Designing for Flexible Space Operations

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Astronauts usually follow procedures. However, they have also to solve difficult problems in unexpected situations, where operations procedures do not work. Facing the unexpected is always a challenging issue that relies on human knowledge and skills, appropriate organizational setups and good technological support. This position paper presents an approach that combines computer-supported cooperative work (CSCW), supervised machine learning and human systems integration (HSI) towards improved support to space operational problem-solving. Two space cases are presented, which combine technological, organizational and training support for imperative the improvement of safety, efficiency and comfort.

CCS CONCEPTS • Human-Computer Interaction • Computer Supported Cooperative Work • Collaborative & Social Computing

Additional Keywords and Phrases: Human-Centered Design, Human Systems Integration, Machine Learning, Problem-Solving, Situation Awareness, Space Operations

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1 FROM RIGID AUTOMATION TO FLEXIBLE AUTONOMY

This position paper addresses the difficult question of operational problem-solving in space operations when unexpected events occur. It presents an approach that combines computer-supported cooperative work (CSCW) and human systems integration (HSI) – two fields of research and practice that were developed in silos up to now. HSI is a mix of systems engineering and human-centered design (HCD), which involves human factors and ergonomics and information technology (more specifically human-computer interaction and artificial intelligence).

In well-known situations, operational procedures are developed and used. These procedures can be provided to astronauts in the form of checklists and/or dolists. They can also be implemented into algorithms, supervised by astronauts at operations time. Conventional procedures lead to the automation of human functions (i.e., human operators have to follow procedures), and when they are implemented into a machine, usually a computer, we talk about machine automation. These two types of automation work very well within their definition context (i.e., when all possible situations can be expected). However, outside of these contexts, problem-solving is at stake. This kind of task is usually left to operational people involved (i.e., astronauts in space operations). Dealing with the unexpected, such as in the case of Apollo 13 successful accident, requires strong problem-solving capabilities that rely on good **t**echnological support, appropriate **o**rganizational setups, and **p**eople's knowledge and skills (referring to the TOP Model, Boy, 2020). This is a question of function allocation, where rigid automation is good in expected situations, but should lead to flexible autonomy required to solve problems in unexpected situations (Figure 1).

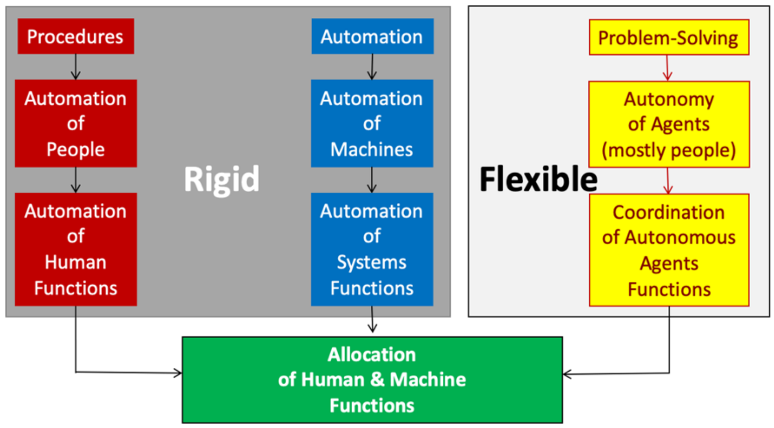

Figure 1: From rigid automation to flexible autonomy.

Problem-solving in life-critical systems is a matter of creativity and collaborative work among a team of experts, who master domain knowledge and skills (e.g., aerospace engineers, computer scientists, astronauts and ground operators). Abductive reasoning is required, where a set of reasonable possible futures should be anticipated and tested as viable solutions together with the steps to reach them. This is the reason why upcoming human missions to the Moon requires creativity and design thinking, involving various kinds of expertise and experience owned by a selected group of subject matter experts. However, problem-solving should not be only allocated to operations people when they are facing unexpected events, it should be part of all phases of the life cycle of a space system. For example, on May 30-31, 2017, I participated in a Mars Social Sciences Workshop at NASA Kennedy Space Center, where we addressed and discussed a set of key research questions such as technology, time, environment, number of colonists, simulation, highest priority problems and showstoppers, Earth-crew connectivity, budget and government decisions, task allocation, privacy, technology lifecycle and HSI (Griffith, 2017). We also addressed and discussed methods and approaches for the design of support systems such as analogs (e.g., Mars 500), not only artificial reality, and actual scenarios, going to the Moon before Mars, look at the government, industries and transportation, and life support systems (e.g., how do we produce the food) in such an extreme environment. One of the recommendations was to test prototypes at different levels that lead to Human Missions to Mars and use analogs and simulations both virtual and physical.

2 FROM HCI TO HUMAN SYSTEMS INTEGRATION (HSI)

Before providing solutions, it is crucial to focus on stating the overall problem correctly. Problem stating is a matter of creativity. Creativity can be defined as integration (i.e., synthesis of several ingredients toward a novel entity). As a metaphor, a painter who wants to create a new color, a kind of orange for example, mixes red and yellow. He or she incrementally integrates red and yellow until a satisfactory orange comes up. Dealing with space sociotechnical systems, the same schema applies. More specifically, manned space missions require appropriate function allocation among human and machine agents, where some potential solutions to a problem could be available on the ground and implemented by the space crew. This requires shared situation awareness among the various agents – this where CSCW is a great support, especially between space crew and ground control.

