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Human-model interactivity: what can be learned from the experience of pilots with the glass cockpit?

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Abstract

Systems engineering is rapidly evolving to a model-centric paradigm, with significant progress on modeling languages, approaches and practices. Within the context of a larger research program on interactive model-centric systems engineering, this paper focuses on the cognitive and perceptual aspects of intensive human-model interaction. Lacking a specific body of empirical evidence, we investigate relevant findings and lessons learned from the experience of aircraft pilots with glass cockpits and virtual displays. We postulate that relevant similarities exist for system designers and decision makers within immersive model-centric environments, with increased automation, interactivity and abstraction of systems information. The paper discusses the findings of this case investigation, along with implications for an ongoing project on heuristics and biases of relevance for interactive model-centric engineering theory and practice.

Keywords: Models; Human-Model Interaction; Glass Cockpit; Interactive Model-Centric Systems Engineering

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1. Introduction

Models are increasingly used in decision making in systems engineering, yet while human users are an essential piece to a model's success, research into human-model interaction has been lacking[1]. Rhodes and Ross express that models "represent an abstraction of reality," and "can come in a variety of forms and formats, but fundamentally they are an encapsulation of reality that humans use to augment their ability to make sense of the world and anticipate future outcomes"[1]. The idea that "humans use" models highlights human interaction as a necessary factor for all models. Given this common characteristic of human interaction, we propose that experiences gained in one model-centric situation can offer insight into entirely different model-centric environments.

Within aircraft, cockpit displays present pilots with models of the aircraft's state in order to facilitate appropriate decision making and action. This paper explores the experience of aircraft pilots with digital "glass cockpit" displays in an effort to draw out lessons learned from the glass cockpit's impact on human and system performance. Through case studies of aircraft accidents and subsequent research findings, areas of concern in the interaction between glass cockpits and human pilots are identified. Lessons are drawn from substantial research that has been conducted to not only retroactively address accidents, but also to identify areas susceptible to failure and to determine the causes of these failures, with an end goal of mitigating future occurrences of accidents. Operating on the premise that the cognitive and perceptual issues found in the cockpit transcend to broader terms of human-model interaction, we investigate these lessons in order to spark discussion and thought into the role of human-model interaction within the emerging field of interactive model-centric engineering.

Background – Interactive Model-Centric Systems Engineering

The Interactive Model-Centric Systems Engineering (IMCSE) project aims to develop transformative results in engineering projects through intense human-model interaction. Designers conceive of large sets of feasible designs and interact with models to make rapid trades and decide what design is most effective given present knowledge, future uncertainties, and practical resource constraints. An invited workshop held in January 2015 seeded a research agenda around the topic of human-model interaction, identifying research needs from both a model-centric perspective and an interactive perspective. Participants agreed that progress has been made on standards, methods and techniques for model-based systems engineering, yet little attention has been given to human-model interaction. A science of human-systems interaction has emerged, but focuses on operational systems[2]. Human-computer interaction is another similar field with useful knowledge and principles extensible to IMCSE, but the emphasis is on the design of displays. IMCSE focuses on human interaction with models and model generated information, and enabling effective model-centric decision making.

1.1. Shift to Model-Centric Paradigm

Over the past several decades the work environment of the engineer has shifted from a hands-on workbench type of environment to model-centric work stations and collaborative laboratory environments (Fig 1). As model-based engineering continues to evolve, engineers will increasingly work with many types of models. These models will range from highly abstracted representations to realistic multi-dimensional models. Systems of the future may also have digital twins, a model-centric replica of the operational system. Advances in model technology and computational resources have been steadily made, and the laboratory environments have become increasingly sophisticated. Yet, the many facets of the human-model interaction experience remain relatively unexplored. Learning from past situations with similar considerations is a useful place to start in investigating the human aspects.

