Supervised Machine Learning for Effective Missile Launch Based on Beyond Visual Range Air Combat Simulations

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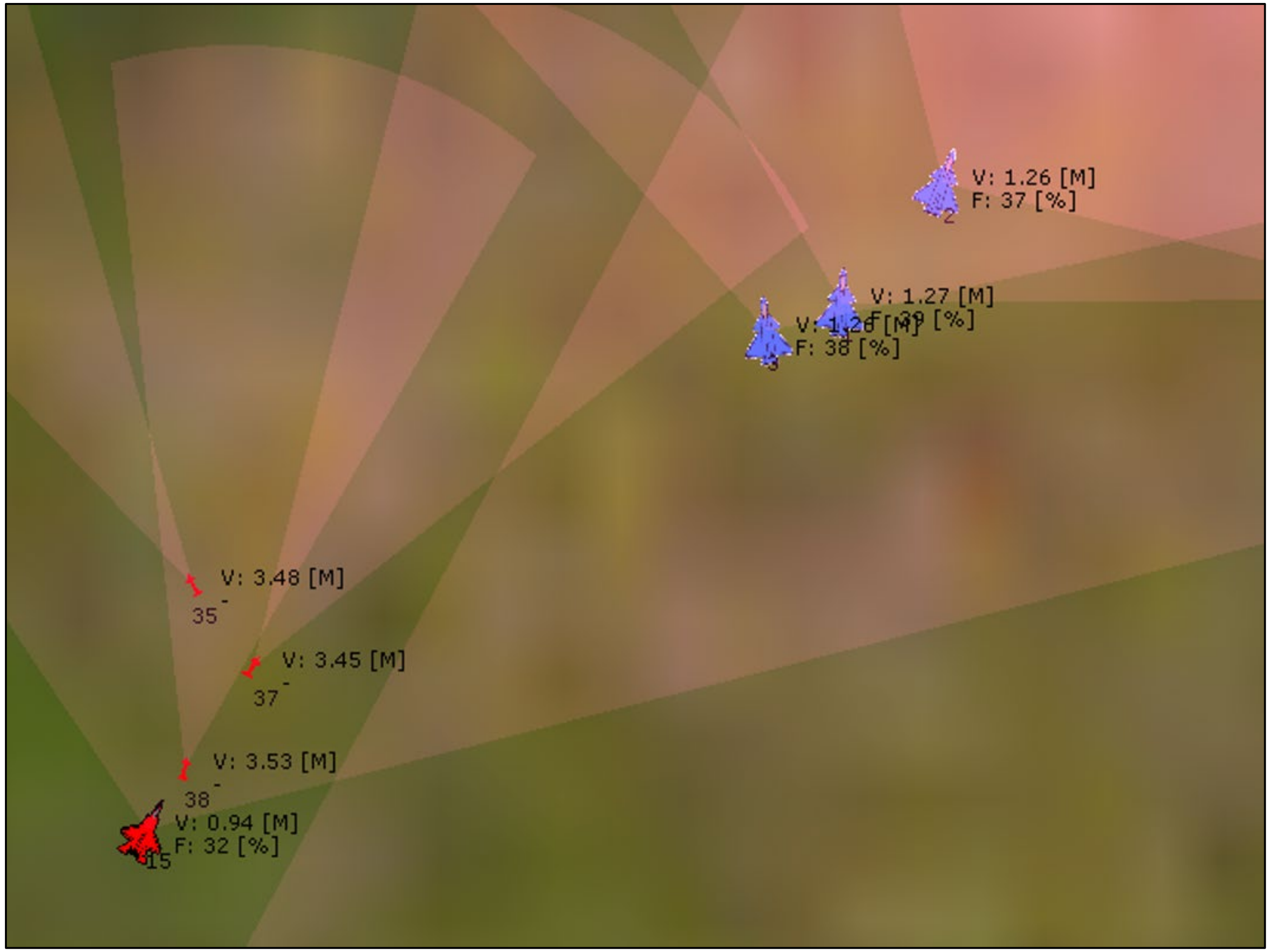
INTRODUCTION

