Human-Automation Interaction for Lunar Landing Aimpoint Redesignation

By
Jennifer M. Needham
B.S. Mechanical Engineering
Rice University, 2006

Submitted to the Department of Aeronautics and Astronautics
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Abstract

Human-automation interactions are a critical area of research in systems with modern automation. The decision-making portion of tasks presents a special challenge for human-automation interactions because of the many factors that play a role in the decision-making process. This is prominent in human spaceflight, where the astronaut must continually interact with the vehicle systems. In future lunar landings, astronauts working in conjunction with automated systems will need to select a safe and achievable landing aimpoint. Ultimately, this decision could risk the safety of the astronauts and the success of their mission. Careful study is needed to ascertain the roles of both the human and the automation and how design can best support the decision making process.

The task of landing on the moon was first achieved by the Apollo program in 1969, but technological advances will provide future landings with a greater variety and extensibility of mission goals. The modern task of selecting a landing aimpoint is known as landing point redesignation (LPR), and this work capitalizes on an existing LPR algorithm in order to explore the effects on landing point selection by altering the levels of automation. An experiment was designed to study the decision-making process with three different levels of automation. In addition, the effect of including a human-generated goal that was not captured by the automation was studied.

The experimental results showed that the subjects generally used the same decision strategies across the different levels of automation, and that higher levels of automation were able to eliminate earlier parts of the decision strategy and allow the subjects to select a landing aimpoint more quickly. In scenarios with the additional human goal, subjects tended to sacrifice significant safety margins in order to achieve proximity to the point of interest. Higher levels of automation allowed them to maintain high levels of safety margins in addition to achieving their external goal. Thus, it is concluded that with a display design supporting human goals in a decision-making task, automated decision aids that make recommendations and assist communication of the automation's processes are highly beneficial.

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Publication of this thesis does not constitute approval by Draper Laboratory of the findings or conclusions herein. It is published for the exchange and stimulation of ideas.

Jennifer M. Needham

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Chapter 1 Introduction

1.1 Motivation

The Human Interactive Mission Manager (HIMM) is an extension of Draper's autonomy technology, the All-Domain Execution and Planning Technology (ADEPT) framework (Ricard and Kolitz, 2002) to enable human interaction. ADEPT-based autonomous systems have been developed and demonstrated in several domains, but with the addition of human interaction mechanisms, the capabilities and relevant domains will be broadened to include missions that require an operator in the loop, either onboard or remotely.

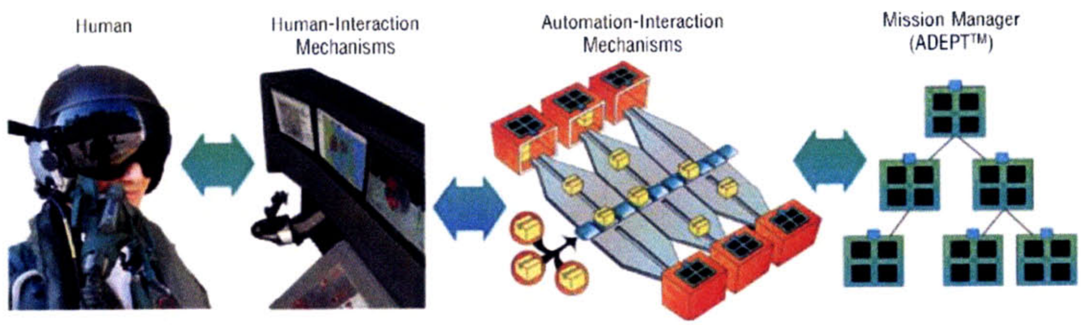

Figure 1: Representation of the HIMM (Draper Explorations Magazine, 2008)

The automation-interaction mechanisms, shown in Figure 1, translate the data that is exchanged between the human and the autonomous mission manager (Furtado, 2008). The human interaction mechanisms include the displays and the input mechanisms that the operators will need to understand the system and to formulate and provide input. The displays are crucial components of the HIMM because they are the primary source of information to the operators, allowing them to see into the so-called "black box" of automation. Depending on the application, operators can have a limited understanding of the automation and therefore form their understanding on what the automation is currently doing based on information that is communicated through the display interface.

Since the operator depends on the displays for information about the system, the displays must account for the operator's limitations concerning the amount and types of information that he or she can understand. The display designs must also account for the impact of time constraints on the information to be displayed, and how an operator will use this information to make decisions to guide the automation. These decisions can lead to mission success or failure, so the display design becomes increasingly critical.

1.2 High Level Research Objectives

The goals that need to be addressed for an effective HIMM design are: (1) establish the human workload at an appropriate level; (2) capitalize on human insight for the knowledge-based tasks; (3) evaluate strategies on the types/levels of data the operator can manipulate; and (4) develop methods for conveying autonomy information to the human in a consumable manner. These four goals are intended to shape the human-automation interaction design at the level that is appropriate across multiple domains.

To address these goals, an example problem was used. The HIMM is most useful for complex, time-critical applications, in which a human alone cannot effectively monitor and intervene when necessary, but there is an opportunity for a person to be a part of the decision process. This opportunity arises either because there are people onboard the vehicle or because there is a remote connection with the vehicle. The problem used in this thesis addresses an aspect of lunar landing, specifically the tasks surrounding selecting a safe landing aimpoint at the end of a lunar lander's descent.

The concern for human workload as the human interacts with automation is based on workload issues that have emerged with other automation systems. Although automation has been shown to reduce task workload (Wickens and Hollands, 2000), it can also change the nature of the workload from primarily physical to primarily mental. Parasuraman et al (2000) suggested that correctly designed automation provides an appropriate level of mental workload that prevents the user from becoming overwhelmed. However, inappropriately designed automation can have the opposite effect.

The Skills, Rules, Knowledge (SRK) framework was developed by Rasmussen (1983) to describe different operator behaviors. Skill-based behaviors are primarily sensorimotor tasks, requiring little or no conscious control to perform or execute an action once an intention is formed. Rule-based behaviors are characterized by organized rules and procedures. Knowledge-based behaviors primarily occur in novel and unexpected situations and rely on knowledge of the system to analyze the system and form goals and actions. Since knowledge-based tasks represent a more advanced level of reasoning, it is appropriate to capitalize on human insight for these tasks.

An important aspect of human-automation interaction is the detailed nature of the interaction capabilities. From both the operator's and automation designer's viewpoints, unlimited interaction capabilities are undesirable and unrealistic. No single rule exists about which types of data and which levels of automation are most appropriate for the operator. Yet there are strategies that can be derived, theoretically or empirically for the HIMM. In this thesis relevant theories on expert decision making are presented and applied to a lunar landing problem. This analysis leads to information requirements used to develop operator displays, which were then evaluated through experimentation.

1.3 Specific Research Objectives

It will be discussed in detail in future chapters that the landing point redesignation (LPR) decision is a knowledge-based task, especially in off-nominal situations. The human's insight is important in this human-automation interaction when the human brings to the table information that is outside of the automation's programming and knowledge sources. However, to capitalize on this insight in a highly automated system, allowance for the expression of such insight should be made early in the design phases of the system. This allowance is given in the choice of levels of automation that will be studied; levels of automation that are too high risk shutting out the human's insight for knowledge-based tasks.

Data manipulation by an operator is affected by the previous two concepts of workload and knowledge-based tasks. Especially in the lunar landing domain, time is a limiting factor to any operator's strategy for data manipulation. For the LPR decision, the primary data is the safety criteria and the position of the landing aimpoint. By increasing the level of decision making automation, the operator is manipulating higher, more abstract levels of data. By adding a point of interest, the operator is incorporating a different, non-automated type of data.

A research goal that will be indirectly addressed by the experiment is the development of the algorithm representation to convey information about the algorithm to the human. Since the representation will be used in all three levels of decision making automation being tested, the subjects' ability to understand and use the representation will only be indirectly studied. Since Sheridan's 10 levels are purposely generic in nature, specific implementations of these levels are left to designers. Thus, the representation is a significant research goal because of its role in defining the levels of automation.

1.4 Thesis Organization

Chapter 2 provides the background research on levels of automation, designing for human-automation interactions, decision-making, the lunar landing domain, relevant display design principles, and current lunar landing work including the landing point redesignation (LPR) algorithm. It provides a summary of the research considered for this thesis.

Chapter 3 discusses the Apollo lunar landing and applies principles of cognitive task analysis to analyze the role of humans and automation in lunar landing. A human decision-making model, which is based on Klein's (1998) recognition primed decision-making model, is presented to analyze the impact of automation in the lunar landing aimpoint decision. In addition, a landing aimpoint representation is designed based on the existing LPR algorithm and the information needs identified in the cognitive models.

Chapter 4 describes the experiment objectives, equipment and testbed, display design features, experimental design and procedure, participants, data collection, and methods of data analysis.

Chapter 5 analyses and discusses all of the results of the experiment. Interview results are explained and discussed to provide further insight into the performance data.

Chapter 6 draws conclusions about the role of automation in lunar landing and the influence of automation on human decision making, as tested in the described experiments. Future work is also discussed with respect to the role of the algorithm in human decision-making, recommendations for future designers, and suggestions for displaying the algorithm functions.

Chapter 2 Background

This section summarizes the necessary considerations for human-machine interactions in the lunar landing domain. It introduces ten levels of automation and their application to collaborative human-automation decision making. Further, it broadly describes the decision making process and addresses the situations when humans and automation have the same or differing goals. The chapter continues with a description of the lunar landing domain, including a comparison of Apollo and future lunar landings. In addition, it summarizes recent work done in this domain as well as the landing point redesignation algorithm used and referenced throughout this work.

2.1 Levels of Automation

To complete the various function needed to achieve a task, system designers must consider how to allocate these function between human and automated elements of the system (Sanders and McCormick, 1997). Recommendations of human-computer integration were based on guidelines of the respective strengths of humans and computers, such as Fitts' List (Fitts 1951, 1962).

The concept of levels of automation was first introduced by Sheridan and Verplank in 1978. As summarized in

Table 1, increasing levels imply greater autonomy for the computer and a smaller role for the human.

Table 1: Ten Levels of Decision and Action Selection Automation (Modified from Parasuraman, Sheridan, & Wickens, 2000)

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

Level 1 automation refers to a human performing a task without automation, and level 10 automation refers to the computer performing a task autonomously, independent of the human. This framework of discrete levels has been broadly applied, especially since it is a generic, domain-independent naming scheme.

Sheridan further expanded his concept of levels of automation to include Wickens's model of human information processing: sensory processing, perception/working memory, decision making, and response selection (Wickens, 1984). This research is concerned with the landing point redesignation decision, and thus the levels of automation directly related to decision making.

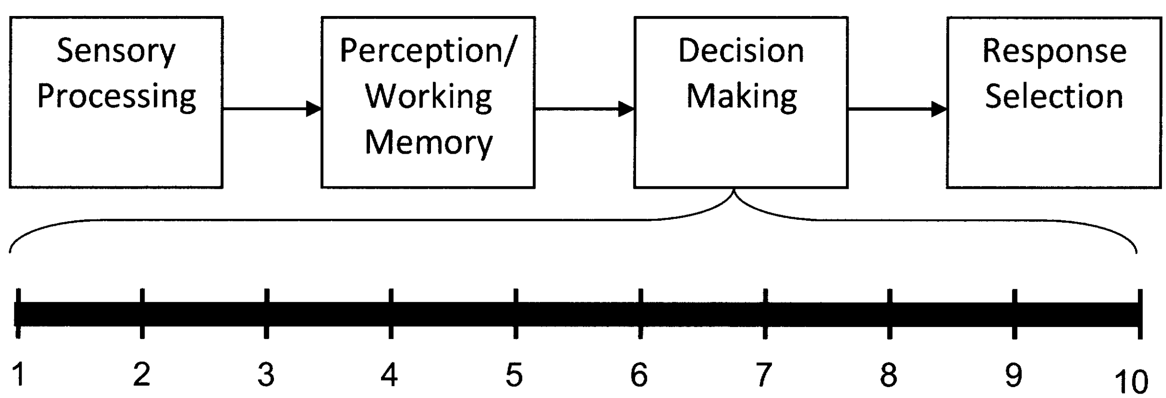

Figure 2: Ten Levels of Automation (Adapted from Sheridan, 2000)

Similar to the original ten levels of automation, level one of decision making automation means that the human must make all decisions. Level ten of decision making automation means that the computer decides autonomously, ignoring the human, which corresponds to a fully automated system (Sheridan, 2000). These levels of automation will be further explained and referenced throughout this work.

The chosen level of automation may also affect workload. In human factors research, workload is broadly divided into physical or mental workload and is measured by objective or subjective measures (Sanders and McCormick, 1993). In this research, the primary workload is mental since the main task is decision-making, and very little physical effort is required. Workload can be increased by the number of tasks, the difficulty of the task, or restrictions on the information given to complete the task (Sanders and McCormick, 1993). The appropriateness of a level of workload for a given task is well described by the modified Cooper-Harper scale (Harper and Cooper, 1986), which can be used for cognitive, perceptual, and communications tasks. It is a subjective workload measure with ten discrete ratings: (1) operator mental effort is minimal and desired performance is easily attainable to (10) the instructed task cannot be accomplished reliably (Wierwille & Casali, 1983). The scale reflects the fact that humans link their performance of a task with the process used to produce that performance. In addition, the modified Cooper-Harper scale is a subjective workload rating, and some investigators have suggested that subjective ratings of mental workload are the best existing method for truly reflecting workload (Sheridan, 1980).

2.2 Collaborative Human-Automation Decision Making

Many models of human decision making have been set forth, and the models can be roughly divided into rational and naturalistic decision making. Rational decision making, also known as rational choice strategy, describes a particular model in which an 'optimal' solution is sought among many options (Klein, 1997). In contrast, all options are not considered in naturalistic decision making, and generally, a single solution is quickly produced. One notable naturalistic model, Klein's Recognition Primed Decision-making (RPD) model (1998), was developed after observing and interviewing expert fire fighters. His team found that experience led the firemen to make quick decisions without considering all the possible solutions. In the RPD model, four elements of situation recognition are used to generate solutions: expectancies, relevant cues, plausible goals, and action sequences known from previous situations (Klein, 1998). Concepts from the RPD model will be further discussed and applied to the lunar landing domain in the next chapter.

Decision making automation is generally encapsulated in algorithms, and some work has been done in the area of human interactive algorithms. In studies such as Klau et al (2002), humans partnered with automated systems to guide solution searches. Similar studies with algorithm interaction have focused on Unmanned Aerial Vehicle (UAV) path planning, such as Forest et al (2007). These studies employed scenarios where the automation and human worked on a common task with common goals, and the resulting decisions were analyzed for their ability to reach these goals. In addition, the scenarios were conducted over several minutes, a period appropriate to the associated domain and task.

What about when humans and automation work on common tasks but with differing goals? Specifically, how are decisions reached when the human has a goal that is external to the automation? When the human merely has a poor understanding of the automation and is surprised by an action of the automation, this phenomenon is called automation surprise (Palmer 1995). But in the case where the human has a goal external to the automation, the human may understand the automation but still need to make a decision that goes against the automation's programming. One could almost say that the automation has a poor 'understanding' of the human, 'surprised' by what the human does.

2.3 Lunar Landing

To address these goals, an example problem was used. The HIMM is most useful for complex, time-critical applications, in which a human alone cannot effectively monitor and intervene when necessary, but there is an opportunity for a person to be a part of the decision process. This opportunity arises either because there are people onboard the vehicle or because there is a remote connection with the vehicle. The problem used in this thesis addresses an aspect of lunar landing, specifically the tasks surrounding selecting a safe landing aimpoint at the end of a lunar lander's descent.

As discussed in Chapter 1, the HIMM emphasizes human-automation interactions in complex, time-critical application in which the human is a significant but not solitary portion of the decision making process. Both the history and the future of lunar landing involved significant human-automation interactions, and technological advances have opened the role of automation in terms of its assistive capabilities. While the human will certainly be required to make many decisions during the lunar landing, one fundamental decision is the choice of a place to land. The landing aimpoint decision may be studied in the Apollo lunar landings and modeled for future lunar landings based on current technologies and the basic task requirements. Thus, with an emphasis on the landing aimpoint decision, the lunar landing domain is an appropriate and realistic application for this work.

There are many differences between the Apollo lunar landings and the next lunar landings, yet any consideration of the new cockpit cannot neglect the work done as part of the Apollo program. Despite considerable advances in technology since the 1960s, modern engineers can benefit from an analysis of the challenges of lunar landing found and faced by astronauts and engineers in Apollo. As will be discussed below, the results of such an analysis must not be carried out of context; the availability and use of automation in the Apollo program should be examined as history and experience but not as rules or limitations for future missions. It would be dangerous and ignorant to assume that the landing task can be approached as it was two generations ago. The moon may not have changed, but the landing task must be reconsidered to achieve the new goals in the lunar landing domain today.

The Apollo lunar landing consisted of three major phases: the braking phase, final approach phase, and landing phase as shown in Figure 3.

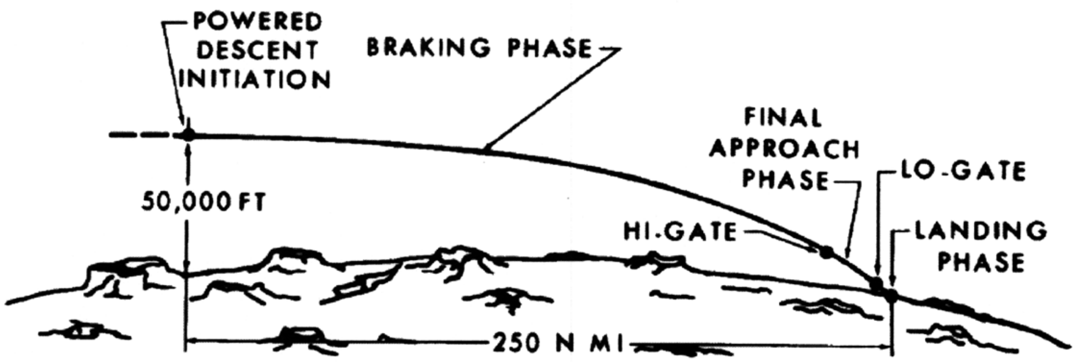

Figure 3: Apollo Landing Profile (Cheatham and Bennett, 1966)

A computer program generally corresponded to each of the phases, and the first human-computer interactions to select a landing aimpoint occurred after hi-gate, a trajectory 'checkpoint' for the computer, at which pitchover occurred. The computer also initiated a program called Program 64 (P64), which was the specific automation that worked with the human. A schematic of the human-computer interaction during P64 is shown in Figure 4.

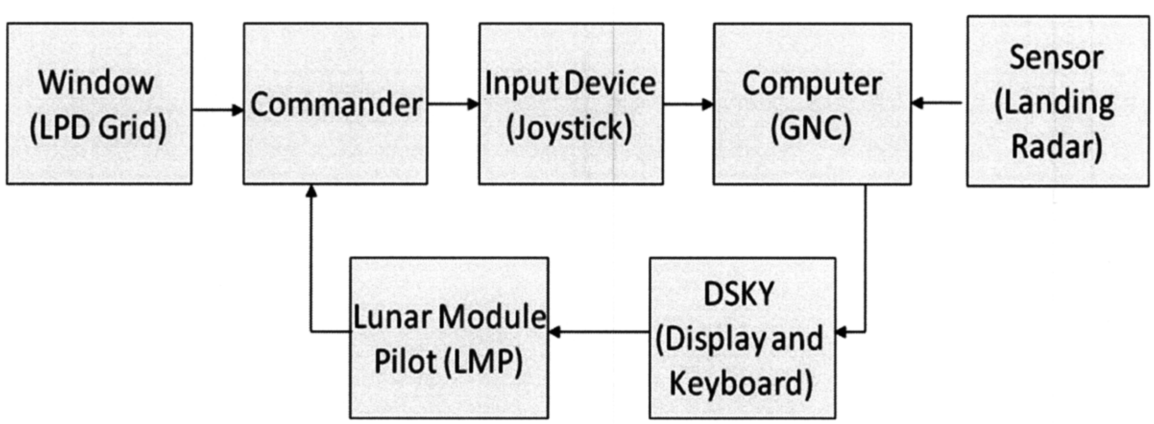

Figure 4: Apollo P64 Landing Point Redesignation

When P64 was initiated, it displayed a specific 2-digit look angle on the DiSplay and KeYboard (DSKY). The Lunar Module Pilot (LMP) read this number aloud to the Commander. The number was correlated to vertical and horizontal scales etched onto the inside and outside layers of the vehicle window -- the Landing Point Designator (LPD). When the commander aligned the inside and outside etches, he could see where the computer projected it was going to land by observing where the 2-digit number was located. If a different landing site was desired, joystick inputs communicate to the computer redesignations of the landing aimpoint (Klumpp, 2003).

The Apollo landing strategy only required "landing at any suitable point within a reasonably small area, constrained in size primarily by the guidance dispersions" (Cheatham and Bennett, 1966). Visual assessments of the lunar surface are significantly affected by lighting conditions. Apollo landings relied very heavily on visual assessments, so the Apollo landing strategy was also limited by particular lighting conditions. This requirement constrained the Apollo missions to landing near the equator of the moon (Cheatham and Bennett, 1966).

For the next lunar landing, the ESMD requirements include the capability to land anytime and anywhere (Fuhrman et al, 2005). However, the current ESMD landing strategy requires landing at a pre-specified point, a strategy noted by Cheatham and Bennett (1966) and exemplified by the desire to land "with[in] 100 ft. of the position of a surveyor spacecraft, or perhaps another type of spacecraft." The new requirements for landing anywhere and anytime on the moon implies landing in any lighting conditions, requiring backup capabilities to visual assessments. Because Apollo landings relied so strongly on visual assessments, these requirements lead to fundamental reconsiderations of the lunar landing strategy and cockpit needs. Combining these new requirements indicates the need for a true partnering between humans and automation to achieve the next generation of lunar landings.

The next lunar landing has been envisioned as a three-phase landing, similar to the Apollo landings. The three major phases are the braking phase, the approach phase, and the terminal descent phase as shown in Figure 5.

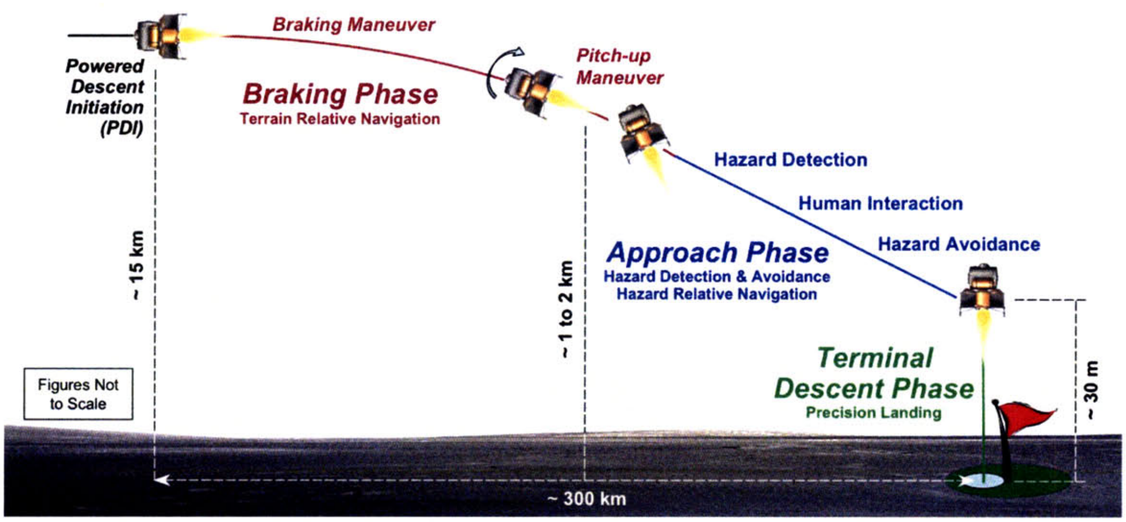

Figure 5: Future Lunar Landing Profile (Epp, Robertson, & Brady, 2008)

The human's input for selecting a landing aimpoint will occur during the human interaction portion of the approach phase as shown above. Although the process is not fully defined, a rough schematic of this human-machine interaction is shown in Figure 6. Upon vehicle pitchover, sensors will scan the surface for hazards. The Hazard Detection and Avoidance (HDA) algorithm will then have the capability to recommend safe landing aimpoints to the pilot. This information will be displayed in an as yet unspecified way to the crew. They may also have a window with augmented vision capabilities, as a source of raw data, display support, or as a backup for system failures. The pilot will have input capabilities to provide inputs to the computer and to complete the interaction.

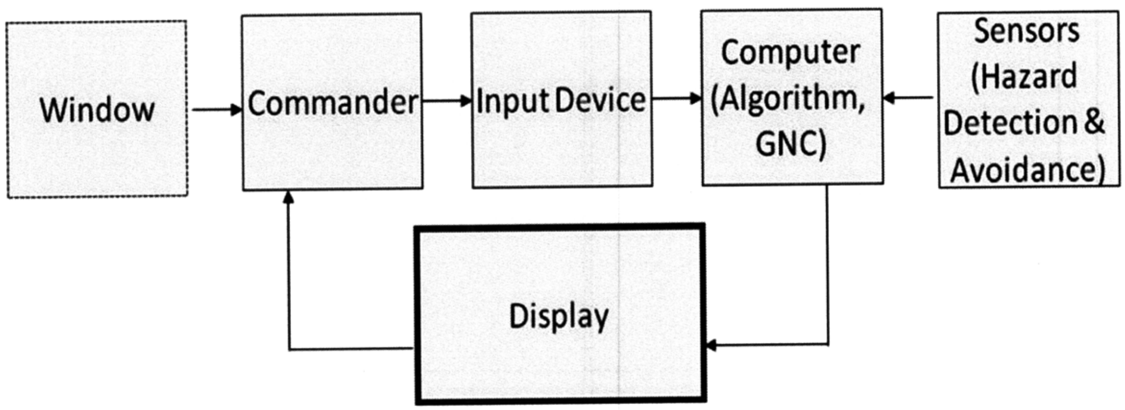

Figure 6: Landing Point Redesignation (LPR)

Referring to Sheridan's ten levels of decision making automation, the Apollo program may be considered a LOA 2 because it offers a full set of decision alternatives. Of the remaining choices, only LOA 3 offers more than one option and waits for human input before implementing the decision, making these levels appropriate for selecting a landing aimpoint.

The types of goals that the human may have outside the automation depend on the capabilities of the automation or algorithm. During Apollo, the crew was responsible for assessing the safety of the trajectory as it related to the landing aimpoint, including appropriate speed and altitude estimates and the avoidance of terrain obstructions. Also noted was the possible presence of points-of-interest, specific targets including "previously landed spacecraft and natural landmarks of special interest such as specific craters" (Klumpp, 1966). The goal of a point-of-interest is especially interesting because it requires external knowledge rather than judgments of existing data. In addition, it is a goal that might be present in a nominal mission.

2.4 Related Work

Despite the resurgence in lunar landing interest, there are only a few projects considering the new challenges of the next generation lunar lander cockpit. The Lunar Access project (Cummings et al., 2005) was a response to President Bush's Vision for Space Exploration (NASA, 2004), examining the challenges of the lunar landing. The scope of Lunar Access included a broad look across lunar landing focusing on information requirements. The project resulted in a preliminary display design solution, including a cursory redesignation display. Lunar Access started before automation capabilities were thoroughly considered or defined, and therefore were only implicitly assumed, and essentially no mission manager discussed.

A current program involved in studying precision lunar landing is called the Autonomous Landing and Hazard Avoidance Technology (ALHAT). ALHAT is a technology development program primarily exploring guidance, navigation, control, automation, and sensors for the lunar landing. Recently the project scope was expanded to include the human interaction mechanisms, particularly display design. Although ALHAT has only begun to examine human interaction mechanisms, my research draws upon much of their current precision work, particularly in terms of the automation algorithms designed for the HDA phase.

Landing re-designation to avoid hazards has been identified as a key decision for the crew (Smith et al 2008). The HIMM incorporates a specific landing point redesignation (LPR) algorithm developed by engineers under the ALHAT program. The LPR algorithm (see Figure 7) offers a ranked list of candidate landing aimpoints using four parameters: slope of the terrain, roughness of the terrain, distance to the nearest hazard, and the fuel required to divert from the nominal aimpoint. The slope and roughness of the terrain have thresholds dictated by the spacecraft vehicle limits. A sensor will collect surface elevation data from which slope and roughness values may be calculated. If these values exceed pre-defined thresholds, the algorithm will mark that position as hazardous. It is from these hazards that the parameter distance to nearest hazard is calculated.

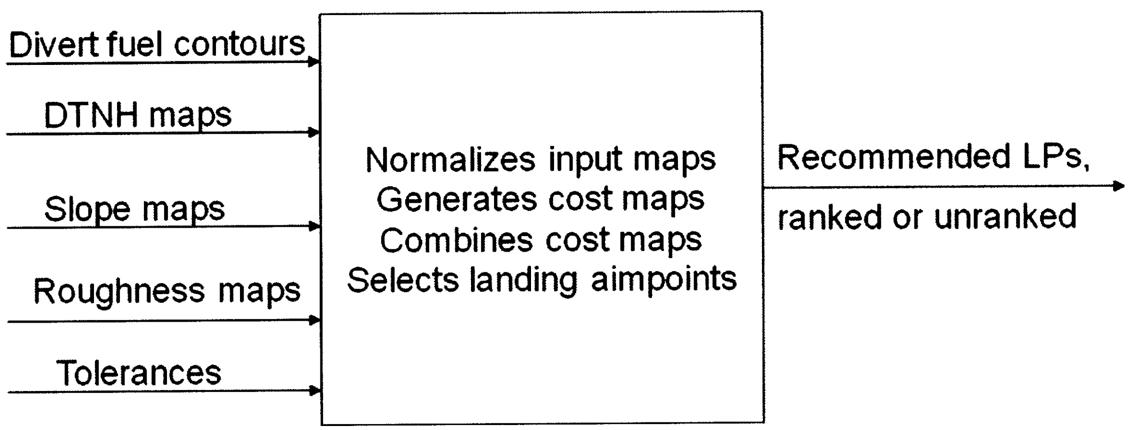

Figure 7: Schematic Representation of the LPR Algorithm (interpretation of the description in Cohanim & Collins, 2008)

Chapter 3 Decision Making Model and Application to LPR

This chapter presents a task analysis of the Apollo landing point selection to study the role of humans and automation in the lunar landing. This task analysis is updated to take into account current lunar landing goals and technologies. The decision making process is further examined, various decision making methods are discussed, and a general decision making (DM) model is suggested. In addition, a landing aimpoint representation is designed based on the existing Landing Point Redesignation (LPR) algorithm, and recommendations for the display design are also presented.

3.1 Cognitive Task Analysis

The LPR task includes both the cognitive and physical processes of choosing a landing aimpoint that achieves the mission goals. These processes can be explored through a technique called cognitive task analysis (CTA) (Schraagen et al, 2000). CTA is a proven technique in the design of cockpits for space environments; analysis of the Space Shuttle cockpit, including interviews with astronauts, lead to a series of proposed improvements called the Space Shuttle Orbiter Cockpit Avionics Upgrade (McCandless et al 2005).

