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SYNTHETIC TEAMMATE COMMUNICATION AND COORDINATION WITH HUMANS

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A synthetic teammate based on ACT-R cognitive architecture has been developed to function as an Air Vehicle Operator in the context of a three-agent Unmanned Aerial Vehicle (UAV) ground control team taking part in studies in a Synthetic Task Environment (STE). In order for the synthetic teammate to function as team player with human teammates, it needs to skillfully handle the subtleties of team communication and coordination. Data from early synthetic teammate interactions with two human teammates are presented here to illustrate team communication and coordination challenges for the synthetic teammate. In turn, the synthetic teammate limitations have highlighted the intricacies involved in effective teamwork. Communication, though a terrifically challenging problem in itself, is only a foundation for coordinated teamwork or interacting as a team player.

INTRODUCTION

Teams are important for tasks with high cognitive complexity. They have been defined as heterogeneous and interdependent groups of individuals who adaptively interact (i.e., coordinate and communicate) to reach a common goal (Salas, Dickinson, Converse, & Tannenbaum, 1992). Teams have to effectively coordinate their activities in order accomplish their tasks. Therefore, team coordination is especially useful in strategically important industries: from interdisciplinary scientific institutions to medical care to military command-control. For instance, a heterogeneous surgical team that has highly trained team members (e.g., chief, assistant surgeon, anesthesiologist, and scrub nurses) needs to interact effectively as a coordinated unit. Teams also need to be able to adjust their coordination in order to meet with high environmental variances. In addition to coordinating effectively during routine procedures in the operating room, the surgical team needs to adjust coordination based on the patient conditions and team goal. Thus, team coordination involves both the dynamics of team member interaction and the environmental dynamics to which the team is subjected (Gorman, Amazeen, & Cooke, 2010).

Technological innovations have allowed teams to incorporate highly automated systems (e.g., synthetic teammates, robots) to replace human teammates. However, using automation, i.e., a synthetic teammate, to fill the role of a human teammate has proved to be extremely challenging (Klein, Woods, Bradshaw, Hoffman, & Feltovich, 2004). In order for synthetic teammates to function as team players with their human teammates, they need to finesse team communication and coordination. This paper highlights team communication and coordination challenges in the context of a project that is integrating a synthetic teammate into a team with two humans. During the last decade, a large project in collaboration with government entities has sought to develop a human-like agent serving as a fully-fledged synthetic teammate. In this project, the synthetic teammate is part of a three-agent Unmanned Aerial Vehicle (UAV) ground control team taking part in studies in a Synthetic Task Environment (STE). The core of this system is the ACT-R cognitive architecture (Anderson, 2007). The use of ACT-R pushes the system's development in cognitively plausible directions that are more likely to lead to human-like behavior (Ball et al., 2010; Cooke, Gorman, Myers, & Duran, 2013)

In the UAV STE task, well-coordinated information sharing among the team members in an adaptive and timely manner is vital for team effectiveness. The synthetic teammate is being evaluated to see how well it succeeds in communicating and coordinating with human teammates.

In some preliminary tests of the synthetic teammate we have observed examples of good and bad communication and coordination that highlight the challenges faced in developing synthetic teammates that are good team players.

We present these examples and conclude by providing lessons learned regarding effective interaction that includes *both* communication *and* coordination.

TEAM DYNAMICS IN A UNMANNED AERIALVEHICLE – SYNTHETIC TASK ENVIRONMENT

The Cognitive Engineering Research on Team Tasks Unmanned Aerial System Synthetic Task Environment, or CERTT-UAV-STE, provides the context for this study (Cooke & Shope, 2004). An updated version of the CERTT-UAV-STE, CERTT-II, will be used to simulate teamwork aspects of UAV operations. CERT-II hardware includes the following features to support the current study: 1) text chat capability for communications between human teammates and the synthetic teammate; and 2) eight hardware consoles: four consoles for teammates and four for experimenters (Cooke, 2013).