Fig. 1. Shift from the ‘workbench’ to model-centric environment

2. Glass Cockpits and Automation Related Accidents

The term “glass cockpit” began making its way into the aviation community in the 1970s with the transition from the use of electromechanical instruments to electronic flight displays. Used initially to describe displays incorporating cathode ray tubes, “glass cockpit” has since evolved into a descriptor for digital flight displays and automation systems within aircraft in general[3]. The arrival of the glass cockpit equipped Boeing 757 and 767 in the early 1980s ushered in the use of glass cockpit and automation technology within commercial aviation, progressing to become standard design in nearly all modern aircraft[4]. This new technology sought to improve system functionality by increasing human capability and efficiency through automation of flight operations and ultimately allowed the crew composition of commercial aircraft to be reduced from three to two members[5]. As noted by Endsley, however, these benefits from automation also accompanied changing the pilot’s role from flying to monitoring an automated system, a “role people are not ideally suited to.[6]” Analysis of aircraft accident case studies provides insight into challenges that glass cockpits and associated automation have caused for pilots within the cockpit environment.

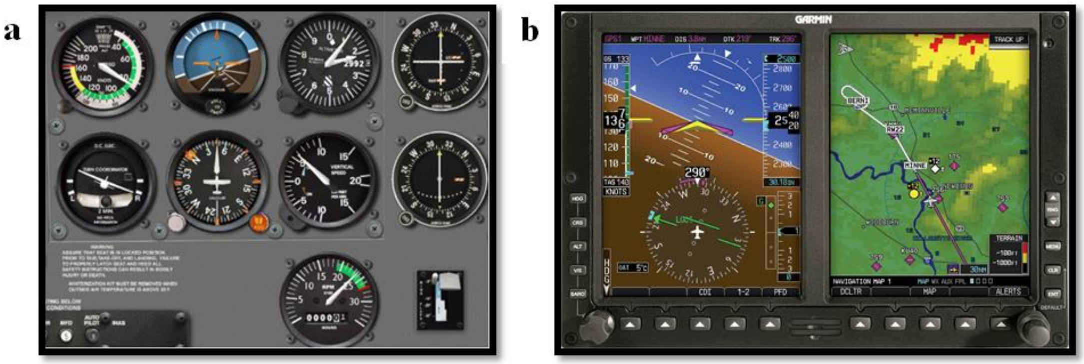

Fig. 2. (a) traditional, analog cockpit; (b) glass cockpit.

3.1 Nagoya

On April 26th, 1994, while piloting an Airbus A300-600 on landing approach in Nagoya, Japan, the First Officer (FO) mistakenly engaged the Go-Around mode as the aircraft neared 1000ft above ground level. The aircraft appropriately responded by autonomously adding power and initiating a climb that the FO tried to manually counteract in order to keep the plane on the appropriate glide path. While the Captain noticed the erroneous initiation of the Go-Around mode and told the FO to disengage the mode, the FO failed to do so. The FO managed to halt the plane's ascent and engaged the autopilot; 19 seconds later, however, the autopilot caused the plane to pitch up again and the FO subsequently disengaged the autopilot. Around 570ft, the aircraft sensed near-stall conditions and autonomously staged a stall recovery which began a climb once again. This time the pilots were unable to stop the climb which ultimately led to a stall, inadequate time for recovery, and a tail-first crash landing killing 264 of the 271 individuals onboard[7].

3.2 Strasbourg

The next case example occurred in Strasbourg, France on January 20, 1992 when an Airbus 320 impacted the ground while on descent for landing. Prior to beginning the approach, the crew received last minute instructions from Air Traffic Control to complete a straight in landing rather than the expected circling approach. This unanticipated guidance resulted in an increased workload for the crew as they worked to complete the preparations for landing in an earlier than expected manner. As part of the preparations, the crew entered the number "33" into the flight computer to set the appropriate glide path angle of -3.3 degrees. They failed to realize, however, that the computer's mode was set to rate of descent and that they actually commanded the aircraft to descend at 3,300 ft/min. The aircraft proceeded as was mistakenly directed and subsequently crashed into the ground well short of the runway, with only nine of the 96 individuals onboard surviving[4,8].

3.3 Cali

Reminiscent to the event at Strasbourg, an American Airlines Boeing B757 received Air Traffic Control guidance on December 20, 1995 to complete an unplanned, straight-in landing approach for its destination, Cali, Colombia. Needing to adjust their flight plan to complete the approach, the crew proceeded to enter in the next appropriate navigation waypoint, "ROZO," into the flight computer. After inputting "RO," however, the waypoint "ROMEO" was the first available point on the list which the crew mistakenly selected; the aircraft then began navigating to a waypoint located 132 miles away from the destination. Approximately a minute following the plane's course adjustment away from Cali, the crew realized their mistake and reprogrammed the flight to the appropriate point, ROZO. Assuming the situation rectified, the crew failed to realize the deviation from the original flight path set the airliner on a collision course with a mountainside. Only 4 individuals out of 163 survived the crash[4,9].

