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Past, present and future implications of human supervisory control in space missions

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Abstract

Achieving the United States' Vision for future Space Exploration will necessitate far greater collaboration between humans and automated technology than previous space initiatives. However, the development of methodologies to optimize this collaboration currently lags behind development of the technologies themselves, thus potentially decreasing mission safety, efficiency and probability of success. This paper discusses the human supervisory control (HSC) implications for use in space, and outlines several areas of current automated space technology in which the function allocation between humans and machines/automation is sub-optimal or under dispute, including automated spacecraft landings, Mission Control, and wearable extra-vehicular activity computers. Based on these case studies, we show that a more robust HSC research program will be crucial to achieving the Vision for Space Exploration, especially given the limited resources under which it must be accomplished.

Keywords: Human supervisory control; Human–computer collaboration; Space; Exploration; Automation

1. Introduction

Recently NASA announced a new Vision for Space Exploration that calls for a sustained program of joint robotic and human exploration of the solar system. This Vision mandates a human return to the Moon by 2020 as a stepping stone for Mars and beyond [1]. Achieving the Vision will require far closer collaboration between humans and robots than previous exploration initiatives, particularly given a limited budget [2–4]. Modern technology provides increasing possibilities for convergence of human and robotic space operations and augmentation of both through various degrees of autonomy [5]. However, the allocation of responsibility between humans and automated agents in order to maximize exploration capabilities remains unclear. There is considerable disagreement regarding the degree to which human spacecraft systems should be automated, particularly during critical mission phases such as rendezvous, docking, and landing [6]. Even in successful robotic missions such as the Mars Exploration Rovers, Cassini and Stardust, regular human intervention is required on a daily basis for mission accomplishment and contingency management, despite the autonomy of these spacecraft.

For potential deep-space human missions, increased on-board automation will be essential for providing maximum situation awareness to the crew and

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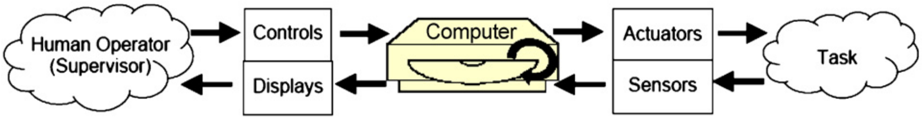

Fig. 1. Human supervisory control (adapted from [10]).

minimizing support from the ground. To achieve this, a new partnership or 'collaboration' between the onboard crew and the system's automation capabilities is necessary. Therefore, a key requirement for future space exploration will be the development of collaborative software and displays that integrate and manage all relevant system and mission data, including spacecraft system health and status, caution and warning, activity execution and mission timeline [7].

Even in current missions, the distinction between human and robotic operations is becoming increasingly blurred, and the number and types of human–machine supervisory interfaces will expand accordingly [8]. For example, unmanned resupply vehicles dock with the International Space Station (ISS) either autonomously or through manual control, either by Earth-based Mission Control or by the astronauts aboard the Station [9]. Similarly, future exploration missions will increasingly feature attributes of distributed control akin to network-centric military operations of today. Again, the development of methodologies to optimize the synergy between humans and machines in utilizing these technologies lags well behind the development of the technologies themselves.

These examples are currently key issues in the field of human supervisory control (HSC), in which a human operator intermittently interacts with a computer, receiving feedback from and providing commands to a controlled process or task environment that is connected to that computer (Fig. 1) [10]. A human is thus not in direct continuous control, which is what occurs in manual control but only intermittently interacts with a system, and attention is typically divided across numerous tasks. The Department of Defense has recognized that a lack of appropriate automation and understanding of relevant HSC issues, as experienced both by individuals and teams, are among the primary barriers limiting exploitation of the full potential of network-centric operations [11]. Similarly, the increasing use of automation in future space systems is a fundamental component of future space exploration which will resemble remote distributed operations; as such, the design of both manned and unmanned future space systems is a HSC problem, which has thus far received limited attention in the space research community. A strong HSC research program will therefore be crucial to achieving the Vision, especially given the limited resources under which it must be accomplished.

To this end, this paper discusses the space exploration HSC implications and presents several areas of current space technology in which the function allocation between humans and machines/automation is sub-optimal or under dispute. First, the longstanding debate over spacecraft automation, particularly automated versus manual landings, is discussed. The possibility of automating aspects of Mission Control Centers (MCCs) in support of space mission operations is then analyzed from two perspectives: the need for automated MCC tools to cope with increasingly complex missions, and the need to reduce operational reliance on MCC, particularly for deep space missions in which real-time communication is impossible. With regard to space exploration, the importance of synergistic human-automation collaboration is highlighted in recent operations with the Mars Rovers. Finally, the case for developing wearable decision support tools for astronaut extra-vehicular activity is presented.

