Simulating Changing Environments with Socio-Technical Modeling: An Air Combat Example

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ABSTRACT

Training people to work together and with automation requires simulations that model ever-changing environments. This paper explores a modeling approach and computational tool designed to capture and simulate socio-technical processes needed to train today's forces for changing conditions. Our approach models not only individual entity behaviors but also the processes and data that capture their interactions and inter-dependencies. For instance, training should not only model how denied communications or navigation can disrupt an individual, but also simulate and predict the adverse effects of coordination lapses on the systemic effectiveness of operators and their intelligent systems. Our approach is inspired by a U.S. government-developed agent-based modeling framework called Brahms, based on socio-cognitive theories of perception, inference, communication, and collaboration, that employs an activity-based approach to represent how functions are carried out in practice. While the models and data structures in Brahms are well-suited to our enhanced notion of simulation, Brahms' realtime performance is limited by a resource-heavy architecture inadequate for developing socio-technical models of complex, realistic tactical scenarios. In response, we developed Brahms-Lite, a simulation environment that encapsulates the Brahms model in a modern, supported, efficient and interoperable computational framework. We report on an implementation of Brahms-Lite recently applied in air-to-air combat scenarios to illustrate a broader interpretation of socio-technical systems. We report on third-party performance evaluations of the Brahms agents and conclude with a discussion of how this technique can be applied more broadly to extend simulations of complex environments under ever-changing conditions for building a better tomorrow.

ABOUT THE AUTHORS

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INTRODUCTION

Simulations of complex, highly-engineered human-system environments are invaluable tools for training people to work with each other and with automation. Today's warfighters use such simulations for training in information-rich, networked, automated battlespaces. But despite continuing improvements in simulations, modeling how people and technology (a "socio-technical system") behave under a variety of conditions requires new approaches. Several examples reinforce the notion that socio-technical processes are needed, not just as a backdrop for simulation, but as explicit factors in a scenario. Learning multi-aircraft air combat tactics (*e.g.*, in "2-v-2" scenarios) requires training in overcoming problems with communications and data disruptions. Learning to fight through these socio-technical lapses, whether benign or the result of hostile action, requires simulations that capture how intelligent systems work together under a range of conditions. And realistic adversary behaviors must be adaptive to the socio-technical context as the tactical dynamics change.

Our work explores a modeling approach and computational tool designed to represent socio-technical processes needed to train today's forces for changing conditions with realistic adversaries. Our approach models not only individual entity behaviors but also the processes and data that capture their interactions and inter-dependencies. This research builds on previous work that resulted in a U.S. government-developed agent-based modeling framework called Brahms, based on socio-cognitive theories of perception, inference, communication, and collaboration, that employs an activity-based approach to represent how functions are carried out in practice. While the models and data structures in Brahms are well-suited to our enhanced notion of simulation, Brahms' realtime performance is limited by a resource-heavy architecture inadequate for developing socio-technical models of complex, realistic tactical scenarios. In response, we developed Brahms-Lite, a simulation environment that encapsulates the Brahms model in a modern, supported, efficient and interoperable computational framework.

The remainder of this paper describes our current research that employs this simulation approach for realistic constructive adversaries. We report on an implementation of Brahms-Lite that we apply in air-to-air combat scenarios to illustrate a broader interpretation of socio-technical systems. We report on third-party performance evaluations of the Brahms-Lite agents and conclude with a discussion of how this technique can be applied more broadly to extend simulations of complex environments.

PROBLEM CONTEXT: AIR COMBAT SIMULATION AND THE NOT-SO-GRAND CHALLENGE

Since 2013, the U.S. Air Force Research Laboratory (AFRL) has been developing an air combat simulation testbed for intelligent constructive agents (Doyle, 2017). The motivation for this work is to replicate expertise in tactical flight (as embodied in human pilots flying adversary roles in tactical simulation) in intelligent agents, to overcome the cost and limited availability of expert pilots to role-play adversaries. Although simulations widely employ Computer Generated Forces (CGFs), these agents seldom have the capacity for adaptive tactics, and their predictability erodes their training value. The Not-So-Grand Challenge (NSGC) was established to develop lower cost, intelligent adversaries to expand access to and quality of training. Specifically, NSGC is creating synthetic adversary (Red air) pilots by engaging a team of seven industry partners to build agent models and test them in a Government-owned common demonstration environment. At the beginning of each annual cycle, new challenge scenarios are released, and are parameterized to generate a large space of combinations and to discourage purpose-built solutions. Each industry team then refines its models, and participates in a concluding evaluation that scores agent performance with both automated, objective metrics and subjective metrics generated by subject matter experts (SMEs).

