Human-Autonomy Teaming Guidelines with a Spacesuit Example

Michael Matessa and Jake Rohrig
Collins Aerospace
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With the growing capability of autonomy, there is a growing interest in how humans interact with autonomous systems. This paper shows the development of a human-autonomy teaming (HAT) framework as well as general and specific HAT guidelines. Specific guidelines are made for a spacesuit assistant. Guidelines can be used to aid in the development of concepts of operation, procedures, or interfaces. The HAT framework is based on a crew resource management evaluation system, and so this work shows that a system used to evaluate human teaming can be used to provide general HAT guidelines and to develop specific HAT guidelines. Guidelines that are specific to particular projects help to make more concrete suggestions and can also inform general guidelines.

INTRODUCTION

With the growing capability of autonomy, there is a growing interest in how humans interact with autonomous systems. The definition of autonomy can be confusing, so in this paper "autonomy" is used to describe increasingly autonomous systems. This phrase covers today's flight management systems and future advanced autonomy. With the increasing independence of these systems, it makes sense to refer to the human interaction as human-autonomy teaming, or HAT (Chen & Barnes, 2013; Endsley, 2017; Lyons et al., 2021; NATO, 2020; O'Neill et al., 2022; Shively et al., 2018).

To understand human-autonomy teaming, it is useful to develop a HAT framework describing important factors. To make use of that framework, it is useful to develop guidelines to aid in the development of concepts of operation, procedures, or interfaces.

This paper shows the development of a HAT framework as well as general and specific guidelines. The framework is based on a crew resource management evaluation system, and so this work shows that a system used to evaluate human teaming can be used to provide general HAT guidelines and develop specific HAT guidelines.

HAT FRAMEWORK

Previous work has identified important factors in human-autonomy teaming (e.g., McDermott et al., 2018; NATO, 2020; Shively, et al., 2018). NASA's Human-Autonomy Teaming Lab identified three HAT tenets: An Operator-directed interface, Transparency, and Bi-directional communication (Shively et al., 2018). Operator-directed interfaces are commonly referred to as playbook interfaces, where a play encapsulates goals, tasks, and a task allocation. Operators can use the playbook to call a play to quickly adapt to a new situation. (Miller et al., 2005; Shively et al., 2018; Tokadlı et al., 2019). Bi-directional communication can make systems less brittle and can help ensure that the human and the autonomy have the same information (Shively, et al., 2018).

MITRE (McDermott et al., 2018) grouped HAT themes into the following categories:

- Transparency
  - Observability
  - Predictability
- Augmented Cognition
  - Directing Attention
  - Exploring Solution Space
  - Adaptability
- Coordination
  - Directability
  - Calibrated Trust
  - Common Ground

NATO and NASA (NATO, 2020) reviewed several lists of HAT challenges and developed the following aggregated list:

- Communication
- Functional Division
- Shared Understanding
- Decision Making
- Learning
- Trust
- Performance

Human-autonomy teaming can be informed by human teaming. Holbrook et al. (2019) looked at the actions human teams take to improve safety and found that important skills are Anticipate, Monitor, Respond, and Learn. Pilots are taught team skills as part of crew resource management training. These skills are evaluated at a team level (LOSA: Helmreich, 2000; O'Connor et al., 2002) or individual level (NOTECHS: Flin et al., 2003). The LOSA system categorizes team skills into Planning, Execution, Review, and Overall. The NOTECHS system categorizes skills into Cooperation, Management, Situation Awareness (SA), and Decision Making. Research has shown the importance of situation awareness in teaming (Endsley, 1995; Endsley, 2023; Grimm et al., 2018). In particular, Endsley describes a Level 3 SA as a projection of events into the future. This projection is related to the Anticipate skill of Holbrook (2019) and allows teams to address issues before they become problems. NOTECHS was used by Matessa (2018) to develop quantitative measures of HAT skills in order to have the same system that evaluates human teaming skills used to evaluate autonomy teaming skills. NOTECHS was used instead of LOSA to focus on the individual skills that lead to team performance.