3.4 Human-Automation Breakdown

The three case examples underline a similar theme in that they would not have occurred in the absence of highly automated equipment within the cockpit – all demonstrating a breakdown of human interactivity with the aircraft that ultimately led to devastating results. This evidence opens the door to questions concerning the causes and potential mitigations of these errors along with presenting an opportunity to gain insight into human-model interactivity, specifically in highly automated environments like those found in aircraft.

3. Cognitive Coherence

The transition of aircraft cockpit technology has largely changed the role of the pilot from one that requires "stick-and-rudder" skills, to one primarily concerned with programming and monitoring the aircraft's automation[10]. As described by Mosier, this shift in the pilot's role also accentuates the importance of coherence competence: "an individual's ability to maintain logical consistency in diagnoses, judgments, or decisions"[10]. The displays within aircraft present nearly all of the necessary data to safely fly the plane, and if the pilot can maintain coherence and take appropriate action throughout the entirety of the flight then the pilot has succeeded. Mosier also notes that many piloting errors manifest themselves as failures of coherence in that they fail "to note or analyze important information in the electronic 'story' that is not consistent with the rest of the picture"[8]. The outcomes of the previous cases all resulted from a failure to maintain coherence throughout the entire flight. While maintaining coherence is a primary objective for pilots, there are many means through which automation can contribute to the breakdown of effective coherence.

3.1. Automation Bias

Mosier and Skitka define automation bias as “the use of automation as a heuristic replacement for vigilant information seeking and processing,” which can result in commission errors (incorrectly following an unverified automation directive) and omission errors (failing to identify an issue not identified by an autonomous system)[11]. An everyday example of a commission error would be a driver blindly following a GPS navigation aid’s incorrect directive to turn the wrong way onto a one way street. Additionally, missing the proper highway exit due to lack of warning from the navigation system would constitute an error of omission[12]. Specifically related to human interaction with automated decision aids, automation bias seems to be influenced by three different factors. First, humans often choose to proceed down the path of least cognitive effort. This can lead to using automated aids as strong decision making heuristics while failing to seek out all relevant information to develop the full, coherent picture of the situation. Humans also exhibit a tendency to perceive automated decision making and performance as superior to their own, leading to an overestimated trust that the system is performing appropriately for the given situation. A third factor influencing automation bias is the phenomena of perceiving automated aids as fellow crew members and diffusing responsibility. This can lead to a “social loafing” behavior where human operators perceive themselves as less responsible for the system performance and outcome[12].

The accidents at Strasbourg and Cali offer examples that manifest potential instances of automation bias. At Strasbourg, after the initial mistake of entering the data as a descent rate rather than flight path angle, the crew failed to vigilantly validate the aircraft’s descent against other relevant forms of information, thus committing an error of omission. In the landing approach to Cali, the flight computer suggested the incorrect waypoint, ROMEO, and the crew committed a commission error by blindly following the automated suggestion and not adequately processing the information they received.

3.2. Complacency

Definitions of complacency include: “self-satisfaction that may result in nonvigilance based on an unjustified assumption of satisfactory system state,” and “a psychological state characterized by a low index of suspicion”[12]. Pertaining to aviation, one can readily imagine the negative impacts pilot complacency can have on the safety of flight; in fact, an early 1970’s study by NASA on the effects of automation in the cockpit identified complacency as a key area of concern for pilots when questioned on their perspective on automation’s potential impact on safety[13]. Research by Parasuraman and Manzey goes on to define automation complacency as “poorer detection of system malfunctions under automation control compared with manual control”[12]. This failure in achieving a fully coherent picture typically manifests itself under periods of high, multi-task work load, and constitutes an active diversion of attention from automation to other manual tasks[12]. While this relocation of attention resources may be an understandable reaction of pilots under high workloads, it is by no means an acceptable response as it is the pilot’s job to remain aware of all relevant information and processes, and failure to do so can produce devastating results. Although readily understood and accepted as undesirable, complacency presents a challenge in that complacent behavior may seldom produce negative results since systems typically operate as expected. This can lead to failure of awareness and even possible acceptance of the behavior. In highly intensive and unforgiving systems like aircraft, however, all it can take is one unnoticed failure for there to be grave consequences.