Traditionally, CTA is done through in-the-field observations and interviews (Schraagen et al, 2000). However in the case of the Apollo lunar landings, a retrospective task analysis must be done. Such analysis is strongly supported through documentation and recordings of individuals performing the task, since CTA interviews performed months or years after the event are susceptible to subjective bias and long-term memory inaccuracies (Horselenberg et al, 2004).

3.1.1 Apollo landing point selection

The cognitive task analysis in this thesis purposely examined a fixed time period of activities. The analysis was centered on the LPR decisions made in the phase between pitchover and low gate. This period was chosen because it was believed to best express the human automation interactions done to perform the LPR task during the Apollo landings. In addition, only the nominal LPR task was considered, and many potential off-nominal scenarios and tasks were excluded. This reflects the materials available for the CTA, particularly the voice transcripts of the landings (Jones, 2007). The task is shown in Figure 8.

The CTA models are separated into the tasks of the human on the left and the processes and contributions of external sources on the right. Both the human and the external entities enter the LPR decision with a set of previous knowledge obtained from training, previous mission phases, or previous programming in the case of automation. These items are listed at the top of the diagram. The interface between the human and external entities is centered in the diagram, and although its physical nature varies between the Apollo and modern systems, its role is analogous. The arrows circling through the interface suggest that the human-automation interactions occur in two waves. First, there is an initial evaluation, which is a short period of initial connection between the human and external sources. This is followed by a longer period of refining interactions that eventually lead to the LPR decision.

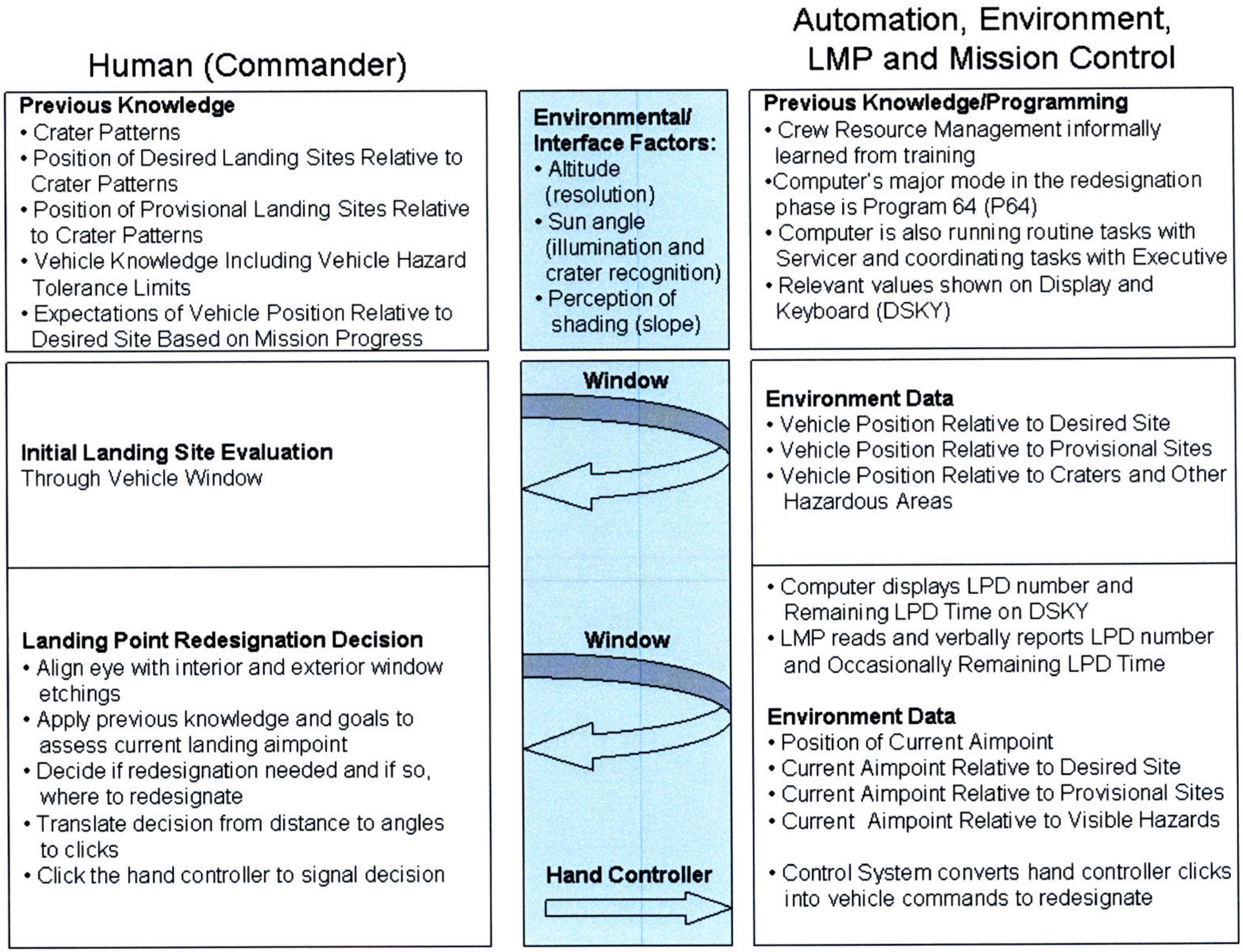

Figure 8: Task Analysis of the Apollo Lunar Landing

3.1.2 Effect of current lunar landing goals

As emphasized by Smith et al (2008), analyses of the Apollo lunar missions assist considerations of current lunar landing goals because the functional requirements of the missions are similar. There are differences which include crew responsibilities and interactions with the automation. For example, it is assumed that a single pilot will have the responsibility of the LPR decisions and that the pilot will only interface with the automation.

It is more difficult to perform a cognitive task analysis on a conceptual task for future missions than on a task performed many years in the past. Cognitive analysis of tasks in the design phase must be assembled from designers as well as general human factors knowledge, but it must continue to be updated as the task evolves. Thus, the following analysis should be seen as one snapshot along that evolutionary path. The task with updated elements is shown in Figure 9.

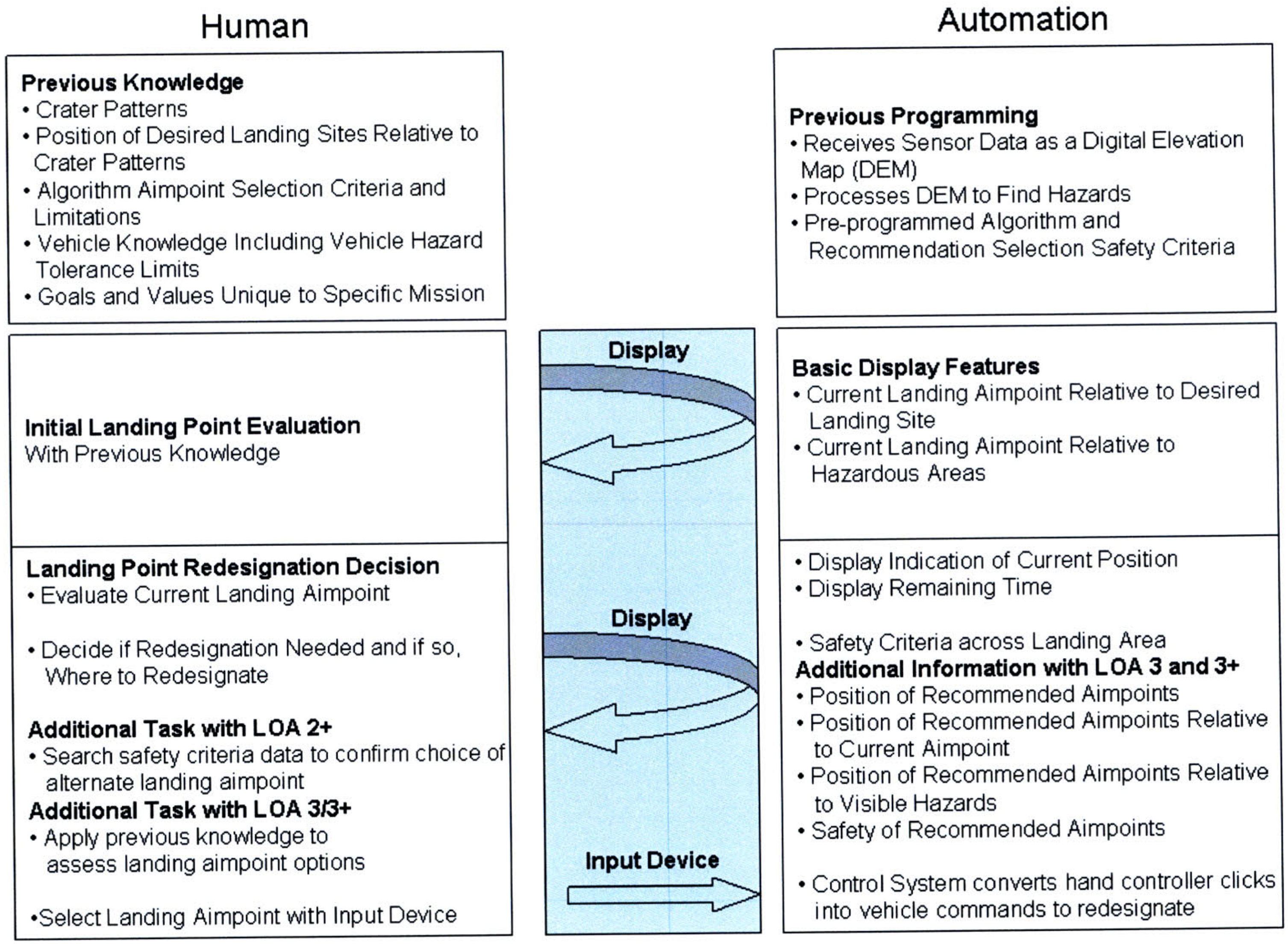

Figure 9: Updated Task Analysis of Lunar Landing

This analysis has more simplistic results than the Apollo analysis, and this is the result of much of the design being still undecided. For example, it is unclear what the human's expectations of the situation will be as shaped by previous mission phases. It is also unclear what the effect of the algorithmic aimpoint recommendations will be on the final LPR decision.

The environmental observations are assumed to be only given to the automation through an automated sensor, as described in Chapter 2. This data will be different in nature than the observations gathered by the human from the window described above in the Apollo CTA. The sensor will be able to offer much more detailed information, such as specific elevation and distance values, which the human was only able to infer heights and lengths with a window view of the surface.

Certainly, the analysis shows the criticality of the display as an interface mechanism. The automation is limited by the capabilities of the sensor and the logic and calculations within the LPR algorithm. Thus, the clear expression and transmission of this data must be a substantial design concern in this system. In a way those limitations are reflected by the fact that the LPR decision will ultimately be made by the operator and the role of the automation may be seen as advisory and informative. However, the augmented role of the automation appears to alter the human's primary focus, and thus cognitive resources, to primarily evaluation and decision-making and de-emphasizing information gathering.

3.2 Decision Making Model

Since the landing point redesignation task is a decision-making process, a designer would be greatly assisted with knowledge about how that decision is made and how he or she can provide the correct information in the decision-making process. Researchers have established that theories of classical decision making do not apply as well for most human decision making (e.g., Beach & Lipshitz, 1993, and Klein, 1999). At the same time, research has explored human decision making in applied settings and have created models of the behavior they found, an area known as naturalistic decision-making.

Many naturalistic decision-making models exist, as exemplified by Lipshitz (1993), but not all apply to the LPR decision. The LPR decision may be characterized as a time-pressured decision made by an expert. As assumed in the above analysis, choosing a landing aimpoint is not a novel activity, but one approached with previous, albeit simulated, experiences and a significant amount of prior knowledge. It is more mentally than physically challenging, and even the physical actions resulting from the decision are simple, few, and constrained.

The above characterization of the LPR task defines what type of decision-making model is required. The model should account for a time limitation, which restricts the amount and type of information that a human can process as part of their decision, as well as the number or number of mental simulations that the human can make through the decision-making process when considering alternatives. In addition, the model should be geared toward well-trained experts who can incorporate long-term knowledge of a situation, and the model should focus on the cognitive challenges of the decision, de-emphasizing the link with physical actions.

One aspect rarely included with most naturalistic decision-making models is the impact of and interaction with automated systems. It has also been noted that studying the interaction of expert decision makers with automated decision aids could produce a set of guidelines for the design of those aids (Mosier, 1994), and that principles should be extensible to broader categories of automation. One example of naturalistic decision-making theory (Smith and Marshall, 1994) applied schema theory in the decision of a decision aid for anti-air warfare. They argue that schema theory is the most appropriate theory for this domain because other theories, like Klein (1992) and Norman (1993), pre-suppose that there is a pre-existing structure for experts to recognize.

However, as the LPR task has been described in this text, it has a well-formed structure, and the resulting action may be viewed as a simple binary decision, either selecting a new aimpoint or taking no action. Like the application of schema theory, a decision-making model should not restrict the decision aid design to a single type of knowledge, strategy, or performance (Smith and Marshall, 1994).

3.2.1 Existing Decision-Making Models

Three decision-making models were chosen that represent the span of naturalistic decision making models and contain components of the desired DM model set out previously -- Recognition Primed Decision-making (RPD) (Klein, 1999), image theory (Beach, 1993), and the dominance search model (Montgomery, 1993). These three models vary slightly in both their depth and breadth, as well as in their specific details;

however the significant overlay allows the decision models to be combined to model the LPR decision.

The RPD model (Klein, 1999) is one of the most widely accepted naturalistic decision-making models. The model was developed based on observations and interviews of expert firefighters, and it describes how experts are able to quickly recognize appropriate courses of action based on recognition of elements of a previously encountered situation. Recognition has four aspects: goals, cues, expectations, and actions. In addition, the model includes the evaluation of potential actions through mental simulation.

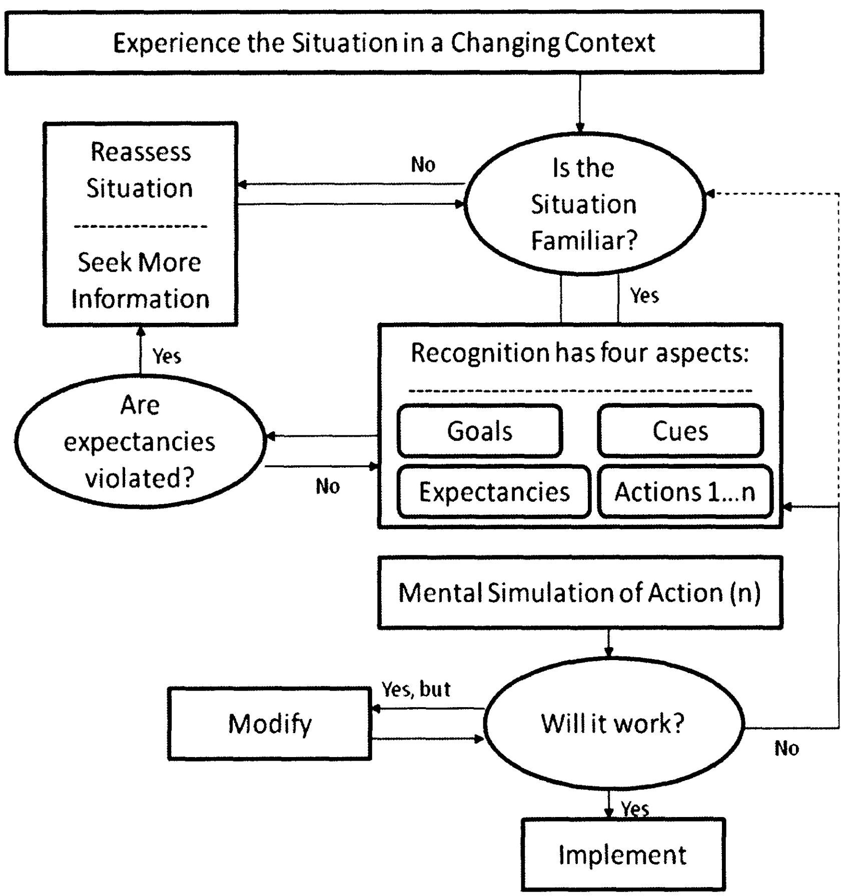

Figure 10: Recognition Primed Decision Making (Klein, 1999)

The model has many elements that are applicable to the LPR decision. The fundamental concept of recognition requires an expert. Further, the development of the model reflects situations in which time was a critical element. However, the model does not include some key elements of the LPR decision. Decision alternatives are developed and evaluated sequentially and independently; thus, the situation where a group of alternatives are presented together is not considered. Certainly, the model excludes interactions with automation, which is a crucial part of the LPR decision.

Image theory (Beach, 1993) is a decision-making model that emphasizes decisions guided and constrained by three types of images: values, goals, and plans. Like RPD, image theory asserts the importance of goals in decision making, and its use of plans is equivalent to the actions included in RPD. The addition of a value image gives shape to the four elements of recognition, that is, it allows for one goal to take precedence over another or for one cue to be more important than all others. Further, image theory explicitly models a decision between alternatives with so-called compatibility and profitability tests. The compatibility test assumes that an alternative will be eliminated if it does meet the decision maker's three images beyond a threshold. In effect, this test is a process by elimination, quickly screening out unacceptable options. The profitability test is then used to choose the best of the acceptable options through an unspecified method.

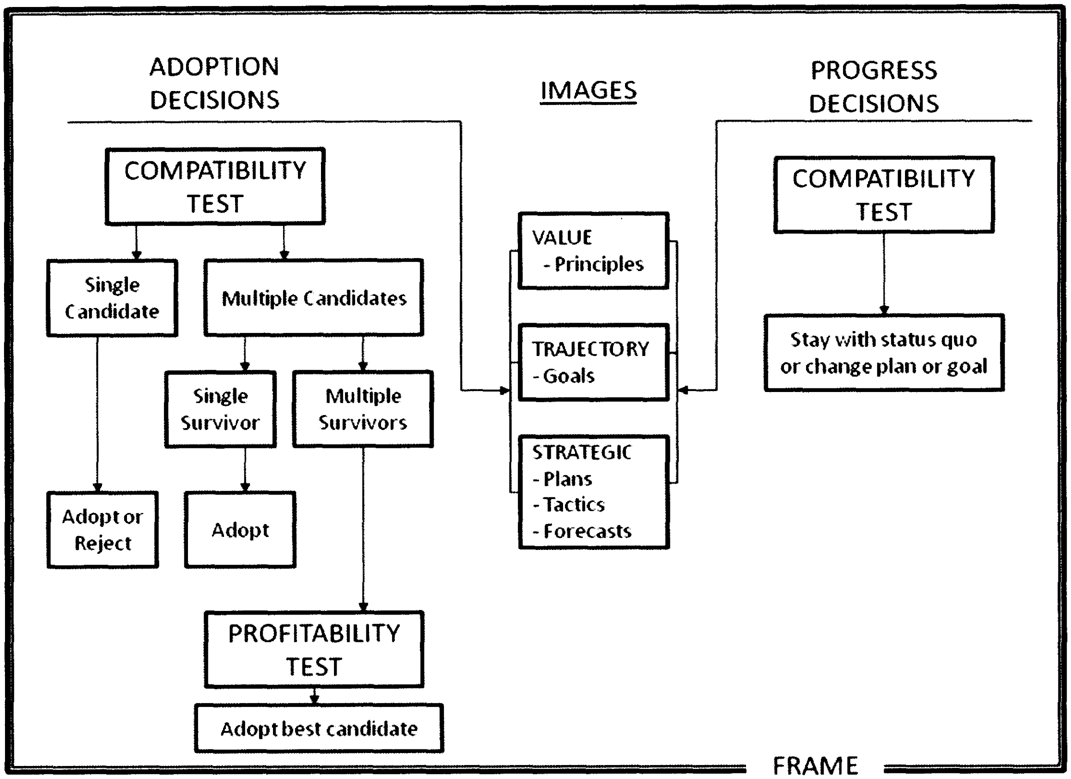

Figure 11: Image Theory (Beach, 1993)

The dominance search model of decision making (Montgomery, 1993) proposes a naturalistic method for evaluating alternatives. The model suggests that decision makers pass through several phases to redefine goals and alternatives until one option becomes dominant. The dominance search model has essentially the same structure as image theory, by first screening out unacceptable alternatives and then evaluating the remaining options. The main difference is that the dominance search model specifies a specific method for selecting the best alternative; an unspecified criterion of dominance is selected to evaluate the remaining options, and that criterion is altered if no dominant method is found. This method is fairly specific in the decision making process, but it fails to suggest which categories of attributes are used to pre-screen alternatives, or what elements compose the criterion of dominance. The combination of recognition-primed decision making, image theory, and the dominance search model provide sufficient tools to develop a decision-making model for the LPR decision, as shown in section 3.2.4.

3.2.2 Effect of higher levels of automation

In this research, increasing the levels of automation above those used during Apollo is explored. The addition of automation changes the way that the human must process the goals, cues, expectations, and actions. Now they must contend with not only the cognitive processes related to the situation, but also seek cues given by the automation, understand the goals of the automation, determine whether the automation is conforming to their expectations, and perform the associated actions. Although the search space is reduced with increasing LOAs, the cognitive processes related to the goals, cues, and expectations have increased.

With regards to the LPR task, three levels of automation are considered in this work. As discussed in Chapter 2, Sheridan's LOA 2 offers a complete set of decision alternatives. However, automated capabilities can display hazardous landing aimpoints to the human to reduce this complete set of decision alternatives to a recommended safe set. The addition of this decision aid encourages a slightly different name for this LOA; thus a complete set of landing aimpoints with the additional display of hazardous aimpoints is called LOA 2+.

With LOA 2+, the human must spend time searching for a solution across the entire space of solutions, so this LOA will require the greatest number of physical actions. However, the decision is more straightforward when not dealing with additional automated features, which are present in higher levels of automation. The human does not need to understand more detailed computations involved in the automation, and his or her expectations are only that of the situation and not of other dependencies (such as expectations of an automated system's performance or output). Their analysis of existing or missing cues is also only based on the situation.

As also discussed in Chapter 2, Sheridan's LOA 3 narrows the selection to a few decision alternatives. In the lunar landing domain, a LOA 3 means that the automation recommends landing aimpoints such that only a few are available for the human's decision. An extension of LOA 3 is the capability of the automation to rank these landing aimpoints from best to worst. Although all the automation's recommendations are non-hazardous, it is likely that some would require more fuel, are closer to hazards, etc than others. Thus, displaying a rank order of the aimpoint recommendations is a form of decision aiding. To distinguish this extension from LOA 3, it is called LOA 3+.

The LOAs 3 and 3+ may have slightly different effects on the DM model. The rankings are intended to simplify the DM task since it is a single value that combines the LPR safety criteria, making it simpler to decide based on a single criterion rather than based on multiple criteria. However, the additional ranking offered by the LOA 3+ may require the human to compare his or her personal opinions about the recommended landing aimpoint to the computer's ordered recommendation. Specifically, the human will be concerned about whether or not he or she agrees that the top ranked aimpoint deserves that ranking according to the relevant criteria. If this question is answered negatively, then the human would need to evaluate if the second ranked aimpoint is truly the best, and so on. Generating a ranked order of the recommended landing aimpoints and then comparing this self-rating with the automated rankings becomes a much more complex task than only considering self-ratings when the goals of the human and the automation are not identical.

3.2.3 Effect of goals external to automation

Often times a person considers extra goals in addition to those that are encoded within the automation. A person is able to integrate the details of an evolving situation and adapt their goals, emphasizing certain goals more or less as the situation unfolds. This leads to a mismatch in the goals of the automation and the goals of the person, which significantly changes the decision since goals are a key portion of the RPD model, image theory, and the dominance search model. As was discussed in the previous section, this mismatch increases the complexity of the task for the operator because the results of the automation are different than what the operator expects.

In the experiment presented in the following chapter, the effect of a goal external to the automation is further explored. For LOA 2+ the effect of external goals is hypothesized to be minimal. The human will have an additional goal to consider, but he or she will proceed in the same fashion as when only a single goal was present, assessing the landing area and searching through the solution space.

However, for LOAs 3 and 3+, the impact of the additional goals is expected to be more significant because the need for a separate evaluation of the automation's recommendations is now important. The automation only uses safety criteria to generate the landing aimpoints, whereas the recommendations do not incorporate an additional external goal. It is unclear how this will affect the decision. One possibility is that the human would use the resulting recommendations to represent the safety goal, create a set of internal rankings corresponding to the second goal, and combine these rankings to decide which aimpoint is the best overall. In this scenario, the rankings should assist the human relative to having unranked recommendations.

Further, there is no rule that the goals need to be equal; in fact, one goal could be much more important than the other. Since the algorithm was programmed long before the mission, the human's internal goal might be more urgent. As the importance of the human's independent goal increases, his or her consideration of the automated recommendations will change. The rankings according to the safety criteria may become less relevant, exchanged for the human's internal rankings. Thus, it is likely that as the human's external goal becomes more important, the task will become more challenging, especially when rankings are present, as the human must decide to what extent to utilize these rankings and to what extent to rely on his or her estimations.

3.2.4 Decision making model for LPR

The decision making model for LPR offers a general framework, drawing elements from both image theory and recognition-primed decision making. The model is shown in Figure 12 below and is based on the results of the cognitive task analysis. The decision making model for LPR does not attempt to predict which specific decision process the operator will use; that must be studied experimentally. It does, however, suggest the important role of the safety criteria which, combined with location, make up the attributes of each landing aimpoint.

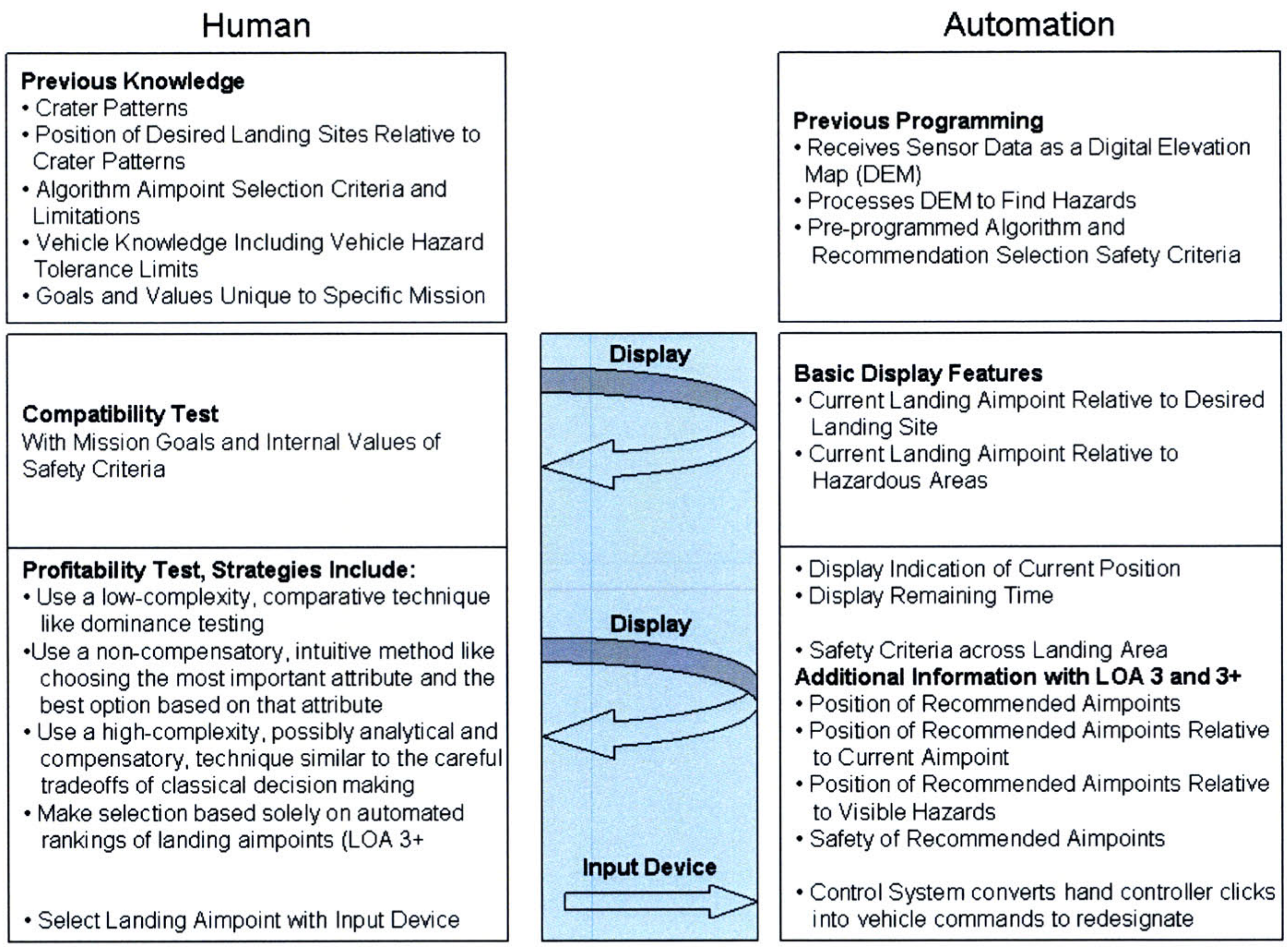

Figure 12: Decision Making Model for the LPR Decision Based on Existing Models

3.3 Safety Criteria Representation

A graphical representation was created to display the safety criteria used to select and rank the landing aimpoints in the algorithm. Safety in this case refers to the ability to safely land at a given point on the surface of the moon. It incorporates the topography of the terrain, the tolerance of the vehicle in relation to the terrain and the amount of fuel required to reach the landing point in relation to the amount of available fuel. There are two parameters representing the terrain: slope and roughness. Whether or not the vehicle terrain tolerance will be met is determined with a parameter that returns the distance to the nearest hazard. The representation of these criteria plays double roles in allowing the human to both view the data considered by the algorithm and make an independent evaluation about the ranking of the landing aimpoints, for LOAs 3 and 3+.

The criteria are represented as margins instead of the raw values. Representing the data as a margin provides not only the data value but also the value of the data. If a particular roughness value is given, for example, it still must be interpreted relative to the appropriate vehicle threshold for roughness. The slope and roughness margins are measured relative to vehicle tolerances. The distance to hazard is a natural margin, and the fuel margin is a well-known margin. Further, by showing the margins rather than the raw slope and roughness values, the most desirable landing aimpoint is made the most visually compelling. Thus, displaying the margins makes salient the safety of the landing aimpoint, aiding the LPR task. The design concept is shown in Figure 13 below.

