Barriers to Robust and Effective Human-Agent Teamwork

Fei Gao, M. L. Cummings
Massachusetts Institute of Technology
Cambridge, MA 02139, USA
feigao@mit.edu

Abstract

Building a robust and effective human-agent team is difficult, as teams can fail for many reasons. In this study, we investigated the performance of human-agent teams with divisional and functional team structure under different level of task load uncertainty. Divisional teams show robustness against uncertainly but can lead to poorer performance. Three reasons related to team coordination were identified for the poor performance, namely duplicate work, underutilization of resources and infrequent communication. We proposed a conceptual model to explain the mechanism of team coordination. In future studies, we hope to quantify this team coordination model, connect it with team performance, and test the effect of different solutions using the model.

Introduction

By relieving the operator from manual control tasks, enhanced autonomy enables operators to potentially work with multiple agents and do higher-level cognitive tasks requiring monitoring, coordination, and decision-making. However, the required cognitive load for working with multiple agents could easily exceed the capacity of a single operator, even with high levels of automation. Teams of humans are increasingly called upon to perform complex cognitive tasks that are less efficiently done or impossible to be done by an individual. Although teamwork may impose extra workload related to coordination and communication, teams have the potential of offering greater adaptability, productivity, and creativity than any one individual can offer (Gladstein, 1984).

However, the benefits of teamwork do not always occur naturally, and teams can fail for many reasons (Salas & Fiore, 2004). Factors such as poor combination of individual efforts, a breakdown in internal team processes (e.g., communication), and improper use of available information have been identified as potential sources of team failure (Salas, Sims, & Burke, 2005). To achieve robust and effective teamwork, we must understand the nature of such teamwork, including structure, outcomes, processes and dynamics.

Team structure determines how individual efforts are combined in the team, which is influenced by task assignment and coordination processes. For a team of operators working together to supervise a complex system such as multiple heterogeneous unmanned vehicles, there are several ways to organize the vehicles. One common method is functional organization, in which individuals specialize and perform certain roles. For example, a manufacturing plant can be organized by separating engineering, account, manufacturing, personnel and purchasing specialists into different departments based on their functions. Through specialization of each member, groups are able to tackle problems more efficiently.

Another way to organize the team is divisional organization, in which each working unit can be responsible for all type of tasks. In divisional organization, each member is allocated with some resources of each type. By creating self-contained tasks, it reduces the amount of information processed within an organization when the level of uncertainty is high (Galbraith, 1974). For example, a company can have several divisions each responsible for one product. Each division has its own set of functional units like research, design, marketing etc. Divisional structure was designed in order to have a fast response to the market (Macmillan, Entin, & Serfaty, 2004). In one command and control scenario, it was found that the effectiveness of teams using the divisional and functional structures depends on the nature of the tasks to be accomplished and the uncertainty in the situation. Specifically, functional teams perform better when the environment and tasks are predictable. Divisional teams have a higher level of robustness and perform better when the environment and tasks have more uncertainty (Macmillan, Entin, & Serfaty, 2004).

Communication, an important coordination mechanism, influences the share of information among team members. Over the course of a conversation, units of shared information are transformed into mutual team knowledge, which is the foundation of successful team coordination. Team knowledge consists of background knowledge that is long-lived in nature, as well as more dynamic and fleeting

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**
4. TITLE AND SUBTITLE **Barriers to Robust and Effective Human-Agent Teamwork**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Massachusetts Institute of Technology,Cambridge,MA,02139**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
AAAI 2014 Spring Symposium, Mountain View, CA.

14. ABSTRACT
Building a robust and effective human-agent team is difficult as teams can fail for many reasons. In this study, we investigated the performance of human-agent teams with divisional and functional team structure under different level of task load uncertainty. Divisional teams show robustness against uncertainly but can lead to poorer performance. Three reasons related to team coordination were identified for the poor performance, namely duplicate work, underutilization of resources and infrequent communication. We proposed a conceptual model to explain the mechanism of team coordination. In future studies, we hope to quantify this team coordination model, connect it with team performance and test the effect of different solutions using the model.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

understanding that an operator has of a situation at any one point in time (Cooke, Kiekel, & Helm, 2001). It is influenced by team process behaviors, such as communication, coordination and situation awareness (Cooke, et al., 2001). If the team members don't have a clear understanding of the situation, it may result in delayed actions, errors, and a suboptimal distribution of team resources.