The UAV-STE involves three heterogeneous and interdependent teammates, each of which has a different task role in taking good photos for critical waypoints. More specifically, the teammates are: Air Vehicle Operator (AVO or pilot) who controls the UAV in regard to heading, altitude, and airspeed; Data Exploitation, Mission Planning, and Communications (DEMPC or mission planner) who provides a dynamic flight plan and also speed and altitude restrictions; and Payload Operator (PLO) who monitors sensor equipment, negotiates with the AVO, and takes photographs of target waypoints (Cooke & Shope, 2004).

In the UAV-STE teams coordinate during the missions at target waypoints by sending and receiving normative information (Cooke, Gorman, Duran, & Taylor, 2007). These coordination events are of three types: "Information" (I), the DEMPC provides information about upcoming target waypoint information to the AVO; "Negotiation" (N), a negotiation occurs between the PLO and the AVO regarding an appropriate altitude and airspeed for the target's required camera settings; and "Feedback" (F), the PLO provides feedback about the status of the target photo.

The coordination events (collectively referred to as "INF") will be used for a dynamical systems analysis of team coordination, which will take into account both the dynamics of team member interaction and the environment to which teams are subjected (Cooke & Gorman, 2009; Gorman et al., 2010).

The Synthetic Teammate

The key research question that we are attempting to answer in the development of the synthetic teammate is how much functionality is required to allow human teammates to successfully perform their individual and team tasks, in order for the team as a whole to improve across missions, in collaboration with a synthetic teammate. We have adopted a research approach that focuses on building a synthetic teammate that is human-like in its behavior, so that team improvement will generalize to situations involving all human teams. To achieve human-like behavior, we have chosen to leverage the ACT-R Cognitive Architecture (Anderson, 2007). ACT-R is a theory of human cognition implemented as a computer program. ACT-R combines a declarative memory representing knowledge of facts with a procedural memory representing skilled behavior. ACT-R also provides perceptual-motor mechanisms for interacting with a computer monitor, keyboard, and mouse. ACT-R is designed to support the research and development of high-fidelity computational cognitive models of human behavior.

Within ACT-R, we have implemented and integrated five key components, which together constitute the synthetic teammate. The key components of the synthetic teammate include: 1) language analysis, 2) language generation, 3) dialog modeling, 4) situation modeling, & 5) agent-environment interaction.

For language analysis, we are using the Double-R Grammar (Ball, 2011). Double-R Grammar is a linguistic theory of the grammatical encoding of referential and relational meaning implemented as a large-scale cognitive model in ACT-R. Double-R has been under research and development over the past 11 years. The other components of the synthetic teammate have been under research and development for the past 4 to 7 years. To represent the synthetic teammate's situation and task awareness, we are developing a situation model (Rodgers, Myers, Ball, & Freiman, 2012). The situation model receives input from the language analysis and agent-environment interaction components (Myers, 2009). The agent-environment interaction component implements the task behavior of the synthetic teammate, interacting with the CERTT-simulated task environment to fly a remotely piloted aircraft. The language generation component generates messages, which are sent to human teammates. Basic dialog management capabilities have also been implemented.

The focus on building a large-scale, functional model differentiates the research from typical cognitive modeling research. The synthetic teammate is one of the largest cognitive models ever built. Overall, the synthetic teammate consists of more than 1,500 production rules to implement skilled behavior and 58,000 facts to represent declarative knowledge.

The focus on cognitive plausibility, or human-like behavior, differentiates the research from typical AI research. We are attempting to demonstrate that adhering to well-established cognitive constraints may facilitate development of functional systems of complex human behavior. Such constraints may prove functional in that they guide research in directions that will ultimately lead to human-like behavior. For training purposes, it is essential that the synthetic teammate act like a human, not an intelligent agent. A synthetic teammate which failed to model human capabilities and limitations would reduce the training benefit to human teammates.