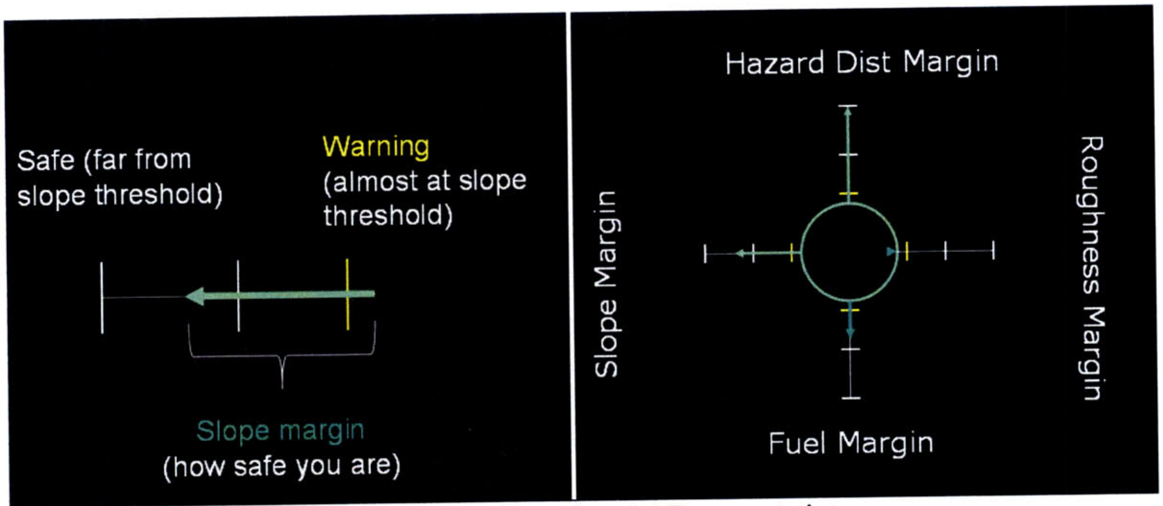

Figure 13: Landing Aimpoint Representation

The hazard distance margin is unique in that it has a non-zero minimum threshold. The largest value of the margin is not when the distance to hazard is zero; that point actually corresponds to the minimum margin value. However, this non-zero threshold is unclear. For example, in the extreme case, it is clear that if the nearest hazard were infinitely far away, that hazard will have no effect on the safety of the landing aimpoint. For the representation design, it is assumed that hazards more than two lunar footprints away are considered as safe as hazards greater than two lunar footprints away from the landing aimpoint. The values corresponding to the maximum and minimum margins are included in Table 2 below.

Table 2: Maximum and Minimum Safety Parameter Margins

	Safest Value (Max)	**Least Safe Value (Min)**
Slope Margin	0 degrees	12 degrees (Apollo)
Roughness Margin	0 meters	0.5 meters (Apollo)
Hazard Distance Margin	24 meters	0 meters
Fuel Margin	1 (normalized to expected fuel consumption to reach center of the landing area)	0 (normalized, corresponding to the corner of the scanned landing area)

3.4 Requirements

The requirements that were developed in this research to describe the essential functionality revealed in the task analysis and decision making model. The display design used for this experiment was based on the requirements. While the LPR decision is crucial to lunar landing, similar human-automation decision-making scenarios in other domains would benefit from parallel principles.

1. The displays should include the following data to enable a user to analyze a candidate landing site:
    a. the landing area including geometry and the position of significant landmarks
    b. the landing aimpoints including position and attributes
    c. safety criteria information across the landing area for expert pattern recognition and decision aiding through trends
    d. hazards, minimally showing their position relative to the landing aimpoints, ideally including elevation, slope, and/or a severity coding
    e. existing assets or other pieces of information related to the mission goals
    f. time remaining in the task
2. The displays should be graphical and ecological in nature to expedite the task.
3. The displays should not cater to a single decision-making methodology, but should be adaptable and supportive to a range of methods.

Chapter 4 Experiment Methods

An experiment was conducted to evaluate the levels of automation and decision making process of participants using the displays described in Chapter 3. Participants were given one of the three missions that influenced their goals and priority of those goals. They then interacted with one of the three levels of automation to decide which landing aimpoint seemed best to them. At the end of the experiment, the participants and experimenter reviewed recordings of the participant's actions, and the participant described his or her decision-making process as well as the influences of the mission and level of automation on that process.

4.1 Experiment Objectives

The objectives of this experiment focus on the LPR decision and assessment of the human-computer collaboration to make this decision. The specific objectives are to test different levels of automation and scenarios both when the goals of the human and the computer are the same and when the goals are different. The performance and decision strategy of the human will be examined.

4.1.1 Level of Automation

In Chapter 3, three levels of decision making automation were shown to be important in human automation interactions for the landing point redesignation decision. These three levels have also been shown to influence the human's decision through the level of automated decision support. LOA 2+ offers a full decision set to the human, showing hazards in the landing area but not restricting the human's decision. Level 3 automation restricts the human's decision space to aimpoints recommended by the LPR algorithm. LOA 3+ additionally computes rankings that order the aimpoints from best to worst according to the particular criteria used by the algorithm. In the baseline scenario, the human and algorithm have the same goals and criteria for a successful decision. With an automated system to assist in the decision, the human will be able to fully utilize the algorithm to achieve the task. Since the decision is physically expressed when the human inputs his or her decision, the person's performance can give insight into the decision itself. The following hypotheses capture the performance using the three levels of automation.

Hypothesis 1: the time needed to complete the LPR decision is expected to be longest for scenarios with level 3+ automation, and shortest for scenarios with level 2+ automation

Hypothesis 2: the quality of the landing aimpoint chosen is expected to be best for scenarios with level 3+ automation and worst for scenarios with level 2+ automation

4.1.2 Point of Interest

The proximity to a point of interest (POI) is a goal that the human must consider that is external to the algorithm. Two missions are defined that guide the human's valuation of the POI: the geological and rescue missions. In the geological mission, the human is given a point of interest representing an interesting surface feature; in the rescue mission, the point of interest is the location of a stranded astronaut. The geological and rescue missions are example scenarios that put increasing importance on the goal of proximity to the POI. With level 2+ automation, the human considers the location of the point of interest as well as safety, and only the locations of hazardous areas are shown to support the person's decision. Since the algorithm does not consider the point of interest in its aimpoint recommendations, the human and automation have different goals although they are working together to perform the same task. Thus, the human must now consider the external goal of the point of interest in addition to understanding the computer's recommendations. Although there are only a limited number of recommendations to consider, the human must decide how to incorporate the point of interest into his or her decision. Again, the person's performance can give insight into the decision itself; therefore, the following hypotheses capture the decision performance across POI conditions.

Hypothesis 3: the time needed to complete the LPR decision will be longer compared to the baseline condition, for higher levels of automation when the POI goal is more important in the decision

Hypothesis 4: the quality of the landing aimpoint, based on safety criteria, is expected to be lower compared to the baseline condition, for lower levels of automation when the POI goal is more important in the decision

4.1.3 Decision Strategy

Although the decision performance may be analyzed, the strategy leading to that decision should also be assessed due to the numerous possible strategies available, as discussed in Chapter 3. Strategies fall broadly into either naturalistic or rational decision making and can be further categorized based on different traits. Naturalistic decision making strategies have been shown to be employed by experts making quick decisions in the field. Klein and others cite the significant role of goals in their decision making models. In contrast, rational decision making begins by an assessment of all possible decisions followed by careful analysis and comparison. In the scenarios with level 2+ automation, subjects are given a limited amount of time to make their assessment and decision. In the scenarios with levels 3 and 3+ automation, the decision space is significantly narrowed such that a more rationalistic strategy is more likely. Thus, the following hypotheses capture the decision strategies:

Hypothesis 5: decision making strategies will be different between scenarios with different levels of automation

4.2 Participants

Fifteen participants served as the subjects for the experiment. They were Draper Laboratory Fellows pursuing Master or PhD Degrees, focusing on aeronautical and aerospace engineering or mechanical engineering. None of the participants had detailed knowledge of the lunar landing redesignation decision or previous experience with the display interface or the hazard detection and avoidance (HDA) algorithm. Two participants had piloting experience, and 11 participants had some experience reading maps with elevation contours.

Table 3: Study Demographics

Category	N	Min	Max	Mean	Std. Dev.
Age (years)	15	22	29	24.2	1.8
Pilot Experience (years)	2	1	1	1	0
Computer Experience (hours)	15	20	60	45	11.8
Comp. Exp. With Mouse (hours)	15	17.5	55	34.5	11.5
Video Game Experience	10				
Maps/Elevation Contours Experience	11				
Student	15				
Gender (M/F)	11/4				

4.3 Testbed

The testbed for this experiment was the Draper fixed-based cockpit simulator. Implementation of the displays components was done by Draper staff. The subjects interacted with the LPR display with a standard computer mouse. Since only a single display was required, the experimental setup was configurable for both right and left handed participants. The test environment was dark, and external noises were minimized.

4.4 Experimental Design

There are two independent variables: the level of automation (LOA) provided in a given scenario and the point of interest missions. As previous discussed in Chapter 3, there are three LOAs under consideration: levels 2+, 3, and 3+. Also discussed in Chapter 3, the point of interest missions represent increasing importance of additional information possessed by the human but not by the algorithm. In the specific example of a point of interest, the human's decision making will be affected, reflecting the changes to the goals of the situation.

There are two dependent variables to represent performance improvements between the factor levels of the independent variables. These dependent variables are task time (the time taken to complete the task), and quality of response (a measure based on the safety criteria shown in the algorithm representation and the distance to the point of interest, if present). The task time is measured in seconds and will always be less than or equal to the decision time limit of thirty seconds. The quality of the response is a summation of the four normalized safety margins corresponding to the chosen aimpoint. If a point of interest is present, the distance from the chosen aimpoint to the point of interest is computed and normalized relative to the farthest possible distance to the point of interest on the corresponding terrain map. This normalized distance to point of interest value is then included in the quality summation. The normalized values used to compute the quality are not averaged because an average would imply a particular weighting scheme, which may not reflect the participant's strategy.

4.5 Experimental Task

Sensor data in the form of terrain maps was obtained from Andrew Johnson, an engineer at the Jet Propulsion Lab (JPL). Slope and roughness thresholds within the Apollo limits (less than 12 degrees of slope and 0.5 meters of roughness) were chosen for each of the terrain maps such that the maps would be equally hazardous. A value of thirty percent hazardous was chosen for the maps after a trial-and-error process found that the HDA algorithm recommended less than five landing aimpoints if a higher percentage of hazards were selected.

The HDA algorithm was run a priori for each of the terrain maps. In the algorithm, the safety parameters were all equally weighted; however, that fact is not an algorithmic limitation, but was specifically chosen to simplify the experimental factors. A point-of-interest was selected for each of the three terrain maps. The point-of-interest was chosen to be equidistant from multiple recommended landing aimpoints to pose a more challenging decision to the participants. The recommended landing aimpoints, their associated rankings (LOA 3+), and the respective points-of-interest are shown below.

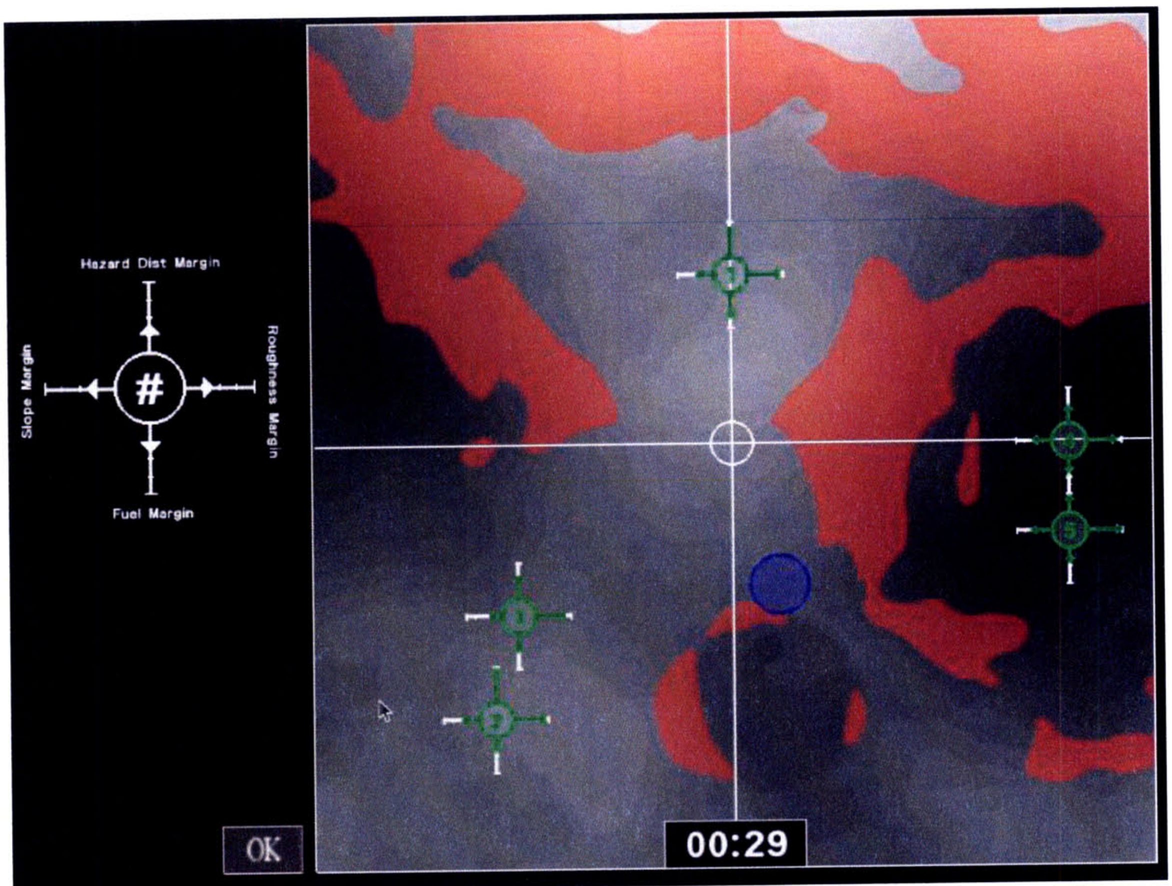

Figure 14: Point of Interest and Recommended Landing Aimpoints for Terrain Map 1

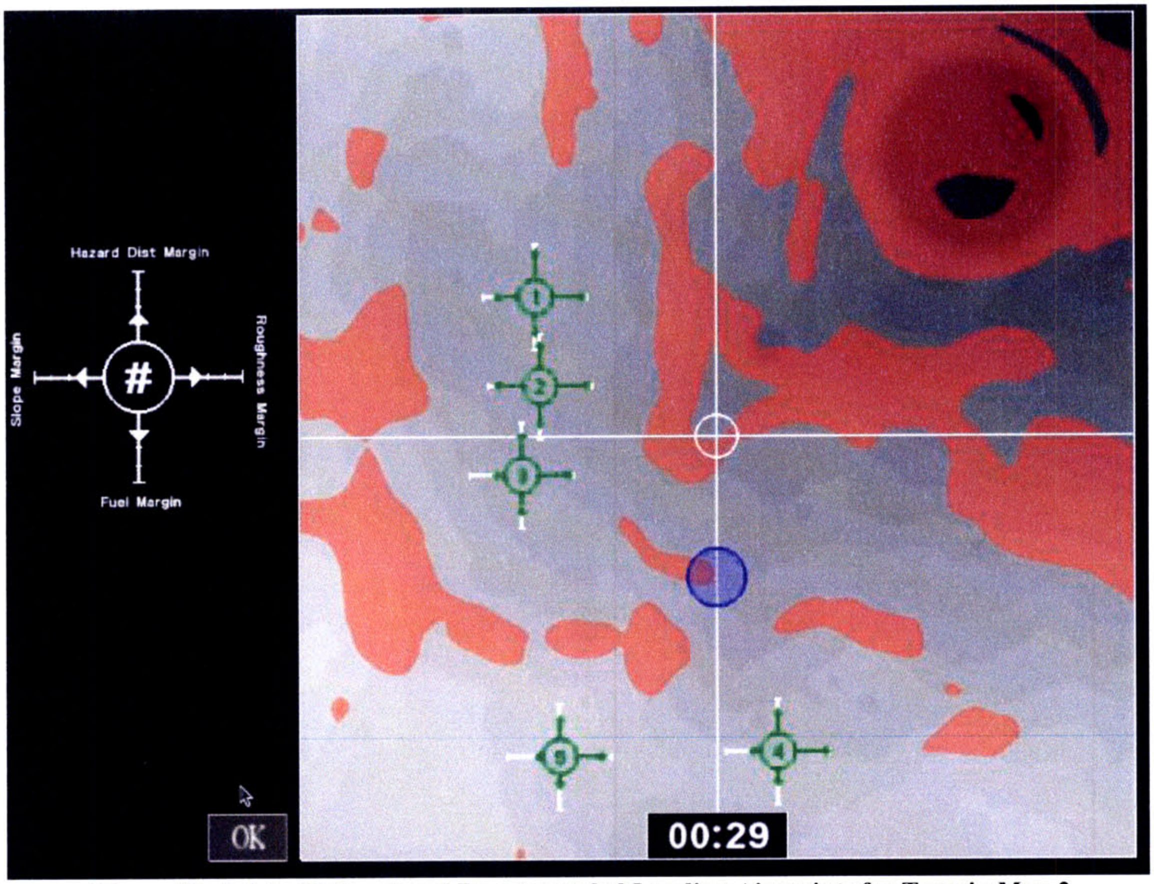

Figure 15: Point of Interest and Recommended Landing Aimpoints for Terrain Map 2

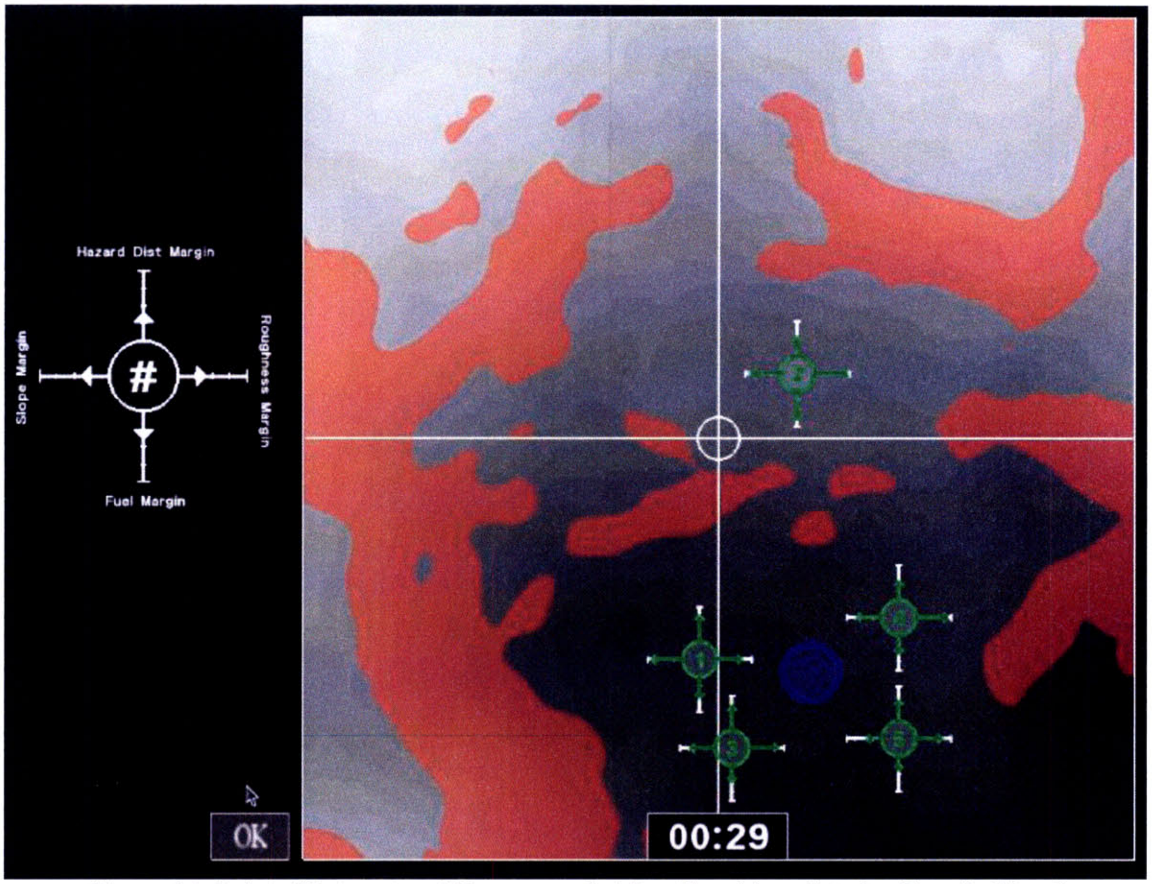

Figure 16: Point of Interest and Recommended Landing Aimpoints for Terrain Map 3

4.6 Procedure

The following is an outline of the experimental procedures used for each participant. A detailed explanation of the procedures follows the outline.

1. Participants received off-line training on display features, including algorithm representation, and also on the missions related to the point-of-interest.
2. Participants received off-line training on level 2+ automation.
3. Participants completed a paper test ordering five generic landing aimpoints.
4. Participants performed training and trials with level 2+ automation.
5. Participants received off-line training on level 3 automation.
6. Participants performed training and trials with level 3 automation.

7. Participants received off-line training on level 3+ automation.
8. Participants completed a paper test, as before, but with instruction to order the landing aimpoints as they believed the algorithm would.
9. Participants performed training and trials with level 3+ automation.

Each experiment lasted approximately an hour. The experiment was a fully crossed, within subjects design, such that the participants experienced all three levels of automation with all three POI missions. During the experiment, the levels of automation were blocked because it was noticed in pre-testing experiments that the algorithm's recommendations significantly affected the performance when there were no recommendations (LOA 2+). In addition, participants would partially memorize the rankings of landing aimpoints (LOA 3+), and these memories affected the performance in scenarios without rankings (LOA 3).

For each block of scenarios, corresponding to the three LOAs, the subjects received the initial training through viewgraphs. Participants proceeded through this section of training at their own pace and were allowed to ask questions at any time. Before beginning the experimental trials, participants were also given training scenarios of each of the experimental conditions for practice using the experimental setup in the cockpit simulator. The experimenter was required to initiate each of the scenarios, so generally the subject received 10-15 seconds of rest between scenarios. The participants were again allowed to ask questions at any time.

The paper tests were given to assess the subject's understanding of the aimpoint representations and of the algorithm's ranking logic. The test consisted of five aimpoints on a black background as exemplified in Figure 17. Three versions of the test were given each time to allow for repetitions of the data. The subjects completed these tests untimed and were allowed to use the training slides that they just viewed to aid them.

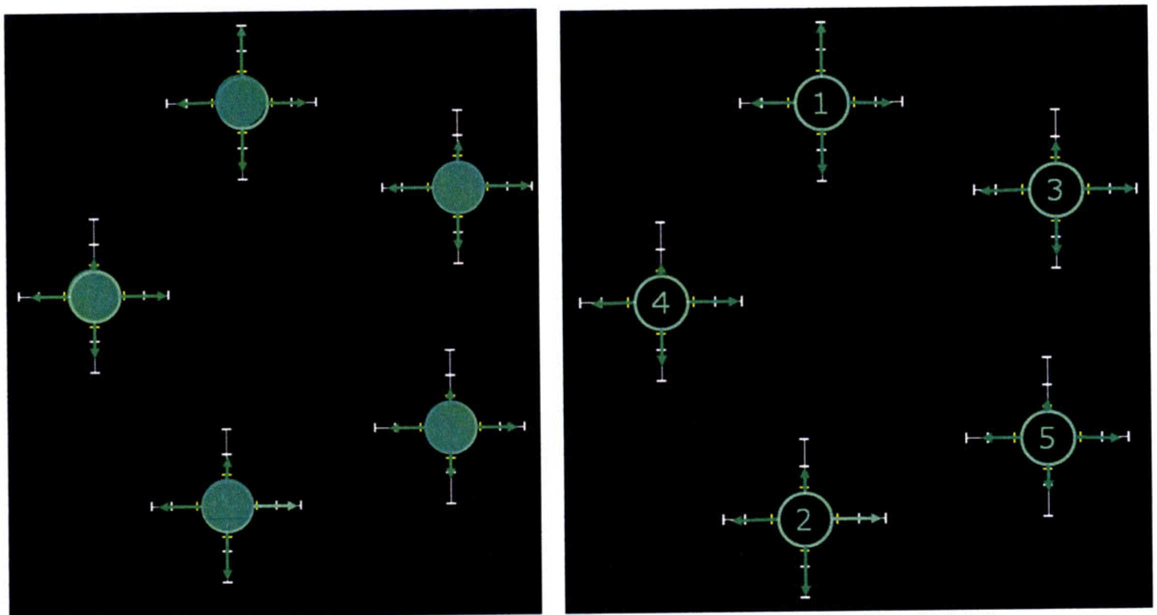

Figure 17: First Paper test as given to Subjects (left) and Solution (Right)

The experimental conditions were given in the same order for each subject; randomization was achieved through the randomized ordering of the three terrain maps. The POI missions were given in the order of (1) no POI, (2) geological POI, and (3) rescue POI. This order corresponds to increasing importance of the POI in the subject's decision-making subjects. Since the same three terrain maps were repeated for each experimental condition, there was concern that participants would base their decision on memories of previous trials. However, it was determined from pre-tests that subjects were truly evaluating each scenario based on the unique conditions of that scenario. This reflects the strong role that goals play in the decision-making process.

The interview probed the following topics:

- General decision making strategy for each level of automation

- Effect of POI missions on decision making strategy
- Integration of POI goal with safety goal, especially when landing aimpoints are recommended by the algorithm (LOAs 3 and 3+)
- Preferences of the levels of automation
- Challenges of the decision making process
- Use of display features
- Desired additional features

4.7 Data collection

Data was collected during the experiment in the form of screen recordings and raw performance data described under the dependent variables. The performance data included which landing aimpoint was chosen, its corresponding safety parameters, and the time needed to make the decision. Additional notes on subject posture and behavior were written by the experimenter. The screen recordings were then replayed to the participants during the retrospective interview. The interview was recorded with permission into a handheld digital audio recorder, and these interviews were later reviewed by the experimenter for analysis.

4.8 Statistical Analysis

Statistical Analysis was performed with SYSTAT 10.0 (Systat Software Inc.). In addition to evaluating various plots and descriptive data, the following tests were performed on the appropriate data:

- Kolmogorov-Smirnov One Sample Test: A non-parametric test to compare the distribution of a variable to a normal distribution. A significant p-value means that the variable is non-normal.
- Sign test: A non-parametric test to compare the distributions of two related variables. A significant p-value means that the variables are significantly different. No assumptions on the variables.

In this thesis, all results with a p value < 0.05 are reported as significant unless otherwise stated. The plots presented in the following chapter represent the data averaged over the participants. In addition to the quantitative analysis, a qualitative analysis was performed, evaluating the subject responses given in the interviews.

Chapter 5 Results and Discussion

This chapter explains the results obtained from the experiment described in Chapter 4. Qualitative and quantitative effects of the levels of automation and points-of-interest are described. In addition, the participants' strategies are explored through the recorded subjects' actions and subsequent verbal protocols. Finally, a discussion highlights conclusions drawn from the experiment.

5.1 Level of Automation

There is one independent, within-subjects variable: LOA, with three factor levels: 2+, 3, and 3+. The type of terrain, as represented in the three terrain maps, must be viewed as a separate within-subjects variable because fundamental differences in those data sets might cause unintended variation if not monitored in the analysis.

5.1.1 Task Time to Select Landing Aimpoint

One assumption of using a within-subjects ANOVA is that the distribution of the dependent variable must be normal at each factor level. A Kolmogorov-Smirnov One Sample Test revealed that the task time data does not satisfy this requirement, and the following histogram also reveals that the different biases in the data distribution.

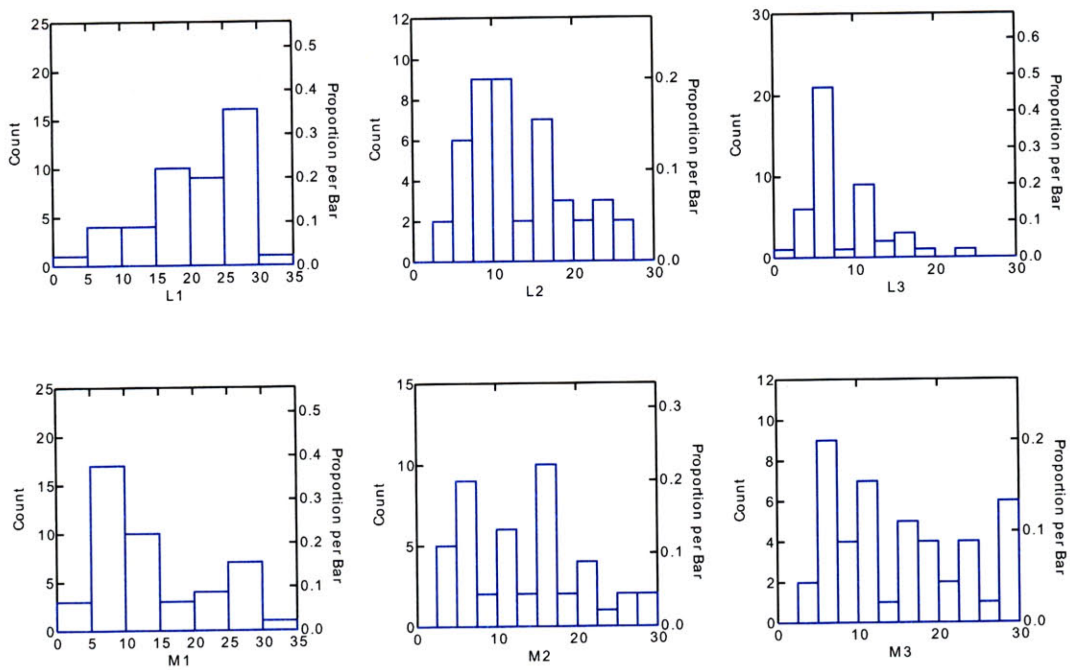

Figure 18: Histogram of the Task Times for the factor levels of the Level of Automation (L: L1=2+, L2=3, L3=3+) and the Terrain Maps (M)

It can be seen from the plot of the means in Figure 19 that the task times are significantly lower for LOA 3+ and significantly higher for LOA 2+. A nonparametric test, the Sign Test, was performed on pairs of factor levels. This test is appropriate since it has no requirements on the pairing of the data nor on the normality of the distribution. The results also show that there is there is a significant difference in task time between the levels of automation.

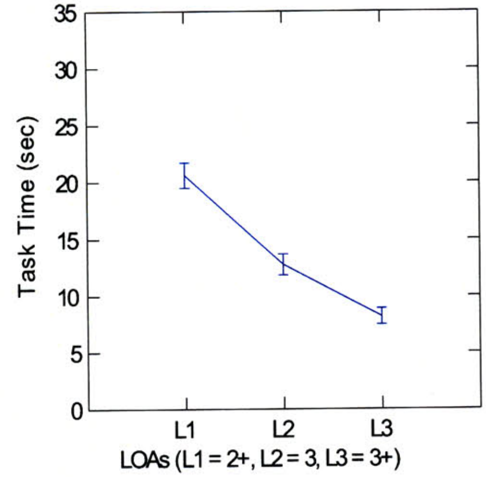

Figure 19: Means Plot of the Levels of Automation with Lines to Assist in Visual Comparison Only

As expressed in Figure 20, the terrain maps do not have a significant effect on task time. This implies that the variability in task time is due to differences between the levels of automation and not to variability among the maps.