- Beyond Visual Range (BVR) Air Combat: sensors and missiles
- New technologies in the modern warfare
- Constructive Simulations: autonomous agents
- Some research addressed the application of artificial intelligence, game theory, and heuristics in modeling decision-making for autonomous agents in different phases of simulated BVR air combat



RELATED WORK

Threat assessment and target selection

- Fuzzy logic and Bayesian network: Rao et al. (2011).
- Case-Based Behavior Recognition: Borck et al. (2015)
- Zero-sum game: Ma et al. (2019)
- Genetic algorithm with deep learning: Li et al. (2020)
- Bayesian optimization: Fu et al. (2021)
- Neural network: Yao (2021)

Selection and execution of tactical maneuvers

- Bayesian networks: Du and Liu (2010)
- Behavior trees: Yao et al. (2015)
- Finite state machines: Toubman et al. (2016)
- Reasoning based on objectives: Floyd et al. (2017)
- Simulated annealing: Weilin et al. (2018)
- Minimax method: Kang et al. (2019)
- Genetic algorithm: Kuroswiski (2020)
- Hierarchical multi-Objective evolutionary algorithm: Yang et al. (2020)
- Markov decision processes: Piao et al. (2020)
- Zero-sum differential game: Garcia et al. (2021)
- Deep reinforcement learning: Hu et al. (2021)

RELATED WORK

Decision-making process of launching a missile

- **Ha et al. (2018)**
  - Modeled the BVR air combat between two aircraft swarms as a zero-sum stochastic game
  - Probabilistic function: the target's evasive ability, the missile's speed on the final approach, and the accuracy of the target's information to guide the missile
  - It has not been tested in simulations with higher fidelity concerning real BVR air combat
  - All aircraft in the same swarm fire at the same time
  - The missiles can pursue targets without the need for support from the radar aircraft

- **Lima Filho et al. (2021)**
  - Modeled the BVR air combat between two aircraft and analyze the missile launch process
  - Single machine learning method was employed
  - One aircraft each team

CONTRIBUTION

- Estimate the most effective moment for launching missiles during a BVR air combat
- Supervised Machine Learning Techniques can streamline the missile success predictions for real-time applications
- The missiles could not hit their targets in most of the scenarios: imbalanced dataset
- Resampling techniques were employed to improve the predictive model.