2. Should spacecraft landings be automated?

The role of humans versus automation in manned spacecraft has been vigorously debated since the beginning of human spaceflight. Fig. 2, for example, presents the problem of function allocation between astronauts and automated control systems that was raised at a very early stage during the design of the Apollo spacecraft. Engineers initially believed that they could design a highly automated system (Fig. 2(a)) in which astronauts had essentially no tasking other than to make a single decision as to whether to abort in the event of an emergency. The astronauts, however, fought for more flying and operational control over their spacecraft, with the extreme case (Fig. 2(b)) causing the astronauts to struggle with the heavy operational workload when fully immersed in the complex control loop Despite its antiquity, the cartoon still depicts today's primary concern for HSC design more than 40 years later; how to

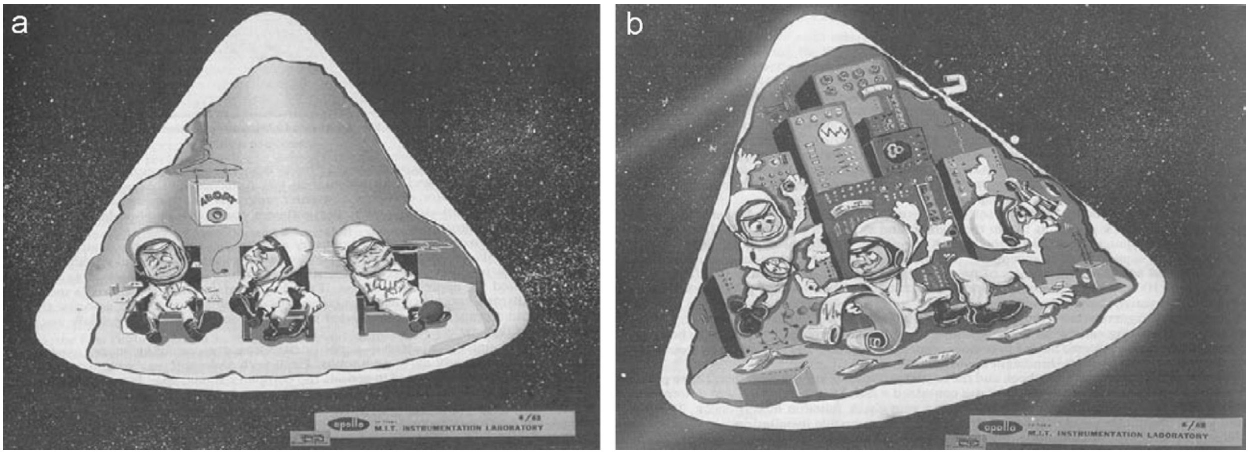

Fig. 2. Caricature of (a) completely automated, and (b) manually controlled Apollo Command Module (MIT Instrumentation Lab (now Draper Lab), 1963).

determine the optimal balance between these two extremes, and design accordingly?

In current space operations, there has been particularly vigorous debate throughout the Space Shuttle program about whether final approach and landing of the Space Shuttle Orbiter should be flown with or without pilot input. The Orbiter has an automatic microwave landing system that has never been flight tested as the risk has been deemed too high, given that there are only a few Orbiters in existence. Furthermore, Shuttle pilots feel use of the automated system would reduce their situation awareness and vehicle control [12]. They may also hold a cultural resistance to automation that is similar to that seen in the US military today. For example, while Army UAVs such as the Shadow are landed using automated systems, the Air Force dictates that human pilots land their Predator UAVs with similar missions, despite the UAVs' onboard auto-land capabilities.

However, even when Shuttle landings are performed manually, the Shuttle pilots do not have complete manual control of the vehicle as their input is filtered by a fly-by-wire control system, as depicted in Fig. 1. The extent to which the fly-by-wire flight control system should alter or limit a pilo's input if the pilot attempts unusual, dangerous, or out-of-envelope maneuvers is also a matter of some debate. The history of the Shuttle program has shown that increased fly-by-wire filtering was necessarily implemented to avoid off-nominal situations such as pilot-induced oscillations that occurred during a subsonic test flight (ALT-5, 1977). Even the addition of a PIO filter, however, did not prevent the occurrence of a PIO during one of the early Shuttle missions, requiring further modifications to the PIO control gains to cope with ground effects [12].