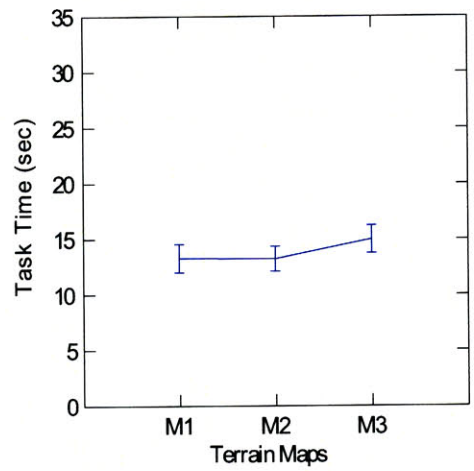

Figure 20: Means Plot of the Task Times as a Function of the Three Terrain Maps (Lines to assist visual comparison only)

The main result is that the task time is significantly lower for LOA 3 than LOA 2+ and for LOA 3+ than both LOA 2+ and LOA 3.

5.1.2 Quality of Landing Aimpoint

The dependent variable, quality of the landing aimpoint, is essentially an ordinal variable in LOA 3 and 3+ because there are only fifteen possible values for this variable, and only five possible values for each terrain map. Since the landing aimpoint decision is constrained, a nonparametric statistical test must be used. The Sign Test was again applied, and the p-values are listed in Table 5 (Appendix D). With one exception, the results show that the quality values of the aimpoints are significantly different across the levels of automation when the terrain map variable is held constant. However, when the levels of automation are considered separately, there are some differences between the maps, as shown in the italicized font in Table 5.

Across most of the maps there is a significant difference between the levels of automation. As shown in the plot of the means in Figure 21, the safety quality values are significantly lower for LOA 3+ and significantly higher for LOA 2+.

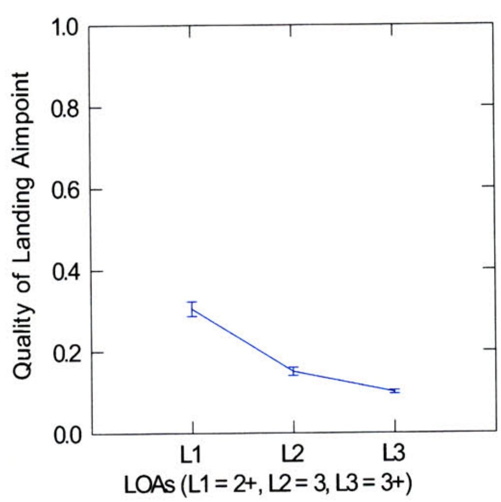

Figure 21: Means Plot of the Levels of Automation with Lines to Assist in Visual Comparison Only

Further, as shown in Figure 22, the second map shows some differences relative to the first and third map. However, the main result is that the task time is significantly lower for LOA 3 than LOA 2+ and for LOA 3+ than both LOA 2+ and LOA 3.

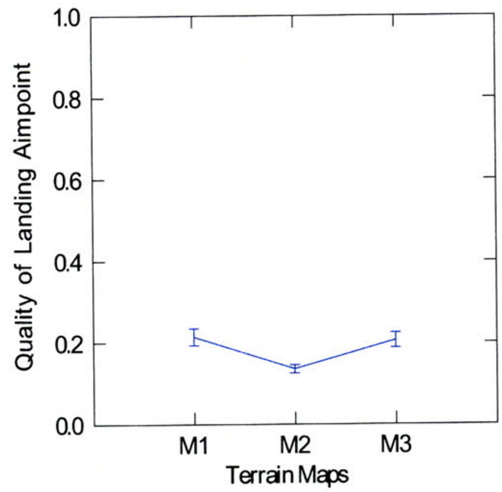

Figure 22: Means Plot of the Safety Qualities as a Function of the Three Terrain Maps (Lines to assist visual comparison only)

5.1.3 Discussion

The hypotheses surrounding the effect of the level of automation were:

Hypothesis 1: the time needed to complete the LPR decision is expected to be longest for scenarios with level 3+ automation, and shortest for scenarios with level 2+ automation

Hypothesis 2: the quality of the landing aimpoint chosen is expected to be best for scenarios with level 3+ automation and worst for scenarios with level 2+ automation

The first hypothesis was rejected by the results. The LPR decision was longest for scenarios with level 2+ automation because the subjects opted to spend a long time searching for the "best" landing aimpoint, where best was a combination of the safety criteria presented to them and untaught internal bias. The automation's narrowing of the possible decisions led to significantly quicker task times even despite the need for the subjects to consider the automation's recommendations and interpret the aimpoint representations. The rankings appeared to further assist the interpretation of the aimpoint representations and thus lead to quicker task times.

The second hypothesis was supported by the results. The automation's recommendations proved to be significantly safer than the human recommendations. While this result is not expected, it is an important indicator regarding the benefits of automated aiding of human decision-making. One supporting reason for this result is that the human was instructed to search the map using information that was already electronically coded in such a way that a computer could perform the task more efficiently.

5.2 Point-of-Interest

5.2.1 Task Time to Select Landing Aimpoint

A Kolmogorov-Smirnov One Sample Test again reveals that the task time data does not satisfy the normality requirement, and the following set of histograms show that the different biases in the data distribution.

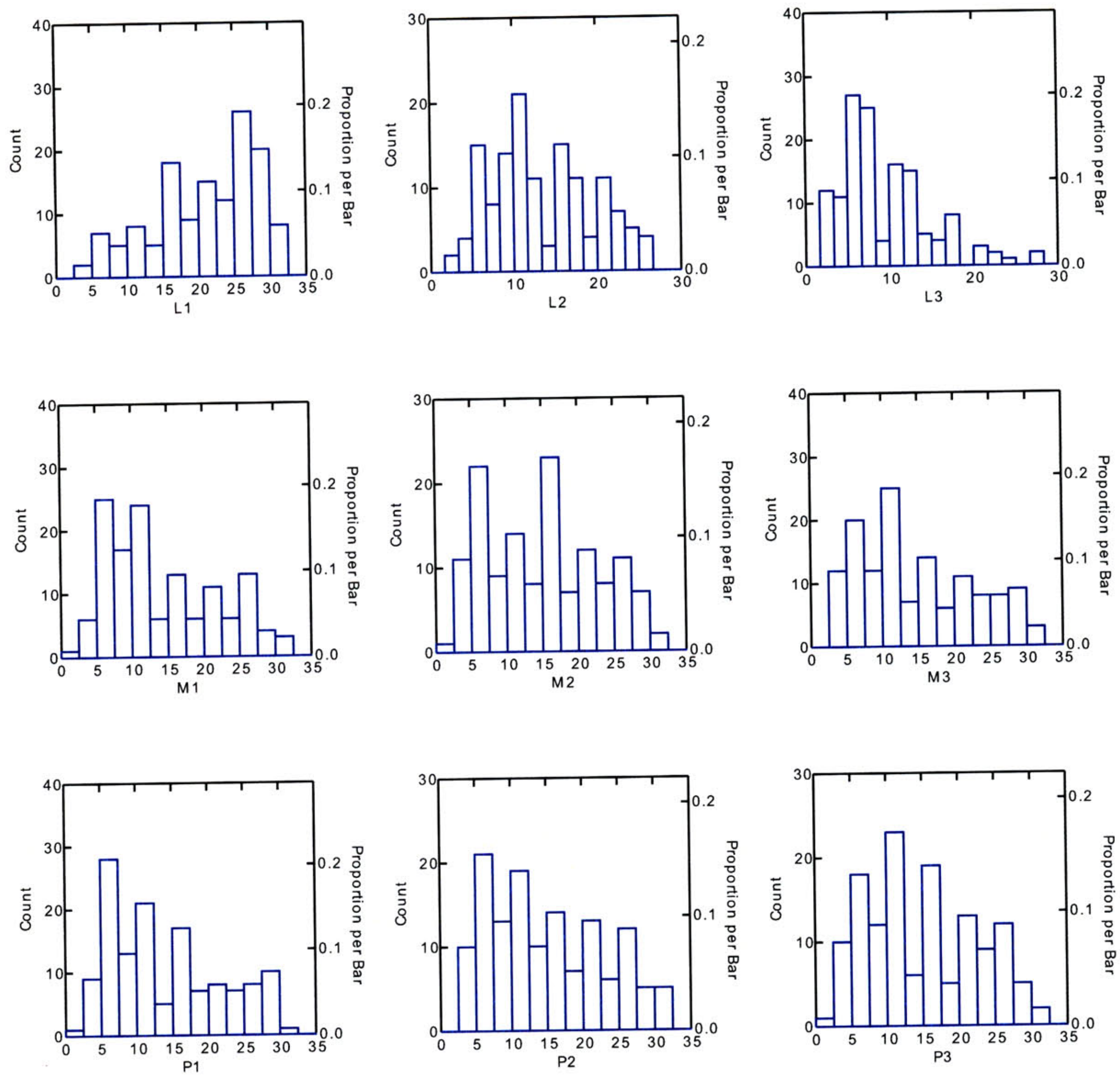

Figure 23: Histogram of the Task Times of the Levels of Automation (L: L1=2+, L2=3, L3=3+), the Points of Interest (P: P1=None, P2 = Geological, P3 = Rescue), and the Terrain Maps (M)

The Sign Test was again performed on pairs of factor levels. The results reveal that there are very few factors levels in which the POI is a significant factor. However, looking at the probabilities for the geological (P2) and rescue (P3) missions, the levels of automation generally do have an effect, most significantly when comparing LOA 3+ (L3) to LOAs 2+ and 3. The predominance of the LOA effect is shown in Figure 24 relative to the POI and map effects, in addition to being seen in the histograms above. In summary, across the relative levels of point-of-interest, the task time is generally a significant amount lower for LOA 3 than LOA 2+, and for LOA 3+ than both LOA 2+ and LOA 3.

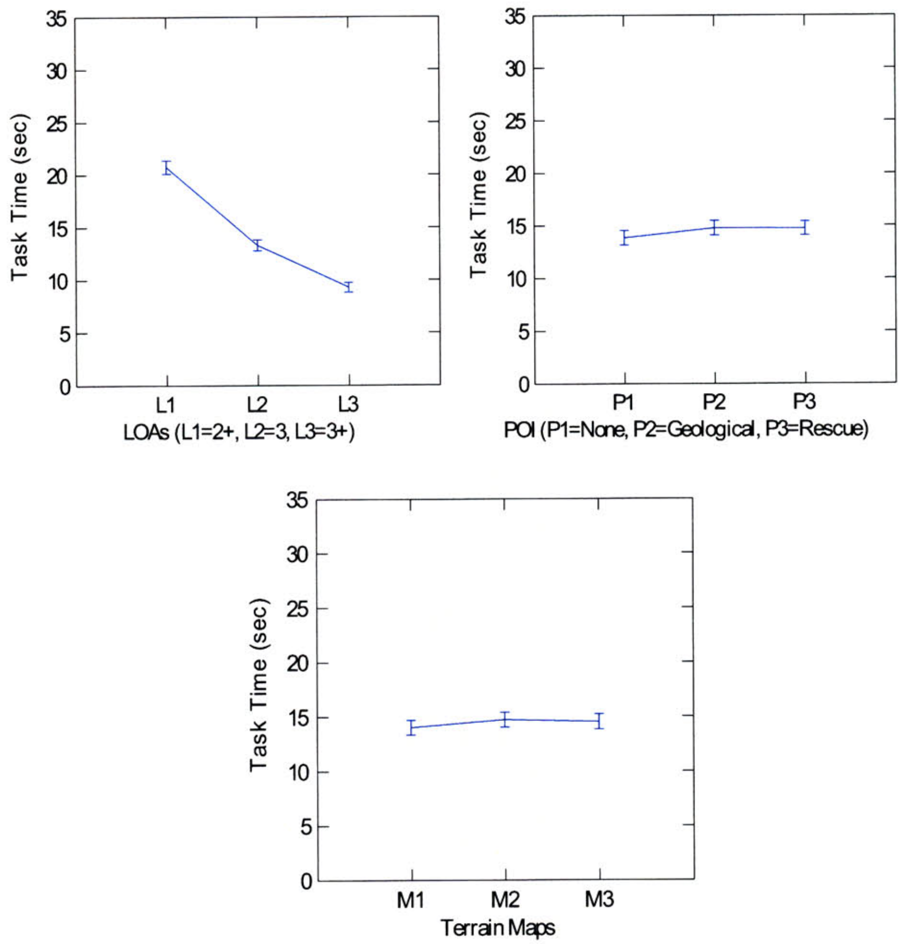

Figure 24: Means Plots of the Levels of Automation (L), the Points of Interest (P), and the Terrain Maps (M) (lines to assist in visual comparison only)

5.2.2 Quality of Landing Aimpoint

Since the landing aimpoint decision is constrained, the Sign Test was again used, and the results are listed in Table 7. The same coding is used: p-values in bold font are the factor levels comparisons between all of the LOAs and POIs, p-values in both bold and italicized font are the factor level comparisons between the different POI levels, and the boxed p-values are the factor level comparisons between the different LOAs.

Across most maps there are several factor levels with significant differences due to the effect of the POI, primarily between the scenario without a POI (P1) and the scenarios with POI (P2 and P3). This result, as well as the significant effects due to the LOAs, is shown in Figure 25. The analysis also reveals that the level of automation has an effect for geological and rescue missions, even across all three maps when LOA 2+ is compared to both LOA 3 and 3+ in the rescue mission. It is most likely that the significance of terrain map 1 was due to the hazards between the position of the POI and the landing aimpoint recommendations.

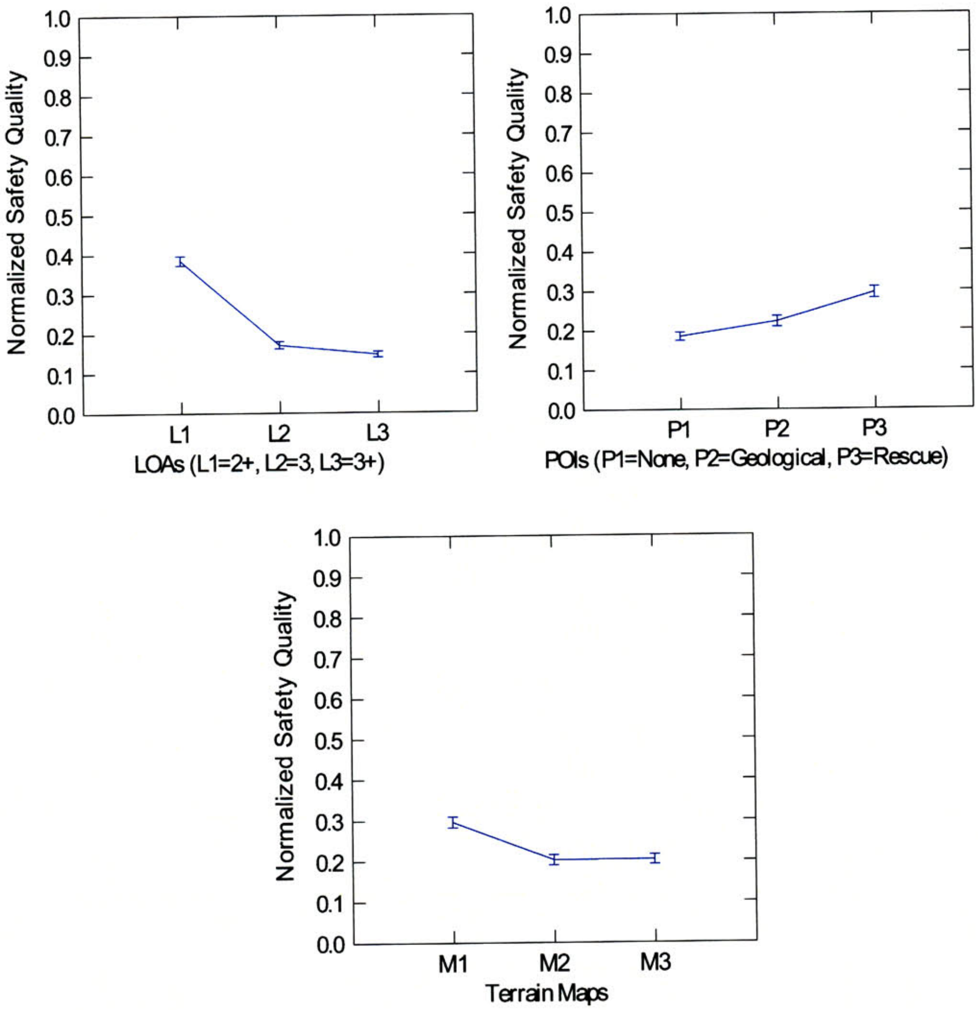

Figure 25: Means Plots of the Aimpoint Quality as a Function of the Levels of Automation (L), the Points of Interest (P), and the Terrain Maps (M); Lines to assist in visual comparison only

5.2.3 Discussion

The hypotheses surrounding the effect of the level of automation combined with the point-of-interest were:

Hypothesis 3: the time needed to complete the LPR decision will be longer compared to the baseline condition, for higher levels of automation when the POI goal is more important in the decision

Hypothesis 4: the quality of the landing aimpoint, based on safety criteria, is expected to be lower compared to the baseline condition, for lower levels of automation when the POI goal is more important in the decision

The former hypothesis was rejected. The additional goal that the human had did not affect task time as strongly as the level of automation. The result suggests that the LOA 3+ assisted faster task completion even when the human and automation had different goals. Certainly the design of the LOA was critical to that effect since it was purposefully designed to support human goals in decision-making by providing the more detailed aimpoint representation. In addition, it is reasonable to assume that a more complex or more poorly defined goal that the human possessed would cause a larger effect.

The latter hypothesis was supported. The rescue mission in particular highlighted that the subjects accepted significantly lower safety quality aimpoints when they chose the aimpoint rather than selected from the automation's recommendation. This experiment was designed such that the human's external goal had an obvious meaning of 'good' or 'bad' and needed to be weighed against the goal of safety. For that reason, one way to interpret these results is that automation can prevent the human from accepting too much risk, or prevent the human from focusing on a single goal to the point of neglecting other important goals.

5.3 Decision Strategies

Verbal reports are one indicator of the thought processes behind problem solving. In this section, results from the retrospective verbal protocol are presented, analyzed and discussed for their indications about the subjects' decision making processes. These results are compared with the DM models presented in the Cognitive Models Chapter.

5.3.1 Verbal protocol results

Following the experiment, subjects were interviewed using two methods. First they were asked a series of questions about specific aspects of the decision-making processes. Then subjects were asked to describe their "play-by-play" thought process while watching a recording of their scenarios in order to elicit more detail about their decision making process. Across the three LOAs, several interesting trends emerged.

The first interesting trend was that in LOA 2+, most subjects searched for many options of their own to compare. In their verbal responses, this technique was often referred to as "optimizing". Other subjects described this search for alternatives as "checking to be sure [that there was not a better aimpoint]" or looking "to see if there was something I was missing". An individual with a military background described his/her strategy of searching for many options as trying to "fire all your guns". One subject summarized this approach in the following way: "I wanted to just check and see if there was a surprise somewhere else that I wouldn't have first thought of....just to check since I had time....I feel like after the first ten or fifteen seconds, I was just optimizing for that last little bit of margin, which really wasn't that important I guess." The main trend was that the subjects preferred to be presented with options and generally used the time allotted to find the safest aimpoints that they could.

The second interesting trend in LOA 2+ was the "honing in" or "zoning in" technique that many of the subjects utilized. Many subjects started by clicking over the map to decide which area they felt was the best, and then explored that particular area more closely. One subject described her decision process as gathering "quick snippets of the general region" and then "tuning" the margins in the region she thought was safest. Another subject described a similar strategy as searching for the "local optimum close to global optimum" since he felt that the time limit prohibited finding the so-called global optimum. This narrowing down technique often led to the final aimpoint decision, as described by a third subject, "When I tried moving in any direction and started losing margin, then I decided that was a maximum and stayed with it." It is especially interesting that the subjects would take a single aimpoint examination to be representative of a particular region.

A third interesting trend in LOA 2+ came from an interview question surrounding what the subject's particular criteria for "good enough" was, that is, the point where they stopped searching for a safe landing aimpoint and selected the one chosen. Although time came into play in terms of how long they could search, many subjects eventually selected the criterion that if all four margins were above fifty percent, then that would be an acceptable landing aimpoint. The fifty percent criterion for search termination was so unexpected, yet so common, that a follow-on question was added to probe more deeply into the development of this strategy. Some of these subjects cited developing this criterion in the practice trials, while others could not explain why they chose fifty percent as the cutoff other than it seemed reasonable to them. In addition, even subjects who stated this as their criterion got greedy, often finding an acceptable point, and still searching for a better one "just to be sure".

The primary trend in the LOA 3 automation was the method of comparing the recommended landing aimpoints. Most subjects performed an initial elimination of options that had one safety margin below a threshold that the subject was willing to accept. This exclusion criterion was not taught to the subject in any way, but a new tolerance value was always established somewhat above the preset safety tolerance and varied based on the subject's personal preference, although it often fell at around a quarter of the aimpoint representation arm length. One subject described this elimination as internally asking, "Are any obviously bad?" Once some aimpoints had been eliminated, the subjects had narrowed their options to the top two or three, and then performed a final comparison between those options, sometimes double checking the final decision with all of the alternatives. Some subjects made their final decision quickly, while many others followed the words of one subject who admitted that, "Sometimes I would sit there just fine tuning mentally."

Two subjects noted the role of what they felt were less conscious parts of their mind. When pushed to describe in more detail how the "best" of the aimpoint recommendations was chosen, one subject stated, "You kind of take them [the aimpoints] in all at once. I feel like it's almost a subconscious decision; you don't have to think about it that much." S/he also didn't feel like a "proper check" was necessary when the aimpoints were very similar in safety since both would be acceptable places to land. Another remarked on the role that the hazards played somewhat unconsciously into the decision: "I think I rejected those [two landing aimpoints] kind of early. I guess something about them being completely surrounded by hazards didn't strike me as ok. I know that wasn't given as a criteria (sic), but it seemed like something I should do." While the verbal protocol was able to uncover some of these effects, subjects offered such differing levels of detail that it is very likely the more reticent neglected to mention such phenomenon.

The trend seen in LOA 3+ reflected concurrent use of both the ranking numbers and landing aimpoint representations. The general strategy of most of the subjects was to only consider the top two landing aimpoints as ranked, and sometimes to compare the margins on these two aimpoints. When the second ranked aimpoint was chosen in scenarios without a POI, subjects said they perceived that the margins seemed largest for that aimpoint, revealing their use of both the automated ranking as well as the "backup" information inherent in the aimpoint representation. Other reasons for not choosing the top ranked aimpoint included the presence of a hazard between the top ranked aimpoint and the center of the map and preferring a landing aimpoint that had more balanced safety margins among the four safety parameters. In addition, some subjects also noted doing very brief scans of all five aimpoint representations as a "sanity check". One subject describes this check as, "I figured the computer could measure lines probably better than I could, so I just chose 1 [the top ranked] and then sort of thought it over, trying to figure out what the computer was doing…. I said, OK, let's look at 1. It looks pretty good. Now how did the computer rank 1 to 2 to 3 to 4?" Certainly the ranking played a role in the subject's psychological willingness to consider a landing aimpoint. One subject expresses that "Sometimes I'd look at 2, but then I'd be like, well why would

I pick that? It doesn't really make sense. So I'd just go with the first one....Sometimes I'd look at the arrows of 1 and 2, just to see how much the difference was between the safety, maybe 3, but 4 and 5 I don't think I ever looked at usually." However, subjects seemed to focus on the utility of the rankings, as this subject remarks, "For anything without a point of interest, I just went toward the aimpoint that the computer ranked number 1 because I figured that the technology is much more methodical and has more accurate counts on the length of the safety margins than I would just by looking and comparing with my naked eye." The overall trend for LOA 3+ was a use of the rankings to narrow the number of comparisons made using the margins on the aimpoint representations. Most subjects did not depend exclusively on the rankings, but nor did they totally neglect to use them.

An interesting trend affecting all LOAs and related to both the elimination criteria and general aimpoint evaluation strategies was many subject's clearly expressed preference for landing aimpoints that had relatively similar safety margins on all four safety parameters. In LOA 2+, one subject describes this effect: "the value of it [a safety margin] being a very low margin was very low, but as it got higher and higher margin, the marginal benefit decreased. So I'd rather have a lot of things far from low margin than one thing [safety parameter] close to low margin and other things far from low margin. I was looking for a uniform distance from the center circle [of the landing aimpoint representation], thinking that since it was margin, once you have a lot of margin, adding a little more doesn't really improve you." In LOA 2+, the subjects used this strategy to quickly decide if a landing aimpoint had potential or if they needed to continue their search. This effect again showed up in LOA 3, as described by another subject: "As a crude approximation, I looked to see how many of the arrows were over fifty percent [of the length on the aimpoint representation]. I tried to get a qualitative judgment of weighting between them [the landing aimpoint recommendations]. Like if one had all four [arrows] over fifty percent and the other ones didn't, then I thought that would give me a qualitative way of picking quickly which one had the highest utility." In LOA 3, this strategy again shows up as elimination criteria. It was further encountered in LOA 3+, as related to the automation's ranking algorithm: "when I was choosing them [the landing aimpoints], I was doing an exponential weighting on the arrows. When you're [the margin is] really small, that's really bad, whereas, if you're really large versus half large, it's almost equal. Whereas, I assume the computer was doing a uniform cost function, taking the overall amount of green….I figure humans would go with the more exponential distribution: the closer you get to the warning sign, the more nervous you get about picking that. Whereas the computer wouldn't really care." The trend seen in all three levels of automation was the human's desire to equally weight the four safety parameters, and additionally to consider the best landing aimpoints to be ones with equally high margins on all four safety parameters.

5.3.2 Discussion

The hypothesis surrounding the decision making strategies was:

Hypothesis 5: decision making strategies will be different between scenarios with different levels of automation.

A meta-analysis of the verbal protocols suggests that this hypothesis should be rejected. The subjects appeared to establish a decision making strategy that they then maintained throughout the remainder of their testing, making only minor modifications to their approach when presented with different LOAs. In LOA 2+, the subjects were required to search for candidate landing aimpoints, but the overall trend suggests that subjects had enough time and desire to find several viable options for comparison and pseudo-optimization. Since specific aimpoints could not be saved in LOA 2+, subjects often developed evaluation criteria and search termination criteria. In LOA 3, the step of searching for options was already completed, and the evaluation and termination criteria were combined into several levels of evaluation. The first round usually included some form of quick elimination and identification of the best couple aimpoints. Second and third rounds of evaluation were generally for comparing the top two options, deciding which was best, and then occasionally a last check to approve this option. In LOA 3+, both the search for landing aimpoints and the first level of evaluation were eliminated, since the rankings identified the best aimpoints. Subjects were able to very quickly compare the best options and make their selection.

Of the general decision making frameworks discussed, image theory is most like the decision strategies that the subjects describe using, with the theory's compatibility test serving as the search and elimination rounds and the theory's profitability test reasonably describing the aimpoint evaluations. It was surprising that the DM strategy for LOA 2+ was not more similar to Klein's RPD, where experts select one decision alternative and do not consider other solutions until their selection proves to be invalid. One potential difference between the scenarios supporting Klein's model and the scenarios used in this experiment is the time limitation. The firefighters studied by Klein were literally making split second decisions and did not have the luxury of the thirty second time frame used for this experiment. Although this experiment only tested one time period, it is likely that the decision strategies would become less and less of an optimizing strategy, tending towards a satisficing strategy, if the allowed time were shortened.

Based on the observations in this section, the decision making model can be augmented as shown in Figure 26.

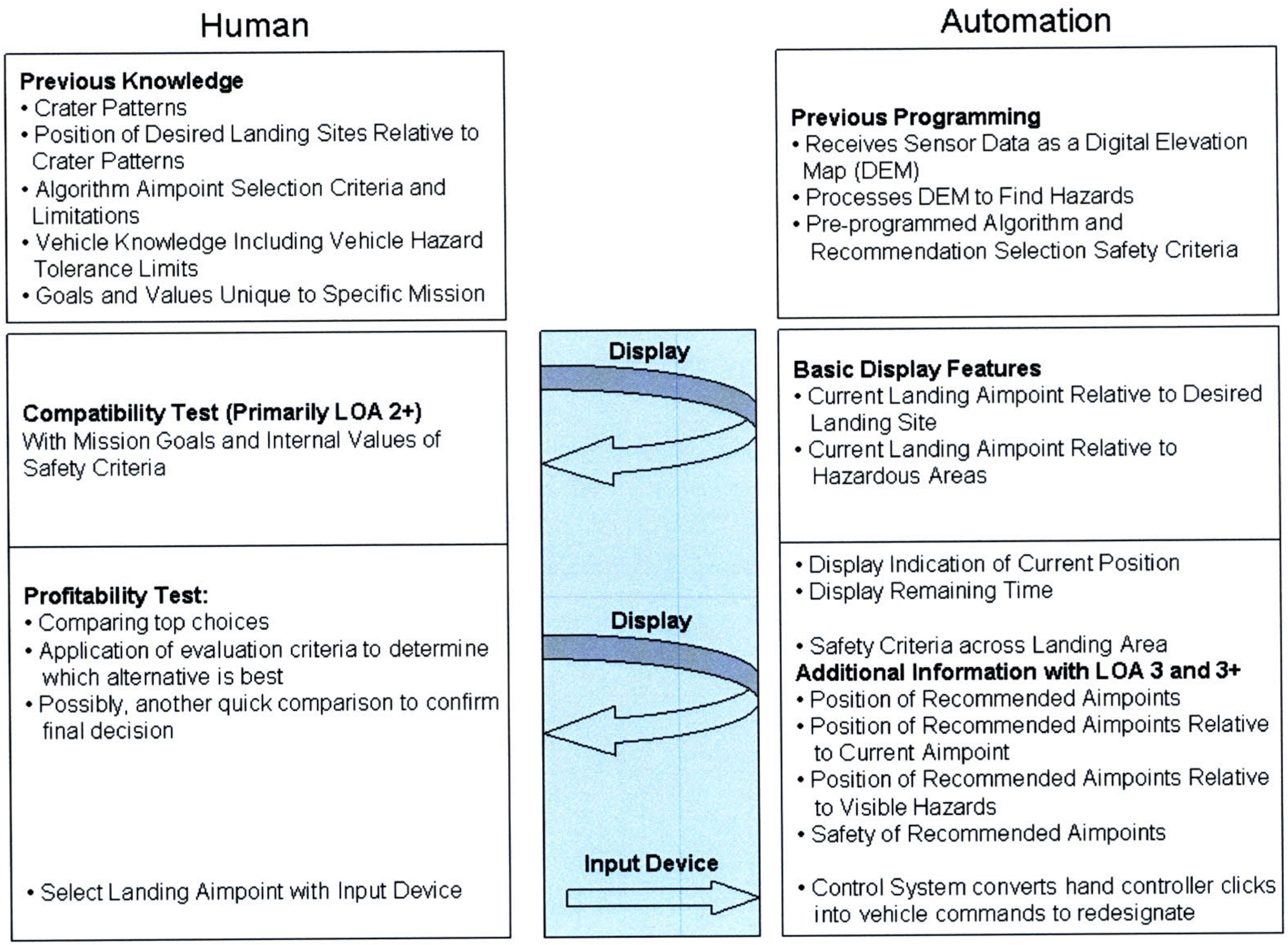

Figure 26: Revised Decision Making Model

Chapter 6 Summary and Future Work

This thesis has explored human-automation interaction components of the landing point redesignation (LPR) task and has studied the role of the level of automation and points of interest in addition to the decision-making processes. This chapter summarizes the work presented in the thesis and suggests areas of extension for future research.

