Name: IEEE Communica-tions Surveys & Tutorials, ISSN: 1553-877X. DOI: 10.1109/COMST.2016.2603518.
- [2] G. Wang, F. Yang, J. Song, and Z. Han, “Free space op-tical communication for inter-satellite link: Architecture,potentials and trends,” IEEE Communications Magazine,vol. 62, no. 3, pp. 110–116, Mar. 2024, ConferenceName: IEEE Communications Magazine, ISSN: 1558-1896. DOI: 10.1109/MCOM.002.2300024.
- [3] J. Zhang, Y. Cao, P. Guo, et al., “Estimation of directionand zero errors of satellite laser terminals in low-lightconditions based on machine learning,” JOSA A, vol. 41,no. 12, pp. 2316–2326, Dec. 1, 2024, Publisher: OpticaPublishing Group, ISSN: 1520-8532. DOI: 10 . 1364 /JOSAA.533672.
- [4] H. Kaushal, V. K. Jain, and S. Kar, “Acquisition, track-ing, and pointing,” in Free Space Optical Communica-tion, H. Kaushal, V. Jain, and S. Kar, Eds., New Delhi:Springer India, 2017, pp. 119–137, ISBN: 978-81-322-3691-7. DOI: 10.1007/978-81-322-3691-7 4.
- [5] N. Maharjan and B. W. Kim, “Machine learning-basedbeam pointing error reduction for satellite–ground FSOlinks,” Electronics, vol. 13, no. 17, p. 3466, 2024, NumPages: 3466 Place: Basel, Switzerland Publisher: MDPIAG. DOI: 10.3390/electronics13173466.
- [6] A. Sharma, “Analysis and mitigation of receiver pointingerror angle on inter-satellite communication,” 2015.
- [7] A. Ananthaswamy, Why Machines Learn. Jul. 16, 2024.
- [8] C. Peng, D. He, Y. Huang, et al., “Pointing-error cor-rection of optical communication terminals on motionplatforms based on a k-nearest neighbor algorithm,”IEEE Photonics Journal, vol. 14, no. 6, pp. 1–7, Dec.2022, Conference Name: IEEE Photonics Journal, ISSN:1943-0655. DOI: 10.1109/JPHOT.2022.3220400.
- [9] N. Maharjan and B. W. Kim, “Reduction of beam point-ing error on free space optical communication links us-ing tree based machine learning multi-output regressionmodel,” in 2023 Fourteenth International Conferenceon Ubiquitous and Future Networks (ICUFN), ISSN:2165-8536, Jul. 2023, pp. 664–668. DOI: 10 . 1109 /ICUFN57995.2023.10200700.

Thank You

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