Human-Automation Teaming on Next-Generation Spacecraft

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The sleek exterior of a human-rated spacecraft gives little hint to the very complex (and often interconnected) guidance and navigation systems, propulsion systems, electrical and mechanical power generation and delivery systems, command and data processing systems, communication systems, and environmental control and life support systems that lie within. Operating a spacecraft is thus a combination of familiar flight-related activities, such as docking with another orbital vehicle, and less well-known systems-management activities, such as diagnosing and recovering from mechanical faults and failures.

NASA is currently designing a new generation of crewed spacecraft to return humans to the moon and explore destinations beyond. A fundamental issue for the designers of these vehicles is how to divide operational duties between crewmembers and onboard computers. The issue of *human-automation function allocation* is not new. By the early 1960's, experience with supersonic aircraft had already established that many flight-related operations, such as real-time vehicle guidance, navigation, and trajectory adjustment during ascent and entry, would be difficult or impossible for humans to perform. Fortunately, that era also saw the development of the first digital computers, which enabled those operations to be automated. By contrast, systems-related tasks, such as diagnosing the cause of a caution and warning alarm, tend to involve complex forms of information integration and decision-making that were well beyond the capabilities of 60's era software. Combined with the fact that the operational configuration of the onboard systems (e.g., which valves are open, which are closed) could only be changed by manually toggling hard physical switches in the cockpit, the seeds were sown for a natural division of labor for the vehicles of the Apollo era. In general, flight-related operations were handled by onboard computers, while systems operations were handled by the crew.

The division is less clear-cut on the space shuttles, where many systems operations are performed by software-based controllers. However, the role of these controllers is still largely confined to monitoring normal operations and making pre-determined changes to operational configurations. The controllers have little role in diagnosing systems malfunctions, or in making configural changes to restore a system to normal operations following a malfunction. Thus, even on the shuttles, a relatively sharp division still exists between automated activities and manual activities. Cases where computers and astronauts share operational duties in a truly cooperative fashion, with some task elements being handled by computers and some by crewmembers, are rare.

This situation may be about to change, however. Unlike the shuttles, next-generation vehicles cockpits will feature largely electronic (soft) operational interfaces. This fact, combined with decades of advances in the capabilities of machines to represent knowledge, make inferences, and diagnose systems failures, has created a wealth of opportunities for automation to assist the crew with many more aspects of spacecraft operations than they do at present. However strong the temptation to exploit these opportunities, however, designing an operational concept for a spacecraft that blends human and computer activities effectively presents significant challenges. Today's highly automated aircraft cockpits come complete with many examples of "clumsy" automation that results in pilots being unaware that the onboard automation had taken an action, or having an incorrect or incomplete understanding of automation behavior. In most (but not all) cases, the operational environment of the aircraft is forgiving enough that these problems don't escalate into catastrophic situations. Spacecraft, however, operate in much harsher and more dynamic environments that leave far less margin for recovery from crew confusion or crew error. To be considered for a spacecraft, automation has to meet extremely stringent requirements for reliability, operational consistency and predictability, and behavioral transparency. Moreover, the automation has to buy its way onboard via a careful cost/benefit analysis that directly pits the vehicle weight, computational hardware, and software development requirements associated with the automation, against the performance and safety enhancements that the automation is expected to deliver.

Here in the Human Systems Integration Division of NASA Ames Research Center, we address these challenges with a human-centered approach to the design and testing of cooperative human-machine operations concepts for next-generation vehicles. The first step in the process is to make an empirical determination of what components of a currently manual operation are most difficult for humans to perform. We make these determinations via fine-grained analyses of task performance, including the recording and analysis of eye movements, in ground-based simulations. For example, in a recent study of fault detection, isolation, and recovery in a simulated spacecraft electrical power system, our analyses established that the time taken by operators to bring up and display the appropriate set of reconfiguration procedures added 25 seconds to fault management time. We then developed the underlying software needed to automate this activity, re-designed the operational concept to incorporate the automation (including the development of new crew-automation interfaces), and re-examined performance with the new, more automated concept. It turned out that automating the process of retrieving and displaying fault management information involved a relatively trivial software development effort that functionally linked a pair of onboard databases. Yet, this relatively modest investment resulted in a very significant enhancement in operational efficiency and reduced workload.

These results are encouraging us to pursue more human-machine teaming opportunities that enhance the crew's operational capability. Eventually, we envision that spacecraft will evolve to the point where most onboard operations are team efforts between human and machine agents. Crewmembers will then be able to operate their vehicles in locations too far from Earth to allow for real-time operational assistance from the ground.

References

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