The HAT framework developed in this paper (Figure 1) is mostly based on the NOTECHS system of Cooperation, Management, Situation Awareness, and Decision Making. By using this framework, the same factors used to evaluate human teaming skills at the individual level can be used to evaluate system teaming ability. These factors are mediated through machine interfaces that need to provide Transparency to the system and enable Bi-directional Communication. The teaming activity results in team Performance and Trust in the system.

This framework covers most of the HAT factors found in previous work. Management incorporates Functional Division, Operator-directed, and Directability. Situation Awareness (and the Transparency that allows situation awareness of the system) incorporates Shared Understanding, Transparency, Monitor, Anticipate, Observability, Directing Attention, and Common Ground. Decision Making incorporates Exploring Solution Space. Cooperation represents functionality that isn't represented well in previous work and includes activity such as taking the condition of the human into account and offering assistance to the human. The resulting Performance of the team incorporates Learning, Respond, Predictability, and Adaptability. The Trust resulting from the teaming activity incorporates Calibrated Trust.

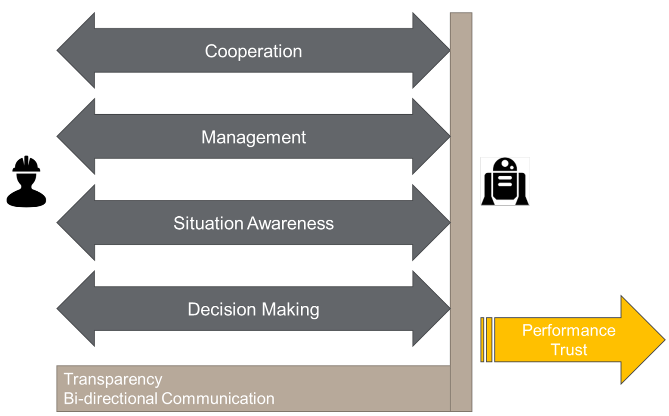

Figure 1: HAT Framework

GENERAL GUIDELINES

Using the framework described above, guidelines can be created to aid in the development of concepts of operation, procedures, or interfaces. Previous work has developed guidelines for interacting with autonomy (Billings, 1996; Endsley 2023; Helldin & Erlandsson, 2012). Endsley (2023) developed general HAT situation awareness design principles and showed how those principles can be applied by giving an example of creating displays to support driving with Tesla autopilot.

This paper uses the framework in Figure 1 to develop general HAT guidelines (Figure 3). Under the category of Cooperation, autonomous systems should consider the workload of the operator by adapting a communication modality to one that is not being used, or by waiting to give a lower-priority message when the operator has lower workload. Under the category of Management autonomous systems should allow easy re-tasking and use an operator-directed playbook. Under the category of Situation Awareness (SA), systems should use trends to give suggestions that avoid incidents, use acknowledgements to establish mutual SA, display time to future events, and display the current goal and next step (given by playbook). Under the category of Decision Making, systems should provide decision options to the operator and accept new options from the operator, and allow easy changing of assumptions and priorities. And under Communication, systems should use use bi-directional communication and use a language common to the operator (e.g., use a map instead of latitude/longitude values). Figure 3 also shows guidelines for a spacesuit assistant that will be described below. Grayed-out text are general guidelines that were not applied to the prototype spacesuit assistant but should be included going forward.

ANALOG SPACESUIT STUDY

The 2021 Haughton-Mars Project (HMP) field campaign evaluated a new spacesuit digital assistant as part of the suit's prototype informatics system (Rohrig et al., 2022). The team studied assistant functions enabling communication, navigation, spacesuit and human health monitoring, human-robot collaboration, and exploration. An image of the analog spacesuit with the embedded digital assistant is shown in Figure 2. The campaign successfully demonstrated the value of the informatics system and the usefulness of the digital assistant as a mechanism to help with spacewalk activities. Reflecting on the results of the experience in conjunction with the proposed HAT guidelines, spacesuit digital assistant guidelines can be derived.

