Simulating Cognitive Complexity in Work Systems

William J. Clancey (wclancey@IHMC.US)
Florida Institute for Human and Machine Cognition, 40 S. Alcaniz Street
Pensacola, FL 53706 USA

Abstract

The Brahms Generalized Überlingen Model (Brahms-GÜM) is a cognitive-behavioral simulation of aviation work practices that reveals how normally complicated situations become cognitively complex for people in a dynamic environment of malfunctioning tools and non-routine workload. Brahms-GÜM was developed by analyzing and generalizing the roles, systems, and events leading to an aircraft collision, a scenario that can be simulated as a particular configuration of the model. Brahms-GÜM demonstrates the strength of the Brahms framework for simulating behaviors of asynchronous (or loosely coupled), distributed processes in which the sequence of spatial-temporal interactions can become mutually constrained and unpredictable.

Keywords: Work practice; cognitive process model; behavioral simulation; situated cognition; complex systems.

The Brahms Generalized Überlingen Model (Brahms-GÜM; Clancey et al. 2013) was developed as part of ongoing aviation safety research to extend human-system performance modeling from the individual level (one user, one task, one display) to the level of multi-agent teams (a choreography of people and automated systems). In particular, the research theme of "authority and autonomy" focuses on how roles and responsibilities are distributed and reassigned among people and automated systems to handle routine tasks (e.g., autopilot modes) or resolve dangerous situations (e.g., collision avoidance alerts).

Brahms is a multi-agent simulation system in which people, tools, facilities/vehicles, and geography are modeled explicitly (Clancey et al. 1998; 2005). In Brahms-GÜM the air transportation system is modeled as a collection of distributed, interactive subsystems (e.g., airports, air-traffic control towers and personnel, aircraft, automated flight systems and air-traffic tools, instruments, crew). Each subsystem, whether a person, such as an air traffic controller, or a tool, such as the Air Traffic Control Center (ATCC) radar, is modeled independently with properties/states, beliefs/models, and contextual behaviors. The simulation then plays out the interactions among these separately existing models of subsystems.

The 2002 Überlingen mid-air collision was chosen for this experiment using Brahms because systems like the Traffic Alert and Collision Avoidance System (TCAS) deliberately shift authority from the air-traffic controller to an automated system. The Überlingen accident provides a starting point for exploring authority–autonomy conflict in the larger system of organization, tools, and habitual behaviors (practices) that contextually affects attention, deliberation, and action (Clancey 1997). In particular, a person/system can have more than one role at a given time, and responsibilities can be reassigned during operations in a situation-dependent manner. For example, we can simulate that when an air traffic controller (ATCO) goes on a break, as occurred at Überlingen, another ATCO shifts to handling multiple workstations. Simulated pilots and ATCOs also have context-dependent behaviors for communicating, following directions, and interacting with automated systems.

A work practice simulation represents chronological, located behaviors of people and automated systems. In contrast with task models, which represent abstractly what behaviors accomplish (i.e., functions), a *behavioral model* represents what people and systems do, called *activities* (Clancey 2002). Activities include monitoring (looking, attending), moving, communicating, reading and writing, all of which require time and occur in particular places with other people, tools, materials, documents, and so on. In terms of work, a function/task model characterizes what a person or system does (e.g., "determine the altitude"), and a cognitive-behavioral model of practice represents how the work is carried out in the world (e.g., simulate a person moving, changing the state of a control, perceiving a display's representation, and inferring a problem exists).

The simulation is based on a fine-grained analysis of the published events of the Überlingen collision, relating spatial and temporal interactions of: 1) information represented on displays and documents at the air traffic control center and in the cockpit, 2) what controller(s) and cockpit crew were individually doing and observing, 3) alerts provided by automated systems, 4) communications within the cockpit and with air traffic control, 4) control actions to change automation and aircraft flight systems, 5) people's beliefs and reasoning regarding responsibilities of individuals and automated systems, progress appraisal of assigned responsibilities, and resolution of conflicting information/directives.

The Überlingen case is of special interest because TCAS gave advice to one flight crew just seconds after they had already begun to follow a different directive from the Zurich air traffic controller. Psychological, social, and physical coordination issues are potentially involved in disengaging from an action in process that may make it difficult or impossible to follow the required protocol of following TCAS and ignoring the ATCO.

The Brahms simulation model constructed in this research is not merely a replication of the Überlingen collision, that is, a hand-crafted, single scenario of events. Rather Brahms-GÜM consists of a *generalization* of all the subsystems (e.g., phones, radar, alert systems, aircraft, pilots, air-traffic

controllers, ATCCs) that played a role in the Überlingen collision. Rather than only representing the states and behaviors of subsystems at the time of the collision, Brahms-GÜM represents their normal states and behaviors, and allows for them to be configured for each simulation run to characterize alternative behaviors, including absent, alternative, and dysfunctional or off-nominal forms (e.g., a pilot can follow TCAS or ignore it; the phones in an ATCC are not operating; a scheduled flight departs late).