Another argument for performing automated landings is that it may reduce the tremendous cost of training Shuttle pilots to perform manual landings; each pilot typically accumulates 600 practice landings in the Gulfstream Shuttle Training Aircraft before making his/her first spaceflight, and the Shuttle Commander usually logs several thousand [12], incurring millions of dollars annually in training costs [13]. However, these flights are not only designed to train pilots to land but to also train them to deal with contingency and emergency operations during which the onboard automation may not function correctly. Thus, for systems that cannot guarantee high autoland reliability, human training for automated flight control intervention is a safety-of-flight concern. Moreover, it is recognized that higher levels of automation (LOA) cause skill degradation [14], which is of particular concern for an autoland system that is not robust and requires human intervention, albeit rarely.

Viewed from a HSC perspective, these debates can be described using the concept of LOA. As demonstrated by the previous examples, automation is not simply 'on' or 'off', and there is a range of levels where allocation of function can be shared between a human and a computer, [15] outlined a scale from 1 to 10 where each level represents the automation performing progressively more tasks than the previous one (Table 1). The problem of spacecraft automation can then be expressed as the need to determine the optimal LOA, or function allocation that maximizes the probability of mission success.

Table 1
10-point Levels of Automation (LOA) scale developed by Sheridan and Verplank [15]

Level	Description
1	The computer offers no assistance: humans 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

Not surprisingly, the optimal LOA is under dispute not only for the Space Shuttle Orbiter, but also for the next-generation lunar lander, known as the Lunar Surface Access Module [1]. Some are in favor of giving pilots manual control during the final phases of touchdown, as was the case in Apollo, in order to find safe, level landing sites which is a task that detailed mapping and advanced automation may not be able to perform as well as humans [6]. Others contend that modern sensor technology and human-centered design are sufficiently reliable to perform the landing autonomously with the crew taking on a HSC role [16]. Such autonomous landings have the potential to considerably reduce workload, and this and other aspects of higher LOA may even reduce the crew size necessary to manage the landing [17]. Like the debate regarding Shuttle landings, these arguments have thus far been largely qualitative and have not yet been resolved objectively [18].

3. The need for improved Mission Control situation awareness

Space mission operations are a major cost concern, especially as mission duration and complexity increase. During a Space Shuttle mission, for example, more than 150 personnel work directly at MCC alone, in addition to the many engineering staff who are on call in case of an off-nominal situation [1]. This cost may increase further as future exploration programs are conducted over multiple years with increasing mission complexity and capabilities. Furthermore, there may be different elements of the space program operating in parallel, such as a Lunar base and a Mars expedition, with low-Earth orbit components supporting both missions [7].

Despite the number of highly trained personnel, MCC systems generally do not provide ground controllers with sufficient situation awareness to manage those complex missions envisioned for the future. First, MCC systems are not equipped with advanced technology to manage the terabytes of raw data generated daily. Previous attempts to do so have resulted in cumbersome, disjointed databases that lack structure and search capabilities, making information retrieval frustrating and sometimes unsuccessful [19].

Second, Mission Control displays are poorly designed from a HSC aspect. While most displays provide a densely packed screen of telemetry data, only a few provide graphical representation of vehicle systems status. New technological advances in user interface design have not penetrated the MCC, most likely due to the fact that the Shuttle and ISS systems were developed when these technologies were not available [20]. As such, the next generation Mission Control needs to develop new systems not only to intelligently manage large volumes of telemetry, but also to extract predictive information from the raw data and present it to ground controllers, and perhaps even flight crews, in ways that will enhance situation awareness. These improvements will permit fewer controllers to perform higher-level HSC management, rather than the current state in which a large workforce performs comparatively low-level, repetitive tasks.

Developing predictive tools is particularly important because they would have the greatest impact in improving controller performance in their HSC tasks. HSC generally comprises five generic functions, usually accomplished in the following cyclical order: planning a computer-based task, teaching the computer what was planned through various inputs, monitoring the computer's actions for errors and/or failures, intervening when the plan has been completed or the computer requires assistance, and finally learning from the experience [10]. Of these, the planning function has the greatest influence on those discussed throughout this paper, especially determining the proper LOA, minimizing information overload and optimizing distributed operations [11]. Accordingly, development of predictive tools will provide the greatest benefit for MCC operations. A few predictive tools based on fuzzy logic, neural networks and other artificial intelligence concepts have been developed by the European Space Agency for Mission Control operations [21]. However, these tools are, to date, only applicable to small subsystems, e.g. a gyroscope monitoring system or a space weather data warehouse and analyzer, and are only at the prototyping stage.