6.1 Summary of Findings

Human-automation interaction mechanisms are a challenging design problem of manned systems. For operations where safety is critical, such as lunar landing, the human is given final responsibility for important decisions, such as selecting a landing aimpoint. Experimental results demonstrated that people generally use the same decision strategies across different levels of automation. In addition, when objective criteria are applied, it was found that the subjects used the automation to assist in completing some portions of their landing aimpoint selection. The higher levels of automation examined in this work allowed the subjects to more quickly select a landing aimpoint. When an external goal is present, in opposition to the automation's recommendations, it was found that the human can adjust his or her decision strategies and utilization of the automation to incorporate both objective and subjective task goals. Although the subjects chose lower safety margins to achieve closer proximity to the point of interest, the assistance of higher levels of automation allowed subjects to maintain large safety margins while layering their external goal for high achievement of both goals.

6.2 Future Work

The following chapter discusses potential next steps in this research on lunar landing, LPR, algorithm design, and human-automation interactions.

6.2.1 LPR Algorithm Design

From this research, it is clear that the automated algorithm used for landing point redesignation should be developed at the same time as the development of the human-interaction mechanisms. For successful human-automation interaction to occur, the human should be able to have an external verification for the algorithm's solution. This external verification could be further explored in a number of ways. Including a so-called out-the-window view of realistic, albeit synthetic, lunar terrain introduces a number of different human factor issues relating to a person's perception of terrain compared to the terrain as analyzed and displayed by the automation. Analysis such as comparisons of the human's expectations based on the window view alone compared to the displayed view alone could reveal underlying issues or challenges in the algorithm design.

Increasing the allowed interaction with the algorithm would be a very interesting follow-on experiment, both for algorithm designers and human factors engineers. The limitations to manipulating parameters or thresholds or cost functions are unknown. In particular studying the role of interaction as function of time, level of automation, and interaction type and amount would all be essential if additional algorithm interaction is desired.

Further, a number of different off-nominal scenarios could also be considered to study the role of trust in the automation. The LPR algorithm is not a standalone technology, but instead relies on imperfect data obtained from sensor hardware and other algorithms. For that reason, it might be interesting to study the effect of errors propagated through the system. In addition, trust in automation is a much broader topic that will likely become critical in lunar landing due to the high risk of each lander mission.

6.2.2 Decision Aiding Capabilities and Display Design

There is another level of abstraction from the algorithm itself to the display design. This thesis has identified key design components for inclusion in the display, but perhaps removing these components would reveal their true effect on the decision. For a particular level of automation, it is unknown if the design requirements would significantly change. Subjects noted that they paid little attention to the map once aimpoint recommendations were given.

Increasing the allowed interaction with the algorithm would introduce the possibility for a range of display design and interaction mechanism studies. What time of prediction will the human require for their interaction? How do the limitations of the human (their understanding and ability to manipulate the tool) relate to the limitations of the environment (amount of time and display interaction options) relate to the limitations of the algorithm (interactions allowed and processing time for each different interaction)? These questions are still open for examination.

6.2.3 Extensions to Broader Lunar Landing Challenges

The period of time during the landing that was studied in this thesis is relatively small. Before reaching pitchover, the human will most likely have garnered significant expectations about their progress. These expectations may play a role in the LPR decision. If the modern lunar landing design follows the Apollo design, at some point, the astronaut will desire to shift to a lower level of action automation. In the Apollo missions, the astronauts generally guided the automation short of their intended landing aimpoint for better visibility during the more manually flown period. Even before the prediction of such effects, it remains to be studied how the transition from a highly automated LPR decision period to a more skill-based terminal landing may be completed.

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Appendix A: COUHES form

MIT Committee On the Use of Humans as Experimental Subjects

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
Building E 25-143B
(617) 253-6787

To:	Jennifer Needham
From:	Leigh Firn, Chair COUHES
Date:	03/25/2008
Committee Action:	**Expedited Approval**
COUHES Protocol #:	0803002640
Study Title:	Decision Aiding Displays for Landing Aimpoint Selection
Expiration Date:	03/24/2009

The above-referenced protocol was approved following expedited review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

If the research involves collaboration with another institution then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. You may not continue any research activity beyond the expiration date without approval by COUHES. Failure to renew your study before the expiration date will result in termination of the study and suspension of related research grants.

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol that impact human subjects, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated.

Prospecitve new study personnel must, where applicable, complete training in human subjects research and in the HIPAA Privacy Rule before participating in the study.

COUHES should be notified when your study is completed. You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with COUHES, original signed consent forms, and study data.

	Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects	Application # (assigned by COUHES)	
		Date	

APPLICATION FOR APPROVAL TO USE HUMANS AS EXPERIMENTAL SUBJECTS (STANDARD FORM)

Please answer every question. Positive answers should be amplified with details. You may mark N/A where the question does not pertain to your application. Any incomplete application will be rejected and returned for completion. ***A completed CHECKLIST FOR STANDARD APPLICATION FORM must accompany this application.***

I. BASIC INFORMATION

1. Title of Study	
Decision Aiding Displays for Landing Aimpoint Selection	
2. Principal Investigator	
Name: John Hansman	Building and Room #: 33-303
Title: Professor	Email: rjhans@mit.edu
Department: Aeronautics and Astronautics	Phone: (617) 253-2271
3. Associated Investigator(s)	
Name: Jennifer Needham	Email: jneedham@mit.edu
Title: Masters Candidate Research Assistant	Phone: (832) 326-6888
Affiliation: Aeronautics and Astronautics	
4. Collaborating Institutions. *If you are collaborating with another institution(s) then you must obtain approval from that institution's institutional review board, and forward copies of the approval to COUHES)*	
5. Location of Research. *If at MIT please indicate where on campus. If you plan to use the facilities of the Clinical Research Center you will need to obtain the approval of the CRC Advisory Committee. You may use this form for simultaneous submission to the CRC Advisory Committee.*	
Draper Laboratory (555 Tech Sq)	
6. Funding. *If the research is funded by an outside sponsor, please enclose one copy of the research proposal with your application. A draft of the research proposal is acceptable.*	
Source: N/A	Contract or Grant Title: N/A
Contract or Grant #: N/A	OSP #: N/A
7. Human Subjects Training. *All study* personnel **MUST** *take and pass a training course on human subjects research. MIT has a web-based course that can be accessed from the main menu of the COUHES web site. COUHES may accept proof of training from some other institutions. List the names of all study personnel and indicate if they have taken a human subjects training course.*	
John Hansman, completed; Jennifer Needham, completed MAR07	
8. Anticipated Dates of Research	
Start Date: April 2008	Completion Date: December 2008

II. STUDY INFORMATION

1. Purpose of Study. *Please provide a concise statement of the background, nature and reasons for the proposed study. Use non-technical language that can be understood by non-scientist members of COUHES.*

The study is designed to understand the operator's performance and decision making process in choosing a landing aimpoint for a simulated lunar landing mission using different levels of a decision-making aid. In the next lunar landing, astronauts will need to land in areas that have poor visibility with the unaided eye. This research is intended to explore decision making using levels of automation that support human understanding of an algorithm for landing aimpoint redesignation.

2. Study Protocol. *For* ***biomedical, engineering and related research****, please provide an outline of the actual experiments to be performed. Where applicable, provide a detailed description of the experimental devices or procedures to be used, detailed information on the exact dosages of drugs or chemicals to be used, total quantity of blood samples to be used, and descriptions of special diets.*

For applications in the ***social sciences, management and other non-biomedical disciplines*** *please provide a detailed description of your proposed study. Where applicable, include copies of any questionnaires or standardized tests you plan to incorporate into your study. If your study involves interviews please submit an outline indicating the types of questions you will include.*

You should provide sufficient information for effective review by non-scientist members of COUHES. Define all abbreviations and use simple words. Unless justification is provided this part of the application must not exceed 5 pages.

Attaching sections of a grant application is not an acceptable substitute.

(1) Training will be given for understanding of the general experiment and to orient the subjects to use the features of the displays. A paper test will then be given to test the subjects' understanding of a display feature representing the landing aimpoints. The experimenter will record the accuracy of the paper test.
(2) Training will then be given on how to select the landing aimpoints without a decision aid. The subjects will have several practice trials corresponding to the training. A practice trial will be identical to the scenarios below, except that no data will be recorded for analysis.
(3) Following this training, six 30-second scenarios will be given without a decision aid. The subject will use a mouse to click on the landing area to prompt for information about the clicked landing point. The subject will use the mouse to indicate their final decision, and the responses will be timed and also measured for quality of response.
(4) Training will then be given on how to select the landing aimpoints with a two different levels of a decision aid. The subjects will have several practice trials corresponding to the training.
(5) Following this training, 24 30-second scenarios will be given with a decision aid. The interactions will be same as described in (3).
(6) Following the experiment, the subjects will be asked to describe their decision making process, and their interview will be recorded for later review by the experimenter.
(7) A paper test similar to that given early in the experiment will again be given to assess their understanding.

3. Drugs and Devices. *If the study involves the administration of an investigational drug that is not approved by the Food and Drug Administration (FDA) for the use outlined in the protocol, then the principal investigator (or sponsor) must obtain an Investigational New Drug (IND) number from the FDA. If the study involves the use of an approved drug in an unapproved way the investigator (or sponsor) must submit an application for an IND number. Please attach a copy of the IND approval (new drug), or application (new use.).*

If the study involves the use of an investigational medical device and COUHES determines the device poses significant risk to human subjects, the investigator (or sponsor) must obtain an Investigational Device and Equipment (IDE) number from the FDA.

Will drugs or biological agents requiring an IND be used? YES☐ NO☒

If yes, please provide details:

Will an investigational medical device be used? YES☐ NO☒

If yes, please provide details:

4. Radiation *If the study uses radiation or radioactive materials it may also have to be approved by the Committee on Radiation Exposure to Human Subjects (COREHS). COUHES will determine if you need COREHS approval.*

Will radiation or radioactive materials be used? YES☐ NO☒

If yes, please provide details:

5. Diets

Will special diets be used? YES☐ NO☒

If yes, please provide details:

III. HUMAN SUBJECTS

1. Subjects

A. Estimated number: 30	**B. Age(s): 21-65**

C. Inclusion/exclusion criteria

i. **What are the criteria for inclusion or exclusion?**

Must be able to pass security clearance to get access to Draper Laboratory where the experiment is held.

ii. **Are any inclusion or exclusion criteria based on age, gender, or race/ethnic origin?** *If so, please explain and justify*

These are the approximate age ranges of the astronaut population.

D. Please explain the inclusion of any vulnerable population (e.g. children, cognitively impaired persons, non-English speakers, MIT students), and why that population is being studied.

N/A

2. Subject recruitment *Identification and recruitment of subjects must be ethically and legally acceptable and free of coercion. Describe below what methods will be used to identify and recruit subjects*

Through Draper Laboratory email network

Please attach a copy of any advertisements/ notices and letters to potential subjects

3. Subject compensation *Payment must be reasonable in relation to the time and trouble associated with participating in the study. It cannot constitute an undue inducement to participate*

Describe all plans to pay subjects in cash or other form of payment (i.e. gift certificate)

Subjects will be given t-shirts and refreshments.

Will subjects be reimbursed for travel and expenses?

No

4. Potential risks. *A risk is a potential harm that a reasonable person would consider important in deciding whether to participate in research. Risks can be categorized as physical, psychological, sociological, economic and legal, and include pain, stress, invasion of privacy, embarrassment or exposure of sensitive or confidential data. All potential risks and discomforts must be minimized to the greatest extent possible by using e.g. appropriate monitoring, safety devices and withdrawal of a subject if there is evidence of a specific adverse event.*

What are the risks / discomforts associated with each intervention or procedure in the study?

Boredom, dry eyes

What procedures will be in place to prevent / minimize potential risks or discomfort? Subjects will proceed through the scenarios at their own pace.
5. Potential benefits
What potential benefits may subjects receive from participating in the study? None **What potential benefits can society expect from the study?** The results from this experiment will provide critical insight into the human cognitive abilities for astronauts using decision aids to select a landing aimpoint for a scenario like lunar landing.
6. Data collection, storage, and confidentiality
How will data be collected? using a computer archiving program and survey **Is there audio or videotaping? YES ☒ NO☐** ***Explain the procedures you plan to follow.*** There will only be audio recording during the post-experiment interviews. Consent form and interview questions are attached. **Will data be associated with personal identifiers or will it be coded?** **Personal identifiers ☐ Coded ☒** ***Explain the procedures you plan to follow.*** Each subject will be assigned a subject number which will become the identifier for all groupings of data. **Where will the data be stored and how will it be secured?** Subject test data will be stored on a password-protected laptop computer. **What will happen to the data when the study is completed?** It will be archived on said computer, and will also be archived in CD format and kept in a locked cabinet at Draper Laboratory. **Can data acquired in the study affect a subject's relationship with other individuals (e.g. employee-supervisor, patient –physician, student-teacher, family relationships)?** No
7. Deception *Investigators must not exclude information from a subject that a reasonable person would want to know in deciding whether to participate in a study.*
Will information about the research purpose and design be withheld from subjects? **YES ☐ NO☒** ***If so, explain and justify.***
8. Adverse effects. *Serious or unexpected adverse reactions or injuries must be reported to COUHES within 48 hours. Other adverse events should be reported within 10 working days.*
What follow-up efforts will be made to detect any harm to subjects and how will COUHES be kept informed? No adverse effects are anticipated
9. Informed consent. *Documented informed consent must be obtained from all participants in studies that involve human subjects. You must use the templates available on the COUHES web-site to prepare these forms. Draft informed consent forms must be returned with this application. Under certain circumstances COUHES may waive the requirement for informed consent.*
Attach informed consent forms with this application.
10. The HIPAA Privacy Rule. *If your study involves disclosing identifiable health information about a subject outside of M.I.T., then you must conform to the HIPAA Privacy Rule and complete the questions below. Please refer to the HIPAA section, and to the definitions of protected health information, de-identified data and limited data set on the COUHES web-site.*

Do you plan to use or disclose identifiable health information outside M.I.T.?
YES ☐ NO ☒
If YES, then the subject must complete an Authorization for Release of Protected Health Information Form. Please attach a copy of this draft form. You must use the template available on the COUHES web-site.

Alternatively, COUHES may grant a Waiver of Authorization if the disclosure meets criteria outlined on the COUHES web-site.

Are you requesting a Waiver of Authorization?
YES ☐ NO ☒
If YES, explain and justify.

Will the health information you plan to use or disclose be de-identified?
YES ☒ NO ☐

Will you be using or disclosing a limited data set?
YES ☐ NO ☒

If YES, then COUHES will send you a formal data use agreement that you must complete in order for your application to be approved

IV. INVESTIGATOR'S ASSURANCE

I certify the information provided in this application is complete and correct

I understand that I have ultimate responsibility for the conduct of the study, the ethical performance of the project, the protection of the rights and welfare of human subjects, and strict adherence to any stipulations imposed by COUHES

I agree to comply with all MIT policies, as well all federal, state and local laws on the protection of human subjects in research, including:

- **ensuring all study personnel satisfactorily complete human subjects training**
- **performing the study according to the approved protocol**
- **implementing no changes in the approved study without COUHES approval**
- **obtaining informed consent from subjects using only the currently approved consent form**
- **protecting identifiable health information in accord with the HIPAA Privacy Rule**
- **promptly reporting significant or untoward adverse effects**

Signature of Principal Investigator ______________________ **Date** _________

Print Full Name and Title ____

A. Experimental procedures:

B. Type and number of subjects involved:

C. Method of recruitment *(attach recruitment materials flyer, poster,etc.)*

D. Length of subject involvement:

E. Location of the research:

F. Procedures for obtaining informed consent *(COUHES may waive this requirement)*:

G. Procedures to ensure confidentiality:

3. HIPAA Privacy Rule. *If you are in any way working with protected health information you must comply with the HIPAA Privacy Rule. If your study has exempt status you will generally be dealing with de-identified data and your study will not be subject to the Privacy Rue. Please refer to the definition of de-identified data on the COUHES web site.*

Signature of Investigator ______________ **Date** 3/13/08
Jennifer Needham

Signature of Faculty Sponsor ______________ **Date** __________

Signature of Department Head ______________ **Date** 3/13/08

Print Full Name and Title IAN WAITZ

Please return 2 copies of this application (1 with original signatures) to the COUHES office at E25-143b.

Signature of Investigator ______________________ **Date** 3/13/08
Jennifer Needham

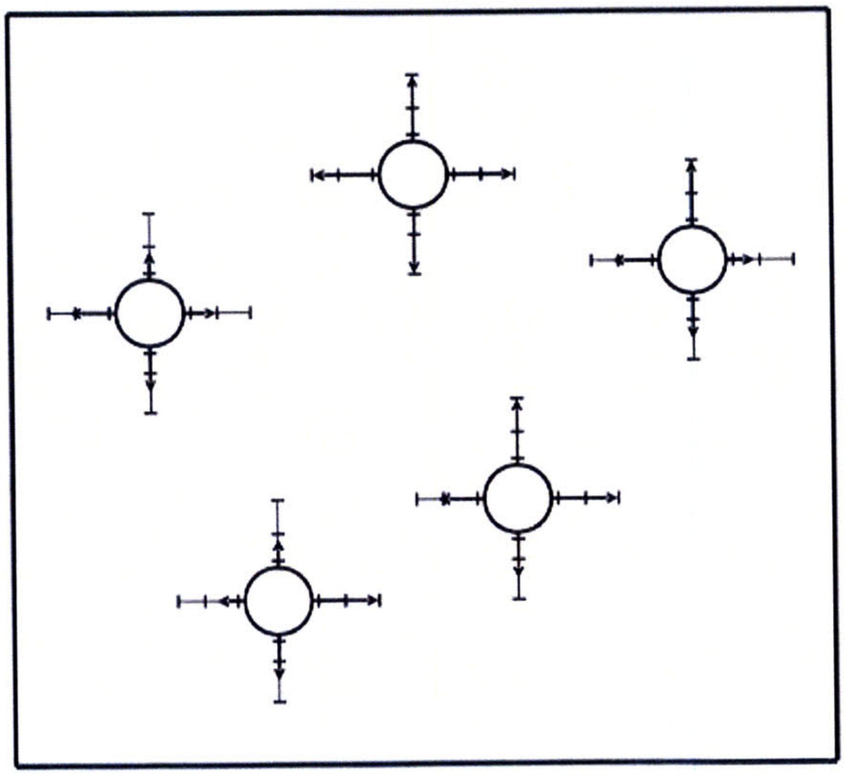
Signature of Faculty Sponsor ______________________ **Date** 3/13/08
R.J. Hansman

Signature of Department Head ______________________ **Date** __________

Print Full Name and Title ______________________

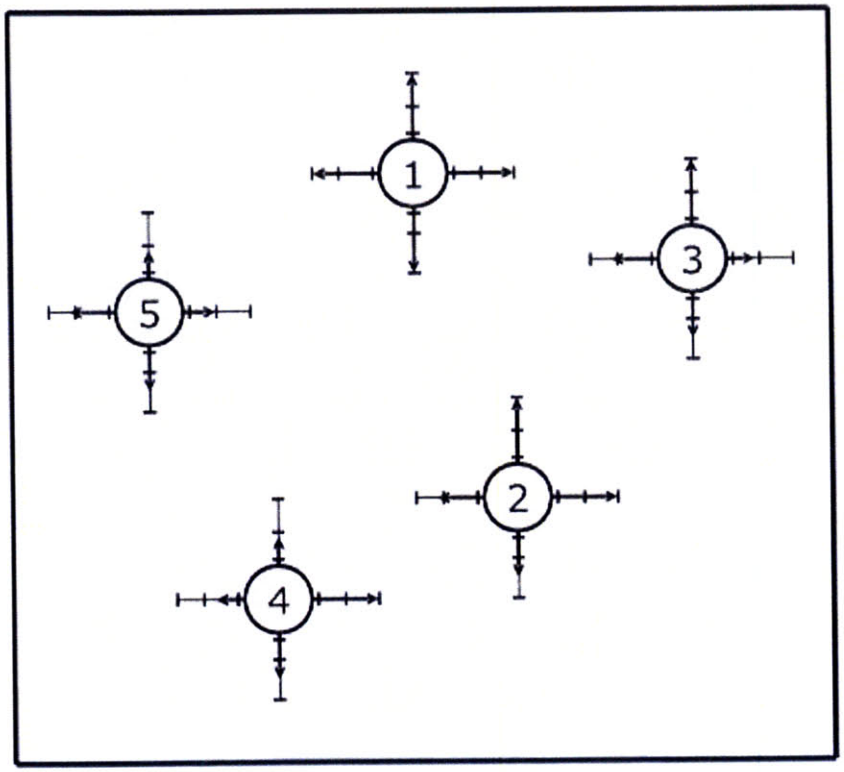
Please return a signed hard copy of this application to the COUHES office at E25-143B.

Test



This is the test as it will be given to the subjects.

Solution



This solution will not be shown to the subject.

Paper Test for Representation Understanding

- The paper test has five representations of the landing aimpoint algorithm with blank centers
- The subjects must order the representations from best to worst, writing the rankings in the centers of the representations.
- The subjects will not be under time pressure to complete this test.

Interview, to occur post-experiment

The purpose of this interview is to thoroughly understand the subject's individual decision making process and information used to make that decision. We will randomly choose one scenario from each of the experimental conditions to test (no repetitions). All questions posed by the experimenter will be in "quotations", and other actions will be *italicized*. After the subject responds, follow-on questions may be needed to clarify a subject's response; these questions cannot be predicted, but their content will only be about the specific decision making process or display content. All experimenter and subject statements and responses will be recorded.

Start the audio recording. Experimenter will state subject ID for coding responses.

"For this part of the experiment, we're going to watch some replays of your scenarios, and I'll ask you about how you used the displays in your decision making process. The video replays are to help you remember your decision making process. We're only going to look at a replay of a subset of the scenarios, and we have the ability to pause the replay at any time. Before we begin, I want you to know that I'm not judging you in any way. It will really help us if you could try to be as honest a possible because your comments will help us improve our design."

Video replay of display simulation begins. Each scenario is discussed separately. The following questions will be asked for each of the different scenarios that we review. These questions ask specifically about the decision making process.

- "The first landing point that you choose was here. Could you tell me why you selected that point?"
- "The next landing point that you choose was here. Could you tell me why you selected that point?"
- "Why did you choose a different landing point than your first selection?"
- "Could you tell me why you selected the landing point that you finally ended up choosing?"
- "What was/were your most important criterion/criteria for selecting that point?
- "It seems like your general decision strategy was __________ (*in non technical words, the experimenter will summarize the decision strategy that the subject has just expressed in the interview*). Would you agree?"

The following questions will be asked at the very end (after each of the individual scenarios has been discussed). These questions ask specifically about the display content.

- "Which of the displayed information was the most useful for you in making your final decision? Is there any other information that could be useful in aiding your decision?"
- "Feel free to critique the design on your answer to this question. What difficulties did you face in the decision making process? Were there any parts of the display that you disliked?"

End the audio recording

CONSENT TO PARTICIPATE IN INTERVIEW

Decision aiding Displays for Landing Aimpoint Selection

You have been asked to participate in a research study conducted by Jennifer Needham from Aero-Astro at the Massachusetts Institute of Technology (M.I.T.). The purpose of the study is to evaluate the ability of an operator to choose a landing aimpoint for a simulated lunar landing mission using different levels of a decision-making aid. The results of this study will be included in Jennifer Needham's Masters thesis. You were selected as a possible participant in this study because you already have access to the Draper Laboratory fixed-base cockpit simulator. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

• This interview is voluntary. You have the right not to answer any question, and to stop the interview at any time or for any reason. We expect that the interview will take about 5 minutes.

• You will not be compensated for this interview.

• Unless you give us permission to use your name, title, and / or quote you in any publications that may result from this research, the information you tell us will be confidential.

• We would like to record this interview on audio cassette so that we can use it for reference while proceeding with this study. We will not record this interview without your permission. If you do grant permission for this conversation to be recorded on cassette, you have the right to revoke recording permission and/or end the interview at any time. ** To create these audio recordings, special permission has been obtained from Eric Grant in the Draper Laboratory Security Office. Absolutely no classified information should be mentioned or discussed.

This project will be completed by April 2008. All interview recordings will be stored in a secure work space until 1 month after that date. The tapes will then be destroyed.

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

(Please check all that apply)

[] I give permission for this interview to be recorded on audio cassette.

[] I give permission for the following information to be included in publications resulting from this study:

[] my name [] my title [] direct quotes from this interview

Name of Subject

Signature of Subject ________________________________ Date ___________

Signature of Investigator ______________________ Date ________

Please contact Jennifer Needham, jneedham@mit.edu (jneedham@draper.com) with any questions or concerns.
If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253-6787.

CONSENT TO PARTICIPATE IN NON-BIOMEDICAL RESEARCH

Decision aiding Displays for Landing Aimpoint Selection

You are asked to participate in a research study conducted by Professor John Hansman Ph.D. and Jennifer Needham from the Aeronautics and Astronautics Department at the Massachusetts Institute of Technology (M.I.T.). You were selected as a possible participant in this study because you already have access to the Draper Laboratory fixed-base cockpit simulator. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

- **PURPOSE OF THE STUDY**

The study is designed to evaluate the ability of an operator to choose a landing aimpoint for a simulated lunar landing mission using different levels of a decision-making aid. In the next lunar landing, astronauts will need to land in areas that have poor visibility with the unaided eye. This research is intended to explore decision making using levels of automation that support human understanding of an algorithm for landing aimpoint redesignation.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:

Training will be given for understanding of the general experiment, several trials will be given without a decision aid, more training will be given, and then several trials will be given with the decision aid. A trial is a 30-second time frame in which the subject will look at the display and decide where to select a landing aimpoint. The subject will be allowed to use a mouse to click on the landing aimpoint options (when given) or to prompt for information about the algorithm's parameters, which will not be shown in some trials. The user will use the mouse to indicate their final decision, and the responses will be timed and also measured for quality of response. A brief paper test asking the subjects to rank a sample of landing aimpoints from best to worst will be given before and after the experiment. The experimenter will record the accuracy of the paper test. Also, following the experiment, the subjects will be asked to describe their decision making process while one of their previous trials is re-played to them, and their interview will be recorded for later review by the experimenter.

This experiment will be performed in the Draper Laboratory fixed-base cockpit simulator and should last approximately 1 hour.

- **POTENTIAL RISKS AND DISCOMFORTS**

There are no anticipated physical or psychological risks in this study.

- **POTENTIAL BENEFITS**

While there is no immediate foreseeable benefit to you as a participant in this study, your efforts will provide critical insight into the human cognitive capabilities and limitations for astronauts using automation to select a landing aimpoint.

- **PAYMENT FOR PARTICIPATION**

No payment will be given for your participation.

- **CONFIDENTIALITY**

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. You will be assigned a subject number which will be used on all related documents to include databases, summaries of results, etc. Only one, separate master list of subject names and numbers will exist.

There is a post-experiment interview that will require a separate consent form. Please read and sign attached document entitled "Consent to Participate in Interview."

- **IDENTIFICATION OF INVESTIGATORS**

If you have any questions or concerns about the research, please feel free to contact the student investigator, Jennifer Needham, by telephone at (832) 326-6888 or via email at jneedham@mit.edu. Her MIT faculty sponsor is Prof John Hansman, who may be contacted at at (617) 253-2271, e-mail, rjhans@mit.edu, and his address is 77 Massachusetts Avenue, Room 33-303, Cambridge, MA 02139.

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

"In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, neither the offer to provide medical assistance nor the actual provision of medical services shall be construed as an admission of negligence or acceptance of liability. Questions regarding this policy may be directed to M.I.T's Insurance Office, (617) 253-2823."

- **RIGHTS OF RESEARCH SUBJECTS**

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143B, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 6787.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Subject

____

Name of Legal Representative (if applicable)

__________________________________ ____________

Signature of Subject or Legal Representative Date

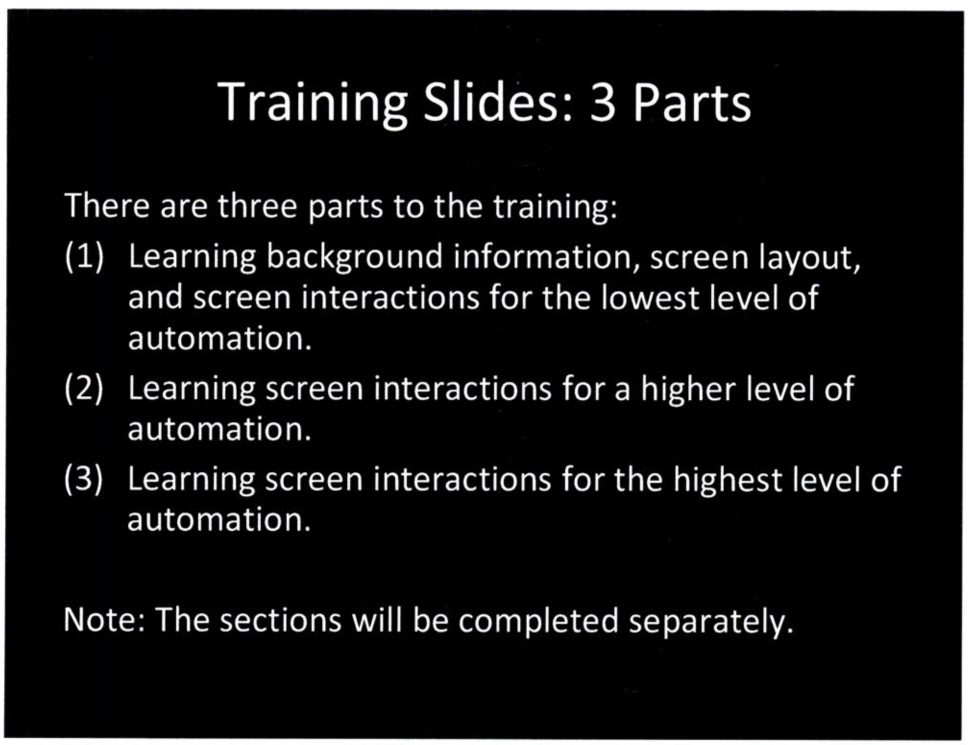
SIGNATURE OF INVESTIGATOR

In my judgment the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to give informed consent to participate in this research study.

