Loyal Wingman Assessment: Social Navigation for Human-Autonomous Collaboration in Simulated Air Combat

Joao P. A. Dantas, Marcos R. O. A. Maximo, Takashi Yoneyama

Institute for Advanced Studies | Aeronautics Institute of Technology

Introduction

- Autonomous aircraft in shared airspace must navigate **safely** and **efficiently**
- At the same time, they should adhere to **social norms** expected in human-centric environments
- These norms include:
  - Respecting a personal space
  - Maintaining comfortable velocities and accelerations
  - Keeping a safe distance from other aircraft
- **Socially aware navigation research**: improve interactions between autonomous agents and humans
- We need **metrics** to evaluate these methods more effectively
- **Air combat domain**: additional layers of complexity to social navigation
- Loyal wingman with human pilot requires not only **safety** and **efficiency** but also a deep understanding of **tactics** and **formation dynamics**
- A mix of **social** and **combat** skills

Contributions

- **Social Navigation Metrics**: Present metrics to enhance the human-AI interaction in the context of air combat
- **User Study Experiment**: Propose a validation process with interactions between real pilots and trained AI agents within a high-fidelity virtual simulation environment

Aerospace Simulation Environment

- *Ambiente de Simulação Aeroespacial – ASA in Portuguese* (Dantas et al., 2022)
- **Custom-made** in **C++** for advanced programming flexibility
- **High-fidelity** representation for accurate scenario reproduction
- Supported by the **Brazilian Air Force**
- Dedicated to **modeling and simulation** of **military operational scenarios**

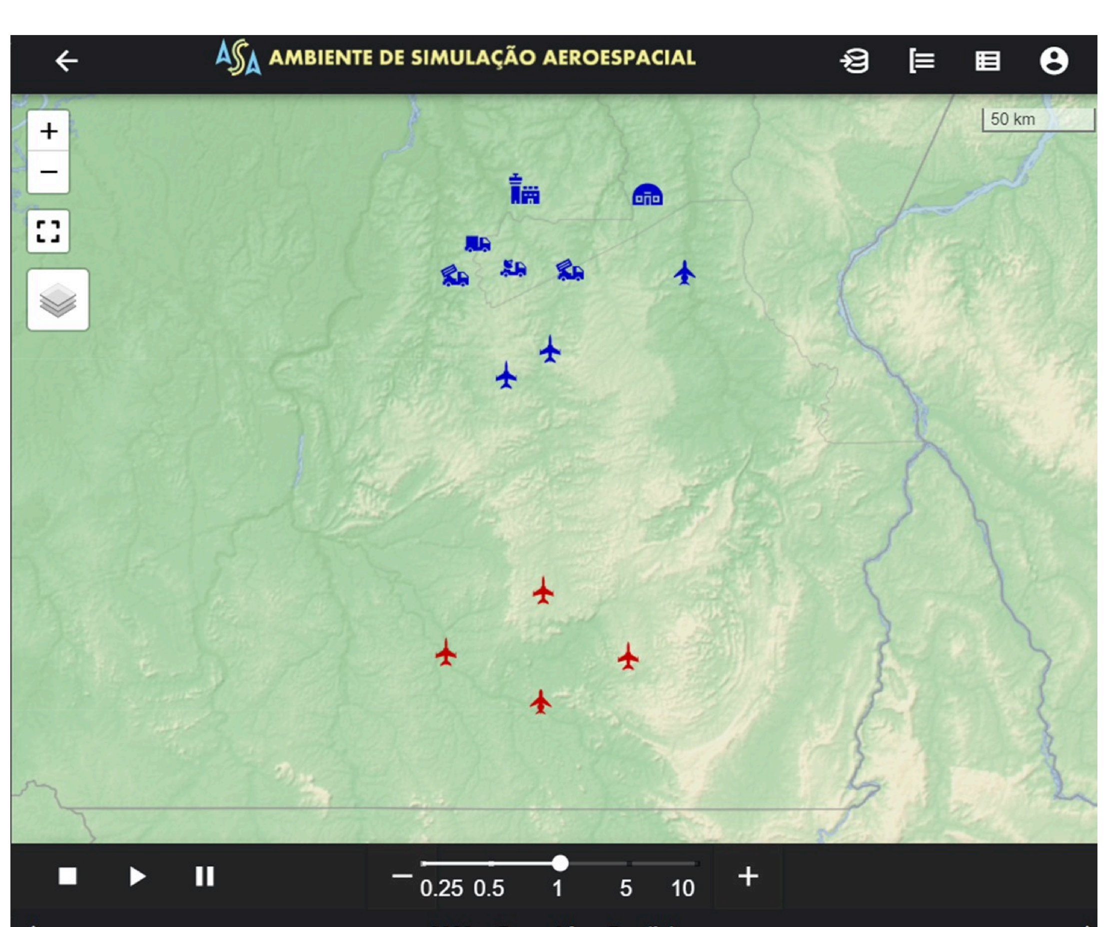

Figure 1. The ASA user interface for scenario creation allows users to define multiple simulation aspects, including aircraft models, sensors, communication links, and mission objectives