Figure 2: Collins' analog spacesuit with digital assistant being used for navigation to waypoints at the Pumice Slopes of Crater Lake, Oregon (Photo NASA Haughton-Mars Project / J. Rohrig)

Spacesuit Assistant Function: Communication

The spacesuit digital assistant communicated with the wearer audibly using a Natural Language Interface (NLI) and visually using a Head-Up Display (HUD). The HUD consisted of a monocular, off-head display in the helmet with a 40-degree field of view to visually relay information to the user.

Through the NLI, the wearer could give commands and queries to the assistant and hear responses. The team noted that the inclusion of a readback function of NLI commands improved user confidence in the performance of the system by providing the suit wearer with feedback that the commands were properly received. This observation verified the significance of the HAT guidelines of Communication and Situation Awareness, specifically applications of bi-directional communication and acknowledgement of mutual SA, respectively. The team also noted that as spacesuit wearers became more exhausted on their simulated spacewalks, they relied more heavily on the audio rather than the visual user interface. When using the digital assistant to navigate via the HUD (a visual assessment of location and orientation) a physical pause was required whereas audible data could be conveyed and understood while in motion; this multi-modal communication system conformed to the HAT guideline of Cooperation, taking the workload of the operator into consideration.

Spacesuit Assistant Function: Navigation

To help the suit wearer with navigation during their simulated spacewalk, the assistant was programmed to present waypoints that would appear on a topology map and navigation ribbon in the HUD. The topology map functioned much like commercial navigation systems, providing the user with the ability to see their position, heading, the distance to the next waypoint, and the route to each waypoint. The navigation information could also be queried audibly via the assistant. Examples of navigation questions that the digital assistant would answer include, but are not limited to, “what is the distance to my next waypoint?” and “what is the bearing to my next waypoint?” In addition to queries, the user could also use the digital assistant to drive relevant commands, such as, “zoom map in” or “maximum map range” to control the displayed area on the topology map.

Notably, the routes were created using a map of the same resolution as current lunar maps provided by satellites. This level of detail proved insufficient and sometimes resulted in the recommended path including areas that should have been avoided. This restriction showcased the need to be able to alter waypoints during the simulated spacewalk, which the prototype was not programmed to provide. By not including this capability, the importance of the Decision Making (providing the ability to accept new options from the operator) and Management HAT guidelines were appreciated. It was also observed that intermediate waypoints could lead to rushed and impractical route decisions when provided without context to the full duration and direction of the mission. This might be mitigated with features that convey information relative to the full mission objectives and timeline, adding to the assistant’s capabilities that align with the Situation Awareness guideline.

Spacesuit Assistant Function: Spacesuit and Human Health Monitoring

In addition to the functions previously mentioned, the digital assistant conveyed spacewalk-relevant health metrics to the suit wearer. These metrics included the performance of the suit, the health of the wearer, spacewalk progress, and life support system consumables status (e.g. how much battery power remains in the spacesuit). Some parameters were simulated to emulate a real spacewalk, while others relevant for the field study were captured with real sensing inputs. Based on the remaining consumables, the digital assistant presented the time remaining to continue the simulated spacewalk. For the 2021 HMP field tests, the battery was the only real consumable used for calculating the remaining safe spacewalk time, though all the metrics provided to the user via the digital assistant were deemed valuable by the test subjects.

Some of the field tests simulated emergency scenarios in which the test subjects needed to find their way back to safe havens. During these simulations, it was also observed that suit wearers would benefit from an assistant that would relay only information relevant to surviving the emergency; in this case such information would be time remaining and navigation to safe haven information. The simplification of information presented to the wearer would have reduced cognitive workload and helped the user make it to the safe haven.

The spacesuit and human health monitoring functions of the digital assistant aligns with the HAT Situation Awareness guideline, displaying the time to future events (i.e. time remaining of the spacewalk) in order to avoid running out of battery power during the field trials. The emergency navigation scenarios also spotlight the Cooperation guideline, considering the workload of the operator and only providing relevant information in times of emergency.