Communication also relates to team trust, which indirectly influences team performance. Previous research found that teams with different levels of trust also have different communication styles. Team members with the highest levels of trust were sociable, exchanged frequent messages, showed interest in other members' responses, showed initiative, provided substantive feedback to one another, and notified others of their expected participation periods or absences. Those with the lowest levels of trust exhibited little initiative and had little social content in their messages. Groups with moderate trust levels had predictable but infrequent communication, focusing their messages on tasks only and devoting a disproportionate level of messages to establishing rules and procedures (Jarvenpaa & Leidner, 1998). Similarly, Dirks (1999) found low trust teams worked more as individuals whereas high trust teams exhibited behaviors more consistent with joint effort. Thus, trust indirectly influences group performance by moderating the relationship between motivation and group process and performance.

Experimental Data Analysis

Human-agent teams often work under uncertainty. One major source of uncertainty is task load. The arrival time and types of tasks are often unpredictable. To achieve adaptability and robustness, teams should be able to properly assign the tasks and balance the workload among team members. In this study, we investigated the communication and coordination process and performance of human-agent teams with different team structures and under different levels of task load uncertainly.

An experimental test-bed where teams of operators controlled multiple unmanned vehicles (UVs) was developed and experimental trials were conducted to gather the data (Figure 1). The main part of the interface is the map with the locations of contacts and vehicles. The operators were able to communicate with each other via instant messaging in a chat interface window. The System Panel presented system messages on vehicle status, conflicts of task assignments, etc. Operators could observe the positions of vehicles controlled by their teammates by clicking and holding the "Monitor Other Vehicles" button, as seen in Figure 1.

The simulation included three ground control stations, with one subject assigned to each station. The three operators were referred as Alpha (A), Bravo (B), and Charlie (C). Each mission scenario required a team of operators to "handle" contacts that appeared intermittently over the map, requiring operators to perform both assignment and payload tasks. Assignment tasks required the operators to send their vehicles to the contacts on the map as they emerged. Once a vehicle reached a contact, the operator identified the contact, and then destroyed the contact or dropped aid packages, depending on its hostile or friendly status.

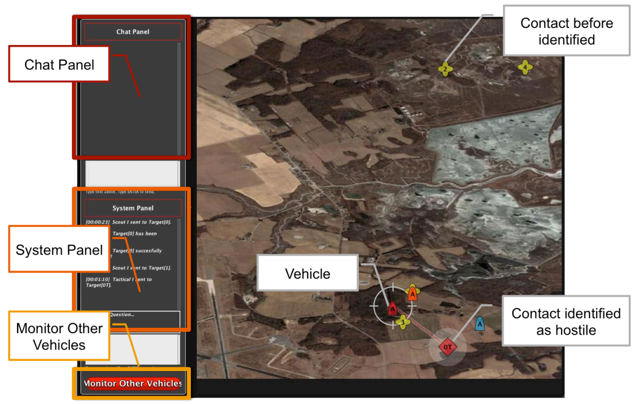

Figure 1: Team-RESCHU Interface

The tasks to identify, destroy or drop aid packages were completed using three different types of vehicles. In other words, two vehicles were required to complete one task. The second vehicle could be assigned before or after the identification. The timeline for processing a task is shown in Figure 2. The time between the appearance of an unknown contact and the time it was destroyed or aided was called objective completion time. Team performance was measured by averaging the objective completion time of each contact during the mission.

A 2x2 repeated measures experiment was conducted where the independent variables were team structure (divisional, functional) and the inter-arrival time of unidentified contacts (constant, erratic). Ten teams of three participants each completed all four treatments. The experimental trials had a total of 16 exogenous events (unidentified contacts emerging). The time between successive exogenous events (the inter-arrival time) was 30 seconds for the constant treatment. For the erratic factor level, the inter-arrival times were generated from a bimodal distribution where the means of the modes were set at 75 seconds and 225 seconds from the start of the trial, with a standard deviation of 15 seconds.

