AFRL-AFOSR-VA-TR-2019-0252

Advanced Orbit Prediction for Resident Space Objects through Physics-based Learning

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07/11/2019
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB1
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
23-08-2019

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
15 Apr 2016 to 14 Apr 2019

4. TITLE AND SUBTITLE
Advanced Orbit Prediction for Resident Space Objects through Physics-based Learning

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-16-1-0184

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
RUTGERS, THE STATE UNIVERSITY OF NEW JERSEY
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2019-0252

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this research is to develop a novel methodology to predict trajectories of resident space objects (RSOs) with orders-of-magnitudes higher accuracy than the current methods. We propose to enhance physics-based orbit prediction with a learning-based system identification well suited for the challenging, unstable, and inactive RSOs that are out of control and have uncertain origins. We have developed a simulation-based space catalog environment to validate the proposed orbit prediction method. For the first time, our simulation results demonstrated three types of generalization capability for the proposed approach. We have also validated the developed ML methodology using publicly available data.

15. SUBJECT TERMS
Astrodynamics, Orbital Dynamics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					NACHMAN, ARJE
Unclassified	Unclassified	Unclassified	UU		**19b. TELEPHONE NUMBER** *(Include area code)* 703-696-8427

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

DISTRIBUTION A: Distribution approved for public release.

Final Report

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- Program: Remote Sensing
- Contract/Grant Title: (YIP) Advanced Orbit Prediction for Resident Space Objects Through Physics-based Learning
- Award Number: FA9550-16-1-0184
- Reporting Period: 15 April, 2017 to 14 April 2018

Project Summary

The goal of this research is to develop a novel methodology to predict trajectories of resident space objects (RSOs) with orders-of-magnitudes higher accuracy than the current methods. Efficient, high precision orbit prediction is increasingly crucial for improved Space Situational Awareness (SSA) due to the escalating number of RSOs and conflicts between them. Current physics-based predictions, however, fail to achieve the required accuracy for collision avoidance and have already led to satellite collisions. We propose to enhance physics-based orbit prediction with a learning-based system identification well suited for the challenging, unstable, and inactive RSOs that are out of control and have uncertain origins. We have developed a simulation-based space catalog environment to validate the proposed orbit prediction method. For the first time, our simulation results demonstrated three types of generalization capability for the proposed approach: 1) the ML model can be used to improve the same RSO's orbit information that is not available during the learning process, but shares the same time interval as the training data; 2) the ML model can be used to improve predictions of the same RSO at future epochs, however prediction accuracy degrades with length of prediction interval; and 3) the ML model based on one RSO can be applied to other RSOs that share some common features. Furthermore, we have validated the developed ML methodology using publicly available data Resources.

Background

The number of resident space objects (RSOs) and the number of conflicts between the objects are rapidly escalating. One challenge for SSA is to predict each object's orbit efficiently and accurately. Current predictions that are solely grounded on physics-based models, however, fail to achieve required accuracy for collision avoidance and have led to satellite collisions already. Failure of the physics-based prediction is fundamentally due to the lack of the required information including space environment conditions and RSOs's features that are challenging to acquire.

This project researches on a new orbit prediction framework that integrates physics-based orbit prediction algorithms with a learning-based system identification process. This is Inspired by learning theory in which the models learn based on large amounts of data and the prediction can be conducted without explicitly modeling space objects and space environment. This approach brings two benefits. First, the approach provides an effective avenue to exploit the knowledge of many good physics-based models that are important and represent the state of the practice.

Second, my approach substantially reduces the dimensionality and thereby the computational complexity of the learning task, as the learning is only required to find the incremental corrections to the physics-based prediction.

Project Outcome

The research outcome of this work has led to seven peer-reviewed articles published on esteemed journals. Significant results we have achieved are briefly discussed below.