__________________________________ ____________

Signature of Investigator Date

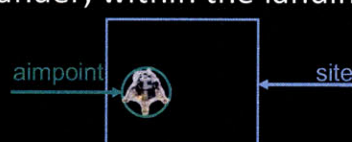
Appendix B: Experimental Training Slides



Training Part 1

Lunar Landing Background

- Landing on the moon requires the astronaut to make a decision about where to land
- A large area called the landing site is typically decided far in advance, and is chosen by mission designers who consider all the mission objectives
- The landing aimpoint is a specific place, the size of the lunar lander, within the landing site



- The final decision about the landing aimpoint is up to the astronaut… his or her life is on the line!

Future Lunar Landings

- In the past, astronauts have chosen the landing aimpoint based on visual judgments of the surface from a window.
- For the next lunar landing, we want to land in places where long shadows and large numbers of hazards make visual judgments risky.

- To assist the astronaut, the lunar landing vehicle will be equipped with an automated sensor that can scan the landing site for hazards. For today, we'll assume the sensor detects all hazards.
- Computer displays have been designed to assist the landing aimpoint decision. Your mission: to select a landing aimpoint.

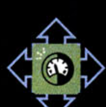
How does the computer help me?

The computer will display 4 parameters related to a chosen landing aimpoint:

Slope: how steep or flat the lunar surface is at a particular landing aimpoint

Roughness: how rocky or smooth the lunar surface is at a particular landing aimpoint

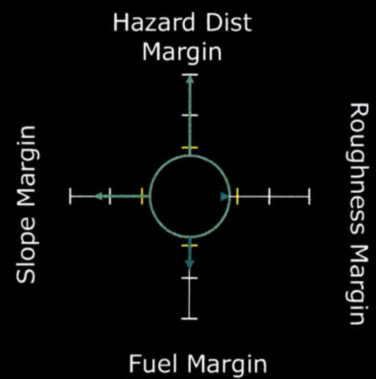
Hazard – a portion of the landing site that is too steep or rocky to land on (the sensor tells you the position of these hazards)



Fuel: a certain amount of fuel is required to reach the landing aimpoint at the center of the landing area, and moving away from the center to a particular landing aimpoint requires more fuel

Safety of the Landing Aimpoint

Your goal is to choose a safe landing aimpoint. The 4 parameters that the computer tells you are related to how **safe** the landing aimpoint is.

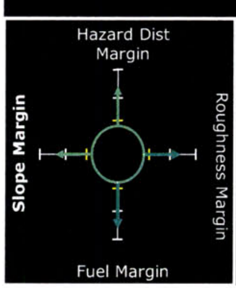


The four arms represent the four criteria for a safe landing aimpoint. The green arrows on each arm show the value for the selected landing aimpoint.

Slope Margin

Slope: how steep or flat the lunar surface is at a particular landing aimpoint

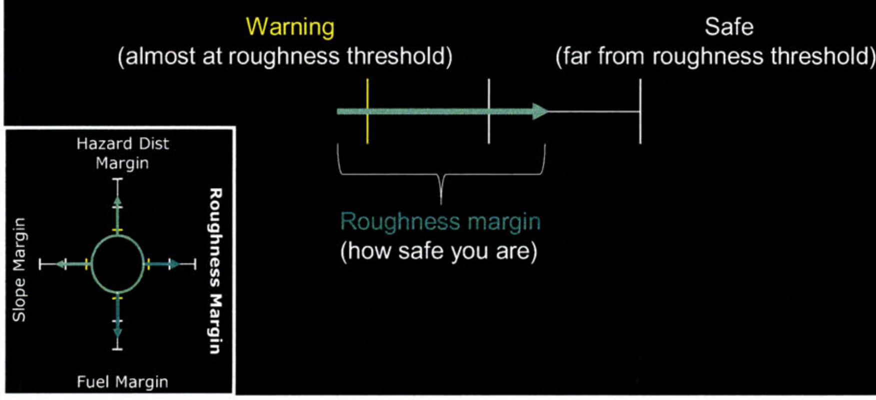
- there is a **slope threshold**, and landing at slopes **above** this threshold will make the landing vehicle tip over, **killing or stranding** you on the moon



Roughness Margin

Roughness: how rocky or smooth the lunar surface is at a particular landing aimpoint;

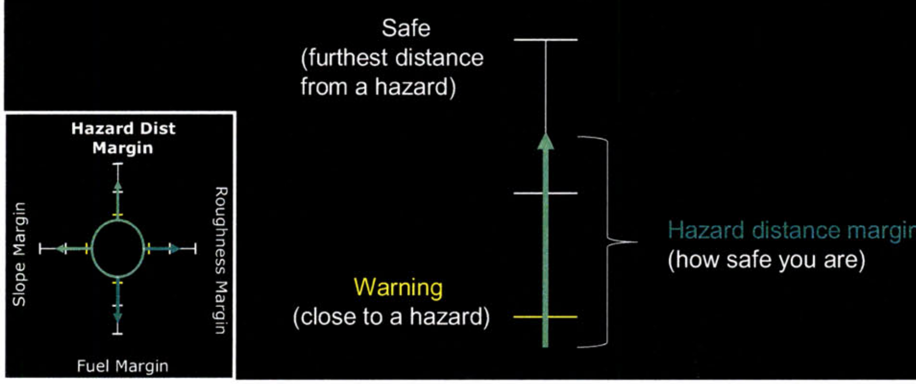
- there is a **roughness threshold**, and landing on rocks **above** this threshold will damage the landing vehicle, **killing or stranding** you on the moon



Hazard Distance Margin

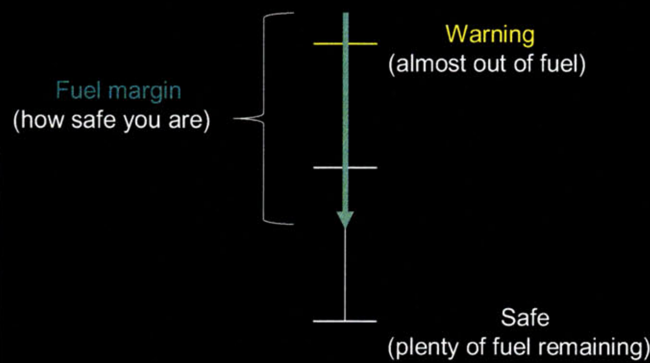
Hazard: A portion of the landing area with a value of either slope or roughness **exceeding** their corresponding thresholds. Choosing a landing aimpoint within a hazardous area will exceed slope and roughness thresholds, **killing or stranding** you on the moon

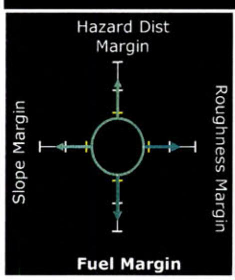
Note: The hazard distance margin is the distance to the nearest hazard.



Fuel Margin

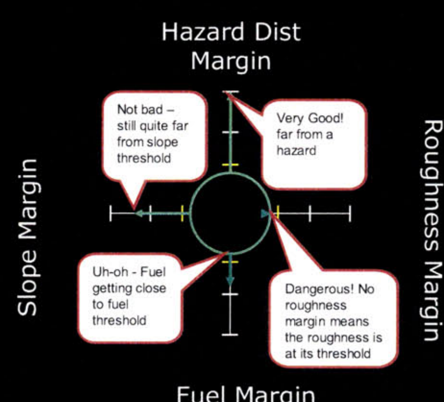
<u>Fuel</u>: a certain amount of fuel is required to reach the landing aimpoint at the **center** of the landing area, and moving **away** from the center to a particular landing aimpoint **reduces** the fuel margin. Running out of fuel may result in **killing or stranding** you on the moon.





Safety – Maximize the Margins

Your goal is to choose the safest landing aimpoint, which means maximizing the margins. Graphically, that means that <u>you want the arms to be as long as possible</u>.

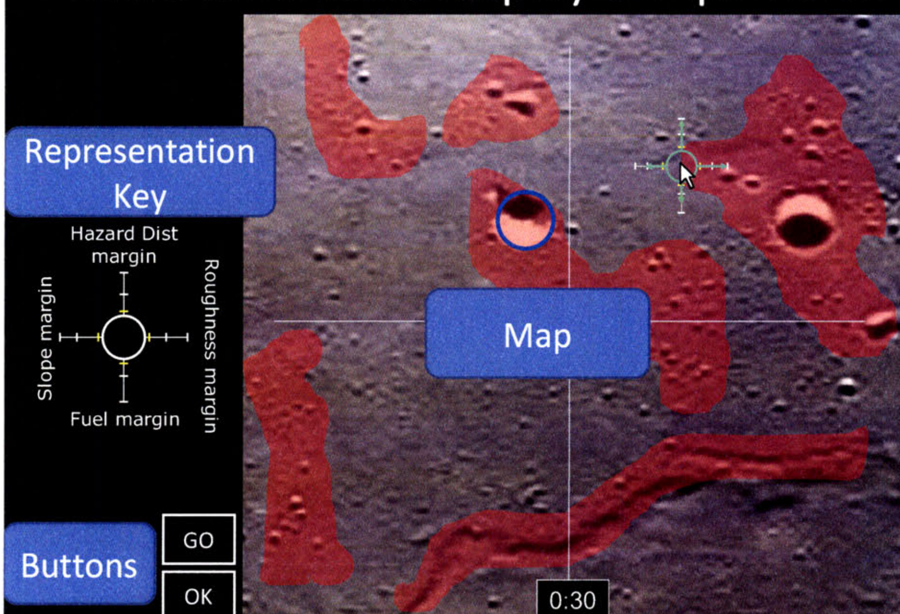


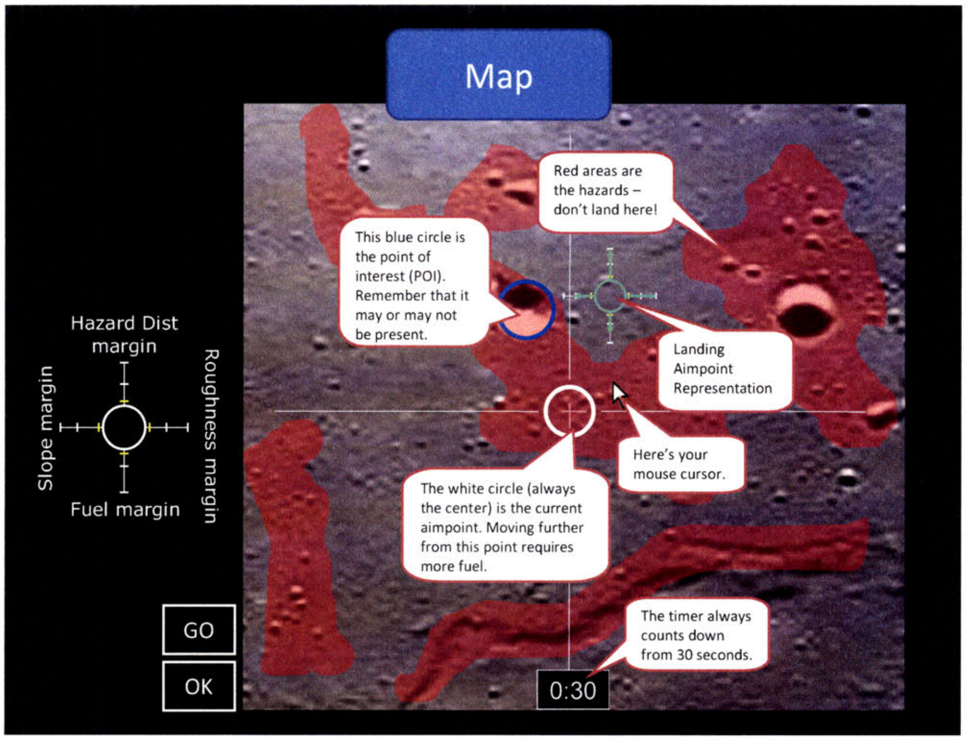
Point of Interest (POI)

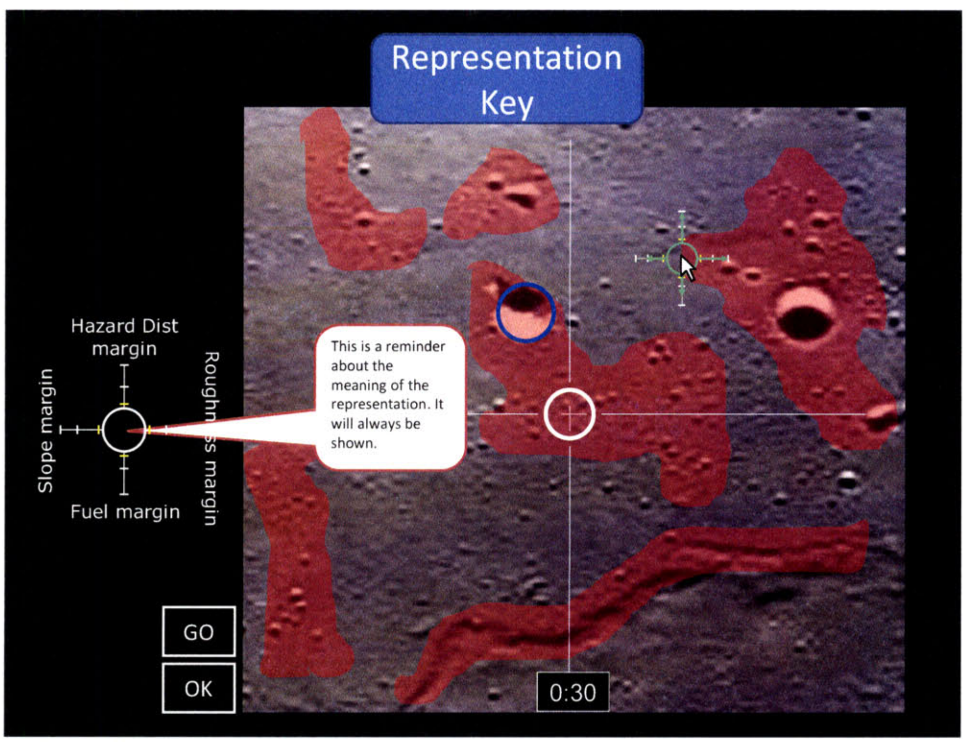
- In some scenarios, there is an additional feature: a point of interest (POI).
- The POI will always be identified. It might be an interesting surface feature, like the crater shown here, but it also might be a piece of lunar infrastructure too small to see.

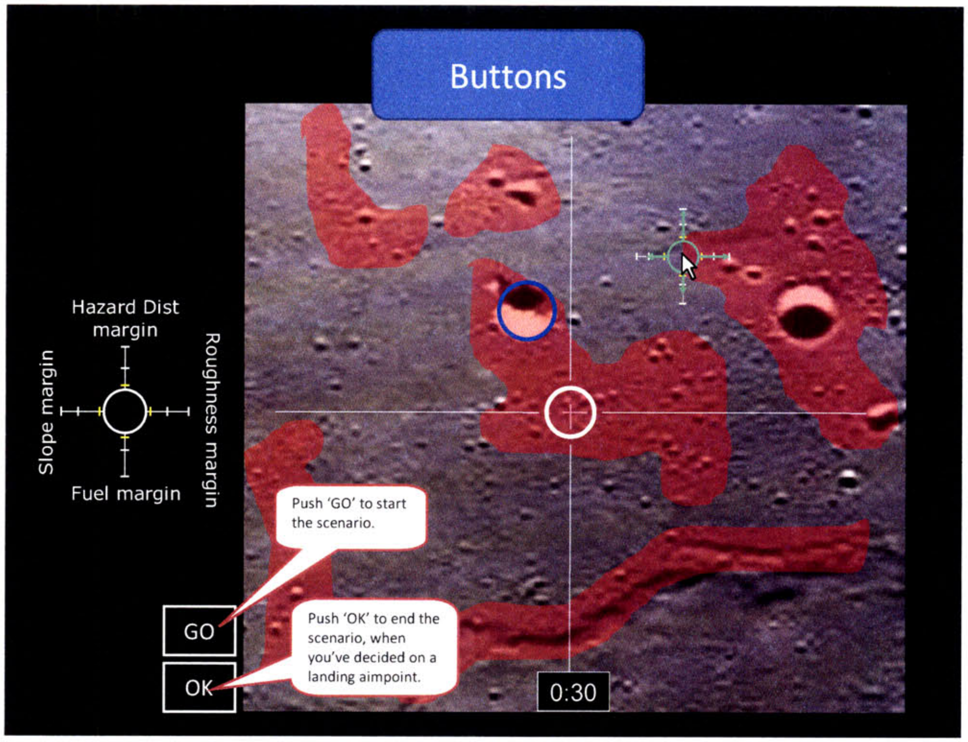
- The sensor may detect the POI as a hazard (as shown) or partly hazardous.
- More details later, but for now, remember how to identify the POI (by the blue circle).

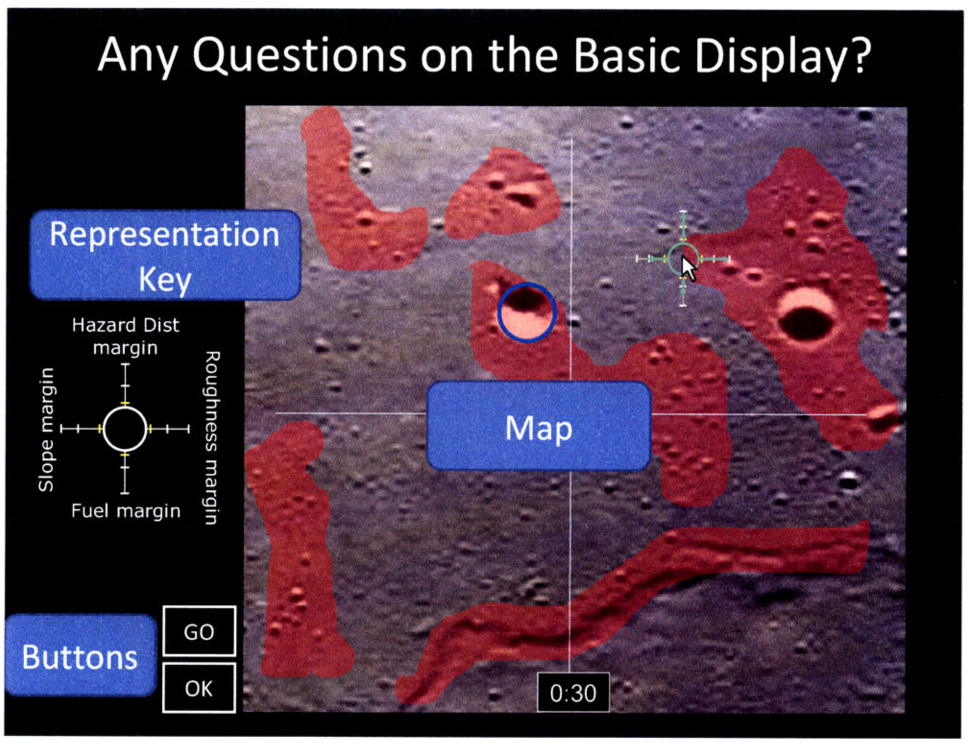
There are 3 basic display components:



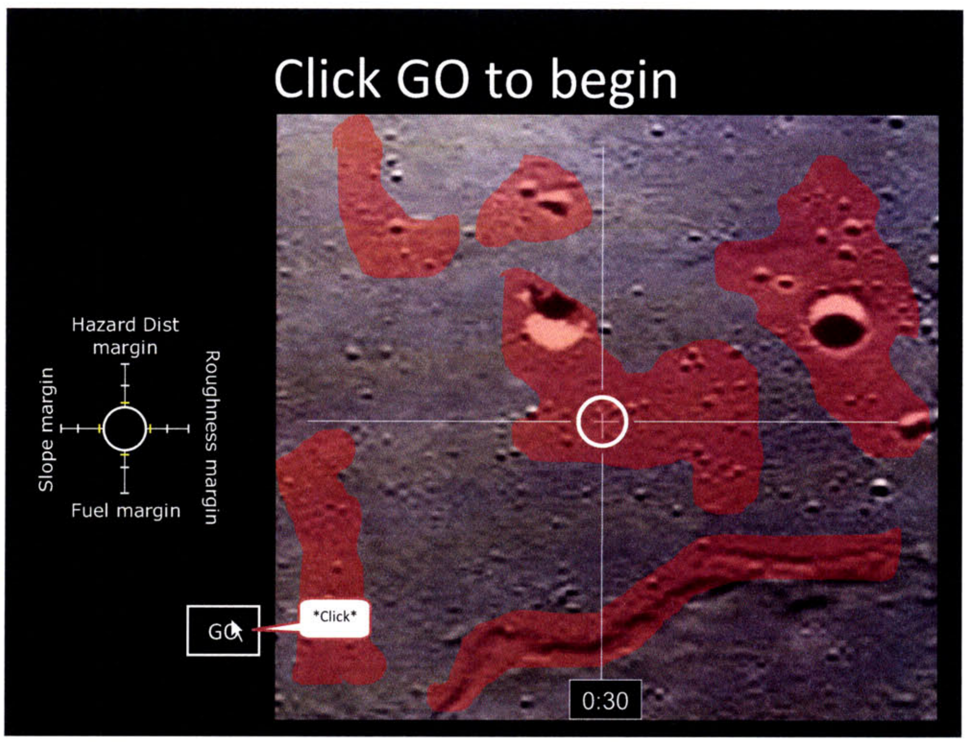

Map
Red areas are the hazards – don't land here!
This blue circle is the point of interest (POI). Remember that it may or may not be present.
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Landing Aimpoint Representation
Here's your mouse cursor.
The white circle (always the center) is the current aimpoint. Moving further from this point requires more fuel.
GO
OK
The timer always counts down from 30 seconds.
0:30

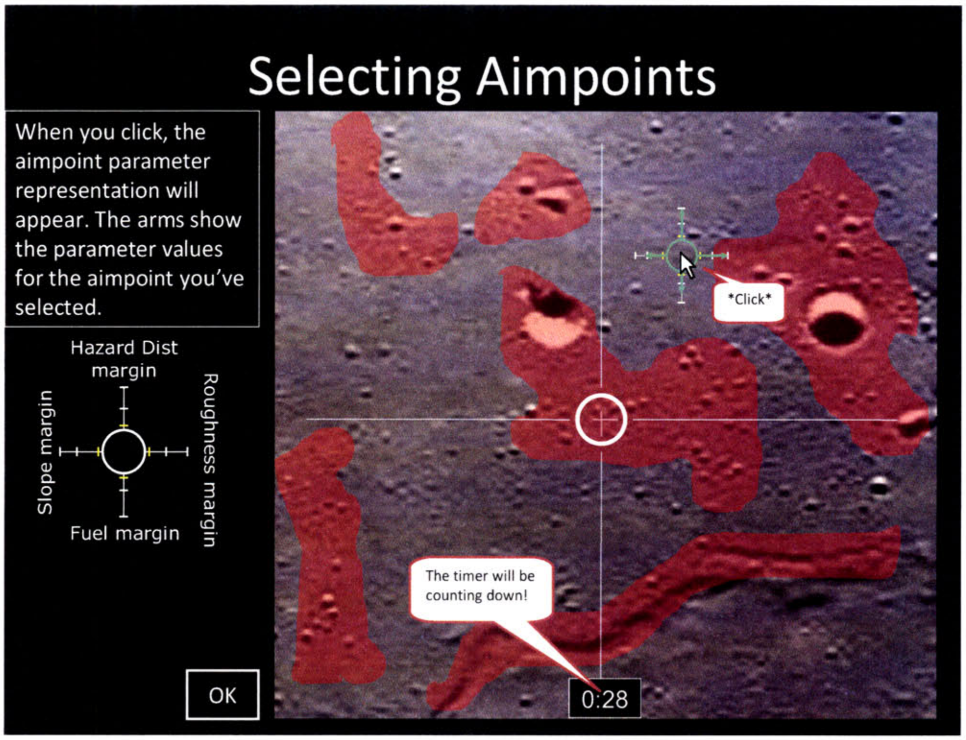

Representation Key
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
This is a reminder about the meaning of the representation. It will always be shown.
GO
OK
0:30

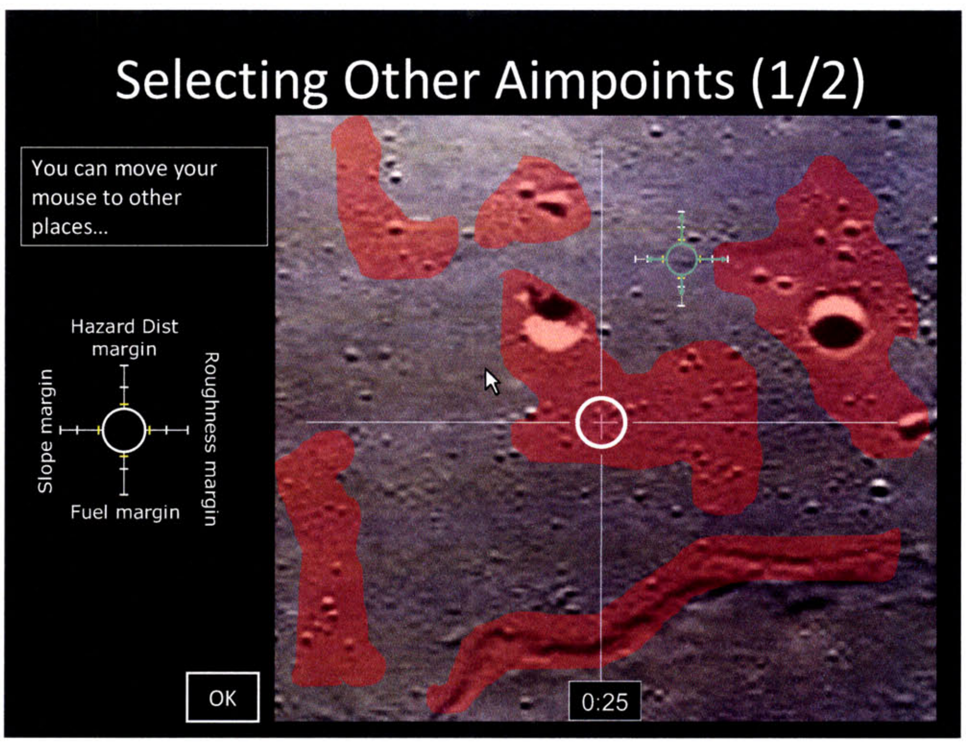

Buttons
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Push 'GO' to start the scenario.
Push 'OK' to end the scenario, when you've decided on a landing aimpoint.
GO
OK
0:30

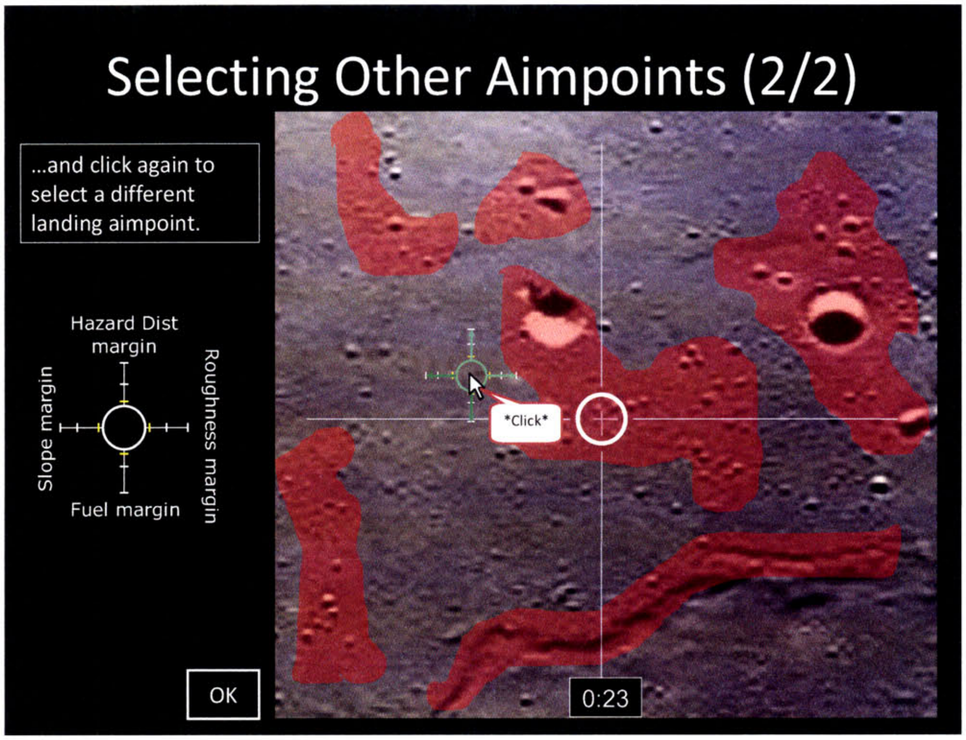

Any Questions on the Basic Display?
Representation Key
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Map
Buttons
GO
OK
0:30

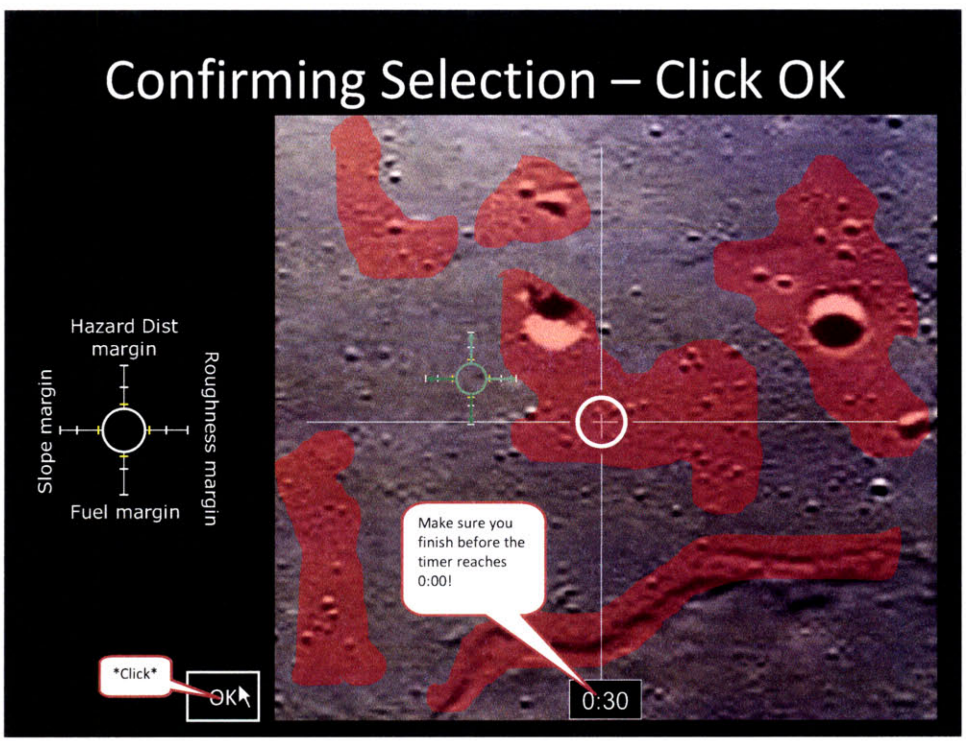
Here's a sample of how you will interact with the display:




Selecting Aimpoints
When you click, the aimpoint parameter representation will appear. The arms show the parameter values for the aimpoint you've selected.
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
OK
Click
The timer will be counting down!
0:28


Selecting Other Aimpoints (1/2)
You can move your mouse to other places...
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
OK
0:25


Selecting Other Aimpoints (2/2)
...and click again to select a different landing aimpoint.
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Click
OK
0:23


Confirming Selection – Click OK
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Make sure you finish before the timer reaches 0:00!
Click
OK
0:30

POI: 2 Missions

The point of interest (POI) will be related to 1 of 2 missions... During the experiment I will instruct you which mission applies to which scenarios.

