Department of Integrated Systems Engineering
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Enhao Liu

Research Interests

Cyber Security Analytics: Cyber Vulnerabilities Maintenance Policies Management

Social Media Analytics: Twitter-based Cyber Vulnerabilities Prioritization

Machine Learning: Explainable AI; Hyper-parameters Optimization

Reinforcement Learning: Partially Observable Markov Decision Process (POMDP); Monte Carlo-Bayesian Reinforcement Learning (MC-BRL); Deep Q-Learning

Education

Aug 2017–May 2020 **Ph.D. Candidate**, *The Ohio State University*, Columbus, OH, USA.
Major: Operations Research; Minor: Machine Learning, Cybersecurity; Advisor: Theodore T. Allen.

Aug 2015–May 2017 **Master of Science**, *The Ohio State University*, Columbus, OH, USA.
Major: Operations Research; Thesis Advisor: Theodore T. Allen.

Aug 2011–May 2015 **Bachelor of Engineering**, *Jinan University*, Guangzhou, China.
Major: Electric Engineering and Automation. Senior thesis advised by Weihua Li.

Awards

2019 Runner-up, Student Paper Competition, The Social Media Analytics Section of INFORMS.

2014 Second Prize of Scholarship for Excellent Students, Jinan University.

2013 Third Prize of Scholarship for Excellent Students, Jinan University.

2013 Yihai Kerry Scholarship for Innovative Undergraduates, Jinan University.

2013 Meritorious Winner, National College Mathematical Contest in Modeling.

2012 First Prize, China Undergraduate Mathematical Contest in Modeling.

Publications

Journal Articles

ASMBI 2019 **Enhao Liu**, Theodore T. Allen, and Sayak Roychowdhury. "Cyber Vulnerability Maintenance Policies That Address the Incomplete Nature of Inspection." *Applied Stochastic Models in Business and Industry*, 2019.

CAIE 2018 Theodore T. Allen, Sayak Roychowdhury, and **Enhao Liu**. "Reward-based Monte Carlo-Bayesian Reinforcement Learning for Cyber Preventive Maintenance." *Computers & Industrial Engineering*, 2018.

Conference Papers

WSC 2019 Akshay Krishna Murali, **Enhao Liu**, and Theodore T. Allen. (in press) "Discrete Event Simulation of Cyber Maintenance Policies According to Nested Birth and Death Processes." *In Proceedings of the 2019 Winter Simulation Conference*, IEEE, 2019.

WSC 2018 Theodore T. Allen and **Enhao Liu**. "Forecasting Cyber Maintenance Costs with Improved Scan Analytics Using Simulation." *In Proceedings of the 2018 Winter Simulation Conference*, IEEE, 2018.

Dissertations

Master Thesis 2017 **Enhao Liu**. "Logistic Regression Model for Predicting Warning "Incident" Rates and Implications for the Common Vulnerability Scoring System." Master Thesis, The Ohio State University, 2017.

Manuscripts in Progress

Book (in writing) Theodore T. Allen and **Enhao Liu**. "Introduction to Machine Learning For Supply Chain Optimization - *Python, Statistics, and AI with Operations Analytics Industrial Datasets*." *Springer*, 2020.

Journal (in writing) **Enhao Liu** and Theodore T. Allen. "Twitter-based Cyber Security Warning and Prioritization System." 2020.

Recent Research Experience

Jul 2019–present **Twitter-based Detection for Exploited Vulnerabilities (in progress)**, *NSF Grant #1912166*.
Team Leader: Enhao Liu; Supervisor: Theodore T. Allen.

- Wrote scraping scripts using Python to collect recent five-year Twitter data and other online resources about 70,000 distinct software vulnerabilities spanned over 9,000 different vendors.
- Developed feature generation and classification models to early detect exploited vulnerabilities based on supervised machine learning methods using scikit-learn framework.
- Wrote a manuscript that has been selected as the finalist for the 2019 student paper competition in the section of *The Social Media Analytics of INFORMS*.

May 2019–present **Explainable AI Study: Optimal Classification (in progress)**, *NSF Grant #1912166*.
Team Leader: Enhao Liu; Supervisor: Theodore T. Allen.

- Wrote the first R package for the algorithm of optimal classification tree proposed by Dr. Bertsimas and Dr. Dunn based on mixed-integer linear programming, which will be used to generate detection rules for distinguishing compromised email accounts of the Ohio State University.

Aug 2016–Nov 2018 **Cyber Vulnerabilities Maintenance Management (major)**, *NSF Grant #1409214*.
Team Leader: Enhao Liu; Supervisor: Theodore T. Allen.