Spacesuit Assistant Function: Human-Robot Collaboration

The analog spacesuit housing the digital assistant also included a gesture input mechanism, called the Astronaut Smart Glove (ASG). The ASG was used to operate a drone. The drone’s live video feed was streamed through the HUD so that the suit subject could fly the drone and view the flight from the perspective of the drone’s onboard camera. Additionally, the digital assistant was capable of conveying voice commands from the suit wearer to the drone so that automated maneuvers and additional drone adjustments could be performed. This capability was added to investigate how working with a robotic asset via the digital assistant can help with navigation and route identification as well as facilitate scientific experimentation and sampling.

The specific pre-programmed commands delivered to the drone by the digital assistant were limited to general maneuvers, like taking off and landing, but these simple functions demonstrated a form of operator-directed playbook that reduced the effort required to pilot the drone; as a result, the importance of the Cooperation and Management HAT guidelines were observed.

Spacesuit Assistant Function: Exploration

A unique experiment investigating suited cave exploration was performed during the HMP 2021 field campaign. Such a test was the first of its kind for a spacesuit manufacturer. Notably, the digital assistant was not intended for use during this part of the testing, but its absence from the experiment resulted in observable technical gaps and perceived importance of HAT guidelines.

The cave exploration trial was conducted in a lava tube, much like caves to be explored on the moon. The cave varied in cross sectional area, floor composition, and brightness. Commercial off-the-shelf products, such as automatic solar lights independent of the suit assistant, provided lighting for the wearer. The lights functioned automatically, turning on or off based on the brightness of the environment. Although at times helpful, it was determined that there should be voice commands or other means of controlling the suit lights, highlighting the importance of the Management HAT guideline.

The complexity and varying size of the cave dimensions also forced the suit wearer to crouch at times to continue forward in the simulated exploration spacewalk. By wearing the suit, the wearer had decreased spatial awareness and reduced mobility while exploring. This resulted in the wearer requiring assistance from support crew to avoid collision with cave walls, identifying a possible function for the digital assistant in the future pertaining to the Situation Awareness guideline.

SPACESUIT GUIDELINES SUMMARY

The Haughton-Mars Project field campaign provided examples of human interaction with a spacesuit assistant (Rohrig et al., 2022). Although currently showing limited autonomous function, the assistant can be seen as an increasingly autonomous system with a future goal of incorporating more autonomy.

Utilizing the general guidelines and results from the campaign, specific HAT guidelines for spacesuit assistants were developed (Figure 3). Under the category of Cooperation, assistants should offer the use of audio during physical exertion. Under the category of Management, assistants should allow the wearer to control lights. Under the category of Situation Awareness, assistants should provide distance to cave walls, give readback of speech recognition, and give information relative to the full mission. And under the categories of Decision Making and Communication, assistants should allow the wearer to alter navigational waypoints.

General Guidelines	**Spacesuit Guidelines**
Cooperation	
Consider workload of operator (ex. adapt modality or wait)	Use audio during physical exertion
Management	
Allow easy re-tasking	Allow wearer to control lights
Use operator-directed playbook	
Situation Awareness	
Use trends to give suggestions that avoid incidents	Provide distance to cave walls
Acknowledge for mutual SA	Give readback of speech recognition
Display time to future event	Give info relative to full mission
Display current goal and next step	
Decision Making	
Provide options to operator, accept new options from operator	Allow wearer to negotiate waypoints
Allow easy changing of assumptions/priorities	
Communication	
Use bi-directional communication	Allow wearer to negotiate waypoints
Common language (ex. map instead of lat/long)	

Figure 3: General and spacesuit-specific HAT guidelines

CONCLUSIONS

This work shows that a framework used to evaluate human teaming can provide general HAT guidelines and be used to develop specific HAT guidelines.

There can be a danger that the phrase “human-autonomy teaming” invokes unwarranted anthropomorphizing of systems (Kaliardo, 2022). This paper mitigates this problem by using the term “increasingly autonomous systems” to recognize limitations of current systems and by defining teaming functionality with a framework and specific guidelines.

Future research is needed to improve the general HAT guidelines by developing specific guidelines for individual systems and abstracting these results. Research is also needed to demonstrate the effectiveness of implemented HAT guidelines in improving systems.

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