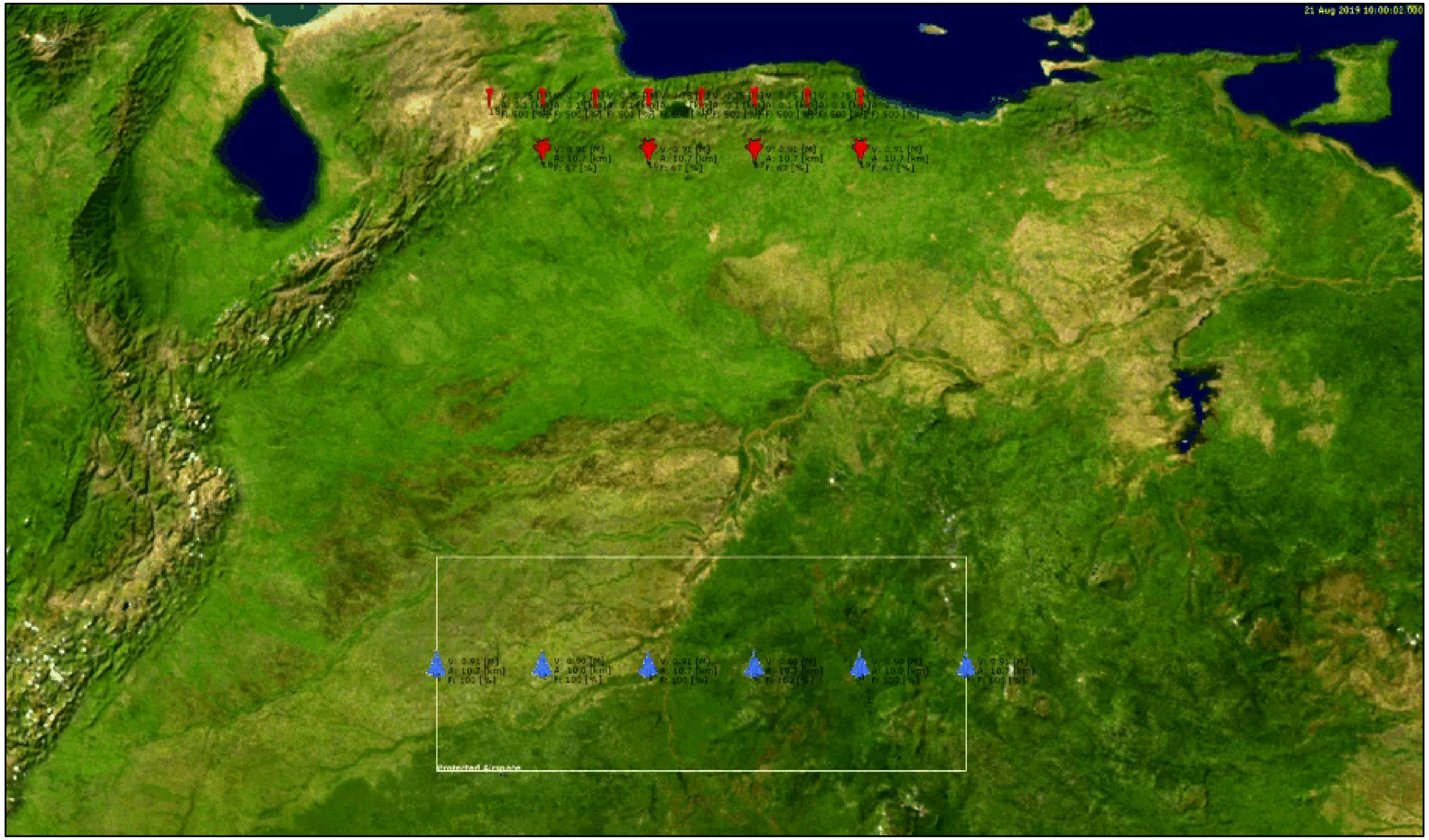
“First work to address the imbalance in the missile launch results within air combat simulation.”

METHODOLOGY

1. Define BVR air combat scenarios
2. Design of experiments
3. Run simulations faster than in real-time
4. Collect the data from the missile launches
5. Preprocessing and exploratory data analysis
6. Model training and hyperparameter tuning
7. Evaluation

SCENARIO DESCRIPTION

- Two forces that engage each other in a tropical area
- **Blue**
  - Combat Air Patrol (CAP)
  - 4- or a 6-aircraft squadron
  - Fourth-generation and Fifth-generation
- **Red**
  - Fighter Sweep
  - 4-aircraft squadron
  - Multi-role fighters



FLAMES
Constructive Simulation Framework

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DESIGN OF EXPERIMENTS

- Latin Hypercube Sampling (LHS)
- 240 cases as simulation inputs
- Each executed 30 times with different seeds (probability of kill and behavior evaluation delays)
- 7200 simulations
- All aircraft destroyed or 30 minutes
- Faster than in real-time

