Using a Crew Resource Management Framework to Develop Human-Autonomy Teaming Measures

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Abstract. Recent developments in technology have permitted an increased use of autonomy. To work best with humans, autonomy should have the qualities of a good team member. But how can these qualities be measured? One way is to use similar measures to those used to measure good teams with human members. For example, the Non-Technical Skills (NOTECHS) framework measures Crew Resource Management (CRM) skills that allow pilots to work together as a team. The framework consists of skill categories, elements of those categories, and behavioral markers that demonstrate good or poor performance in the elements. This paper introduces CMSD (Cooperation/Management/Situation Awareness/Decision Making), a measurement system based on NOTECHS and other widely-used skill level systems, which provides quantitative measures of Human-Autonomy Teaming (HAT).

Keywords: Human-Autonomy Teaming · Crew Resource Management · Measures

1 Introduction

Based on progress in Artificial Intelligence and Human Performance Modeling, Human-Autonomy Teamwork systems are being developed and tested in which humans and increasingly autonomous systems dynamically adjust and cooperate to accomplish a joint objective. In these systems, team members' responsibilities and commitments are managed such that the human and automation jointly enhance performance and manage contingencies. This paper introduces CMSD (Cooperation/Management/Situation Awareness/Decision Making), a measurement system which provides quantitative measures of Human-Autonomy Teaming (HAT). In the following sections, HAT systems are designed using concepts of operation, design patterns, and use cases. CMSD is used to assist the design and evaluation of these systems.

2 Concept of Operation for Reduced Crew Operations

One concept that takes advantage of increasingly autonomous systems is reduced crew operations (RCO) for transport category aircraft. RCO envisions having one pilot on board domestic flights, and two pilots on board long-haul operations, where one of the two pilots is often off of the flight deck resting in the bunk. An important element of RCO research seeks to develop a concept of operation (ConOp) that covers the roles and responsibly of the principal human operators, the automation tools used by them, and the operating procedures for human-human and human-automation. The human-automation function allocation, in particular, has been an ongoing NASA focus, drawing upon insights gathered from subject matter experts in industry, academia and government during technical interchange meetings and from empirical human-in-the-loop research [1,2,3].

The proposed NASA RCO ConOp [4] includes three basic human roles: the pilot on board (POB), the dispatcher, and when necessary, a ground pilot. The POB (unless incapacitated) would serve as the captain and pilot-in-command. As such, s/he would determine when to call on automation and ground support. The POB's main tasks would be to manage risk and resources (both human and automation).

Onboard automation would assist the POB with many tasks currently performed by the pilot monitoring, such as flight management system (FMS) input, assisting with checklists and validating inputs.

Ground-based automation would assist the dispatcher in a variety of tasks. Dispatch tasks would be similar to current operations (e.g., preflight planning, monitoring aircraft positions, and enroute reroutes), but for those tasks currently performed jointly with the pilot, the dispatchers (aided by automation) would absorb some of the POB's workload (e.g., creating new flight plans, vetting them with air traffic control (ATC) and uplinking them to the aircraft). In this ConOp, automation would assist the dispatcher with creation of pre-flight briefings, flight path monitoring, selection of divert airports, and optimizing reroutes. Automation would also be responsible for monitoring many flights and alerting the dispatcher to aircraft needing assistance. In addition, the POB could call the dispatcher for consultation on important decisions where s/he might previously have consulted the first officer (e.g., diagnosing an aircraft system caution light or determining the fuel consequences of a holding instruction).

Commonly occurring HAT situations in the RCO ConOps can be characterized with design patterns.

3 Building a Design Pattern

To put this in context, it is helpful to see how these patterns have been constructed. To that end, I have excerpted this section from our previous work [5]. Schulte [6], in conjunction with Neerincx & Lange [7], proposed using a set of primitives to build HAT patterns. They proposed three types of agents: 1) human operators, 2) intelligent/cognitive agents, and 3) automated tools. The agents, which can either be co-located or distributed, can be connected by a cooperative, supervisory, or communications link.