Development of the synthetic teammate has been guided by the results of two previous all human studies (Cooke et al., 2013; Demir & Cooke, 2014). In these studies, a text chat corpus of 15,000 messages was collected. These messages were analyzed to identify the recurring patterns, and the synthetic teammate was developed to be able to process the most frequently occurring patterns.

Analysis of the text chat corpus reveals (Cooke, Myers, & Rajivan, in press) that human teams settle on particular ways of conveying information, negotiating aircraft parameters and providing feedback. However, the particular message patterns that become entrenched across missions differ from team to team. Given this, it is not possible to determine in advance what patterns will emerge in mixed teams which include a synthetic teammate. On the other hand, it is not possible to develop a synthetic teammate that is as flexible as human teammates in its ability to accommodate to messages from other teammates. The synthetic teammate will necessarily constrain the range of interactions with human teammates. If human teammates are to succeed in this team task, they will need to accommodate to the capabilities of the synthetic teammate. This means that the use of highly cryptic or esoteric messages, which often emerge across missions in all human teams, will likely degrade team performance, since the ability of the synthetic teammate to handle such messages is limited. An important research question is the extent to which the use of highly cryptic messages reflects improving team performance. Will mixed teams be as successful as all human teams without resorting to highly cryptic messages? In other words, will mixed teams succeed in accommodating to the communication capabilities of the synthetic teammate?

The synthetic teammate has been integrated with CERTT-II UAV and is currently undergoing testing and debugging in preparation for a study of the effects of a synthetic teammate on communication and coordination with human teammates, compared to all human teams. During the process of integrating and testing the synthetic teammate, several types of communication and coordination issues have been identified. These issues and other challenges are reported in the following section.

THE SYNTHETIC TEAMMATE IN ACTION

For testing and debugging, confederate human teammates have been interacting with the synthetic teammate across 20+ missions. These confederate teammates have been instructed on the limitations of the synthetic teammate's communications. Overall individual and team performance has been improving across missions as the capabilities of the synthetic teammate have improved. More recently, we have started to use naïve subjects for testing. These naïve subjects have been given instructions on effective communication (e.g. avoid highly cryptic messages, convey the needed information in a single message), but have not otherwise been coached. The use of naïve subjects has revealed additional challenges in effective communication with the synthetic teammate. At this point, a key research question is how much instruction (or coaching) is needed to insure that human teammates will be able to communicate well enough with the synthetic teammate so that it becomes possible to study coordination. If communication breaks down completely, or nearly so, then our ability to study coordination will be negatively impacted.

In the current study, team member interaction between the synthetic teammate and human teammates occurs over text chat. Effective interaction among the synthetic teammate and the other team members is based on effective communication—i.e., clear messages that are not ambiguous or cryptic. In this study, the DEMPC and the PLO send text-based (chat) messages to the synthetic teammate based on their role and task demands. As previously noted, communication and coordination are two of the most challenging aspects in integrating a synthetic team with human teammates. Below we detail specific examples of good and bad communication and coordination on the part of the synthetic teammate in this context and comment on the impact on teamwork.

Communication with the Synthetic Teammate: The Good & Bad

The DEMPC is in charge of sending all of the waypoint information, such as: type of waypoint (i.e., target, entry, or exit), effective radius, and airspeed and altitude restrictions to the AVO (synthetic teammate). In the following example of good communication, the DEMPC identifies the waypoint name, waypoint type, airspeed restriction, altitude restriction, and, finally, the effective radius to the AVO. For instance: "*The next waypoint is F-Area. It is a target. The airspeed restriction is from 180 to 200 knots. There is no altitude restriction. The effective radius is 5 miles*".

In this case, each piece of information is required by the AVO to complete its task. Therefore, the best form of communication is to include all of this information in one single message.

The PLO requests appropriate speed and altitude restrictions for the target's required camera settings, and also provides feedback about the status of the target photo. For each target waypoint, the PLO needs to communicate the name of the waypoint and the restrictions for required camera settings such as: "*Raise altitude above 3000 feet for F-Area*".