In addition to the predictive tools, future MCC systems need to be designed such that the workload of each MCC operator is optimized. The objective is not necessarily to minimize workload, since operator performance decreases under both excessive and insufficient workload [22]; rather, it is to find the optimal balance between these two extremes that optimizes operator performance and the probability of task or mission success. The balance is dependent on many factors, including the number and type of HSC tasks being performed and the number of personnel working together as a team to accomplish these tasks.

4. Reduced reliance on Mission Control

While improved MCC situation awareness is paramount, particularly in near-term space operations, the role of MCC for human deep space missions is not clear. Current manned spaceflight programs, including the ISS and the Space Shuttle, are dependent on real-time support from MCC for safe and successful mission execution [7,20]. However, potential human missions to Mars, as well as to the dark side of the Moon raise a new set of system design and operation challenges and requirements, particularly due to the communications time delay.

As such, spacecraft for such missions must have the capability to support critical, real-time decision making without dependence on controllers on Earth or even elsewhere in space. The primary challenge will not be the implementation of the onboard computational power necessary to achieve this capability; rather, it will be to design displays and other decision support tools that allow the flight crew to perform a wide range of HSC tasks, particularly monitoring spacecraft system health and status, which previously was the responsibility of many flight controllers at Mission Control.

To achieve this, the cockpit displays must first provide only information that the crew needs or requests rather than displaying all information simultaneously, as occurred in older steam-gage cockpits of Apollo and the early Space Shuttle [12]. Additionally, the crew should have reconfigurable display space for systems management, which will include health and status monitoring, payload management, flight control data, and mission-specific data. Finally, to reduce crew workload, the system must intelligently assist the crew in monitoring system status by presenting, as well as diagnosing, possible problems and aiding the crew in high workload, time-critical settings [16].

NASA initiated the Cockpit Avionics Upgrade (CAU) Project in 1999 to provide the Space Shuttle with exactly such an “intelligent” capability [23]. The goal of the CAU project was to utilize the potential of the Shuttle’s then-recently implemented glass cockpit to improve situation awareness and performance and reduce workload. The CAU would have decreased, but certainly not eliminated, the reliance of the Shuttle on MCC, particularly during critical phases such as launch. Under CAU, enhanced avionics processing power would have been implemented aboard the Shuttle in order to perform much of the lower-level deductive reasoning previously left to the pilots. The project would also have implemented intuitive task-oriented displays that utilized graphical presentation and the use of color to a far greater extent than the Shuttle’s original “steam-gauge” cockpit, which also allowed for tailoring of display information by flight phase and personal preference. However, CAU was cancelled in 2004 due to lack of funding and the impending retirement of the Shuttle fleet in 2010.

5. Computer–human collaboration in unmanned exploration

The previous sections have implicitly advocated higher LOA that leave the human more in a strictly supervisory role. However, increased automation is not appropriate for all situations. Indeed, recent experience has shown that even in so-called ‘autonomous’ unmanned space systems, humans must at times play a collaborative and interventional rather than merely a supervisory role.

The Mars Exploration Rovers, Spirit and Opportunity, have faced several critical software and hardware failures during their mission. Human creativity and intervention through human–computer collaboration that allowed for modifications of the onboard automation must be credited for the sustained success of the Rover missions. During the mission thus far, seven failures have occurred that would have either ended the mission or severely limited the future of the mission if humans were not remotely present to solve unforeseen problems [24]. The first problem occurred just a week after first rolling onto Martian soil; Spirit stopped communicating with Earth for three days. When mission operations were able to begin receiving data again, the software had serious problems, rebooting itself hundreds of times a day. The problems stemmed from the data structure of the flash memory, which stored information even when the rover was not powered. Mission operators initially overcame the failure by commanding Spirit to reboot with random-access memory, identifying the error, and disabling the flash memory. Modifications were later performed on the flash memory to resume normal operations.

Six months later, a hardware failure occurred after Spirit made a long trek across a Martian plain. After the journey, one of the wheels began drawing increasingly more current, signaling damage to the wheel. The rover engineers developed out-of-the-box solutions by using an Earth-based laboratory that simulates Mars environmental conditions. They created Mars-like sand and experimented with their test rover until they discovered that it could be maneuvered by going in reverse [24]. The simulated environment helped to understand the problem and find a work-around solution, which reflects the importance of the role of human judgment and creativity, particularly in dynamic and uncertain environments.