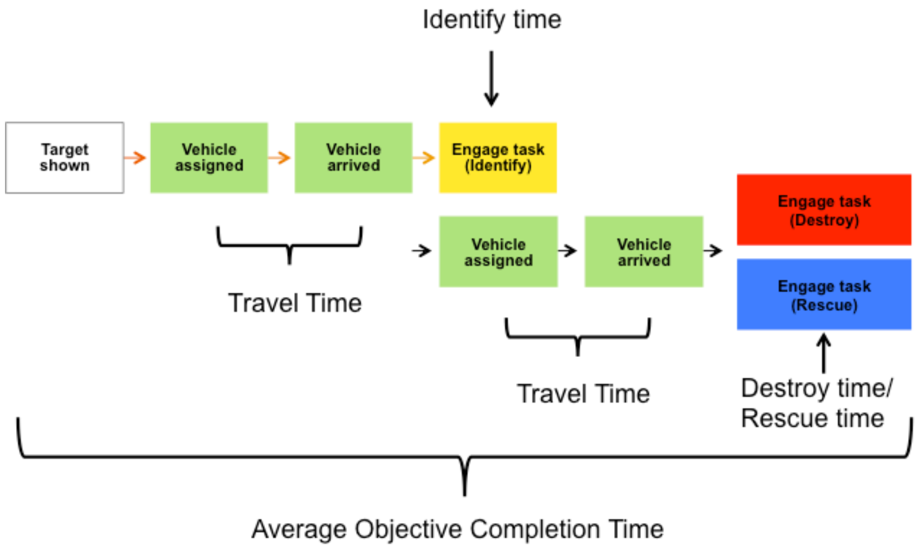

Figure 2: Timeline for Processing a Task

The second independent variable was team structure. A functional team is one where the operators have rigidly defined roles and responsibilities. For instance, when all of the vehicles of one type are assigned to one and only one operator, then that operator is given the full responsibility for performing the tasks that only that vehicle can do. If one of each vehicle type is allocated to a single operator instead, then that team structure would be considered divisional since any operator can perform any task that arises, provided that he has an appropriate vehicle available.

The initial experiment results showed that functional teams performed significantly better than divisional teams in general. Functional teams performed better with constant arrival, while divisional teams perform better with erratic arrival (Mekdeci & Cummings, 2009). Although divisional teams showed their robustness against the uncertainty of task arrival, their performance was not as good as desired. In this effort, we further investigated the teamwork process to identify several reasons for the poor performance: duplicate work, underutilization of vehicles, and infrequent communication.

Duplicate Work

Further analysis on teamwork process shows that teams that have worse performance also tend to have bad team coordination. One example of such poor coordination occurred in divisional teams, where we observed duplicate vehicle assignment. As shown in Figure 3, vehicles of the same type controlled by different operators were assigned to the same task, which resulted in a waste of resources.

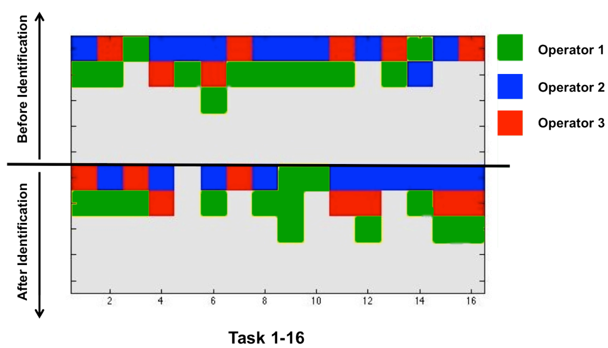

Figure 3: Vehicles Assigned to Each Task by Operators

This requires conflict resolution within the team by explicit communication, which cost time. In the communication transcript, we observed messages such as these:

Bravo: *B 1*
Alpha: *A 1*
Charlie*: Let B take it - he's closer, A you take 2*
Alpha: *Redirecting to 2*

We can see that both Bravo and Alpha wanted to work on contact 1. This conflict was resolved via communication as Charlie asked Bravo to work on contact 1 and Alpha on contact 2. Communication was necessary in this case but cost extra time. If the conflict is not resolved, it may happen that some tasks have multiple operators working on them while others are ignored.

Under Utilization of Vehicles

A second reason for the poor performance of divisional teams is the under utilization of the vehicles. Figure 4 shows the working process of a divisional team with constant task arrival. Each column is the timeline of one emergent contact from its appearance until it is destroyed or provided aid packets. Green is for vehicle travel time, yellow is for identification time, red is for destroy time, and blue is for rescue time. Dark grey is for idle time, during which the target is not assigned a vehicle.