As described by Schulte [6], an important preliminary task in the construction of HAT patterns is the identification of the Work Objective. The Work Objective identifies the aspects that initiate and characterize the mission or purpose of the work. The Work Objective provides a black box description of the Work Process, which includes informational inputs (e.g., ATC clearance), environmental inputs (e.g., airspace) and supply inputs (e.g., fuel). The Work Process, utilizing all of these inputs and the Work Objective, produces a Work Process Output (e.g., reducing target speed) on the Work Object (e.g., speed of aircraft) that distributes meaningful physical and conceptual actions to human-automation team members within the overall Work Environment.

Using these primitives, a pattern was built that describes HAT in an RCO context. An initial use case was identified, and by walking through each step, the agents and links required to depict one such pattern were identified [5]. Fig. 1 provides a legend for the elements that were used in the design pattern.

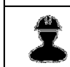
Agents	Links
 Human Operator	Communication Only
 Intelligent/Cognitive Agent	Cooperative
 Automated Tools	Supervisory

Fig. 1. Legend for design pattern elements; Cooperative and Supervisory links imply Communication.

3.1 Use Case: Designing Thunderstorm Alerting

Initial Conditions. FLYSKY12 is en route from SFO to ORD. There is one POB and a dispatcher flight following. The *Work Objective* is to avoid a thunderstorm. The *Work Process* is the set of steps necessary to resolve the situation with the output to divert to an alternate airport.

Step 1. Detection and Alerting of Thunderstorm. Dispatch automation informs dispatcher of convective cell growing on flight path of FLYSKY12. *This requires a communication link between dispatch automation and the dispatcher (covered by supervisory link in the pattern).*

Step 2. Dispatcher informs POB of cell. *This requires a link between the dispatcher and the POB. This link is as a cooperative link (as in the pattern) because, by regulation, the dispatcher and POB share responsibility for safe operation of the flight (including detecting and responding to thunderstorms).*

Step 3. Modification of Flight Plan. Seeing a need to re-route, the dispatcher requests modified flight plan from dispatch automation. Dispatch automation returns modified flight plan. *The delegation of flight path planning to the automation requires a supervisory link. This planning requires consideration of multiple strategies making this automation an agent.*

Step 4. Dispatch uplinks modified flight plan. *Uses the link between dispatch and POB from Step 2.*

Step 5. POB requests clearance for flight plan from ATC. *POB and ATC are both responsible for safety of flight and thus this is a cooperative link.*

Step 6. ATC rejects clearance. ATC tells POB that aircraft must take additional six-minute delay for new arrival slot coming into ORD. *Uses cooperative link from Step 5.*

Step 7. Planning for Delay. POB asks automation for alternatives to take six-minute delay. Automation provides two alternatives: a) Slow down, saves fuel but risks further movement/growth of cell b) Hold past cell, more fuel burn but lower risk of further deviations. *POB is delegating this task to the automation, requiring a supervisory link. The automation is developing multiple strategies for taking the delay, making it an agent.*

Step 9. POB requests clearance from ATC, modified with holding after passing cell; ATC approves request. *Uses the same cooperative link from Steps 2 and 5.*

Step 10. POB tells Agent to implement the new clearance. Agent sets autopilot in accord with clearance. *The POB delegates tasks to the agent, and the agent uses tools to perform the task.*