Complacency is closely related to automation bias as they both present manifestations of similar attentional issues. Most similarly, both automation complacency and automation bias can result in errors of omission. Complacency can result in this error from failure to appropriately monitor the automation itself due to diversion of attention, while automation bias results in failure to adequately monitor the system as a whole due to a bias that the automation will warn the operator if something goes wrong. All the case examples appear to exhibit complacent behavior to some degree. In Nagoya, the FO’s mistake of engaging the Go-Around mode could have been an innocent mistake, but both his failure to appropriately monitor the automation and fix the error along with the captain's failure to ensure situation rectified lend themselves to complacent behavior. Both Strasbourg and Cali also show examples of incorrectly assumed satisfactory state of the system and automation although non-complacent behavior likely would have detected the mistakes in time.

3.3. Mode Error

Modes serve as a means through which automation can extend human capability by structuring complexity and presenting users with varying levels of control styles (i.e. "modes" of operation)[14]. Glass cockpits have capitalized on the use of modes by giving pilots means to tailor the aircraft's automation to specific situations and preferences[14]. Yet, as with most technology, new capabilities are closely paired with new pathways to potential failure. Specific to modes, a breakdown in coherence can occur when the human operator "loses track of which mode the device is in." Known as mode error, this breakdown results in a misinterpretation of the situation and unwanted system responses to given inputs[15]. Research suggests that mode error occurs through a combination of "gaps and misconceptions" in operators' model of the automated systems and the failure of the automation interface to provide users with salient indications of its status and behavior[16]. This propensity for lack of mode awareness in glass cockpits was accentuated by a NASA study in 1989 where 55% of pilots encountered automation surprises after more than one year of flying in glass cockpit aircraft [5,16].

Indeed, the Strasbourg accident clearly shows a crew committing mode error by failing to realize that they entered "33" into the descent rate mode rather than the desired descent angle mode. Had the crew maintained the proper awareness of the system's actual mode, they would have switched to the proper flight path angle mode without an issue and avoided their deadly error. Similarly at Nagoya, the aircraft responded appropriately given the Go-Around mode that was inadvertently commanded, yet the crew failed to understand the response of the aircraft and how to appropriately handle it, which ultimately led to the crash.

4. Perceptual Challenges

A successful system design must not solely take into account how information is cognitively processed, but also how information is perceived. The previous case examples have shown areas where glass cockpit technologies can contribute to cognitive failures, but additional research on the transition from analog to glass has revealed areas of perceptual failure. This aspect of perception must also be addressed in the design of an effective system.

4.1. Human-machine Interface

From a performance point of view, a simple question can be asked when discussing analog and glass cockpits: which results in better performance? The purpose behind transitioning to glass was not only to make the pilot's job easier through increased automation, but also to enhance the performance and safety of the aircraft overall. While glass cockpits have undoubtedly provided benefits in many aspects of flight, they do not necessarily yield better performance in all areas. A study by Wright and O'Hare compared simulator flight performance between participants using traditional analog instruments and those using advanced glass cockpit displays, specifically comparing performance in loss of control events, and accuracy in maintaining altitude, airspeed, and heading[17]. The results showed that the traditional cockpits actually resulted in better overall performance, corroborating with a separate study conducted by Hiremath et al. which demonstrated that glass cockpit users had longer recovery times from unusual attitude situations than traditional cockpit users[18]. One explanation for this disparity stems from the manner in which relevant information (airspeed, altitude, attitude, etc.) is presented and received. Traditional cockpits use individual round dials with indicator needles for each piece of flight information, while glass cockpits integrate much of the data into a computer display and present airspeed and altitude as a moving tape with an exact readout (see Figure 2). Dial instruments offer a means for obtaining information at a glance by allowing pilots to see where the needle is in relation to the whole range of numbers rather than requiring an exact readout as found on glass displays[18]. This ability to take in information at a glance allows the pilot to more quickly assess the state of the aircraft and adjust accordingly. Safe piloting does not necessarily require adherence to an exact number, as it is more important to stay within an appropriate range of numbers. Glass cockpits do not include the entire range of numbers which makes it harder to discern if the aircraft is in the appropriate range. These studies indicate that system designers must not only understand what information must be presented to users, but also understand how to present the information in a manner that most effectively accomplishes the tasks at hand.