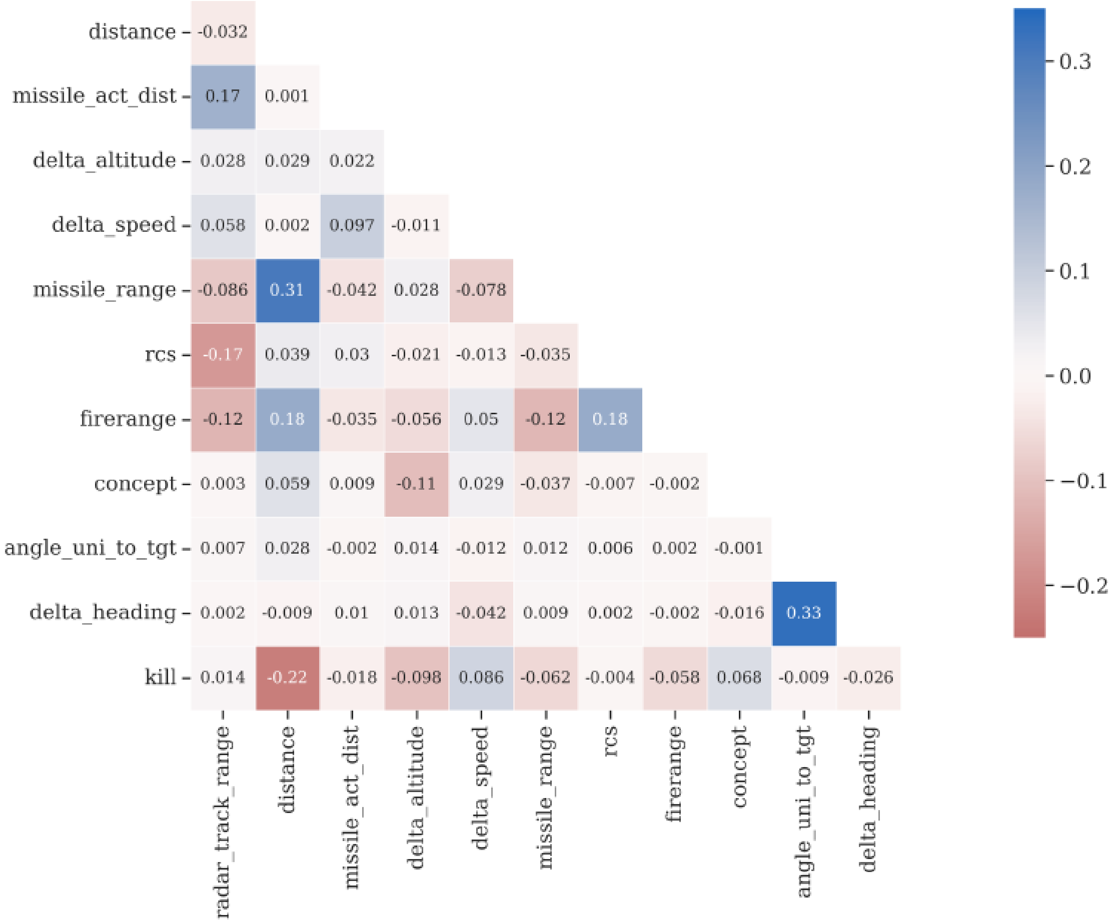
Description	Min	Max	Unit
Blue maneuvering altitude	27.5	42.5	kft
Red maneuvering altitude	27.5	42.5	kft
Blue maneuvering speed	0.9	1.5	Mach
Red maneuvering speed	0.9	1.5	Mach
Blue radar track range	150	300	km
Blue missile range multiplicative factor	1	2	-
Blue RCS	-10	10	dBm^2
Blue missile activation distance	15	30	km
Blue shot philosophy (in percentage of WEZ)	50	70	%
Initial distance between blue aircraft (in longitude)	0.1	1.0	°
Initial distance between red aircraft (in longitude)	0.1	1.0	°
Blue CAP speed	0.7	0.75	Mach
Red CAP speed	0.7	0.75	Mach
Blue aircraft concept (type)	1	2	-
Whether there are six blue aircraft (0) or not (1)	0	1	-