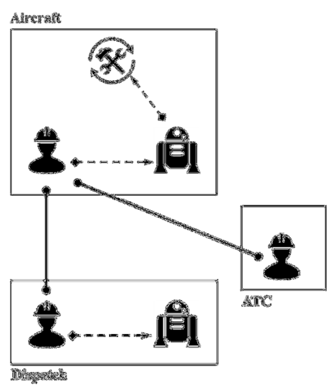


Fig. 2. Use case design pattern

The elements of this use case are captured in the pattern shown in Fig. 2. The POB and the assigned dispatcher are jointly responsible for the flight, assisting each other in a cooperative relationship. Similarly, the POB and the ATC have complementary roles in assuring safety of flight, and thus must also cooperate. Further, the ConOp specifies that both dispatch and the POB acquire significantly enhanced automation. Thus, in most situations the operators, tools, agents, and their underlying relationships are fixed by the ConOp. Further, at a high level, the *Work Objective* remains constant for RCO: getting the aircraft to the best airport possible for the airline (usually its destination and ideally on time) while maintaining safety of flight. The relevant informational, environmental, and supply inputs also remain constant (although possibly with different weightings) across operations.

4 The CMSD Measurement System

The development of the HAT design pattern required several subjective decisions. For example, considerable time was spent determining which piece of automation was a cognitive agent versus a tool and the type of connection between the various agents. To aid in making these decisions, the CMSD measurement system was developed based on a framework that Line Check Airmen use to evaluate Crew Resource Management performance by human pilots. The Non-Technical Skills framework (NOTECHS) has four Categories: Cooperation, Management and Leadership Skills, Situation Awareness, and Decision Making. Each are subdivided into Elements and behavioral markers (Fig. 3).

Category	**Element**	**Behavior**
Cooperation	Considering others	Consider condition of other
	Supporting others	Offer assistance
Management/ Leadership	Authority/Assertiveness	Take Initiative
	Maintain standards	Enforce SOP
	Planning/Co-ordinating	State plan
	Workload management	Distribute tasks
Situation Awareness	System awareness	Monitor/report system (incl. other crew)
	Env awareness	Monitor/report env
	Awareness of time (anticipation)	Monitor/report time constraints
Decision Making	Problem diagnosis	ID problem
	Option generation	Generate/elicit options
	Option selection	Select option
	Outcome review	Review outcome

Fig. 3. NOTECHS CRM measurement framework

The categories are used by CMSD to determine individual and relationship skills in the design pattern. For individual skills, the degree to which agents exhibit situation awareness is indexed by the levels of situation awareness described by Endsley [8], the management capabilities of agents is indexed by Sheridan's levels of automation [9], and decision-making ability is assessed using the Non-Technical Skills framework (NOTECHS) categories [10]. See Fig. 4 for details. In the following, CMSD is used to give a more quantitative assessment of the automation in the use case. Each step is re-examined, giving the reasoning behind these assessments.

Situation Awareness (Endsley)
1) Perceive
2) Comprehend
3) Project

Decision Making (NOTECHS)
1) ID problem
2) Generate options
3) Select option
4) Review outcome

Management (Sheridan)
1) The computer offers no assistance: human must take all decision and actions.
2) The computer offers a complete set of decision/action alternatives, or
3) narrows the selection down to a few, or
4) suggests one alternative, and
5) executes that suggestion if the human approves, or
6) allows the human a restricted time to veto before automatic execution, or
7) executes automatically, then necessarily informs humans, and
8) informs the human only if asked, or
9) informs the human only if it, the computer, decides to.
10) The computer decides everything and acts autonomously, ignoring the human.

Fig. 4. Quantitative HAT measures for SA, Decision Making, and Management

4.1 Use Case 1: Designing Thunderstorm Alerting

Step 1. Detection and Alerting of Thunderstorm. Dispatch automation informs dispatcher of convective cell growing on flight path of FLYSKY12. *No CRM skill indicated.*

Step 2. Dispatcher informs POB of cell. *Requires a cooperative relationship between POB and dispatcher with Collaboration ability (awareness of needs of other) and SA ability (monitoring other) labeled C/S.*

Step 3. Modification of Flight Plan. Seeing a need to re-route, the dispatcher requests modified flight plan from dispatch automation. Dispatch automation returns modified flight plan. *Requires management ability in a supervisory relationship between dispatcher and agent (labeled M), with the agent having a Decision Making ability to select an option (NOTECHS level three, labeled D3).*