Proposed Social Navigation Metrics

Table 1. Summary of the proposed social navigation metrics for human-autonomous collaboration

No.	Aspect	Metric	Description
M_1	Naturalness	Velocity	Computes the mean of the squared velocities over the time period, highlighting significant speed variations from typical human norms
M_2	Naturalness	Acceleration	Calculates the average of squared accelerations to assess how naturally the acceleration changes compare to human-like movements
M_3	Naturalness	Jerk	Evaluates the mean squared jerk to identify abrupt changes in acceleration, aiming for smoother, more human-like trajectories
M_4	Comfort	Minimum Distance	Calculates the smallest distance between two agents by iteratively comparing their positions over a given time period and updating the minimum found
M_5	Comfort	Collision Risk	Assesses the collision risk by determining how often two agents come within a critical distance or have a closing velocity that predicts a potential collision

- Naturalness
  - This aspect evaluates the **similarity** of the wingman's motion to human movements and the **smoothness** of its path
  - Involves analyzing the agent's **velocity**, **acceleration**, and **jerk** to assess **movement smoothness** and **human likeness**

$$M_n = \frac{1}{T}\sum_{t=0}^{T}\left(\frac{d^n p(t)}{dt^n}\right)^2, \quad \text{where } n = \begin{cases} 1 & \text{for velocity,} \\ 2 & \text{for acceleration,} \\ 3 & \text{for jerk.} \end{cases}$$

- Comfort
  - This aspect assesses human comfort by **minimizing disturbance** in interactions with autonomous agents
  - Emphasizes **maintaining safe distances** and **respecting personal spaces** to reduce impact on human activities

Algorithm 1 Calculate M_4: Minimum Distance Comfort Metric

Initialize minimum distance comfort metric: $M_4 \leftarrow +\infty$
for $t = 0$ to T **do**
  Calculate distance for frame t: $d_t \leftarrow \|\mathbf{p}_t^w - \mathbf{p}_t^h\|$
  if $d_t < M_4$ **then**
    Update minimum distance: $M_4 \leftarrow d_t$ ▷ Record new minimum across all frames
  end if
end for

Algorithm 2 Calculate M_5: Collision Risk Comfort Metric

Initialize collision risk comfort metric: $M_5 \leftarrow 0$
for $t = 1$ to T **do**
  Calculate relative position vector: $\mathbf{r}_t \leftarrow \mathbf{p}_t^h - \mathbf{p}_t^w$
  Compute distance: $d_t \leftarrow \|\mathbf{r}_t\|$
  Compute relative velocity vector: $\mathbf{v}_t \leftarrow \frac{d\mathbf{p}_t^h}{dt} - \frac{d\mathbf{p}_t^w}{dt}$
  Calculate closing velocity: $v_{\text{close},t} \leftarrow \frac{\mathbf{r}_t \cdot \mathbf{v}_t}{d_t}$
  if $d_t < \varepsilon$ **then** ▷ If within critical distance
    Increment collision risk comfort metric: $M_5 \leftarrow M_5 + 1$ ▷ Log alert
  else
    if $v_{\text{close},t} > 0$ **then** ▷ If distance decreasing
      Calculate Time to Reach (TTR): $TTR \leftarrow \frac{d_t}{v_{\text{close},t}}$
      if $TTR < t_{\text{critical}}$ **then** ▷ If below critical time
        Increment collision risk comfort metric: $M_5 \leftarrow M_5 + 1$ ▷ Log alert
      end if
    end if
  end if
end for