1. We have developed a methodology to predict RSOs' trajectories with higher accuracy than current methods. Inspired by the machine learning (ML) theory through which the models are trained based on large amounts of overserved data and predictions can be made without explicitly modeling space objects and the space environment, the proposed method integrates physics-based orbit prediction algorithms with a learning-based process that focuses on modeling the prediction errors.
2. Using a simulation-based space catalog environment as the test bed, we have discovered three types of generalization capability for the proposed ML approach: 1) the ML model can be used to improve the same RSO's orbit information that is not available during the learning process, but shares the same time interval as the training data; 2) the ML model can be used to improve predictions of the same RSO at future epochs; and 3) the ML model based on a RSO can be applied to other RSOs that share some common features.
3. We have discovered that that the information of the area-to-mass ratio (AMR) can be recovered from the consistent error between two estimated states in the historical data of a catalog. Specifically, the random forest (RF) data-mining technique is used to exploit the relationship between the consistent error and the AMR. The RF method has a significant advantage in that it will not over-fit the data when the size of the model is increased. Also, we do not need to provide prior assumptions about basis functions since the RF method is a non-parametric method. For the simulated RSOs, we find that the AMR of an RSO can be determined by the RF model through both the classification approach and the regression approach. Moreover, we carried out some experiments and discovered that by simply recording more parameters in the catalog, the RF model can provide a much better prediction of the AMR.
4. We have explored limitations when using the ML methods for improving orbit prediction accuracy. In particular, four questions have been investigated when the Support Vector Machine (SVM) approach is used: 1) We prove that the trained SVM model can capture the relationship between the chosen learning variables and the target orbit prediction error with both good average and individual performances; 2) Through a series of experiments, we find that the performance can be further improved with more training data, until adequate data is provided; 3) We find that the correction capability of the trained SVM model is limited to the future horizon and its generalization capability will be reduced greatly if the orbit is predicted too far into the future. 4) We have investigated the random effect, including an idealistic case without any error and measurement noise with varying magnitudes.
5. The two publicly available Two-Line Element (TLE) catalog and International Laser Ranging Service (ILRS) catalog have been used to validate the proposed ML approach. The position

and velocity components of totally 11 RSOs maintained at both catalogs are studied. Results of the study demonstrate that the designed dataset structure and SVM model can improve the orbit prediction accuracy with good performance on most cases. The performance on RSOs belonging to different orbit types is analyzed using different sizes of training and testing data. Results demonstrate the potential of using the proposed ML approach to improve the accuracy of TLE catalog.

6. We have extended the ML approach by introducing Gaussian Processes (GPs) which can generate uncertainty information about its point estimate. Both the simulation environment and the publicly available RSO catalogs are used to test the advanced ML approach. Numerical results demonstrate that the trained GP model can effectively improve the orbit prediction accuracy and generate uncertainty boundaries with high performance. Insights are learned during the investigation using real data, including suggestions on designing learning variables and the possible causes for some unsatisfying results.
7. The recently developed machine learning (ML) approach to improve orbit prediction accuracy has been systematically investigated using three ML algorithms, including support vector machine (SVM), artificial neural network (ANN), and Gaussian processes (GP). In a simulation environment consisting of orbit propagation, measurement, estimation, and prediction processes, totally 12 resident space objects (RSOs) in SSO, LEO and MEO are simulated to compare the performance of three ML algorithms. The results show that ANN usually has the best approximation capability but is easiest to overfit data; SVM is least likely to overfit but the performance usually cannot surpass ANN and GP. Additionally, the ML approach with all the three algorithms is observed to be robust with respect to the measurement noise.

Publications with the support

Refereed Journal Articles

1. Hao Peng[*], Xiaoli Bai[§], "Comparative Evaluation Three Machine Learning Algorithms on Improving Orbit Prediction Accuracy", *The Journal of Astrodynamics*, accepted on April 18, 2019.
2. Hao Peng[*], Xiaoli Bai[§], "Gaussian Processes for Improving Orbit Prediction Accuracy", *Acta Astronautica*, Volume 161, August 2019, Pages 44-56 https://www.sciencedirect.com/science/article/pii/S0094576518320344?via%3Dihub
3. Gaurav Misra[*], and Xiaoli Bai[§], "Output-feedback Stochastic Model Predictive Control for Glideslope Tracking during Aircraft Carrier Landing", *AIAA Journal of Guidance, Control, and Dynamics*, Publication Date (online): April 08, 2019, https://arc.aiaa.org/doi/abs/10.2514/1.G004160
4. Hao Peng[*], Xiaoli Bai[§], "Machine Learning to Improve Orbit Prediction Accuracy: Validations Using Publicly Available Data", *The Journal of the Astronautical Sciences*, First Online: 14 May 2019:
   http://link.springer.com/article/10.1007/s40295-019-00158-3
5. Hao Peng[*], Xiaoli Bai[§], "Artificial Neural Network based Machine Learning Approach to Improve Orbit Prediction Accuracy", *AIAA Journal of Spacecraft and Rockets*, Vol. 55, No. 5 (2018), pp. 1248-1260. https://arc.aiaa.org/doi/abs/10.2514/1.A34171.