NSGC is an ideal reference case for our agent modeling approach. The large space of possible scenarios exercises the agents' socio-technical framework, exposing the model to a rich variety of conditions. The blue air adversaries, while controlled by conventional CGFs, present sufficient behavioral dynamics to require anticipation and tactically-relevant responses. And the 2-v-2 scenarios require team communication and coordination, activities that our Brahms-inspired agents are well-suited to represent and execute.

SOCIO-TECHNICAL SIMULATION

A premise of this work is that a socio-technical approach to modeling enables constructive red air agents that respond to tactical dynamics with realism and variability. Socio-technical models represent chronological, located behaviors of people and automated systems. In contrast with task models, which represent abstractly what behaviors *accomplish* (Schön, 1987), a socio-technical model represents what people and systems *do*, as activities (Leont'ev, 1979; Clancey, 2002). Activities for air combat simulation can include monitoring (looking, attending), maneuvering, and communicating, each of which requires time and occurs in particular places with other people and systems (Suchman, 1987; Lave, 1988; Ehn, 1989; Wynn, 1991). A task model abstracts what a person or system achieves (e.g., "determine location"), while a socio-technical model represents how the activity is carried out in the world (e.g., simulate a pilot effecting a control input, changing the state of a control, perceiving a display's representation, and recognizing a problem). An activity framework enables modeling how knowledge and expertise of individual players and teams are applied in practice, which includes noticing and characterizing a situation as being problematic and defining goals and methods for handling the situation (Jordan, 1992; Clancey, Sierhuis, Damer & Brodsky, 2005).

SOCIO-TECHNICAL MODELING OF AIR COMBAT AGENTS

A tenet of our work is that socio-technical simulation is well-suited to modeling the combined effects of tactics, maneuvering, communications, weapons state, fuel state, and adversary behaviors. This approach seeks to properly relate people, technology, and processes into a coherent system of interactions. Models in this paradigm must be crafted to be general and adaptable, so they can be configured to simulate a large space of scenarios. The key to this generalizability and adaptability is our conception of activity.

Traditional cognitive models treat activity as operations for transforming information and world states. Our conception of activity includes this aspect, but casts it within a larger simulation of processes and physical interactions in which operations occur in the world. From a psychological perspective, activities are ongoing conceptions of "what I'm doing now" (Clancey, 1997); they encapsulate roles ("I'm the flight lead now" (Wenger, 1998)); norms ("what I should be doing now" (Lave & Wenger, 1991)); and progress appraisals ("how well I'm doing" Feltovich, *et al.*, 2008). Our approach is thus designed to simulate how an agent's activities are triggered, prioritized, interrupted, and resumed, as perception, inference, and communications modify the agent's concept of "what I should be doing now."

To accomplish this flexibility, people and technology (aircraft, weapons, sensors) are modeled as separate entities with their own internal behaviors. Different entities interact by communicating (*e.g.*, data transmission, voice communication), observing through sensory systems (*e.g.*, human perception, datalink), and direct manipulation (*e.g.*, flight controls). Our specific goal in this work is to create agents to operate in the NSGC testbed that model socio-technical factors and effects in order to respond to socio-technical actions and events. Such events can influence human-human teamwork as influencing interaction between an individual and an automation system.