If the text sent to the AVO by the DEMPC or the PLO is highly cryptic, esoteric language or misspelled, then the AVO will not understand due to the limitations of the model supporting the synthetic teammate.

As opposed to human teammates, the AVO does not send misspelled messages or use highly cryptic (or esoteric) language. It sends clear messages. However, the synthetic teammate may have comprehension problems which affect team coordination and, in turn, team performance. For instance, after getting the information about the target waypoint from the DEMPC, if the AVO does not let the PLO know about target airspeed and altitude, then it is possible for the PLO to fail to take a photo of the target waypoint, because the communication did not happen in a timely manner (see Table 2).

Communication quality has a direct impact on team performance. If information is given to the AVO in the wrong way, it will take more time for the synthetic teammate to understand the current situation, or the synthetic teammate might not understand at all. A potential result of poor communication with the synthetic teammate will be the aircraft either circling around the current waypoint or flying in a random direction. Also, in this task coordination relies directly on communication and therefore when communication fails, team performance is adversely affected. If the information is given to the AVO in the correct way, this will create more stable communication, resulting in effective team performance.

Coordination with the Synthetic Teammate: The Good & Bad

An ideal model of coordination in the UAV-STE team would consist of the AVO ensuring timely and adaptive passing of Information, Negotiation, and Feedback (INF) at target waypoints via textual chat communications with the PLO and DEMPC (see Figure 1). In this procedural model of coordination, at each target the following optimal coordination sequence should occur: 1) the DEMPC provides information about the target waypoint to the AVO; 2) a negotiation occurs between the PLO and the AVO regarding an appropriate altitude and airspeed for the target waypoint's required camera settings; and, 3) the PLO provides feedback to the AVO and the DEMPC about the status of the target photo.

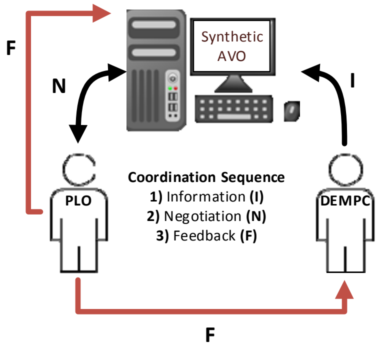

Figure 1. Optimal Coordination Sequence (INF).

It is important to have effective coordination among the team members in order to have good team performance. Table 1 is an example of good coordination among the team members. The effective coordination events (i.e., INF) happen in a timely and adaptively manner. The table includes coordination events among the synthetic teammate and two human teammates. It can be seen that, generally, information (I) about the waypoints is sent to the AVO by the DEMPC a couple of minutes prior to negotiation. After moving to the waypoint, the AVO determines and sends target altitude and airspeed for the current waypoint to the PLO. Under Negotiation (N), there is an altitude request from the PLO for the current waypoint. Based on the PLO's request, the AVO resets the altitude and informs the PLO. In this way, the negotiation happens for the current target waypoint in terms of altitude restrictions. After taking a good photo, the PLO provides feedback to the other team members. Therefore, Table 1 shows a clear example of how a structured coordination among the team members in a timely and adaptive manner needs to be done.

INF	Interaction between the Three Roles
I	**From DEMPC to AVO (Sent Time: 13 min):** ➢ The next waypoint is M-STE. It is a target. The speed restrictions are from 350 to 400. The altitude restrictions are from 1000 to 5000. The radius is 5.
N	**From AVO to PLO (Sent Time: 17:46 min):** ➢ The target altitude for M-STE is 3200. **From PLO to AVO (Sent Time: 18.25min):** ➢ Decrease altitude to below 3000 for M-STE. **From AVO to PLO (18:41min):** ➢ Resetting altitude to 3000.
F	**From PLO to AVO and DEMPC (19:39min):** ➢ Good photo. Let's go.