4.2. Preference-Performance Dissociation

An important factor to consider in evaluating performance is not merely how the user objectively performs, but also how the user *thinks* he or she is performing. In the Wright and O'Hare study, the pilot test participants unanimously rated the glass cockpit superior to the traditional display. In their perception, the glass cockpit offered the "most awareness-enhancing, the least mentally demanding, and the easiest to interpret" display with the "fewest disliked features"[17]. Despite this perceived superiority, the pilots actually performed worse with the display they preferred the most. This highlights a phenomenon known as "preference performance dissociation" where users' preferences do not line up with their performance[19]. In the case of glass cockpits, Wright and O'Hare postulate that simply the use of bright, highly contrasted colors results in the superior feedback as humans have been shown to prefer color as opposed to lack thereof[17]. This presents a need to understand that users do not necessarily know what is best for them, and that sometimes "user-centered" design should involve designing for how the user actually performs, and not just for what the user wants.

5. Implications for IMCSE

No analogy is perfect, and we readily acknowledge that the glass cockpit-to-IMCSE analogy is not excluded from this rule. One of the most obvious differences between flying a plane and model-centric systems engineering is the criticality of time in relation to successful (or unsuccessful) results. In an aviation environment, many decisions and subsequent actions must be performed rapidly to ensure proper control and safety of the aircraft, with an increased time pressure workload demand shown to greatly affect performance and propensity for error[8]. Modeling environments, on the other hand, have much greater margins of freedom in regards to time required between recognition of a need and required action. Basically, modelers do not have the threat of imminent death if they take some time solving a problem. While decreasing time pressure can indeed help mitigate challenges of automation-related errors, it does not completely ameliorate the possibility of humans making mistakes while interacting with automation. Additionally, one can reasonably foresee modeling environments changing with technology for much of the same reasons as cockpits have to include: increased human capability, greater efficiency of operations and human resources, etc. The increased capabilities that automated and intensive modeling environments provide would not only allow for work to be accomplished at a quicker pace, but could also increase time-pressures for modelers, exacerbating the existing propensity for error.

5.1. IMCSE and Automation Scenario

Imagine a new modeling environment like the one illustrated in Figure 1. This environment seeks to create greater efficiency and optimality in decision making by incorporating the benefits of increased modeling autonomy and multi-stakeholder collaboration. Decision makers in this environment can create and share real-time exploration and changes to models, facilitating the understanding of how design choices impact desired stakeholder preferences and system performance. In this example, your team is working on developing an overdue recommendation to determine what design the project will move forward with, and must arrive at a final solution by the end of the day. You and your fellow team members are separately working with different models to perform analysis tasks previously accomplished by multiple people over longer time. Now, automated decision aids and state of the art software help facilitate cross-model analysis and convergence, resulting in an interim outcome that reflects what you expect to see. Assuming the automated system accurately determined what you had requested, you accept the outcome at face value and allow the model to continue further analysis toward a solution as you leave for a quick coffee break. While you are away you fail to realize that the model was operating, and continues to operate, in an incorrect mode. Never encountering any issues before and trusting in the system's high fidelity, you accept the model's flawed recommendation and share the result with your teammates who also consent to the recommendation without critique; there have been no problems before, plus the day is late and everyone wants to go home. While much quicker than previously possible, the decision making process was interwoven with automation bias, mode error, and complacent behavior under increased time pressure which results with settling upon a suboptimal design.

6. Mitigating the Challenges of Human-Automation Interaction

Up to this point, the paper has explored potential areas of failure and challenge in the realm of human-automation interaction with the end goal of extrapolating these lessons to human-model interaction. We have seen how the transition to glass cockpits fundamentally changed the role of the pilot in the cockpit, invariably creating new challenges that the pilot must overcome. This next section serves as an introductory exploration into potential means for mitigating the negative effects of human-automation interaction in the cockpit and implications for the model-centric workplace. By no means are these fully developed solutions, but rather they should serve as an introduction to potential guiding principles for developing interactive model-centric environments.