Each of the many possible configurations of Brahms-GÜM parameters defines a scenario. Because of the variations in initial facts, beliefs, and properties/states and the probabilistic activity durations, each simulation run produces time-space-state interactions with potentially different outcomes. For example, in some configurations of Brahms-GÜM, the Zurich ATCO notices the imminent collision and advises pilots before TCAS issues a traffic advisory. The combinations of all possible parameter settings define a space of scenarios that Brahms-GÜM should be able to validly simulate. What occurred at Überlingen is one scenario in that space.

Experimentation with Brahms-GÜM reveals that timing of events at the level of a few seconds makes a substantial difference in the simulated outcomes. In particular, because TCAS's advice does not consider what the people are saying and deciding among themselves, the work system design is especially vulnerable if ATCO intervenes with pilots a few seconds before TCAS generates a resolution advisory, which is what happened at Überlingen.

We had not encountered such sensitivity to timing and emergent interaction sequences in any of the prior Brahms models created over two decades. Brahms-GÜM simulates how subtle issues of timing in human-automation interactions arise when degraded or missing subsystems result in lack of information and inability to communicate, transforming a given configuration of flights that are routine in a normal work system to a situation too complex for the overall work system to handle safely.

In particular, the events in the air traffic control center reveal how after people develop work practices in which they rely on automation (e.g., a collision warning alert), the absence of automation may cause the workload to increase and the evolving situations to become too causally co-dependent to appropriately prioritize tasks or delegate responsibility. That is, the workload has become *cognitively complex* relative to the person's knowledge, beliefs, roles, habitual procedures, and tools. Specifically, ATCO was required to conceptually coordinate multiple recursively nested action sequences that were interrupted, analogous to limitations in natural language comprehension (Clancey 1999; 2005; 2006).

Brahms-GÜM demonstrates the strength of the framework for simulating behaviors of asynchronous (or loosely coupled), distributed processes in which the sequence of interactions can become mutually constrained and unpredictable. Creating and experimenting with work practice models reveals interactions that are omitted, glossed over, or difficult to comprehensively describe in accident reports. The simulation generates metrics that can be compared to observational data and/or make predictions for redesign experiments.

Acknowledgments

This project was supported (October 2011 to June 2013) by the Authority and Autonomy task within the Aviation Safety Program of the System-Wide Safety and Assurance Technologies Project of NASA's Aeronautics Research Mission Directorate, when the author was on assignment at NASA Ames Research Center. Co-developers of Brahms-GÜM included Charlotte Linde, Mike Shafto, and Chin Seah. Extensive references appear in Clancey et al. (2013).

References

Clancey, W. J. (1997). *Situated Cognition: On Human Knowledge and Computer Representations*. NY: Cambridge University Press.

Clancey, W. J. (1999). *Conceptual Coordination: How the Mind Orders Experience in Time*. Hillsdale, NJ: Lawrence Erlbaum.

Clancey, W. J. (2002). Simulating Activities: Relating motives, deliberation, and attentive coordination, *Cognitive Systems Research*, *3*(3), 471-499.

Clancey, W. J. (2004). Roles for agent assistants in field science: Personal projects and collaboration. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, *34*(2), 125-137.

Clancey, W. J. (2005). Modeling the perceptual component of conceptual learning—a coordination perspective. In P. Gärdenfors and P. Johansson (Eds.), *Cognition, Education and Communication Technology*. Mahwah, NJ: Lawrence Erlbaum Associates.

Clancey, W. J. (2006). How anchors allow reusing categories in neural composition of sentences. Commentary on F. van der Velde and M. de Kamp: Neural blackboard architectures of combinatorial structures in cognition. *Behavioral and Brain Sciences, 29*(1), 73-74.

Clancey, W. J. (2008). Scientific antecedents of situated cognition. In P. Robbins and M. Aydede (Eds.), *Cambridge Handbook of Situated Cognition*. New York: Cambridge University Press.

Clancey, W. J., Linde, C., Seah, C., & Shafto, M. (2013). *Work Practice Simulation of Complex Human-Automation Systems in Safety Critical Situations: The Brahms Generalized Überlingen Model* (Tech. Publ. 2013-216508). Washington, D. C.: NASA.

Clancey, W. J., Sachs, P., Sierhuis, M., & van Hoof, R. (1998). Brahms: Simulating practice for work systems design. *Int. J. Human-Computer Studies, 49*, 831-865.

Clancey, W. J., Sierhuis, M., Damer, B., & Brodsky, B. (2005). Cognitive modeling of social behaviors. In R. Sun (Ed.), *Cognition and Multi-Agent Interaction: From Cognitive Modeling to Social Simulation*. New York: Cambridge University Press.