Step 4. Dispatch uplinks modified flight plan. *Requires a cooperative relationship between POB and dispatcher with Collaboration ability (awareness of needs of other), Decision Making ability (eliciting divert options from dispatcher), and Management ability (delegating divert location task to the dispatcher), labeled C/D/M.*

Step 5. POB requests clearance for flight plan from ATC. *Requires a cooperative relationship between POB and ATC with Collaboration ability (awareness of needs of other), Management ability (maintaining standard of requesting clearance from ATC), SA ability (monitoring of other), and Decision Making ability (eliciting divert options from POB), labeled C/M/S/D.*

Step 6. ATC rejects clearance. ATC tells POB that aircraft must take additional six-minute delay for new arrival slot coming into ORD. *Uses cooperative relationship from Step 5.*

Step 7. Planning for Delay. POB asks automation for alternatives to take six-minute delay. Automation provides two alternatives: a) Slow down, saves fuel but risks further movement/growth of cell b) Hold past cell, more fuel burn but lower risk of further deviations. *Requires management ability in a supervisory relationship between POB and agent (labeled M), with the agent having a Situation Awareness abil-*

ity to project consequences of actions (Endsley level 3, labeled S3) and a Decision Making ability to generate options (NOTECHS level two, labeled D2).

Step 8. POB requests clearance from ATC, modified with holding after passing cell; ATC approves request. *Uses the same cooperative relationship from Step 5.*

Step 9. POB tells Agent to implement the new clearance. Agent sets autopilot in accord with clearance. *Uses supervisory relationship between POB and agent from Step 7. Requires Management ability in a supervisory relationship between agent and aircraft (labeled M).*

Fig. 5 shows how the RCO pattern is labeled using the CMSD system. Note that the final labeling shows the maximum capabilities of relationships and agents. The measure labels permit the reader to quickly determine the capabilities required of the agents and the relationships.

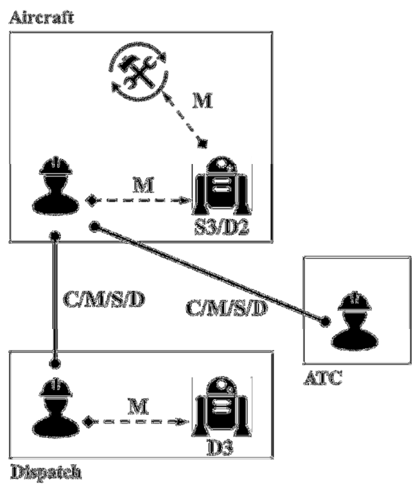


Fig. 5. RCO design pattern with additional CMSD measures

4.2 Use Case 2: Designing Traffic Avoidance

To further exercise the CMSD measurement system, a use case was developed that included an agent with the ability to monitor traffic, predict Loss of Separation, and take evasive action. The following examines each step of the use case and specifies the HAT measure reasoning.

Step 1. **Engaged.** On board agent with Traffic Collision Avoidance capability is engaged. *No CRM skill indicated.*

Step 2. Detection. Agent predicts future LOS with traffic, provides avoidance option, and waits for evaluation of option from POB. *Requires a supervisory relationship between agent and traffic where the agent has Situation Awareness ability to monitor traffic (labeled S). Requires a cooperative relationship between POB and agent with Collaboration ability (offering assistance) and Decision Making ability* *(eliciting options), labeled C/D. The agent needs a Situation Awareness ability to project a future Loss of Separation (Endsley level 3, labeled S3), a Decision Making ability to select an avoidance maneuver option (NOTECHS level 3, labeled D3), and a Management ability to suggest that option (Sheridan level 4, labeled M4).*

Step 3. Lack of response. POB does not react in time. *Lack of Cooperation by POB for not considering the condition of the agent.*

Step 4. Execution. Agent executes maneuver option to avoid traffic. *The agent has a Management relationship with the POB (labeled M) with an ability that allows the human a restricted time to veto before automatic execution (Sheridan level 6, labeled M6).*

Fig. 6 shows the RCO pattern updated using the CMSD system for an agent with TCAS capabilities. A comparison with Fig. 5 shows a need for an onboard agent with increased Decision Making and Management abilities and increased cooperative Collaborative and Decision Making abilities.