6.1. Accountability

The use of social accountability has been demonstrated as effective in mitigating various cognitive biases to include primacy effects, the fundamental attribution error, over-confidence effects, and the "sunk cost" effect[21]. Taking this a step further, Skitka, Mosier, and Burdick go on to test the efficacy of accountability in ameliorating the effects of automation bias. A study by Mosier et al. found that pilots who "reported a higher internalized sense of accountability" verified correct automation functioning more often and committed fewer errors in the automated environment[20]. This matches well with earlier research that found that properly channeled accountability results in mitigating automation bias through lower rates of automation bias related errors[21]. Automation bias presents a clear pathway of coherence breakdown in the human-model interaction, and the use of adding accountability offers a means for ameliorating this issue. While the means of assigning accountability can be varied in application and effectiveness, it is important to note that assignment and internalization of accountability can have important effects towards limiting automation bias. Little research is available that specifically addresses accountability and automation complacency, but the similarity between complacency and automation bias suggests a potential link between accountability and complacency as well.

6.2. Transparent Systems

Achieving coherent mode awareness, the ability to effectively understand, follow, and anticipate the behavior of automated systems, is the understandable solution for preventing mode error[16]. Mode error does not necessarily result from complacent or biased human behavior, but rather from the fact that users can sometimes fundamentally lose track of what mode the system is in. Specifically addressing aviation, Besnard and Baxter, argue that the development of transparent flightdecks begins to address the issue of achieving mode awareness[9]. Along this line of thought, modeling environments should enable transparency as needed and allow the user to understand, follow, and predict the automation's behavior. Designing for model transparency could contribute greatly to reducing automation surprises and subsequent errors by model users by offering increased insight into the actual functioning of the models

6.3. Human-Centered Design

As long as human operators bear ultimate responsibility for system performance, they must be integrated into the system and provided with all relevant information needed to assess the system's performance, state, and behavior[16]. With this in mind, the challenge in design becomes one that focuses on the effective integration of the human into the system rather than forcing the human to adapt to the system; in other words, human-centered design is needed rather than technology-centered[16]. Some of the issues with modern automation in cockpits result from including technology simply because it is technically feasible[9]. This approach can lead to a highly capable system, but very ineffective system if the human is not appropriately designed for. Norman emphasizes this paradigm shift in design thinking by rephrasing the motto of the 1933 Chicago World Fair from "Science finds, industry applies, man conforms" to the contrasting idea of "people propose, science studies, technology conforms"[16]. Continued focus on human-centered design within model-centric environments is needed in order to advance the compatibility, success, and effectiveness of human-automation model interactions.

7. Conclusion and Future Research Directions

As technology has evolved and developed in its capabilities, models have similarly progressed to include greater fidelity and functionality in the pursuit of more adeptly abstracting reality for the use of designers and decision makers. IMCSE stands as a developing field of study which could provide developers effective tools for efficiently realizing successful systems through intense human-model interaction enabled by new technology. With innovative ideas and technologies, however, also come new sources of potential failure. As a means for sparking thought and discussion, this paper has presented the introduction of glass cockpits into aircraft as an analogy case for addressing potential issues to be faced with interactive model-centric environments.

The use of advanced technology in cockpits manifests itself primarily through an increase in autonomy that not only changes the role of pilots, but also adds an additional component: manager of systems[9]. While this technology has been successfully integrated into modern aviation, it also highlights the continued importance of considering the human interaction with technology, as specifically evidenced by disastrous examples. The discussions on the cognitive coherence failures of automation bias, complacency, and mode error combined with perceptual areas of concern provide a starting point for educating model developers, model users and decision makers on ways that effective human interaction with model-centric technology is prone to failure. Offered not as fully developed solutions, but rather initial guiding principles for mitigation, the heuristics on the importance of accountability, transparency of systems, and human-centered design begin to address means for mitigating potential failure points and achieving greater effectiveness in the realm of IMCSE.

Research is ongoing to further explore the lessons from situations where humans interact with abstracted representations and models (e.g., power plant control center, intelligent transportation models, supervisory control systems, etc.). The work seeks to determine the most relevant findings from these studies, as well as the principles adaptable from other fields such as Human-Computer Interaction (HCI)[22]and Human Systems Integration (HSI)[23].

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