The dark grey period is nonproductive, which happens a lot for this team. Contacts are numbered, with a letter T added after the identification for threats or F for friendly. For example, 1 is an unidentified contact. It is updated as 1T if identified as hostile or 1F if friendly. The longest idle time was highlighted by the black box in Figure 4. We looked at the log of communication and the actions of operators during this time, which are summarized in Table 1.

Operator Alpha assigned a vehicle to an unknown contact 4, and later to a threat contact 0T and a friendly contact 3F. All three vehicles operated by Alpha were busy. He also reported his action to his teammates via chat messages. Operator Bravo was working on threat contact 2T. After that, he worked on another threat contact 4T, and later assigned a vehicle to an unknown contact 7. Only one vehicle controlled by Bravo was busy at one time. Operator Charlie assigned vehicles to several contacts (4, 3F, 4T, and 0T) after he finished identifying unknown contact 3. However, all of these contacts had already been claimed by the other two team members. He then asked about task allocation and assigned a vehicle to contact 1F. During this time, none of the vehicles operated by Charlie were busy and none of them were assigned to contact 5.

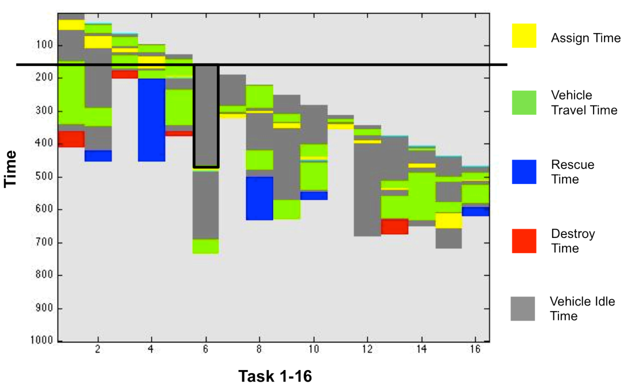

Figure 4: Timeline of Task Completion in a Divisional Team

	Alpha	Bravo	Charlie
Start	Assigned to 4	Arriving at 2T	Identifying 3
Process	*"ok, I will get 4 too." "and 3F"* Assigned to 0T Assigned to 3F	*"alpha, you take 0T"* Destroy 2T *"i got 4T"* Assigned to 7	Assigned to 4, 3F, 4T, 0T *"who got 0F"* Assigned to 1F
#Idle	0	2	3

Table 1: Coordination and Vehicle Utilization

From these we can see the vehicles were not used at their full capacity. While there were enough idle vehicles, some tasks had no vehicle assigned to them.

Infrequent communication

We found that chat density had an influence on the task assignment waiting time, which is the nonproductive time between the appearance of a contact and the time it was assigned a vehicle. We conducted a partial correlation analysis for average objective completion time, average assignment waiting time, and the number of chat messages. Team structure, arrival process, and trial sequence were controlled in order to separate the influence of communication. Although chat density did not have a significant correlation with the overall objective completion time, it negatively correlated with average assignment waiting time with $r = -0.427$, $p = 0.009$. Average assignment waiting time correlated with average objective completion time with $r = 0.3923$, $p = 0.016$. In other words, communication indirectly influenced team performance by reducing the nonproductive time. Thus teams that communicated infrequently likely led to poorer performance.

A Conceptual Model of Team Coordination

In order to explain these barriers systematically, we propose a conceptual model for team coordination as shown in Figure 5. Team Knowledge is represented as a matrix K where K_{ij} stands for Operator i's understanding of Operator j's situation, such as the availability of vehicles v_{ij} and the distance to contacts d_{ij}. Operator i makes a decision on whether to work on a task based on his/her understanding of the situation, which is represented by the matrix K. Specifically, v_{ij} takes a value of 1 if the vehicle is idle or ∞ if it is working. Let $K_{ij} = \min\{v_{ij}d_{ij}\}$ for the multiple vehicles with the matched capability for a task controlled by Operator j, Operator i will decide to work on the task if $K_{ii} < \min\{K_{ij}\}$ for all $j \neq i$. In other words, Operator i would decide to work on a task if he/she thought his/her vehicle was the closest available vehicle.

After a decision is made or an action is taken, the operator may communicate with the teammates by reporting his/her intention, which updates column i of the matrix. Conflict resolution may be necessary if another operator has already taken the task, which leads to a change of task assignment action. If Operator i requests for information from his/her teammates or gets information implicitly, row i of the matrix is updated. An example of implicit information sharing is that Operator i presses the 'Monitor other Vehicles' button (Figure 1) to show the positions of his/her teammates' vehicles on the map in Team-RESCHU.