VARIABLES

Variables	Unit	Description
radar_track_range	km	Radar track range
distance	km	Distance between aircraft
missile_act_dist	km	Missile activation distance
delta_altitude	m	Difference between aircraft altitudes
delta_speed	kt	Difference between aircraft speeds
missile_range	-	Missile range multiplicative factor
rcs	m^2	Radar cross section
firerange	%	Percentage of WEZ
angle_uni_to_tgt	°	Off-boresight angle between aircraft
delta_heading	°	Difference between aircraft headings
concept	-	Which blue aircraft concept type was employed (1 or 2)
kill	-	Whether the target aircraft was killed by the missile

EXPLORATORY DATA ANALYSIS

Variables	Mean	Std	Min	25%	Median	75%	Max
radar_track_range	217,375.7	40,219.6	150,289.2	182,961.3	214,907.9	251,175.8	285,788.2
distance	40,841.9	16,529.9	3,023.6	29,319.6	38,078.3	50,553.9	100,717.4
missile_act_dist	22,442.6	4,353.8	15,197.3	18,742.0	22,735.8	26,224.3	29,828.1
delta_altitude	768.6	2,357.6	-14,168.3	-655.3	641.8	2,284.2	13,573.3
delta_speed	12.2	71.7	-232.4	-38.0	16.6	63.1	263.3
missile_range	1.5	0.3	1.0	1.2	1.5	1.8	2.0
rcs	-0.1	5.8	-9.9	-5.3	-0.1	5.0	9.7
firerange	60.2	5.7	50.2	55.4	60.6	65.2	69.9
angle_uni_to_tgt	-0.8	21.8	-44.9	-9.0	0.0	4.6	44.9
delta_heading	181.9	77.1	-42.8	140.5	180.0	220.0	401.5



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MODEL TRAINING AND EVALUATION

- Scikit-learn and XGBoost libraries
- Data Scaling: Support Vector Machines, Artificial Neural Networks, K-Nearest Neighbors and Naive Bayes (it is not required for Linear Regression, Random Forest and Extreme Gradient Boosting)
- Grid search algorithm
- Train-validate-test split
  - 85% for training and validation using a 5-fold cross-validation technique
  - 15% for testing
- Accuracy, Precision, Recall, and F1-score
- Inference Time

MODEL METRICS

- Accuracy may not be the most appropriate metric: imbalanced dataset
- Precision: avoid unnecessary missile launches
- Recall: not launching a missile that would probably hit a particular target is a massive issue that good pilots try to avoid
- $F_1 = 2 \times \frac{Precision \times Recall}{Precision + Recall}$
- Resampling techniques demonstrated the capacity to increase the recall metric, even with a slight decrease in accuracy and precision

Model	Accuracy	Precision	Recall	F1-Score	Inference Time [ms]
LR	0.877	0.421	0.003	0.006	1.4
LR + SMOTE	0.655	0.215	0.685	0.327	1.1
LR + ADASYN	0.646	0.212	0.694	0.325	1.3
LR + SMOTE-TL	0.661	0.217	0.676	0.328	1.3
LR + SMOTE-ENN	0.625	0.204	0.711	0.317	1.1
KNN	0.889	0.639	0.208	0.314	3903.1
KNN + SMOTE	0.763	0.296	0.678	0.412	5194.4
KNN + ADASYN	0.730	0.272	0.721	0.395	4970.0
KNN + SMOTE-TL	0.763	0.297	0.685	0.414	5090.1
KNN + SMOTE-ENN	0.725	0.273	0.750	0.400	4632.8
SVM	0.891	0.716	0.185	0.294	266.5
SVM + SMOTE	0.766	0.308	0.729	0.433	654.7
SVM + ADASYN	0.722	0.276	0.785	0.409	752.8
SVM + SMOTE-TL	0.766	0.307	0.727	0.432	614.5
SVM + SMOTE-ENN	0.737	0.287	0.775	0.419	321.345
ANN	0.890	0.638	0.227	0.335	116.6
ANN + SMOTE	0.765	0.308	0.735	0.434	94.4
ANN + ADASYN	0.703	0.267	0.814	0.402	163.1
ANN + SMOTE-TL	0.757	0.300	0.744	0.428	157.0
ANN + SMOTE-ENN	0.730	0.283	0.784	0.416	35.7
NB	0.884	0.672	0.096	0.168	4.3
NB + SMOTE	0.641	0.208	0.690	0.320	5.0
NB + ADASYN	0.599	0.196	0.736	0.310	3.3
NB + SMOTE-TL	0.641	0.208	0.691	0.320	3.3
NB + SMOTE-ENN	0.590	0.194	0.743	0.307	3.2
RF	0.895	0.686	0.262	**0.379**	**160.8**
RF + SMOTE	0.851	0.415	0.528	**0.465**	**108.3**
RF + ADASYN	0.844	0.401	0.551	0.464	175.8
RF + SMOTE-TL	0.848	0.408	0.537	0.463	350.0
RF + SMOTE-ENN	0.809	0.351	0.664	0.459	35.2
XGBoost	0.892	0.648	0.255	0.366	17.1
XGBoost + SMOTE	0.826	0.368	0.593	0.454	6.6
XGBoost + ADASYN	0.811	0.347	0.615	0.444	6.4
XGBoost + SMOTE-TL	0.825	0.369	0.609	0.459	6.2
XGBoost + SMOTE-ENN	0.791	0.332	0.699	0.450	6.8