User interface and automation are concepts of the 20th century bridging the gap between technology-centered engineering and users (i.e., where user interfaces are designed once systems are developed). Virtual engineering and systems tangibility are concepts of 21st century bridging the gap between human-centered design, systems engineering and people. Therefore, HCI should be expanded to HSI, where the concept of systems includes humans and increasingly-digital machines during the whole life cycle of systems (Boy, 2020).

In aerospace, automation was, and still is, typically developed incrementally by accumulating layers upon layers of software – progressively isolating actors (e.g., pilots, astronauts and ground personnel) from actual mechanical systems. This approach requires constant revisions and repairs to adapt people to systems, and rarely systems to people. Instead of repairing after it is too late, it is always better to incrementally improve solutions at design time, using an agile approach. For this reason, an HCD environment should be available where both end-users and designers learn from each other. On one side, designers should learn what end-users (e.g., human operators, astronauts) need, can and cannot do in order to design and develop appropriate technology (e.g., machines, spacecraft). On the other side, end-users should learn how to use new technology. Today, end-users need to understand and practice software-intensive systems management (i.e., a very new endeavor in the history of humanity). Pathways for feedback should be provided to end-users for continuous improvement to take place.

Function allocation between humans and life-critical systems requires not only task analysis (i.e., what is prescribed to the human operator), but also activity analysis (i.e., what this human operator can effectively do when he or she executes the task). To do this, human activity must be observed. This cannot be done without having the whole system to be managed. This is the reason why human-in-the-loop simulation (HITLS) should be developed and extensively used from the beginning of the design process. Virtual prototypes are typically developed and used to this end. Cognitive function analysis (CFA) can support such activity analyses (Boy, 1998). Cognition plays an important role in the interaction between humans and software-based systems. This is the reason why we need to better understand the orchestration of human and machine cognitive functions. More specifically, figurative tangibility deals with cognitive load and human performance (Boy, 2016). Trust and collaboration within autonomous and intelligent systems plays a crucial role. In this paper, the virtual camera concept will be presented as an example of flexible space operations support.

3 THE VIRTUAL CAMERA AS EXPLORATION SUPPORT

The Virtual Camera (VC) project is a great illustration of what design for flexibility is about (Boy & Platt, 2013; Boy, 2021). The VC concept emerged from the early test of the Lunar Electric Rover (LER), renamed Space Exploration Vehicle (SEV), developed by NASA for the exploration of the Moon. Indeed, driving a vehicle in a seldom known environment is a difficult task that often requires problem solving. Even in a well-known environment such as reconstructed scenery of the moon at Johnson Space Center, we realized that the astronaut driving the LER needed external advice to move safely. The idea of a virtual camera came up as a “third person view”, as if someone outside the vehicle was able to see the scene and help the driver to move safety and efficiently. We extended the VC concept to more general planetary exploration. In particular, when the exploration is performed from the Earth. A virtual camera basically provides data that experts will further analyze to produce knowledge, e.g., the rock is brittle, round, or sparkly. In addition, current knowledge can be visually represented as complete or incomplete. For example, a planetary surface could be displayed with shaded areas representing unexplored regions, i.e., knowledge holes. These knowledge holes could be assessed by domain experts through possible interpolations or extrapolations, and eventually decide to send scout rovers to explore and appropriately sense terrain. VC is being designed to support risk mitigation by providing the ability to investigate possible futures based on the best possible data as well as choosing the right tools and systems to achieve the mission. A virtual camera includes geometrical information, in the form of a database, which evolves with time – this involves supervised machine learning algorithms. Typically, consecutive versions are incrementally published. They should also be traceable and easily retrieved, possibly over long periods of time. Each version should be published with associated meta-data. New data recently observed should also be easily incorporated into the existing intrinsic VC information and be a departure for new investigations.

Let's assume that we have a very well-known environment that is watchable via appropriate numerical sensing devices, i.e., providing a set of 3D pixels, which we will call a 3D scene. This 3D scene can be approximated by various kinds of finite element representations. A purposeful 3D scene needs to have useful and usable attributes to support the task it is needed for. In the case of planetary exploration, such attributes are typically related to geometrical and/or geological dimensions. A VC is a piece of software that provides such a 3D scene resulting from various kinds of available data. How can we generate purposeful 3D scenes? First, a VC is equipped with a data/knowledge base and a processor that controls what to present to its user with respect to the situation (context) and user's demand. There might be areas of the scene that are not very well known, e.g., either some attributes of the scene are not sufficiently known or the resolution is poor. In this case, VC may adapt the scene using extrapolations. A virtual camera includes augmented reality features that either compensate 3D data-poor scenes or provide useful interpretations and advice to the user. Several kinds of inputs will be available including direct camera view, re-construction of the relative position of the LER with respect to the planetary surface, and laser and mass spectrometry data. These various kinds of data are fused and augmented to provide astronauts with meaningful information for navigation and exploration. Note that VC control can be done either directly in the vehicle itself or from a remote station.

Consequently, a virtual camera is a mathematical object that is able to move in 3D space around physical objects, a rover for example, to provide the view of these objects in their environment from the point where the camera is located. Obviously, we had to test that VC is easy to manipulate and visualization is clearly understandable and affordable. The VC CDU enables its user to get an appropriate mental representation of the actual situation. This kind of feature is a great support for problem solving when needed. Further details will be presented during the workshop, as well as other virtual camera applications.

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