- Implemented comprehensive procedures using R to process and statistically analyze 2.3 million scanned data about vulnerabilities spanned about 50,000 hosts at the Ohio State University, which facilitated the development of data-driven cyber vulnerability maintenance. This part generated my Master's thesis.
- Developed a novel framework based on Partially Observable Markov Decision Processes to derive cyber vulnerability maintenance policies that address the incomplete inspection issue on 50,000 multi-type hosts.
- Worked with Professor Theodore T. Allen and a Ph.D. candidate Sayak Roychowdhury to develop a new Monte Carlo-Bayesian Reinforcement Learning framework to address parameters uncertainty in model-based Markov Decision Processes in which multiple identical-systems have been considered.
- Collaborated with Professor Theodore T. Allen and a graduate student Akshay K. Murali to build simulation models in ARENA to evaluate the cyber maintenance policies under different scenarios in terms of maintenance costs and security hardening.

Mar 2019 **Scholarly Publication Network Exploration (minor)**.
Team Leader: Enhao Liu; Supervisor: Theodore T. Allen.

- Created a visualized and interactive network using R to depict the publication associations among the scholars and their co-authors who are in the section of INFORMS Social Media Analytics (SMA), which presented in the Newsletter of the section of INFORMS SMA in 2019.

Skills

Programming Python, R, Matlab, GAMS

Packages Python: scikit-learn, xgboost, hyperopt, pandas, plotly, Flask; R: caret, forecast, MARSS, MDPtoolbox, pomdp, ompr, CVXR, tidyverse, visNetwork; Matlab: Cplex Class API

Software Minitab, ARENA, Simio

Others LaTeX, Microsoft Office Suite

Coursework Operation Research Models and Methods; Linear Programming; Non-linear Programming; Mixed Integer Programming; Convex Optimization Algorithm; Stochastic Optimization; Stochastic Process; Decomposition Techniques in Mathematical Programming; Intermediate Data Analysis; Mathematical Analysis of Algorithms; Statistical Machine Learning.

Languages Chinese (native), English (fluent)

Employment

Aug 2016–present **Graduate Research Assistant**, *The Ohio State University*, Columbus, OH, USA.

Department: Integrated Systems Engineering; Lab: Security and Efficiency Through Analytics Laboratory; Supervisor: Theodore T. Allen

- Led the project "A Framework For Economical Cyber Security Inspection and Assurance" funded by National Science Foundation (NSF Grant #1912166) starting from May 2019.
- Led and conducted the project "Data-Driven Cyber Vulnerability Maintenance" funded by National Science Foundation (NSF Grant #1409214) from Aug 2016 to Nov 2018.
- Developed a novel warning & prioritization system based on social media to detect exploited vulnerabilities. Worked with Pardee Bob and Geoffery Shoupp from Office of the Chief Information Officer (OCIO) Enterprise Security at Ohio State University to deploy the proposed system as a software product.
- Reviewed several papers from *Computer & Industrial Engineering*.
- Worked with Professor Theodore T. Allen, a Ph.D. candidate Sayak Roychowdhury and a graduate student Akshay K. Murali to publish two journal articles and two conference papers.
- Worked with Professor Theodore T. Allen to write a book about machine learning applications in operations optimization and supply chain optimization.
- Worked with Professor Theodore T. Allen to design a new syllabus and materials for a course "Introduction to Operations Analytics" which will be offered in Spring 2020. The new version of this course is aimed to help undergraduate and graduate students learn how to implement industrial applications using R and Python.

May 2016–Aug 2016 **Student Associate**, *The Ohio State University*, Columbus, OH, USA.

Department: Integrated Systems Engineering; Lab: Security and Efficiency Through Analytics Laboratory; Supervisor: Theodore T. Allen

- Collaborated with a graduate student Tianyu Jiang to develop a software using VB.NET to produce data-driven cyber vulnerabilities maintenance policies based on Markov Decision Processes for about 50,000 hosts at the Ohio State University.

Speaking

Invited Research Talks

2019 "Twitter-based Cyber Security Warning and Prioritization System", INFORMS Annual Meeting – Session of Information Operations in Social Networks, Seattle, WA (Oct 23 2019).

Poster Sessions

2018 "Cyber Vulnerability Maintenance and Optimal Learning", Research Poster Session in the Department of Integrated Systems Engineering, OSU, Columbus, OH (Nov 2018).

2016 "Data-Driven Cyber Vulnerability Maintenance", Research Poster Session in the Department of Integrated Systems Engineering, OSU, Columbus, OH (Sep 2016).