CONCLUSIONS

- Develop decision support tools that may improve flight quality in BVR air combat
- These models might enhance the missile launching process by unmanned combat aerial vehicles (UCAV) or aid pilots in real air combat scenarios
- **For future work**
  - Analyze different scenarios with multiple aircraft equipped with other missiles
  - Analyze not just the missile launching moment but a sequence of several timeframes to understand better the coordination of future events in the air combat scenario
  - Develop different sampling strategies that allow the choice of other input variables to improve the dataset to be analyzed

ACKNOWLEDGMENTS

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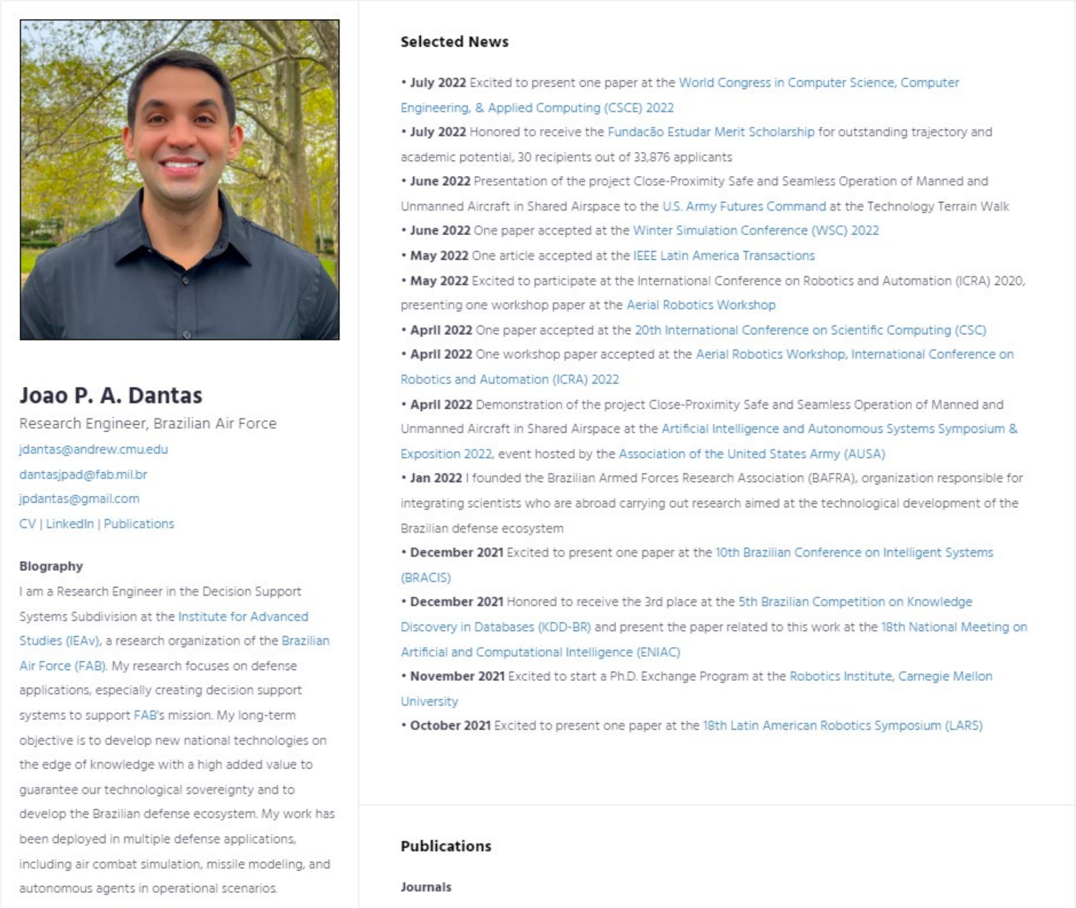
CONTACT