BRAHMS-LITE: A DERIVATIVE SIMULATION FRAMEWORK

Our agent modeling environment is derived from a Government-owned framework called *Brahms* that was created to support design, implementation, testing, and integration of agents created in the socio-technical paradigm discussed above. Brahms adopts socio-technical modeling of perception, inference, communication, and collaboration, and employs an activity-based approach that represents how functions are carried out in practice (Clancey, Sierhuis, Damer, & Brodsky, 2005). Brahms agents reason about beliefs, desires, and intentions using *Thoughtframes*. Behaviors in Brahms agents are encapsulated in representations called *Activities* (describing what agents do) and *Workframes* (describing when activities are performed).

While the underlying process models and data structures in Brahms are well-suited to socio-technical approaches, the Brahms computational environment's realtime performance is limited by a resource-heavy architecture, which was functional for the purposes it was originally designed to fulfill but is inadequate for developing air combat agents in realistic tactical scenarios. To address this limitation, we developed Brahms-Lite, a modeling and simulation environment that encapsulates the Brahms model in a modern, supported, efficient and interoperable computational framework. Brahms-Lite preserves the activity-based theoretical construct and basic data structures and process models that power the legacy Brahms environment, as depicted schematically in Figure 1.

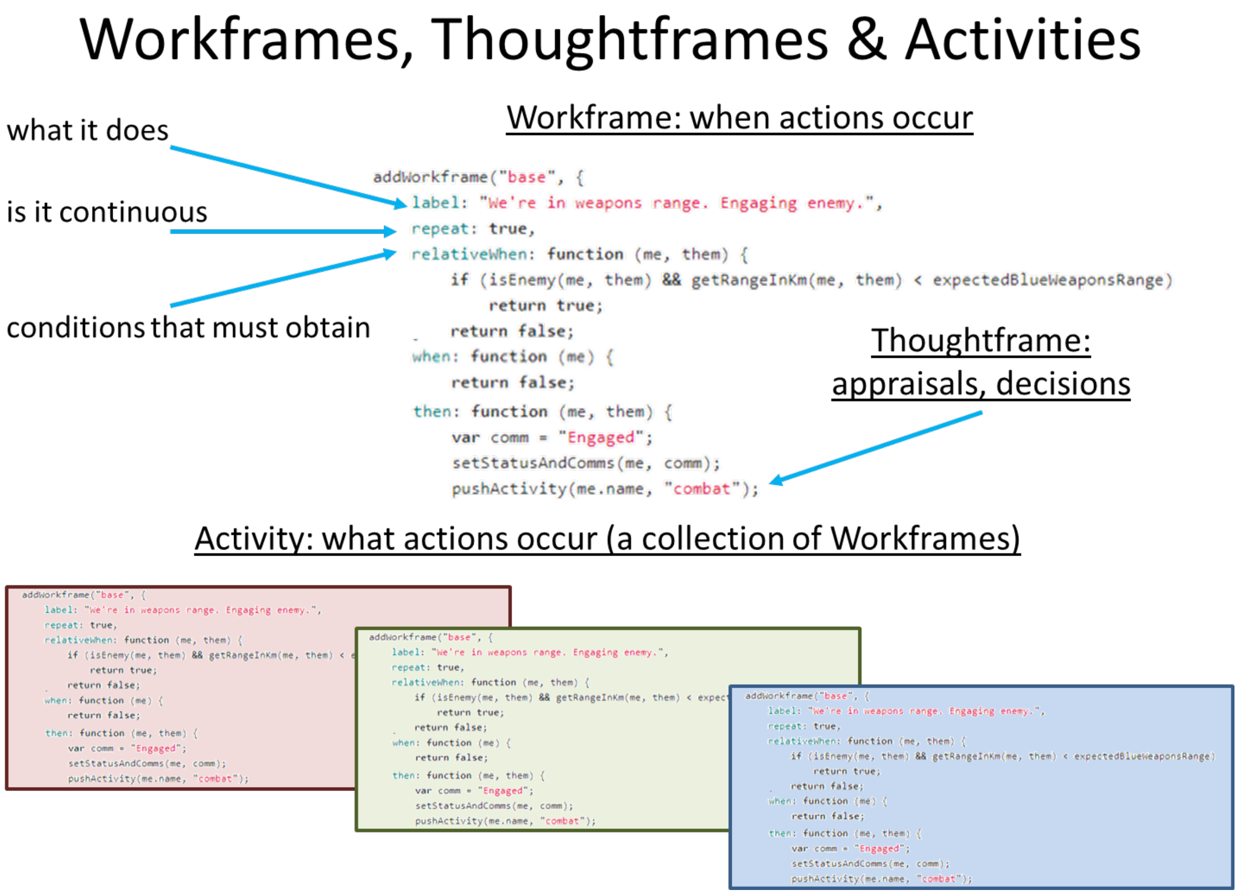

Figure 1. Brahms-Lite adoption of Brahms constructs: Workframes, Thoughtframes, and Activities.