Mission 1: Geological Mission

- Lunar geologists would like you to land close to a particular POI to collect soil samples there.
- However, you must find a landing aimpoint that is as safe as possible, both to keep yourself alive and to maximize vehicle accessibility to load the samples.
- For this mission, your primary goal is safety, but you must also consider proximity to the POI in your decision.

Mission 2: Rescue Mission

- You've been sent to rescue astronauts that are stranded in a habitat module on the surface. Their oxygen is running low, so it is very important to land close to their location, designated as the POI.
- You must choose a safe landing aimpoint to keep yourself and fellow astronauts alive, enabling a journey home!
- For this mission, do not disregard the safety criteria, but consider proximity to the POI to be much more important.

Summary of Goals

To choose a landing aimpoint, make sure you consider all of the following goals:

1. Safety: the largest slope margin, roughness margin, hazard margin, and fuel margin
2. POI: Proximity of the point of interest relative to the intended landing aimpoint (based on the mission)
3. Time: Make your decision as quickly as possible while also considering both of the above goals.

0:30

Any questions before we do some practice runs?

3 practice runs are done in the cockpit simulator. The next slide will be shown during the practice runs.

Training Part 2

Automation

- For the next lunar landing, there is the possibility of additional automation that can compute a set of alternate landing aimpoints based on the sensor data.

- Rather than searching the map yourself, you'll now be evaluating the alternate landing aimpoints that the automation recommends.

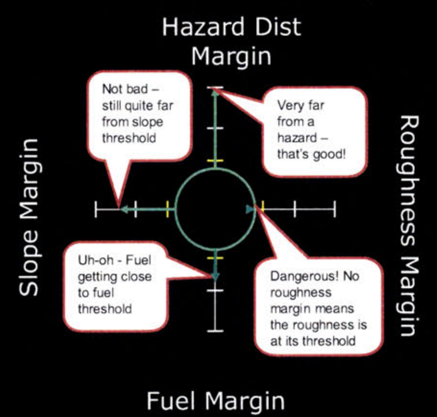
The Automation's Decision

The automation selects alternate landing aimpoints based on the four criteria for safety (same as before).

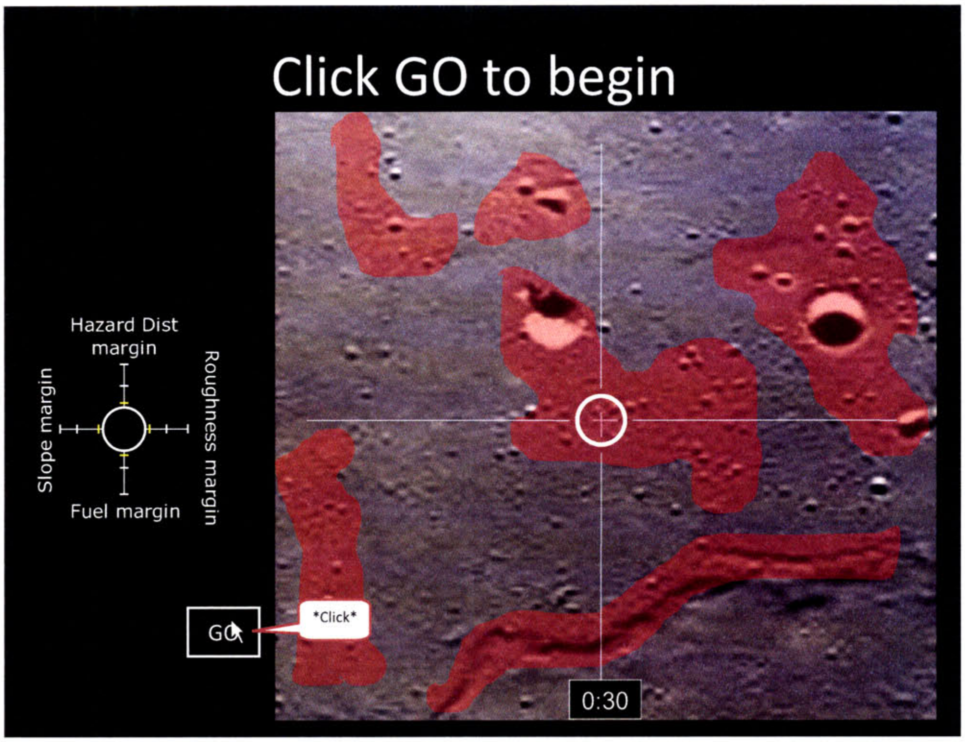
The automation weights the 4 safety parameters equally. Since the location of the POI may be hazardous, the automation does not include the POI in its calculations.

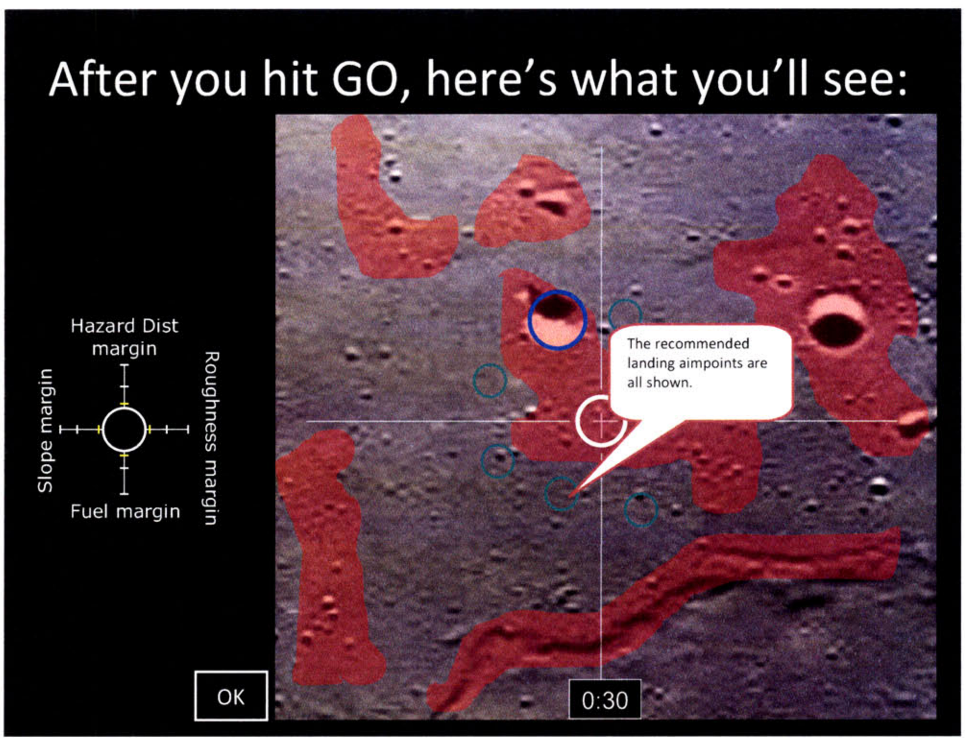
Landing Aimpoint Representation

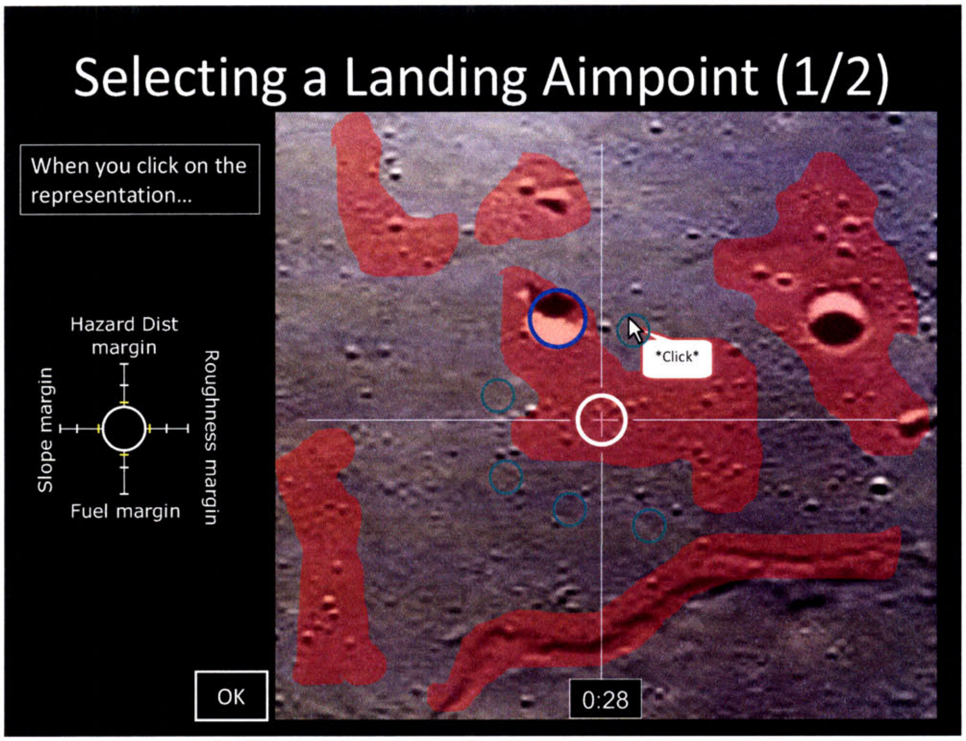
Recall that your goal is to choose the safest landing aimpoint. Graphically, that means that you want the arms to be as long as possible.

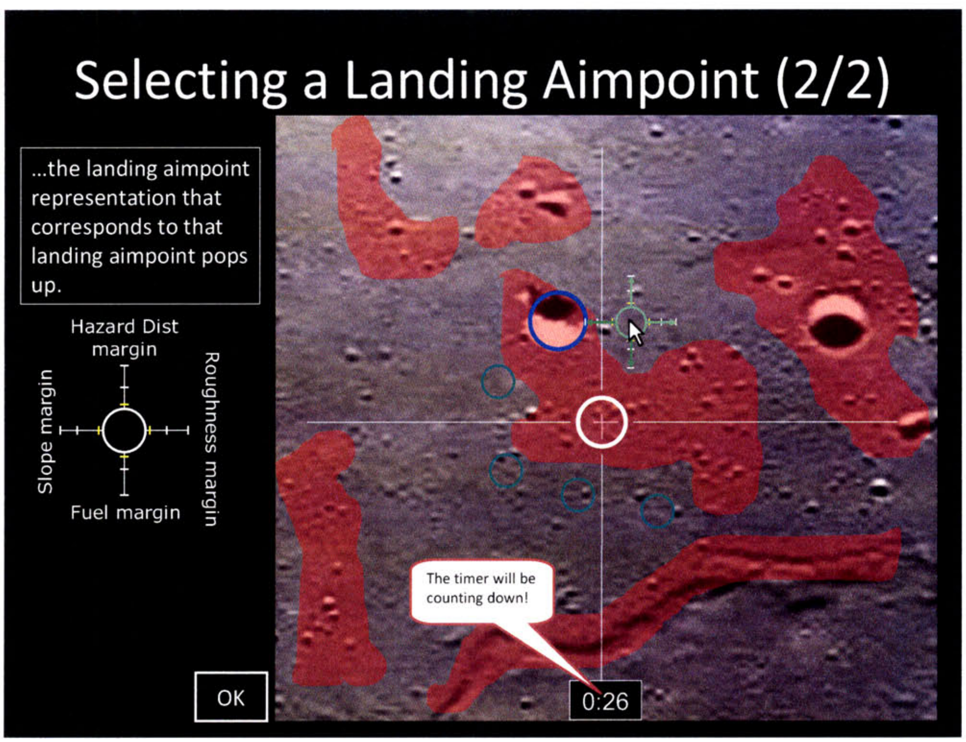


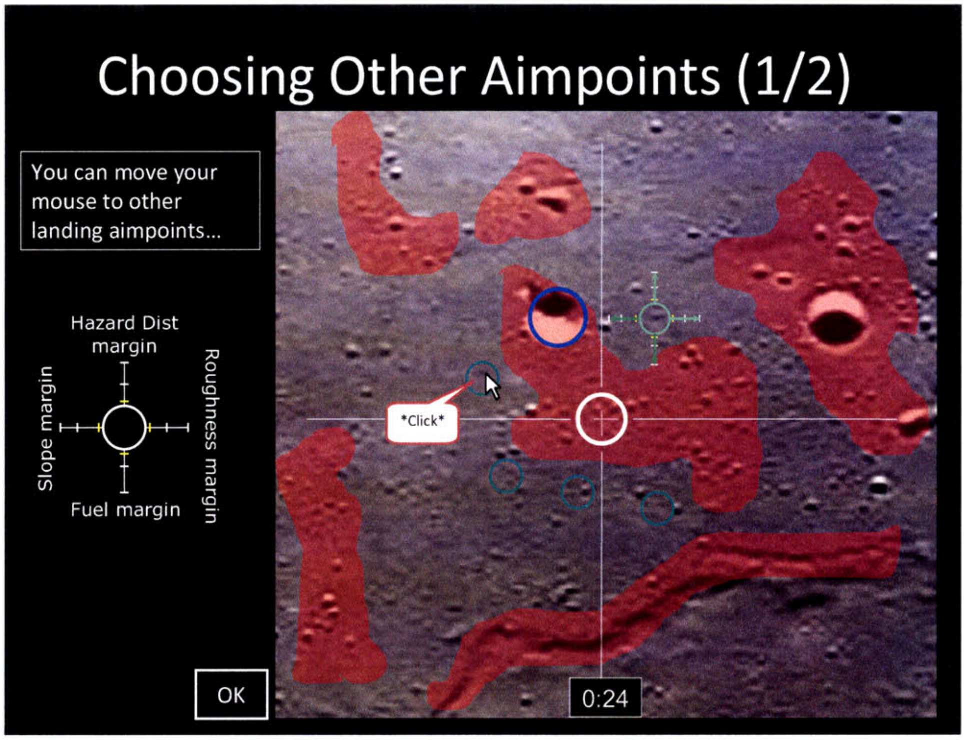
Here's a sample of how you will interact with the display:

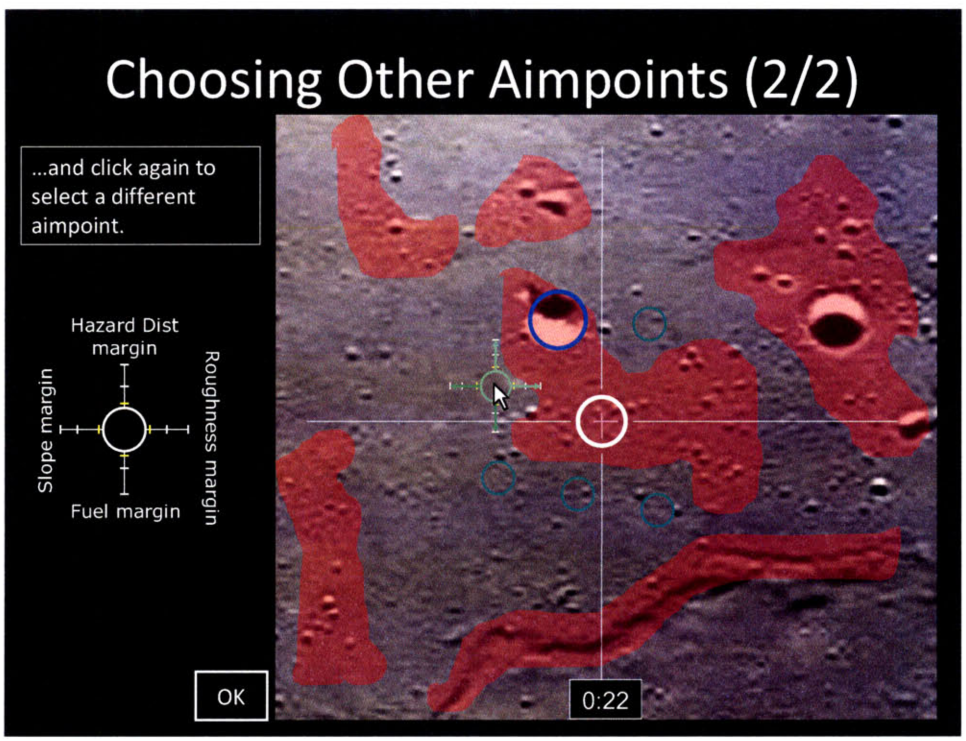

Click GO to begin
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
GO
Click
0:30

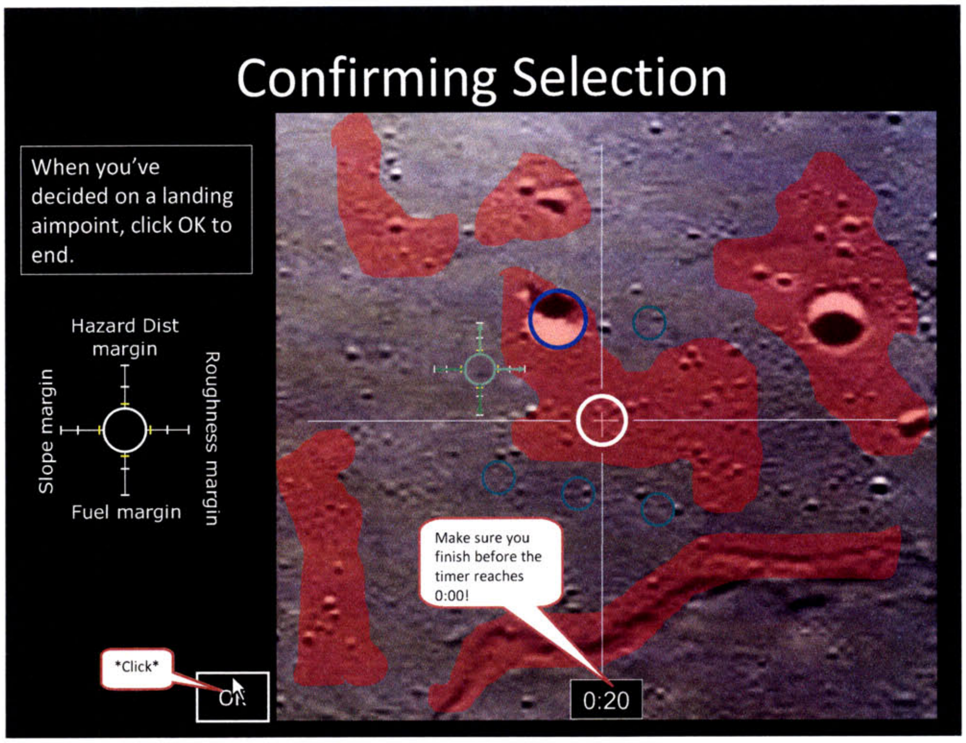

After you hit GO, here's what you'll see:
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
The recommended landing aimpoints are all shown.
OK
0:30


Selecting a Landing Aimpoint (1/2)
When you click on the representation...
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Click
OK
0:28

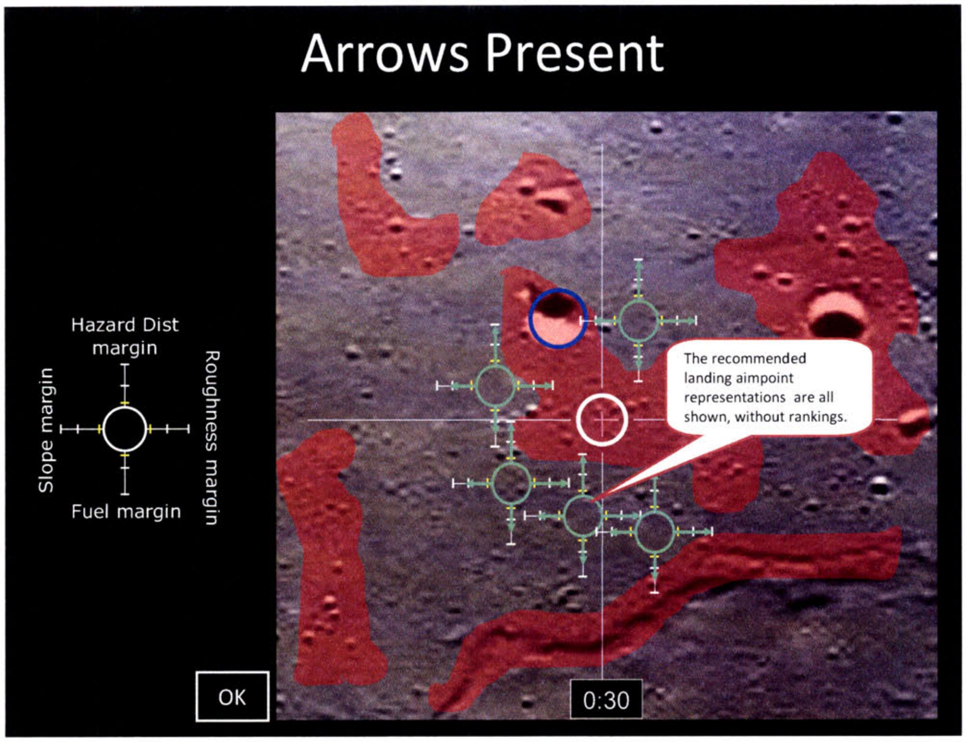

Selecting a Landing Aimpoint (2/2)
...the landing aimpoint representation that corresponds to that landing aimpoint pops up.
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
The timer will be counting down!
OK
0:26

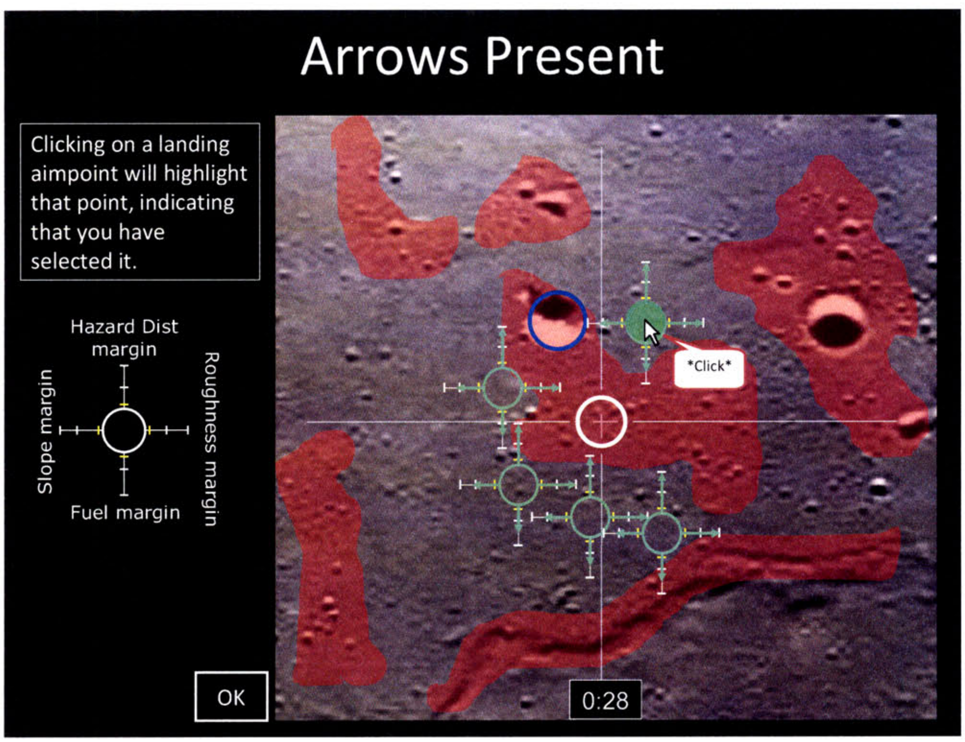

Choosing Other Aimpoints (1/2)
You can move your mouse to other landing aimpoints...
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Click
OK
0:24


Choosing Other Aimpoints (2/2)
...and click again to select a different aimpoint.
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
OK
0:22



Sometimes you will not have to prompt for the landing aimpoint representation, but the process is the same...


Arrows Present
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
The recommended landing aimpoint representations are all shown, without rankings.
OK
0:30


Arrows Present
Clicking on a landing aimpoint will highlight that point, indicating that you have selected it.
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Click
OK
0:28

Summary of Goals

To choose a landing aimpoint, make sure you consider all of the following goals:

1. Safety: the largest slope margin, roughness margin, hazard margin, and fuel margin
2. POI: Proximity of the point of interest relative to the intended landing aimpoint (based on the mission)
3. Time: Make your decision as quickly as possible while also considering both of the above goals.

0:30

Any questions before we do some practice runs?

Practice runs are done in the cockpit simulator. The next slide will be shown during the practice runs.

Training Part 3

The Automation's Decision

1 2 3 4 5

The automation can also **rank** alternate landing aimpoints based on the four criteria for safety (same as before).

1 2 3 4 5

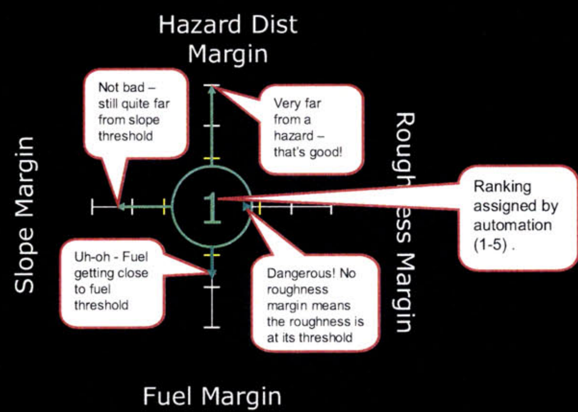
best ⟷ worst

The automation weights the 4 safety parameters equally. Since the location of the POI may be hazardous, the automation does not include the POI in its calculations.

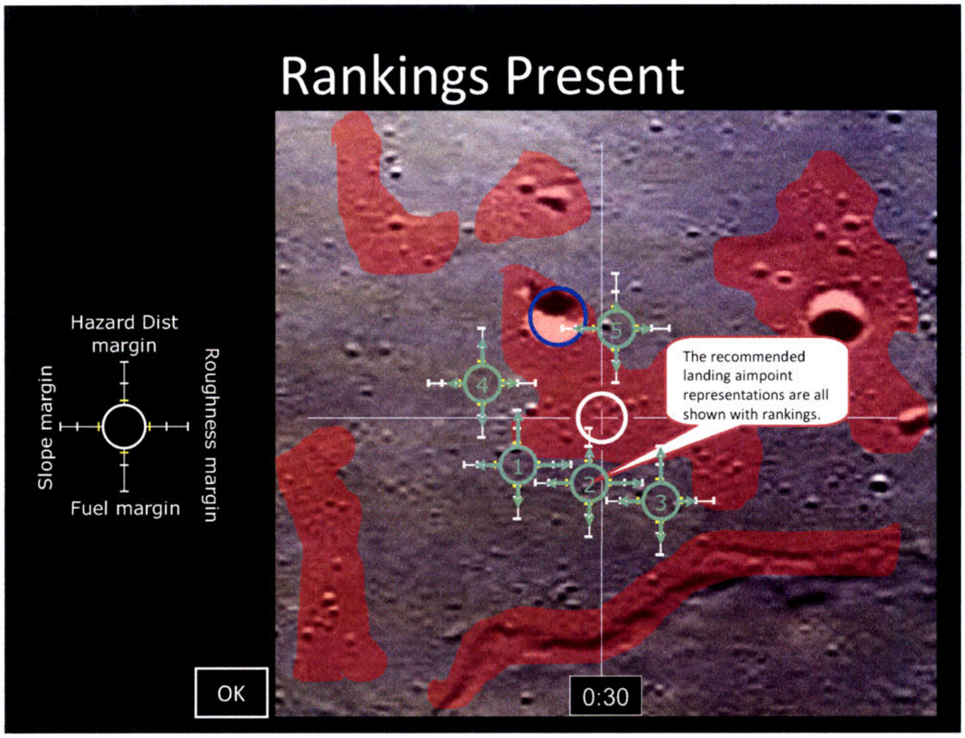
Landing Aimpoint Representation

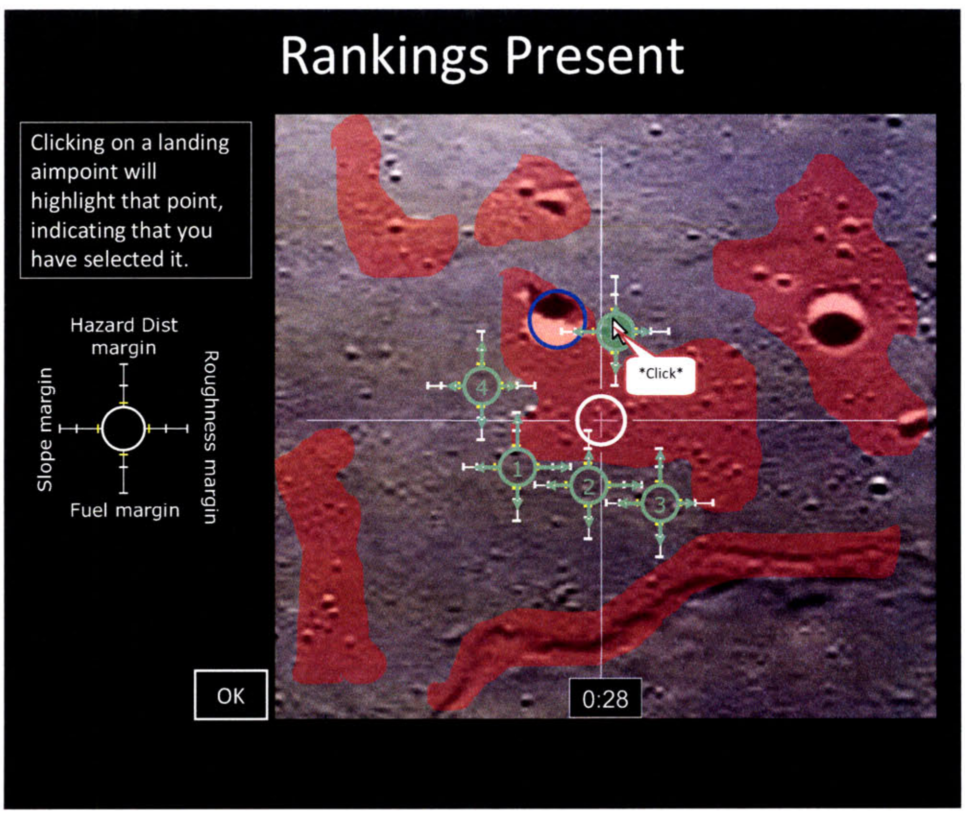
Recall that your goal is to choose the safest landing aimpoint. Graphically, that means that you want the arms to be as long as possible.