In addition, the ability of the human to assist the robot was again seen just prior to the landing of Opportunity. After the landing of Spirit, analysis revealed that flight path and software updates were needed because of the unusual entry dynamics. Since Opportunity was the second of the two rovers to land on Mars, ground operators were able to make the appropriate updates at the last minute, and it is speculated that the second rover would have crashed on landing if the software had not been updated.

These examples demonstrate that the Mars rover missions were only successful because humans were in the loop and actively collaborating with the automation, rather than merely supervising it. The missions would have ended within weeks or even days after landing if ground control operators had not been given the option to interject control of software and hardware when necessary. In cases such as this, lower LOA may be more appropriate for maximizing mission success, and further research is warranted to determine both what LOA are appropriate and whether or not dynamic LOA would be beneficial.

6. Wearable decision support tools and integrated displays

The previous sections have demonstrated the need for improved HSC displays and decision support tools to improve operator performance in many aspects of future space missions. Such displays must be developed not only for major assets such as spacecraft and Mission Control, but also miniaturized to be sufficiently portable for individual explorers, particularly astronauts performing extra-vehicular activities (EVA) in microgravity or in a planetary environment away from their spacecraft. As a result, wearable displays and decision support tools will be essential in optimizing a planetary EVA in real-time, which is a highly challenging task that requires the integration of terrain models, physiological models, life support and other operation constraints.

For example, during the Apollo lunar landings of the late 1960s and early 1970s, astronauts relied on a hand-carried laminated paper map and Mission Control to assist them in real-time traverse planning, considerably limiting their ability to cope with unexpected situations during some of the lunar EVAs [25]. In contrast, today's technology has the potential to provide future planetary explorers with far more powerful hardware and software tools for EVA planning and re-planning. For example, Carr et al. [25] developed a wearable situational awareness terminal (WearSAT) that provides text, graphics and video to an astronaut via a near-eye display, with the terminal acting as client on an external wireless network away from the astronaut. This provides not only enhanced display capabilities but also access to considerable computational power from the network that would otherwise be difficult to implement on a spacesuit.

However, optimizing EVAs goes beyond just hardware considerations, as real-time path planning decision support aids must be sufficiently flexible to support astronauts' knowledge-based reasoning in order to solve unexpected problems in a hostile environment while facing critical constraints such as oxygen limits [26]. However, the way in which these supervisory control decision support tools should synergistically collaborate with human judgment to optimize performance under time pressure and high risk scenarios is not well understood. Only a few studies have investigated the effect of automation on path planning or re-planning performance, and there is little research regarding the effectiveness of various algorithms and visualizations for providing operator decision support [26]. Recent research has indicated that the ability of astronauts to conduct sensitivity analyses on computer-generated solutions is a critical component in effective human–system performance. However, the implementation of sensitivity analysis tools and the associated LOA in time-pressured, high risk EVA scenarios remains an area for further investigation.

7. Conclusions

The increasing use of automation in future space systems is a fundamental component of future space exploration which will resemble remotely distributed, networked operations. As such, the design of both manned and unmanned future space systems has significant HSC implications. However, only a handful of projects have recognized the importance of HSC for future space systems. In addition to those described previously, Cummings et al. [16] described a preliminary design for the systems status display of a future lunar landing vehicle which would have considerably reduced reliance on Mission Control without compromising the probability of mission success by layering and grouping information in categories that could be easily and intuitively browsed on reconfigurable screens. Similar upgrades were planned for the Space Shuttle cockpit as part of the aforementioned Cockpit Avionics Upgrade. Unfortunately, these projects were cancelled before they could be implemented in operational spacecraft.

The case studies presented in this paper demonstrate that quantitative methods for determining optimal levels of automation and the appropriate role allocation for human and automation require further development. Although technology has progressed rapidly during the last 50 years of the Space Age, the issues surrounding collaboration between humans and automation are as relevant today as during the Apollo era, yet space human supervisory control research has not kept pace with technological advancements. Significant investment is therefore required not only to develop methodologies for optimizing human–automation system integration, in order to maximize mission safety and success at reasonable cost, but also to ensure that the resulting human-centered design recommendations and requirements are implemented in operational spacecraft, both manned and unmanned. A strong HSC research and development program will thus be crucial to achieving the Vision for Space Exploration, especially given the limited resources under which it must be accomplished.

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