To build a Brahms-Lite model, we start by identifying the critical phase(s) of an overall activity during which emergent interactions may occur and have a bearing on the intended purpose of the simulation, such as training, or developing tactics. Our methodology thus begins with developing a scenario to identify the players and properly contextualize the activities to be modeled. In the case of NSGC, the scenario is a hypothetical sequence of events depicting a 2-v-2 air engagement against U.S. Air Force tactical aircraft (since the models being developed for NSGC play the Red Air role). The scenario parametrically defines the players, locations, timelines, and in general terms, the sequence of events. Numerous scenarios can thus be generated from the baseline scenario by varying parameters like fuel states, weapon loadouts, initial positions, and adversary tactics. Once the scenario is specified, our process focuses on, in a general way, people, instruments, automated systems, aircraft, and other objects.

From the scenario, we develop the normative model using our socio-technical methodology and implement it in Brahms-Lite. Although derived from the baseline scenario, the model is not "hard wired," but rather a generalized domain blueprint that is variable depending on initial conditions and assumptions. The normative model also defines how tactical disadvantages and disruptions are represented and how the agents respond. The model permits numerous variables and conditions to be probabilistically varied to present a rich array of assumptions and to test their effects on mission outcomes.

CONSTRUCTIVE TRAINING

The Brahms-Lite agents are used to control synthetic entities that realistically respond in tactical air combat training simulations. To demonstrate this approach, we integrated the Brahms-Lite model with the NSGC testbed, a USAF environment developed to facilitate independent exercise and assessment of synthetic Red Air agents. We created a local development and testing environment that did not require access to the full NSGC testbed. Our development suite (Figure 2) provided the functionality we needed to exercise the agent models using NSGC scenarios.