If present, the ranking of the aimpoint from the automation will be in the center of the landing aimpoint representation.



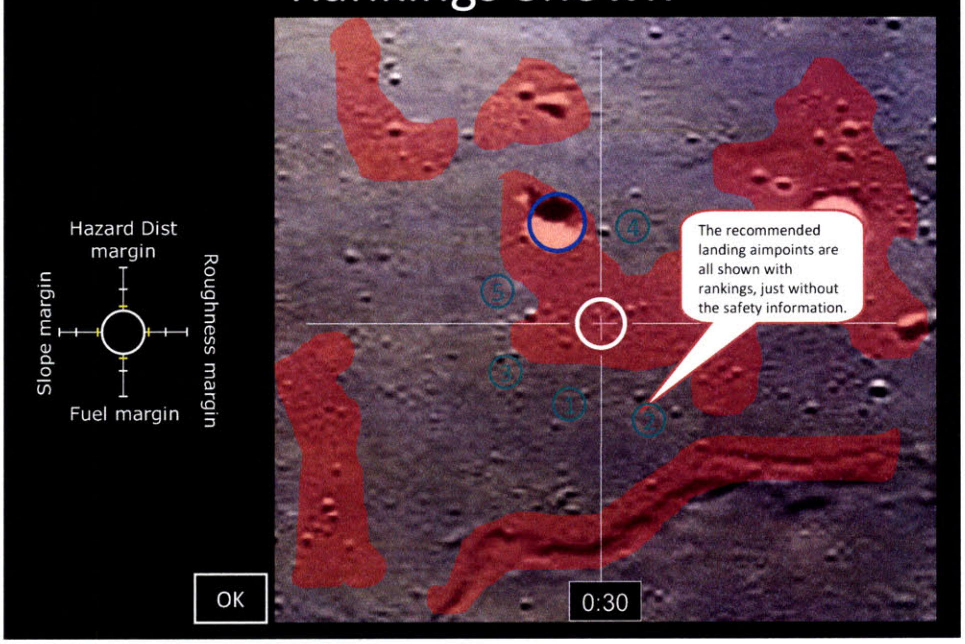
Here's a sample of how you will interact with the display:

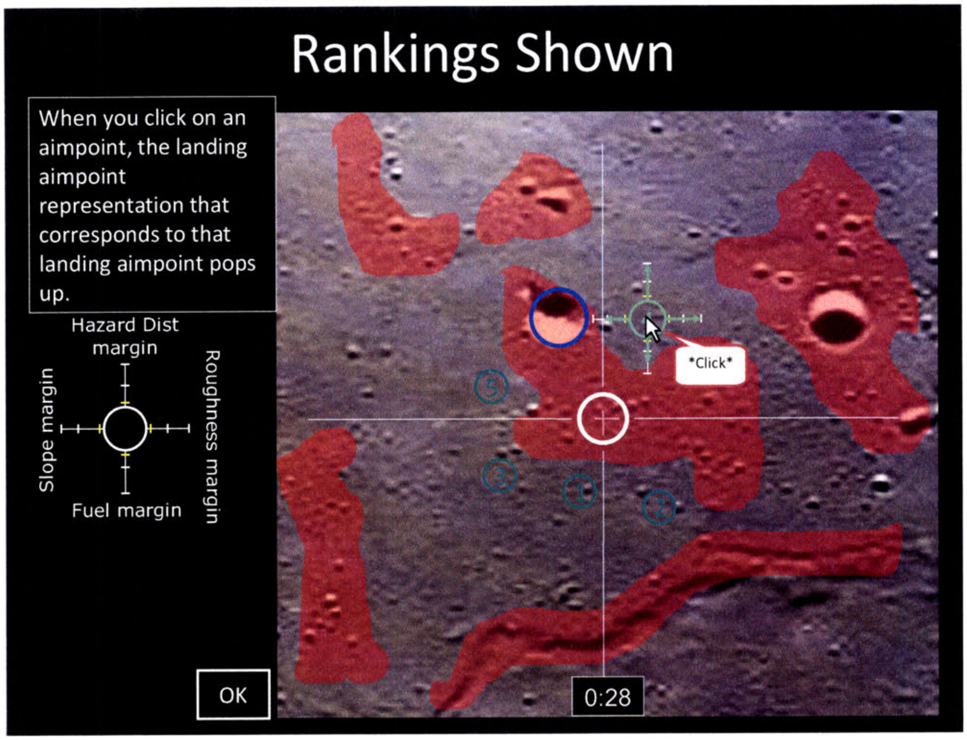

Rankings Present
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
The recommended landing aimpoint representations are all shown with rankings.
OK
0:30


Rankings Present
Clicking on a landing aimpoint will highlight that point, indicating that you have selected it.
Hazard Dist margin
Slope margin
Roughness margin
Fuel margin
Click
OK
0:28

Sometimes you will have to prompt for the landing aimpoint representation:

Rankings Shown



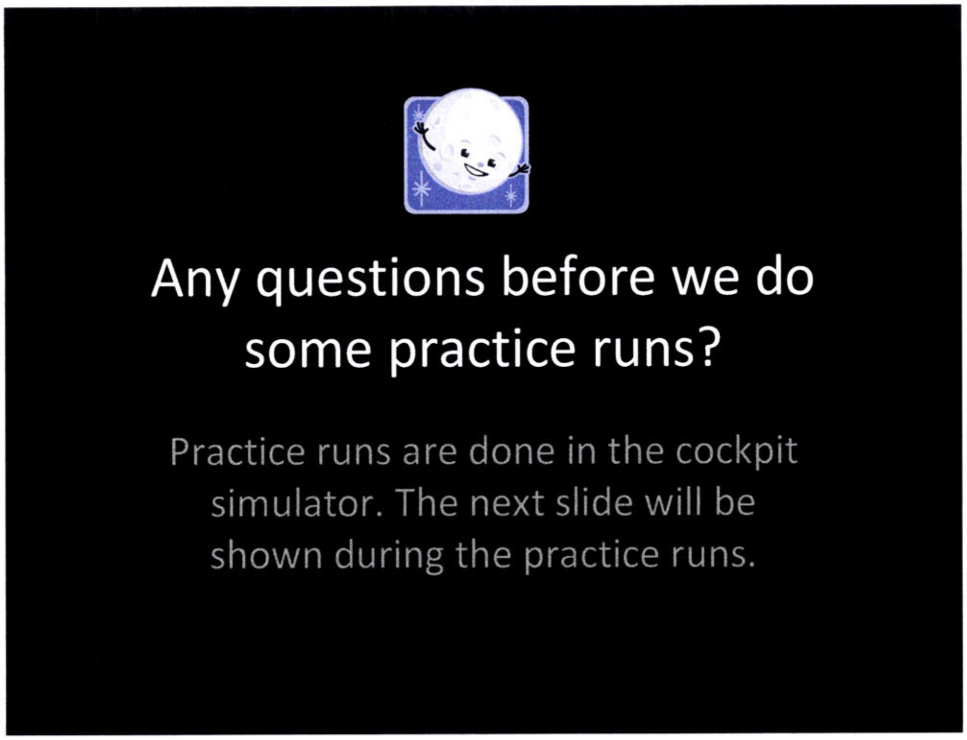


Summary of Goals

To choose a landing aimpoint, make sure you consider all of the following goals:

1. Safety: the largest slope margin, roughness margin, hazard margin, and fuel margin
2. POI: Proximity of the point of interest relative to the intended landing aimpoint (based on the mission)
3. Time: Make your decision as quickly as possible while also considering both of the above goals.

0:30


Any questions before we do some practice runs?
Practice runs are done in the cockpit simulator. The next slide will be shown during the practice runs.


Here are your goals
Click 'GO' to start
1. Safety: the largest slope margin, roughness margin, hazard margin, and fuel margin
2. POI: Proximity of the point of interest relative to the intended landing aimpoint (based on the mission)
0:30
3. Time: Make your decision as quickly as possible while also considering both of the above goals.
Make your decision and confirm it by pushing the 'OK' button

Appendix C: Experimental Data

Task Time										
Map	**Subject**	**No POI, 2+**	**No POI, 3**	**No POI, 3+**	**Geo POI, 2+**	**Geo POI, 3**	**Geo POI, 3+**	**Res POI, 2+**	**Res POI, 3**	**Res POI, 3+**
SM10	1	27	22	6	27	18	11	26	23	12
SM10	2	8	6	6	7	9	5	6	5	11
SM10	3	26	11	6	24	15	7	24	17	11
SM10	4	29	11	13	28	20	12	21	19	18
SM10	5	27	9	7	30	8	9	17	20	6
SM10	6	25	8	6	15	8	9	21	10	12
SM10	7	15	12	24	25	15	17	12	7	27
SM10	8	23	9	3	14	12	9	25	12	8
SM10	9	16	9	5	19	10	11	18	10	8
SM10	10	30	11	5	27	16	6	15	16	7
SM10	11	10	6	2	15	6	5	15	7	4
SM10	12	29	19	12	28	22	14	24	22	13
SM10	13	22	13	10	26	25	10	30	22	8
SM10	14	25	8	10	22	9	11	20	10	7
SM10	15	9	5	3	13	4	4	6	6	3
SM05	1	28	24	7	18	15	14	23	21	10
SM05	2	3	4	6	8	6	5	16	6	5
SM05	3	22	9	5	27	20	6	29	17	8
SM05	4	22	20	18	30	13	13	28	24	15
SM05	5	22	16	11	16	18	17	27	5	8
SM05	6	17	16	6	30	14	8	20	8	7
SM05	7	15	11	17	19	24	23	25	26	17
SM05	8	19	11	6	7	10	7	26	16	4
SM05	9	17	13	5	15	15	7	27	11	4
SM05	10	16	17	4	24	14	5	29	23	7
SM05	11	14	5	3	10	11	3	13	9	4
SM05	12	26	16	7	27	19	20	28	24	20
SM05	13	29	25	11	25	20	17	26	19	21
SM05	14	17	10	10	21	12	16	28	11	12
SM05	15	8	3	5	5	9	4	15	3	2

HU05	1	29	26	11	26	21	7	19	21	14
HU05	2	7	5	11	13	5	7	3	12	7
HU05	3	24	15	5	26	12	8	27	15	11
HU05	4	29	17	12	29	11	27	24	21	14
HU05	5	19	23	16	29	5	7	21	5	9
HU05	6	22	11	7	24	14	4	12	12	8
HU05	7	29	18	17	30	17	22	17	15	14
HU05	8	18	9	5	26	11	4	11	12	12
HU05	9	12	10	5	21	9	5	16	9	7
HU05	10	29	16	6	19	10	4	30	10	12
HU05	11	23	9	3	24	8	3	8	9	3
HU05	12	29	9	6	29	21	12	27	17	16
HU05	13	29	24	13	30	20	12	24	16	11
HU05	14	22	18	8	22	11	6	26	17	13
HU05	15	10	5	4	11	4	3	6	4	3

Quality										
Map	Subject	No POI, 2+	No POI, 3	No POI, 3+	Geo POI, 2+	Geo POI, 3	Geo POI, 3+	Res POI, 2+	Res POI, 3	Res POI, 3+
SM10	1	0.482	0.116	0.116	0.468	0.116	0.184	0.442	0.474	0.332
SM10	2	0.547	0.116	0.116	0.489	0.116	0.184	0.484	0.184	0.332
SM10	3	0.326	0.116	0.116	0.384	0.116	0.116	0.583	0.184	0.116
SM10	4	0.450	0.116	0.184	0.393	0.116	0.184	0.524	0.184	0.116
SM10	5	0.433	0.184	0.116	0.403	0.476	0.184	0.501	0.332	0.332
SM10	6	0.419	0.116	0.116	0.525	0.116	0.332	0.560	0.474	0.332
SM10	7	0.429	0.116	0.116	0.525	0.476	0.184	0.459	0.332	0.332
SM10	8	0.459	0.116	0.116	0.320	0.116	0.184	0.389	0.332	0.332
SM10	9	0.424	0.116	0.116	0.531	0.332	0.184	0.583	0.474	0.332
SM10	10	0.292	0.116	0.116	0.379	0.116	0.184	0.464	0.474	0.332
SM10	11	0.359	0.116	0.116	0.392	0.116	0.184	0.494	0.474	0.332
SM10	12	0.291	0.116	0.116	0.475	0.184	0.184	0.494	0.474	0.332
SM10	13	0.182	0.184	0.116	0.502	0.116	0.184	0.612	0.332	0.332
SM10	14	0.342	0.116	0.116	0.552	0.116	0.332	0.583	0.332	0.332
SM10	15	0.463	0.116	0.184	0.522	0.116	0.184	0.499	0.474	0.332
SM05	1	0.280	0.075	0.075	0.351	0.075	0.075	0.405	0.157	0.157
SM05	2	0.119	0.140	0.140	0.393	0.140	0.075	0.385	0.157	0.140
SM05	3	0.232	0.075	0.075	0.332	0.140	0.075	0.498	0.157	0.140
SM05	4	0.258	0.140	0.140	0.339	0.140	0.075	0.370	0.075	0.140
SM05	5	0.336	0.140	0.075	0.425	0.140	0.140	0.498	0.157	0.157
SM05	6	0.188	0.140	0.075	0.452	0.140	0.157	0.574	0.157	0.248
SM05	7	0.172	0.140	0.140	0.334	0.140	0.157	0.381	0.157	0.157
SM05	8	0.283	0.075	0.075	0.327	0.140	0.075	0.504	0.140	0.157
SM05	9	0.178	0.140	0.075	0.429	0.140	0.140	0.498	0.157	0.157
SM05	10	0.137	0.140	0.075	0.459	0.140	0.075	0.335	0.157	0.157
SM05	11	0.165	0.140	0.075	0.426	0.140	0.075	0.432	0.157	0.248
SM05	12	0.160	0.075	0.075	0.207	0.140	0.075	0.337	0.157	0.157
SM05	13	0.188	0.075	0.075	1.000	0.140	0.140	0.498	0.157	0.157
SM05	14	0.153	0.140	0.075	0.373	0.140	0.075	0.498	0.157	0.157
SM05	15	0.163	0.140	0.075	0.357	0.140	0.075	0.499	0.157	0.248
HU05	1	0.297	0.254	0.087	0.334	0.087	0.087	0.457	0.087	0.087
HU05	2	0.422	0.254	0.087	0.376	0.087	0.087	0.224	0.087	0.087
HU05	3	0.264	0.087	0.087	0.376	0.087	0.087	0.564	0.087	0.087
HU05	4	0.328	0.254	0.087	0.356	0.224	0.254	0.162	0.087	0.087
HU05	5	0.165	0.087	0.087	0.248	0.087	0.224	0.575	0.224	0.224
HU05	6	0.354	0.254	0.087	0.168	0.087	0.087	0.358	0.224	0.224
HU05	7	0.360	0.254	0.087	0.417	0.087	0.087	0.553	0.087	0.285
HU05	8	0.330	0.254	0.087	0.227	0.254	0.087	0.223	0.087	0.087
HU05	9	0.236	0.254	0.087	0.154	0.087	0.087	0.497	0.087	0.087
HU05	10	0.412	0.254	0.087	0.433	0.087	0.087	0.406	0.285	0.087
HU05	11	0.474	0.087	0.087	0.239	0.087	0.087	0.565	0.087	0.224
HU05	12	0.504	0.254	0.087	0.358	0.254	0.087	0.475	0.087	0.087
HU05	13	0.307	0.254	0.087	0.252	0.087	0.087	0.409	0.087	0.087
HU05	14	0.147	0.254	0.087	0.069	0.087	0.087	0.560	0.285	0.285
HU05	15	0.231	0.087	0.087	0.337	0.087	0.087	0.364	0.087	0.087

Appendix D: Statistical Results Data

The bold font in Table 4 and Table 5 indicates the p-values across different LOAs when the terrain map variable is held constant. The results also show that the effect of the terrain maps is minimal as shown in italicized font in these two tables.

Table 4: Task Time Results from the Sign Test Across Levels of Automation (L) and Terrain Maps (M) with No POI

	L1M1	L1M2	L1M3	L2M1	L2M2
L1M1	1.000				
L1M2	*0.118*	1.000			
L1M3	*1.000*	0.057	1.000		
L2M1	**0.000**	0.001	0.000	1.000	
L2M2	0.001	**0.007**	0.001	*0.607*	1.000
L2M3	0.007	0.180	**0.001**	*0.022*	1.000
L3M1	**0.001**	0.007	0.000	**0.057**	0.022
L3M2	0.001	**0.007**	0.000	0.267	**0.057**
L3M3	0.007	0.007	**0.001**	0.267	0.057

	L2M3	L3M1	L3M2	L3M3
L2M3	1.000			
L3M1	0.035	1.000		
L3M2	0.013	*0.549*	1.000	
L3M3	**0.001**	*0.424*	1.000	1.000

Table 5: Safety Quality Results from the Sign Test Across Levels of Automation (L) and Terrain Maps (M) with No POI

	L1M1	L1M2	L1M3	L2M1	L2M2
L1M1	1.000				
L1M2	*0.001*	1.000			
L1M3	*0.118*	0.007	1.000		
L2M1	**0.001**	0.000	0.001	1.000	
L2M2	0.000	**0.007**	0.000	*0.607*	1.000
L2M3	0.001	1.000	**0.007**	*0.118*	0.035
L3M1	**0.000**	0.001	0.000	**1.000**	1.000
L3M2	0.000	**0.001**	0.000	0.035	**0.016**
L3M3	0.000	0.000	**0.000**	0.000	0.302

	L2M3	L3M1	L3M2	L3M3
L2M3	1.000			
L3M1	0.118	1.000		
L3M2	0.000	*0.007*	1.000	
L3M3	**0.001**	*0.000*	0.035	1.000

The results of the Sign test are given in Table 6 and Table 7 are coded for easier viewing. The p-values in bold font are the factor levels comparisons between all of the LOAs and POIs, comparing similar terrain maps to one another. The p-values in both bold and italicized font are the factor level comparisons between the different POI levels, keeping both the LOA and terrain map variables constant. Similarly, the boxed p-values are the factor level comparisons between the different LOA levels, keeping both the POI and terrain map variables constant.

Table 6: Task Time Results from the Sign Test across Levels of Automation (L: L1=2+, L2=3, L3=3+), Points of Interest (P: P1=No POI, P2=Geo POI, P3=Res POI), and Terrain Maps (M)

	L1P1M1	L1P1M2	L1P1M3	L1P2M1	L1P2M2
L1P1M1	1.000				
L1P1M2	0.118	1.000			
L1P1M3	1.000	0.057	1.000		
L1P2M1	***0.791***	0.118	0.146	1.000	
L1P2M2	0.302	***1.000***	0.302	0.118	1.000
L1P2M3	0.118	0.001	***0.039***	0.180	0.118
L1P3M1	***0.118***	1.000	0.057	***0.092***	1.000
L1P3M2	0.424	***0.035***	1.000	0.227	***0.007***
L1P3M3	0.267	0.791	***0.302***	0.035	1.000
L2P1M1	**0.000**	0.001	0.000	**0.000**	0.013
L2P1M2	0.001	**0.007**	0.001	0.001	**0.022**
L2P1M3	0.007	0.180	**0.001**	0.000	0.057
L2P2M1	**0.007**	0.003	0.001	**0.001**	0.022
L2P2M2	0.013	**0.035**	0.001	0.000	**0.424**
L2P2M3	0.001	0.007	**0.000**	0.000	0.007
L2P3M1	**0.000**	0.002	0.001	**0.000**	0.118
L2P3M2	0.001	**0.118**	0.000	0.007	**0.035**
L2P3M3	0.001	0.003	**0.001**	0.001	0.035
L3P1M1	**0.001**	0.007	0.000	**0.000**	0.001
L3P1M2	0.001	**0.007**	0.000	0.000	**0.000**
L3P1M3	0.007	0.007	**0.001**	0.001	0.002
L3P2M1	**0.001**	0.007	0.000	**0.000**	0.001
L3P2M2	0.001	**0.007**	0.000	0.000	**0.013**
L3P2M3	0.001	0.035	**0.000**	0.000	0.001
L3P3M1	**0.007**	0.007	0.001	**0.007**	0.035
L3P3M2	0.001	**0.007**	0.000	0.000	**0.000**
L3P3M3	0.000	0.001	**0.000**	0.000	0.001

	L1P2M3	L1P3M1	L1P3M2	L1P3M3	L2P1M1
L1P2M3	1.000				
L1P3M1	0.000	1.000			
L1P3M2	0.791	0.118	1.000		
L1P3M3	***0.035***	1.000	0.001	1.000	
L2P1M1	0.000	**0.000**	0.000	0.007	1.000

L2P1M2	0.000	0.001	**0.001**	0.180	0.607
L2P1M3	**0.000**	0.057	0.001	**0.424**	0.022
L2P2M1	0.000	**0.035**	0.000	0.035	***0.092***
L2P2M2	0.000	0.057	**0.000**	0.302	0.003
L2P2M3	**0.000**	0.001	0.000	**0.146**	0.581
L2P3M1	0.000	**0.013**	0.000	0.057	***0.007***
L2P3M2	0.001	0.092	**0.001**	0.424	0.092
L2P3M3	**0.000**	0.013	0.000	**0.180**	0.424
L3P1M1	0.000	**0.002**	0.000	0.007	**0.057**
L3P1M2	0.000	0.002	**0.000**	0.002	0.267
L3P1M3	**0.000**	0.007	0.000	**0.002**	0.267
L3P2M1	0.000	**0.001**	0.000	0.002	**0.581**
L3P2M2	0.000	0.002	**0.000**	0.007	0.791
L3P2M3	**0.000**	0.035	0.000	**0.035**	0.035
L3P3M1	0.000	**0.007**	0.001	0.013	**0.180**
L3P3M2	0.000	0.001	**0.000**	0.002	0.302
L3P3M3	**0.000**	0.007	0.000	**0.007**	1.000

	L2P1M2	L2P1M3	L2P2M1	L2P2M2	L2P2M3
L2P1M2	1.000				
L2P1M3	1.000	1.000			
L2P2M1	1.000	0.774	1.000		
L2P2M2	***0.607***	0.607	1.000	1.000	
L2P2M3	1.000	***0.057***	0.424	0.092	1.000
L2P3M1	1.000	0.774	***0.549***	1.000	0.180
L2P3M2	***0.424***	0.791	0.180	***0.791***	0.146
L2P3M3	0.607	***0.581***	1.000	0.302	***0.754***
L3P1M1	0.022	0.035	**0.007**	0.000	0.118
L3P1M2	**0.057**	0.013	0.118	**0.002**	0.180
L3P1M3	0.057	**0.001**	0.057	0.001	**0.092**
L3P2M1	0.180	0.022	**0.424**	0.000	0.227
L3P2M2	**0.607**	0.013	0.092	**0.013**	0.267
L3P2M3	0.057	**0.118**	0.007	0.007	**0.118**
L3P3M1	0.057	0.302	**0.035**	0.035	0.118
L3P3M2	**0.118**	0.002	0.013	**0.057**	0.267
L3P3M3	0.581	**0.035**	0.022	0.118	**0.607**

	L2P3M1	L2P3M2	L2P3M3	L3P1M1	L3P1M2
L2P3M1	1.000				
L2P3M2	0.424	1.000			
L2P3M3	0.791	0.388	1.000		
L3P1M1	**0.013**	0.003	0.007	1.000	
L3P1M2	0.013	**0.013**	0.035	0.549	1.000
L3P1M3	0.007	0.035	**0.013**	0.424	1.000
L3P2M1	**0.057**	0.092	0.057	***0.057***	0.424
L3P2M2	0.013	**0.057**	0.180	0.039	***0.057***

L3P2M3	0.035	0.057	**0.035**	0.549	1.000
L3P3M1	**0.035**	0.180	0.013	***0.057***	0.180
L3P3M2	0.013	**0.035**	0.118	0.118	***0.791***
L3P3M3	0.057	0.092	**0.013**	0.002	0.267

	L3P1M3	L3P2M1	L3P2M2	L3P2M3	L3P3M1
L3P1M3	1.000				
L3P2M1	0.344	1.000			
L3P2M2	0.022	1.000	1.000		
L3P2M3	***0.267***	0.302	0.057	1.000	
L3P3M1	0.180	***1.000***	0.607	0.057	1.000
L3P3M2	1.000	1.000	***0.581***	0.581	0.267
L3P3M3	0.424	0.424	1.000	***0.146***	1.000

	L3P3M2	L3P3M3
L3P3M2	1.000	
L3P3M3	0.302	1.000

Table 7: Safety Quality Results from the Sign Test across Levels of Automation (L: L1=2+, L2=3, L3=3+), Points of Interest (P: P1=No POI, P2=Geo POI, P3=Res POI), and Terrain Maps (M)

	L1P1M1	L1P1M2	L1P1M3	L1P2M1	L1P2M2
L1P1M1	1.000				
L1P1M2	0.001	1.000			
L1P1M3	0.118	0.007	1.000		
L1P2M1	***0.302***	0.000	0.118	1.000	
L1P2M2	1.000	***0.000***	0.302	0.302	1.000
L1P2M3	0.118	0.302	***1.000***	0.001	0.118
L1P3M1	***0.035***	0.000	0.001	***0.118***	0.001
L1P3M2	0.118	***0.000***	0.118	0.302	***0.035***
L1P3M3	0.607	0.007	***0.302***	0.791	0.607
L2P1M1	**0.001**	0.000	0.001	**0.000**	0.000
L2P1M2	0.000	**0.007**	0.000	0.000	**0.000**
L2P1M3	0.001	1.000	**0.007**	0.000	0.001
L2P2M1	**0.007**	0.118	0.035	**0.001**	0.007
L2P2M2	0.000	**0.007**	0.000	0.000	**0.000**
L2P2M3	0.000	0.001	**0.000**	0.000	0.001
L2P3M1	**1.000**	0.035	0.424	**0.118**	1.000
L2P3M2	0.000	**0.035**	0.001	0.000	**0.000**
L2P3M3	0.000	0.035	**0.007**	0.000	0.000
L3P1M1	**0.000**	0.001	0.000	**0.000**	0.000
L3P1M2	0.000	**0.001**	0.000	0.000	**0.000**
L3P1M3	0.000	0.000	**0.000**	0.000	0.000
L3P2M1	**0.001**	0.607	0.007	**0.000**	0.000
L3P2M2	0.000	**0.000**	0.000	0.000	**0.000**
L3P2M3	0.000	0.000	**0.001**	0.000	0.000

L3P3M1	**0.035**	0.035	1.000	**0.001**	0.007
L3P3M2	0.000	**0.607**	0.007	0.000	**0.000**
L3P3M3	0.000	0.118	**0.007**	0.000	0.000

	L1P2M3	L1P3M1	L1P3M2	L1P3M3	L2P1M1
L1P2M3	1.000				
L1P3M1	0.000	1.000			
L1P3M2	0.035	0.013	1.000		
L1P3M3	***0.118***	0.118	1.000	1.000	
L2P1M1	0.001	**0.000**	0.000	0.000	1.000
L2P1M2	0.001	0.000	**0.000**	0.000	0.607
L2P1M3	**0.302**	0.000	0.000	**0.035**	0.118
L2P2M1	0.118	**0.001**	0.001	0.000	***0.375***
L2P2M2	0.001	0.000	**0.000**	0.000	0.035
L2P2M3	**0.007**	0.000	0.000	**0.007**	0.035
L2P3M1	0.118	**0.007**	0.118	0.607	***0.000***
L2P3M2	0.007	0.000	**0.000**	0.000	0.035
L2P3M3	**0.007**	0.000	0.000	**0.000**	0.118
L3P1M1	0.001	**0.000**	0.000	0.001	**1.000**
L3P1M2	0.001	0.000	**0.000**	0.000	0.035
L3P1M3	**0.001**	0.000	0.000	**0.000**	0.000
L3P2M1	0.035	**0.000**	0.000	0.001	**0.000**
L3P2M2	0.001	0.000	**0.000**	0.000	0.035
L3P2M3	**0.001**	0.000	0.000	**0.001**	0.007
L3P3M1	1.000	**0.000**	0.000	0.007	**0.000**
L3P3M2	0.118	0.000	**0.000**	0.000	0.007
L3P3M3	**0.007**	0.000	0.000	**0.000**	0.302

	L2P1M2	L2P1M3	L2P2M1	L2P2M2	L2P2M3
L2P1M2	1.000				
L2P1M3	0.035	1.000			
L2P2M1	1.000	0.607	1.000		
L2P2M2	***0.125***	0.118	0.302	1.000	
L2P2M3	0.607	***0.004***	0.035	0.118	1.000
L2P3M1	0.000	0.007	***0.007***	0.000	0.001
L2P3M2	***0.001***	0.118	0.302	***0.002***	0.035
L2P3M3	0.607	***0.146***	0.035	0.302	***1.000***
L3P1M1	1.000	0.118	**0.687**	0.035	0.035
L3P1M2	**0.016**	0.000	0.007	**0.001**	0.007
L3P1M3	0.302	**0.001**	0.000	0.001	**0.250**
L3P2M1	0.000	0.607	**0.092**	0.001	0.035
L3P2M2	**0.508**	0.001	0.007	**0.065**	0.302
L3P2M3	1.000	**0.012**	0.001	0.035	**1.000**
L3P3M1	0.001	0.001	**0.039**	0.007	0.001
L3P3M2	**0.000**	0.118	0.118	**0.000**	0.035

L3P3M3	0.302	**0.267**	0.035	0.607	**0.727**

	L2P3M1	L2P3M2	L2P3M3	L3P1M1	L3P1M2
L2P3M1	1.000				
L2P3M2	0.000	1.000			
L2P3M3	0.000	0.302	1.000		
L3P1M1	**0.000**	0.007	0.118	1.000	
L3P1M2	0.000	**0.001**	0.035	0.007	1.000
L3P1M3	0.000	0.001	**0.125**	0.000	0.035
L3P2M1	**0.000**	0.001	0.007	***0.000***	0.000
L3P2M2	0.000	**0.000**	0.035	0.302	***0.453***
L3P2M3	0.001	0.007	**0.625**	0.007	0.007
L3P3M1	**0.021**	0.001	0.000	***0.002***	0.001
L3P3M2	0.000	**0.453**	0.035	0.001	***0.000***
L3P3M3	0.000	0.607	**1.000**	0.302	0.007

	L3P1M3	L3P2M1	L3P2M2	L3P2M3	L3P3M1
L3P1M3	1.000				
L3P2M1	0.000	1.000			
L3P2M2	0.302	0.000	1.000		
L3P2M3	***0.500***	0.007	0.118	1.000	
L3P3M1	0.000	***0.006***	0.000	0.001	1.000
L3P3M2	0.000	0.035	***0.000***	0.007	0.007
L3P3M3	***0.062***	0.035	0.007	***0.375***	0.000

	L3P3M2	L3P3M3
L3P3M2	1.000	
L3P3M3	0.035	1.000