- Code: github.com/jpadantas/effective-missile-launch
- E-mail: dantasjpad@fab.mil.br
- Website: www.joaopadantas.com



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CV | LinkedIn | Publications

Biography

I am a Research Engineer in the Decision Support Systems Subdivision at the Institute for Advanced Studies (IEAv), a research organization of the Brazilian Air Force (FAB). My research focuses on defense applications, especially creating decision support systems to support FAB's mission. My long-term objective is to develop new national technologies on the edge of knowledge with a high added value to guarantee our technological sovereignty and to develop the Brazilian defense ecosystem. My work has been deployed in multiple defense applications, including air combat simulation, missile modeling, and autonomous agents in operational scenarios.

Selected News

- **July 2022** Excited to present one paper at the World Congress in Computer Science, Computer Engineering, & Applied Computing (CSCE) 2022
- **July 2022** Honored to receive the Fundacão Estudar Merit Scholarship for outstanding trajectory and academic potential, 30 recipients out of 33,876 applicants
- **June 2022** Presentation of the project Close-Proximity Safe and Seamless Operation of Manned and Unmanned Aircraft in Shared Airspace to the U.S. Army Futures Command at the Technology Terrain Walk
- **June 2022** One paper accepted at the Winter Simulation Conference (WSC) 2022
- **May 2022** One article accepted at the IEEE Latin America Transactions
- **May 2022** Excited to participate at the International Conference on Robotics and Automation (ICRA) 2020, presenting one workshop paper at the Aerial Robotics Workshop
- **April 2022** One paper accepted at the 20th International Conference on Scientific Computing (CSC)
- **April 2022** One workshop paper accepted at the Aerial Robotics Workshop, International Conference on Robotics and Automation (ICRA) 2022
- **April 2022** Demonstration of the project Close-Proximity Safe and Seamless Operation of Manned and Unmanned Aircraft in Shared Airspace at the Artificial Intelligence and Autonomous Systems Symposium & Exposition 2022, event hosted by the Association of the United States Army (AUSA)
- **Jan 2022** I founded the Brazilian Armed Forces Research Association (BAFRA), organization responsible for integrating scientists who are abroad carrying out research aimed at the technological development of the Brazilian defense ecosystem
- **December 2021** Excited to present one paper at the 10th Brazilian Conference on Intelligent Systems (BRACIS)
- **December 2021** Honored to receive the 3rd place at the 5th Brazilian Competition on Knowledge Discovery in Databases (KDD-BR) and present the paper related to this work at the 18th National Meeting on Artificial and Computational Intelligence (ENIAC)
- **November 2021** Excited to start a Ph.D. Exchange Program at the Robotics Institute, Carnegie Mellon University
- **October 2021** Excited to present one paper at the 18th Latin American Robotics Symposium (LARS)

Publications

Journals

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