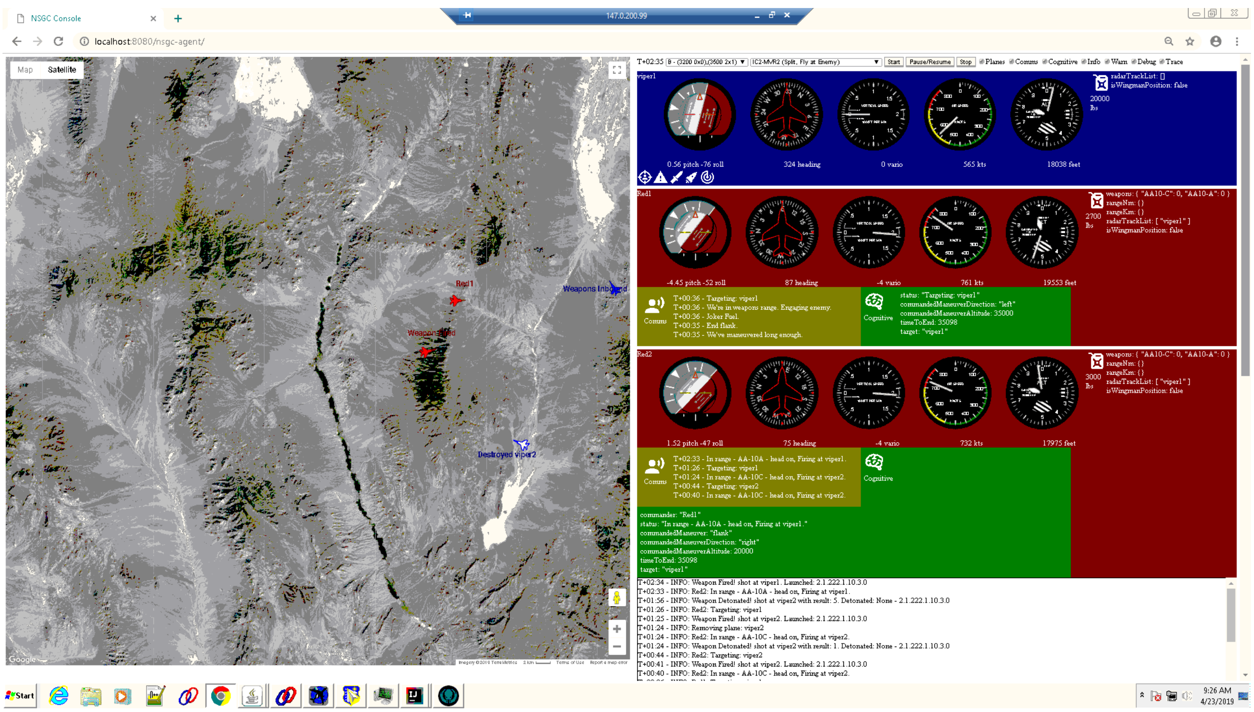

Figure 2. Brahms-Lite agent development and testing environment.

Eduworks' Brahms-Lite development environment consists of two principal components: (1) an executable agent built using Eduworks' Brahms-Lite agent modeling toolkit; (2) a web-based dashboard to initialize the agents, connect with the NSGC interoperability layer, and display a tactical view of the scenario. Scenario control is accomplished through a browser interface that enables a minimal configuration of the NSGC testbed to be run. When a scenario is started, the interface offers details about aircraft entity status as well as the decision-making processes and communications of the red air models. The dashboard presents a tactical map and individual panels revealing system status. The display shows real-time output from the agents, revealing both the communications between Red-1 and Red-2, and the "cognition" process displayed as serial statements explaining agent behavior (Figure 3).