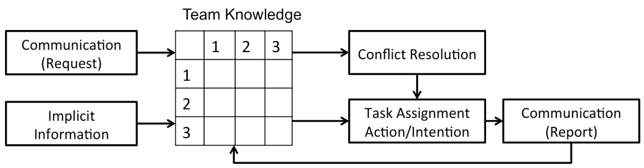

Figure 5: A Conceptual Model of Team Coordination

However, this coordination process may not be as straightforward as depicted. Problems may happen at each step of the process. Team members may not communicate enough about their actions and intensions. Even if they do, communication messages may not be noticed instantly or even be ignored, which leads to biased and outdated team knowledge. Duplication of task assignment can happen if the task assignment actions are decided based on such flawed information, but conflict resolution may not always be triggered. The update of team knowledge via information requests or implicit information sharing often requires extra time and efforts, which may extend the task time and increase the workload.

The purpose of the model is to both explain why team coordination fails, but also to develop solutions to problems at each step. For example, improving information display on the interface can enhance implicit information sharing. For communication, building successful team coordination may aid in building team trust. Behaviors such as communicating frequently, acknowledging others, and being explicit was found to significantly correlate with team trust (Walther, Bunz, & Bazarova, 2005). These behaviors also improve team coordination, and may influence team performance indirectly.

Conclusion

Effective teamwork in highly dynamic environments requires a delicate balance between giving agents the autonomy to act and react on their own and restricting that autonomy so that the agents do not work at cross purposes (Work, Chown, Hermans, & Butterfield, 2008). In this study, divisional teams were designed to create working units that have a higher level of autonomy. They show robustness against uncertainly but poorer performance. Three reasons related to team coordination were identified for the poor performance, namely duplicate work, underutilization of resources and infrequent communication. We proposed a conceptual model to explain the mechanism of team coordination. In future studies, we hope to quantify this team coordination model, connect it with team performance, and test the effect of different solutions using the model.

Acknowledgments

This research was sponsored by the Office of Naval Research and the Air Force Office of Scientific Research. Thanks to Brain Mekdeci for providing the experiment data.

References

Cooke, N. J., Kiekel, P. A., & Helm, E. E. 2001. Measuring Team Knowledge During Skill Acquisition of a Complex Task. *International Journal of Cognitive Ergonomics, 5*(3), 297-315.

Dirks, K. T. 1999. The effects of interpersonal trust on work group performance. *The Journal of applied psychology, 84*(3), 445-455.

Galbraith, J. R. 1974. Organization Design: An Information Processing View. *Interfaces, 4*(3), 28-36.

Gladstein, D. L. 1984. Groups in Context: A Model of Task Group Effectiveness. *Administrative Science Quarterly, 29*(4), 499-517.

Jarvenpaa, S. L., & Leidner, D. E. 1998. Communication and Trust in Global Virtual Teams. *Journal of Computer-Mediated Communication, 3*(4), 0-0.

Macmillan, J., Entin, E. E., & Serfaty, D. 2004. Communication Overhead: The Hidden Cost of Team Cognition. In E. Salas & S. M. Fiore (Eds.), *Team Cognition: Understanding the Factors That Drive Process and Performance*: American Psychological Association (APA).

Mekdeci, B., & Cummings, M. 2009. *Modeling Multiple Human Operators in the Supervisory Control of Heterogeneous Unmanned Vehicles*. PerMIS'09, Gaithersburg, MD, USA.

Salas, E., & Fiore, S. M. 2004. *Team Cognition: Understanding the Factors That Drive Process and Performance*: American Psychological Association (APA).

Salas, E., Sims, D. E., & Burke, C. S. 2005. Is there a Big Five in Teamwork? *Small Group Research, 36*(5), 555-599.

Walther, J. B., Bunz, U., & Bazarova, N. N. 2005. *The Rules of Virtual Groups*. Proceedings of the 38th Annual Hawaii International Conference on the System Sciences, 2005. HICSS '05.

Work, H., Chown, E., Hermans, T., & Butterfield, J. 2008. *Robust teamplay in highly uncertain environments*. Proceedings of the 7th international joint conference on Autonomous agents and multiagent systems - Volume 3, Estoril, Portugal.