Table 1. Coordination between Synthetic Teammate and Human Teammates

However, this ideal example of coordination does not always occur in practice. Sometimes the roles do not communicate with each other in a timely and adaptive manner or adjust the restrictions on time. Ineffective coordination or no interaction among the team members is likely to have negative impacts on team performance. For instance, Table 2 below shows lack of communication between the AVO and the PLO, and in turn, poor coordination. The DEMPC sends the information about the next waypoint (in this case the target waypoint is called M-STE on the mission map) to the AVO. After moving this target waypoint, the AVO (i.e., the synthetic teammate) does not provide the determined target airspeed and altitude restrictions to the PLO, and also the PLO does not request the target altitude for the required zoom settings in a timely manner. When the PLO requests the required altitude restriction, it is too late to take a photo of the target waypoint, and therefore, the PLO does not provide feedback to the AVO and the DEMPC. Because the synthetic teammate failed to communicate the altitude and speed restrictions to the AVO, the team failed to coordinate and failed to get a good photo at that target. This example illustrates that the challenges faced by the synthetic teammate development surpass language production and comprehension and also require that language be properly timed and sequenced.

INF	Interaction
I	**From DEMPC to AVO (Sent Time: 43:55 min):** ➢ The next waypoint is M-STE. It is a target. The altitude restrictions are from 2000 to 5000. The speed restrictions are from 300 to 400. The radius is 5.
N	**From AVO to PLO (Sent Time: 34:42 min):** ➢ Do we have a photo of m-ste? **From PLO to DEMPC (Sent Time: 36:35 min):** ➢ No we don't have a good photo. ➢ Lower the altitude for m-ste below 3000. **From AVO to PLO:** *AVO didn't change the altitude because of late altitude request from the PLO.*
F	**From PLO to AVO and DEMPC:** *No feedback, because the PLO couldn't take a photo, and the AVO moved to next waypoint.*

Table 2. Poor Coordination

Ideal coordination events depend on good communication between the synthetic teammate and human teammates. These examples illustrate the importance of both communication and coordination on the part of the synthetic for effective team performance.

CONCLUSION

Recently, our research team has worked towards the development of a synthetic teammate as a functional team player who interacts accurately and appropriately with real human team members. In this paper, we explain the overall development of the synthetic teammate.

The development of a human-like synthetic teammate is extremely challenging. The commitment to adhering to cognitive constraints in the development of the synthetic teammate has had mixed results. The development of the language analysis and agent-environment interaction components benefited from this research approach. It is less clear that the other components of the system benefited as well. In addition, although we succeeded in creating a broad, general purpose language analysis capability that also handles the most frequent domain specific messages, the other components of the system are predominately domain specific and limited in their capabilities. Overall, the behavior of the synthetic teammate reflects the capability of the less well developed components. In particular, the language generation and dialog modeling components have received less emphasis than the other components due to resource constraints.

Specifically, the needs for the synthetic teammate to be able to both adequately *communicate* and *coordinate* with its human team members are apparent. Through our research with the synthetic teammate, we have learned that both of these aspects of interaction are critical to the success of the overall team interaction. As evidenced by the data in this paper, poor forms of both communication and coordination can result in failed missions. In regards to communication, failures to understand the context and use the right language have often been detrimental to the synthetic teammate's success, resulting in mixed results. Yet, while most synthetic agent work traditionally focuses on language and communication, one of our biggest lessons learned is the equal importance of coordination within the overall interaction between and among synthetic and human team members. The coordination- when communication occurs- has a profound impact on both communication and the entire interaction. If the correct communication is sent, yet it is sent to early or late, the overall meaning of the communication is lost. Therefore, when developing synthetic agents that will be in concert with humans, it is paramount that designers account for *what* (communication), *when* (coordination), and *how* (communication and coordination). The synthetic teammate project has highlighted the intricacies involved in good teamwork. Communication, though a terrifically challenging problem in itself, is only a foundation for coordinated teamwork or interacting as a team player.

Current and future work is focused on additional experimentation with the synthetic teammate. Furthermore, through more experimentation, additional insights and examples of synthetic teammate failures should highlight the necessary additional requirements needed for effective teamwork.

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