6. Hao Peng[*], Xiaoli Bai[§], “Exploring the Capabilities of Support Vector Machines for Improving Satellite Orbit Prediction Accuracy”, *AIAA Journal of Aerospace Information Systems*, Vol. 15, No. 6 (2018), pp. 366-381, https://arc.aiaa.org/doi/abs/10.2514/1.I010616.
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8. Hao Peng[*], Xiaoli Bai[§], “Natural Deep Space Formation Flying in the Earth-Moon Elliptic System”, *Acta Astronautica*, Volume 153, December 2018, Pages 240-258, http://www.sciencedirect.com/science/article/pii/S0094576517313322
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10. Gaurav Misra[*], and Xiaoli Bai[§], “Optimal Path Planning of Free-flying Space Robots via Sequential Convex Programming”, *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 11 (2017), pp. 3026-3033, https://arc.aiaa.org/doi/full/10.2514/1.G002487
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12. Hao Peng[*], Xiaoli Bai[§], Josep Masdemont, Gerard Gomez, Shijie Xu, Libration Transfer Design Using Patched Elliptic Three-Body Models and Graphics Processing Units, *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 40, No. 12, pp. 3155-3166, 2017. https://arc.aiaa.org/doi/abs/10.2514/1.G002692

Conference papers:

1. Hao Peng[*], **Xiaoli Bai**[§], “Covariance Fusion of Orbit Uncertainty Propagation and Gaussian Processes Generalizations”, 2019 AAS/AIAA Astrodynamics Specialist Conference, August 2019. (Accepted)
2. Hao Peng[*], **Xiaoli Bai**[§], Lesley Weitz, Scott Kordella, “Enhance the TLE Catalog through Sharing Machine Learning Models”, 70th International Astronautical Congress, October 2019. (Accepted)
3. Hao Peng[*], **Xiaoli Bai**[§], “Comparison of Effective Machine Learning Algorithms on Improving Orbit Prediction Accuracy of Low Earth Objects”, *69th International Astronautical Congress*, 2018.
4. Hao Peng[*], **Xiaoli Bai**[§], “Obtain confidence interval for the machine learning approach to improve orbit prediction accuracy”, *2018 AAS/AIAA Astrodynamics Specialist Conference*.
5. Hao Peng[*], **Xiaoli Bai**[§], “Generalization Capability of Machine Learning Approach among Different Satellites: Validated Using TLE Data”, *2018 AAS/AIAA Astrodynamics Specialist Conference*.
6. Hao Peng[*], **Xiaoli Bai**[§], “Machine Learning to Improve Orbit Prediction Accuracy: Validations Using Publicly Available Data”, *John Junkins Dynamical Systems Symposium*, College Station, TX, May 2018.

7. Hao Peng[*], **Xiaoli Bai**[§], "Using Artificial Neural Network to Improve Orbit Prediction Accuracy", *2018 Space Flight Mechanics Meeting,* AIAA Science and Technology Forum and Exposition 2018.
8. Gaurav Misra[*], Hao Peng, **Xiaoli Bai**[§], "Halo Orbit Station-keeping using Nonlinear MPC and Polynomial Optimization", *2018 Space Flight Mechanics Meeting,* AIAA Science and Technology Forum and Exposition 2018.
9. Hao Peng[*], **Xiaoli Bai**, "Limitations on Improving Orbit Prediction Accuracy through Support Vector Machine Learning Model", *Advanced Maui Optical and Space Surveillance Technologies (AMOS) Conference*, September 2017.
10. Hao Peng[*], **Xiaoli Bai**, "New Natural Formation Flying Configurations in the Earth-Moon Elliptic Three-body system", *9th International Workshop on Satellite Constellations and Formation Flying*, University of Colorado, July 2017.
11. Jullian Rivera[*] and **Xiaoli Bai**, "Improving the Orbit Propagation Accuracy of Two-Line-Element Satellite Data", *67th International Astronautical Congress*, Guadalajara, Mexico, September 26-20, 2016