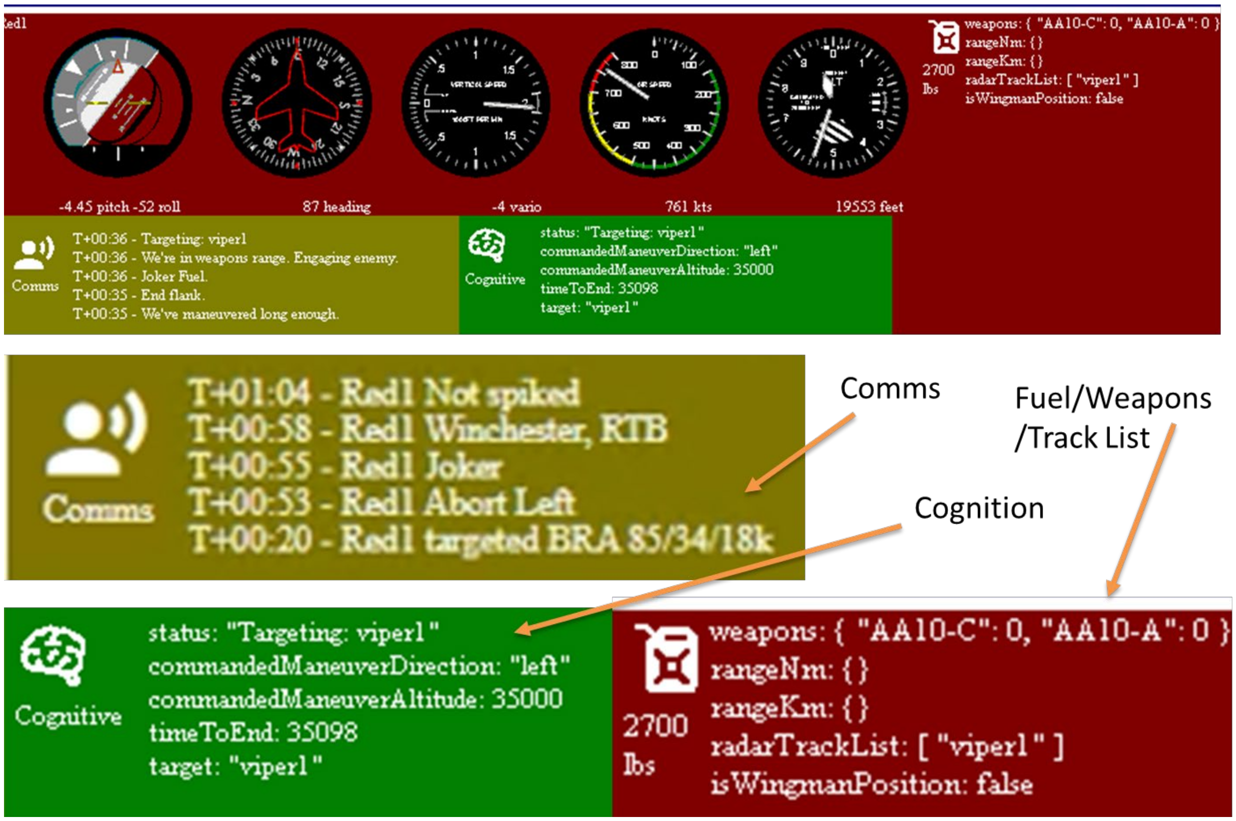

Figure 3. Brahms-Lite environment showing communications and cognition panel detail.

We integrated Brahms-Lite into the NSGC testbed, so that the Brahms-Lite engine controlled the synthetic Red Air models tracked, displayed, and recorded in the testbed (Figure 4).

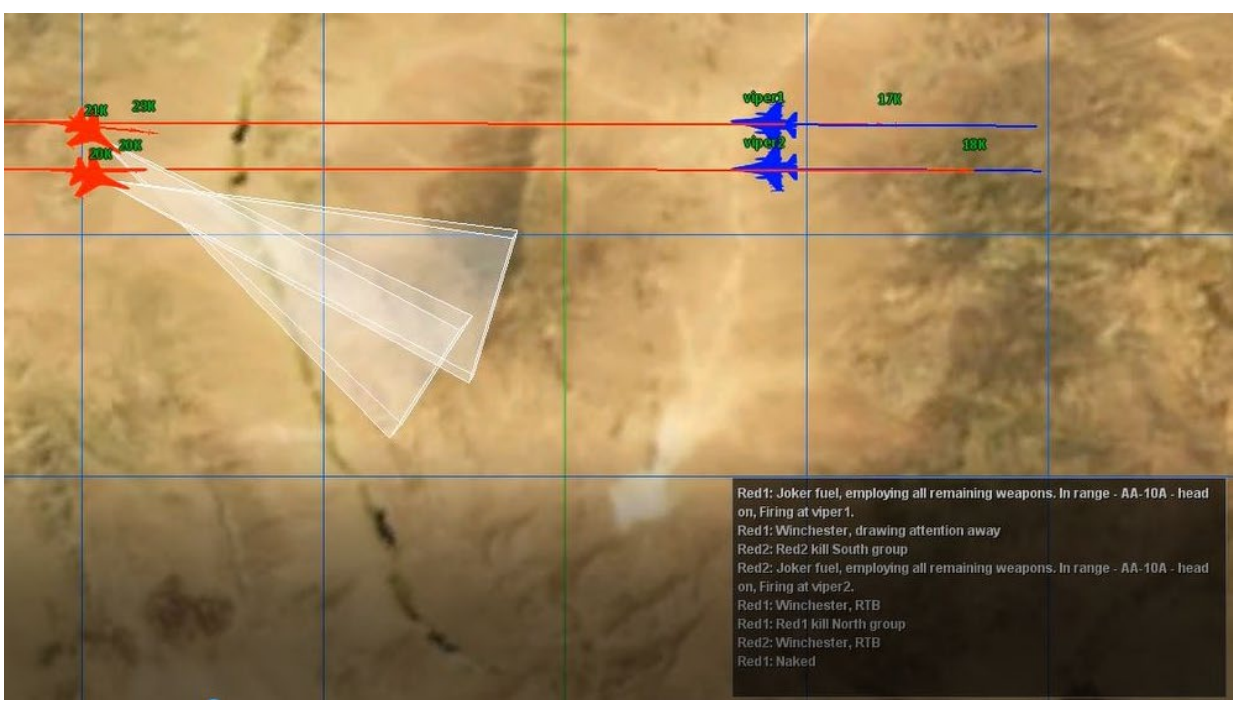

Figure 4. Brahms-Lite-controlled synthetic Red Air integrated with NSGC testbed.