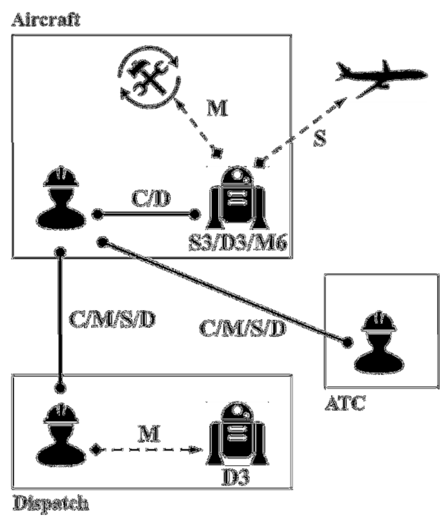


Fig. 6. RCO pattern and CMSD measures for an agent with TCAS capabilities

4.3 Use Case 3: Evaluating Traffic Avoidance

In addition to design, the CMSD system was developed to assist in the evaluation of existing systems. NASA Ames Research Center is developing the J-HATT ground control station to investigate human factors issues involved with the control of Unmanned Aerial Vehicles. Fig. 7 shows a screenshot of the J-HATT and highlights Detect And Avoid (DAA) features. When Loss Of Separation is predicted, a colored arc is presented showing evasive turning options that are safe (green), questionable (yellow), and dangerous (red).

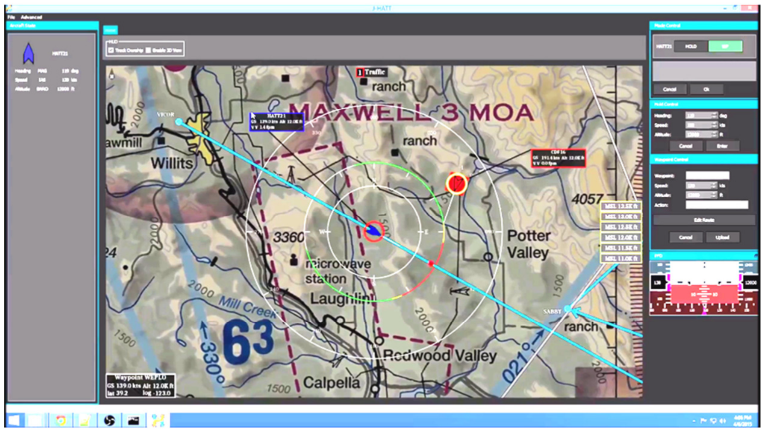


Fig. 7. J-HATT UAV ground control station

Fig. 8 shows an evaluation of the system using the CMSD system. The ability of the agent to monitor traffic demonstrates a supervisory relationship between agent and traffic where the agent has a monitoring Situation Awareness skill (labeled S). The agent demonstrates a Situation Awareness ability to project a future Loss of Separation (Endsley level 3, labeled S3), a Decision Making ability to generate avoidance maneuver options (NOTECHS level 2, labeled D2), and a Management ability to narrow the selection of options down to a few (Sheridan level 3, labeled M3).

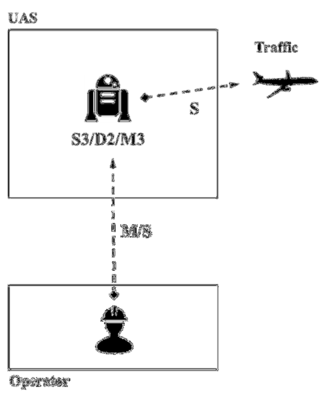


Fig. 8. Pattern and measures of system with J-HATT UAV ground control station

The CMSD system can be used to suggest improvements to J-HATT. For individual agent skills, decision making ability could be improved to select one of the generated options (raising the level to D3) and management ability could be improved to automatically execute the option after giving the operator time to veto (raising the level to M6). For the last option to be seen as cooperative by the operator, the agent would need to indicate that it was able to offer assistance and execute the option, and that it was waiting for the operator to accept or reject the option (C and D labels on a cooperation relationship).