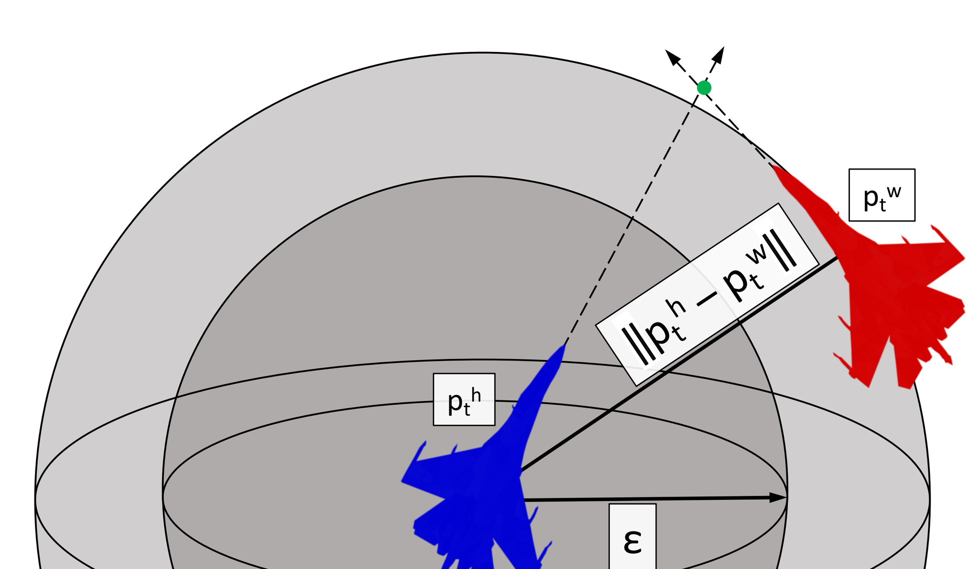

Figure 2. Human-wingman personal space metric depiction

User Study Experiment

- This user study aims to **validate** social navigation metrics by comparing them against human pilot perceptions in simulated air combat scenarios
- Involves military pilots with varied experience selected based on:
  - Flight hours
  - System proficiency
  - Simulation experience
- Pilots will operate alongside a loyal wingman, controlled by an AI, following the evaluated metrics in simulated air combat
- **Scenario Analysis**:
  - The simulation scenario evaluates the **feasibility** and **effectiveness** of continuous **Combat Air Patrol** operations:
    - Aiming to defend a strategic point of interest
    - The **Defensive Counter Air (DCA)** index (Dantas et al., 2021) will be used to evaluate the performance of the human-autonomous team in achieving the mission objectives
  - Data will be gathered via post-trial questionnaires to assessing naturalness and comfort
  - Compare the pilot's evaluation with the social navigation metrics
  - The analysis will be conducted using the AsaPy Library (Dantas et al., 2024)

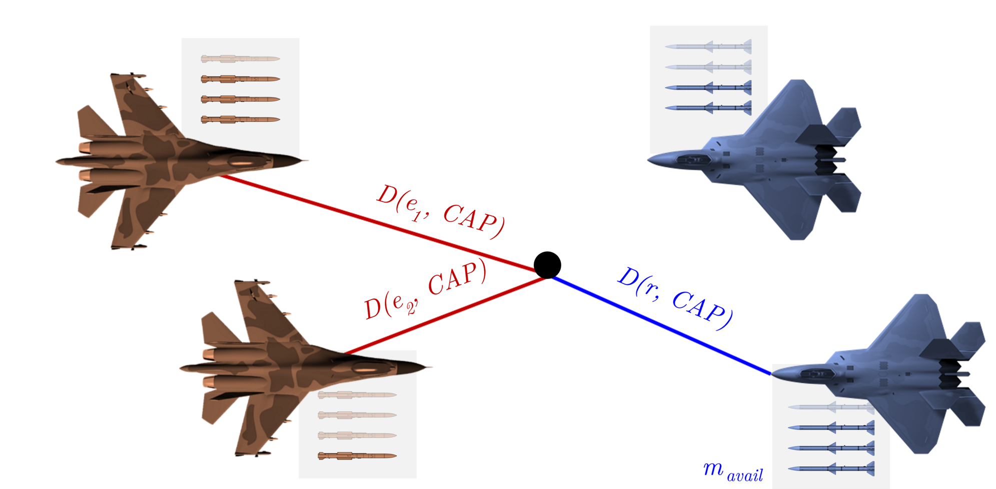

Figure 3. Combat Air Patrol operations for the defense of a point of interest

Conclusion

- This study introduces social navigation metrics to enhance human-autonomous collaboration in air combat:
  - Aiming to align with **human pilot expectations** and improve **team performance**.
  - These metrics can optimize autonomous agents' algorithms, including those based on:
    - Behavior trees
    - Reinforcement learning techniques
  - Enhance the quality of air combat training through the development of socially-aware **Unmanned Combat Air Vehicles**
  - Advancing AI fighters to support pilots or potentially even replace them
- **Future Work**:
  - Execution of **Turing Tests** in collaboration with Brazilian fighter pilots
    - Assessing the competencies of the AI fighter
    - Validate the social navigation metrics proposed

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dantasjpad@fab.mil.br | www.joaopadantas.com