MODEL PERFOMANCE EVALUATION

The Brahms-Lite agents were subjected to a series of assessments conducted by the NSGC project, in which models from across seven industry participants each executed the same two scenarios (from a library of 72). SMEs and program leaders analyzed the recorded scenarios and performed a systematic assessment and comparison of agents. This assessment integrated automated metrics with SME subjective scoring to derive measures for each agent.

The automated, objective measures are generated the Performance Evaluation and Tracking System (PETS), which records Blue kills, Red losses, fratricide, formation deconfliction, and frequency and duration of incursions into Blue Air's minimum abort range (MAR). The SMEs focus on subjective, tactical process measures to include the quality of intercept geometry, adherence to contract, split decision, deconfliction, spike awareness, post-merge maneuver, fuel management, weapons management, and element targeting/sorting. These experts also assess the overall tactical intelligence of the agent and its reported explanations of its decisions and actions.

For the 2019 evaluations, agent performance was evaluated across nine dimensions (Freeman, Watz, & Bennett, 2019). This evaluation was not intended to rank the agents; the principal finding was that the NSGC testbed is effective for accelerating agent development and model realism across multiple agent architectures. However the Brahms-Lite model achieved the highest overall score and the highest categorical scores in 7 of the 9 dimensions (Table 1).

Table 1. Comparison of agent performance measures compiled for 2019 evaluation cycle.

Agent	Effects	Process	Tactical Intelligence	Explanation of Decisions
a	1.0	2.1	1.3	2.8
b	3.2	2.0	2.0	2.5
c	1.3	1.3	0.3	0.8
Brahms-Lite	**4.0**	**3.2**	**2.5**	**3.1**
f	3.3	0.7	1.0	0.0
g	0.5	0.7	0.2	0.0

The columns labelled "Effects" and "Process" reflect composite scores derived from SME-generated ratings and metrics generated automatically by PETS. The columns labelled "Tactical Intelligence" and "Explanation of Decisions" are averages of binary ratings (0, 1) over two SME raters over two scenarios for each evaluation cycle.

This process was repeated in 2020, with new scenarios and tactical parameters (Freeman, Watz, & Bennett, 2020). The Brahms-Lite model again achieved the highest evaluation from SMEs for tactical intelligence and decision explanations, and in the measure of effects (kill ratio) (Table 2).

Table 2. Comparison of agent performance measures compiled for 2020 evaluation cycle.

Agent	Effects	Process	Tactical Intelligence	Explanation of Decisions
1	1.0	1.7	1.0	1.0
2	3.5	3.5	2.8	3.0
3	3.5	2.8	2.3	3.0
Brahms-Lite	**4.0**	**3.0**	**3.3**	**3.0**
5	1.0	2.0	1.0	1.0
6	2.0	1.5	1.3	1.5
7	4.0	3.5	3.0	2.0

CONCLUSIONS AND FUTURE WORK

The NSGC project is intended to create more realistic, tactically dynamic synthetic Red Air constructive adversaries. The testbed accommodates experimentation with agents from multiple architectures and design paradigms. The results reported here validate the utility of Brahms-Lite and the socio-technical modeling approach we employ. Pilots are part of a socio-technical system, where people and agents are inherently part of a network of operations during air combat sorties that require considerable interaction within and across aircraft and remotely with people and agents on the ground. The socio-technical paradigm we adopt can capture and thus enrich a simulation with factors not generally accommodated by most modeling approaches. A circumstantial combination of events can lead to unanticipated interactions, and by simulating people and technology as independent processes in a simulated world, emergent effects are revealed. This work, in concert with related research contributing complementary capabilities under the NSGC program, will thus accelerate the development of a robust Red Air agents for realistic constructive training.

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