As a summary of how the labels of the CMSD system are related to NOTECHS skills, Fig. 9 shows the NOTECHS framework with relationship and individual skill levels.

Relationship skill	**Category**	**Element**	**Behavior**	**Individual skill**
C	Cooperation	Considering others	Consider condition of other	
		Supporting others	Offer assistance	
M	Management/ Leadership	Authority/Assertiveness	Take Initiative	**M1-10**
		Maintain standards	Enforce SOP	
		Planning/Co-ordinating	State plan	
		Workload management	Distribute tasks	
S	Situation Awareness	System awareness	Monitor/report system (incl. other crew)	**S1-3**
		Env awareness	Monitor/report env	
		Awareness of time (anticipation)	Monitor/report time constraints	
D	Decision Making	Problem diagnosis	ID problem	**D1-4**
		Option generation	Generate/elicit options	
		Option selection	Select option	
		Outcome review	Review outcome	

Fig. 9. NOTECHS framework with additional labels for relationship and individual skills

5 Discussion

This paper suggests that defining design patterns and measures can help prescribe and describe human-autonomy relationships and abilities. Based on the same framework that is used to evaluate human teams, the CMSD system can help to design and evaluate human-autonomy teams. Widely-used skill level systems [8,9,10] incorporated into CMSD allows it to give quantitative descriptions of Situation Awareness, Decision Making, and Management abilities.

How does CMSD relate to other methodologies that use quantitative measures of autonomous systems? One such methodology is being used by the National Highway Traffic Safety Administration (NHTSA) to define levels of automation for autonomous vehicles [11]. The NHTSA adopts the SAE International (SAE) definitions for levels of automation:

• At SAE Level 0, the human driver does everything;

• At SAE Level 1, an automated system on the vehicle can sometimes assist the human driver conduct some parts of the driving task;

• At SAE Level 2, an automated system on the vehicle can actually conduct some parts of the driving task, while the human continues to monitor the driving environment and performs the rest of the driving task;

• At SAE Level 3, an automated system can both actually conduct some parts of the driving task and monitor the driving environment in some instances, but the human driver must be ready to take back control when the automated system requests;

• At SAE Level 4, an automated system can conduct the driving task and monitor the driving environment, and the human need not take back control, but the automated system can operate only in certain environments and under certain conditions; and

• At SAE Level 5, the automated system can perform all driving tasks, under all conditions that a human driver could perform them.

Using the SAE levels, a distinction is drawn between Levels 0-2 and 3-5 based on whether the human operator or the automated system is primarily responsible for monitoring the driving environment. For purposes of State traffic laws that apply to drivers of vehicles (e.g., speed limits, traffic signs), the NHTSA suggests that States may wish to deem a Level 3-5 system that conducts the driving task and monitors the driving environment to be the "driver" of the vehicle.

Comparing SAE levels and CMSD, both contain elements of monitoring and control. SAE levels uniquely mention parts of an overall task but do not go into detail on what those parts might be. CMSD explicitly mentions the ability of state projection for situation awareness and option selection for decision making, both of which may be useful in further defining task parts in driving.

Further improvements in CMSD would need to balance the generalizability of more abstract representation of skills with the diagnostic ability of specific representations of skills and tasks. For example, it may be sufficient to say that for all RCO use cases a design would need advanced onboard autonomy to assist the pilot. But to evaluate if a driver is monitoring the automated system and environment sufficiently in order to be able to override the decision of the system, details of subtasks and timing would need to be added to the CMSD system.

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