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Developing Lunar Landing Vehicle Display Requirements through Content Analysis of Apollo Lunar Landing Voice Communications

Cristin A. Smith, M. L. Cummings, and Liang Sim

Abstract

The lengthy period since the Apollo landings limits present-day engineers attempting to draw from the experiences of veteran Apollo engineers and astronauts in the design of a new lunar lander. In order to circumvent these limitations, content analyses were performed on the voice transcripts of the Apollo lunar landing missions. The analyses highlighted numerous inefficiencies in the design of the Apollo Lunar Module displays, particularly in the substantial use of the cognitive resources of the Lunar Module Pilot in the performance of low-level tasks. The results were used to generate functional and information requirements for the next-generation lunar lander cockpit.

Introduction

In January 2004, a new national Vision for Space Exploration was announced that called for a sustained program of joint robotic and human exploration of the solar system. The Vision includes a permanent human return to the Moon by 2020 as a stepping stone for Mars and beyond. The Vision further specifies performance requirements for future lunar landings that are considerably more ambitious than for previous Apollo missions, and therefore new spacecraft systems will be needed with advanced capabilities. In particular, the next-generation lunar lander, currently known as the Lunar Surface Access Module (LSAM), must be capable of achieving an autonomous “anytime, anywhere” landing with up to 10 m precision (Fuhrman et al., 2005). Achieving this will entail not only state-of-the-art avionics and cockpit display technology, but also rigorous application of modern human factors principles to optimize the performance of the human as an integral component in the complex spacecraft system.

A common method for identifying human factors considerations of a proposed system such as the cockpit of the proposed LSAM is to interview or survey the end-users of similar vehicles as part of a cognitive task analysis (CTA) (Schraagen, Chipman, & Shalin, 2000). For example, astronaut input was integral in the proposed Space Shuttle Cockpit Avionics Upgrade, which addresses the human factors deficiencies of the Shuttle glass cockpit (McCandless et al., 2005). In the aviation domain, airline pilots have been surveyed to prioritize their perceived information requirements across different phases of flight, with the purpose of improving the cockpit layout of future airliners (Schvaneveldt, Beringer, & Lamonica, 2001).

However, these CTA interview results are susceptible to subjective bias and long-term memory inaccuracies (Horselenberg, Merckelbach, van Breukelen, & Wessel, 2004), especially if conducted months or years after the event. Furthermore, the possibility of conducting interviews about cockpit design of a retired vehicle becomes increasingly difficult over time as the number of potential interview subjects decreases due to aging and death. Over thirty years have elapsed since the last human lunar landing in 1972, and now NASA now faces the undesirable prospect of designing the LSAM without the ability to draw on the experience of many of the engineers and astronauts who contributed to the Apollo Lunar Module (LM).

Content analysis of real-time voice or written transcripts has the potential to mitigate some of the limitations inherent in cognitive task analysis post-hoc interviews or surveys, especially if subject-matter experts no longer can be interviewed. In content analysis, the words, phrases, or sentences of transcripts are coded and classified into categories for statistical analysis (Weber, 1990). Since transcripts are generated from actual events captured in real-time, they are less likely to be affected by the inaccuracies or biases of post-hoc interviews. Furthermore, they are archival and retrievable years after the event regardless of the availability of the people who actually participated at the time. Content analysis is therefore particularly suitable for use in a cognitive task analysis for proposed space vehicles as the voice communications transcripts of human spaceflights, particularly those of the pre-Shuttle era, have been well documented (Jones, 2006).

Content analysis of voice communications has been used extensively in aviation and transportation research for numerous purposes. For example, it has been used to determine the impact of automation on communication and decision-making performance in airline crews (Cooke et al., 2003; Kanki, Folk, & Irwin, 1991), and to evaluate the use of cockpit displays of traffic information to maintain pre-defined spacing intervals from other aircraft (Prinzo, 2003).

In contrast to these previous studies that generally examined workload and performance through transcript content analysis, this paper proposes the use of content analysis to extract functional and information requirements for futuristic LSAM cockpit design. The generation of accurate and comprehensive functional requirements is critical to the success of any complex engineering system (Blanchard & Fabrycky, 1998), and only in recent years has the importance of capturing accurate functional requirements (and derivative information requirements) from the human perspective been recognized as equally important as those of mechanical and computational systems (Booher, 2003; Chapanis, 1996). Moreover, with the increasing complexity of automated systems and the human role as supervisor of these advanced space systems, the need to identify where, why, how, and when to support human reasoning, without overwhelming the crew, is particularly critical.

From a historical perspective, the lack of understanding the functional and information requirements of the crew was nearly catastrophic for Apollo 13. A poorly designed status display essentially guaranteed that astronauts would not detect the imminent failure of an oxygen tank, which led to an emergency recovery of the spacecraft (Woods, 1995). Thus it is critical that in the conceptual design phases of complex systems that require significant human interaction such as the LSAM, that the functional and information requirements of the crew are identified as early as possible so that they can feed downstream system design requirements. In this paper, we demonstrate the way in which content analysis of the Apollo lunar landing mission voice communications generated functional and information requirements, which contributed to a proposed LSAM cockpit design (Cummings et al., 2005; Fuhrman et al., 2005).

Methods

Context and Background

The crew of Apollo lunar landing missions consisted of three astronauts: the Commander (CDR), Lunar Module Pilot (LMP) and Command Module Pilot (CMP). Only the CDR and LMP flew the Lunar Module to the lunar surface; the CMP remained in lunar orbit in the Apollo Command Module. The Capsule Communicator (CapCom) was an astronaut based at Mission Control in Houston during the mission who acted as the sole communicator between the flight crew and Mission Control.

Every Lunar landing sequence consisted of three distinct, consecutive phases (Figure 1):

1. *Powered Descent Initiation (PDI)*, an approximately 9 minute phase in which the Lunar Module decelerated under autopilot control from the 50,000 ft perilune of lunar descent orbit, with the CDR and LMP holding a human supervisory control role by monitoring spacecraft systems and mission schedule.

2. *Program 64 (P64)*, in which the Lunar Module pitched over at approximately 6,000 ft altitude to provide the crew with their first view of the landing site. In this approximately 1.5 minute phase, the CDR examined the landscape outside the window to search for potential landing sites and, if necessary, manually redesignated the eventual landing site while the computer maintained automatic control of attitude and velocity (Jones, 2006). The LMP monitored and called out pertinent information from the cockpit instruments to prevent the CDR from having to look down into the cockpit.

3. *Program 66 (P66),* in which the CDR assumed manual control of attitude and descent rate for up to 2.5 minutes to guide the Lunar Module from an altitude of 300-600 ft to touchdown, while the LMP continued to monitor and call out position and velocity.

Content Analysis

Motivated by both the difficulties in interviewing many subject matter experts and the inconsistencies in recall from those subject matter experts interviewed (Cummings, et al. 2005), a content analysis was performed with the express purpose of attempting to determine functional and information requirements to be used in the design of a futuristic lunar lander. Using the voice transcripts of the six successful Apollo lunar landings (Apollos 11, 12, 14-

17), a content analysis was performed on the voice communications exchanges spoken by the CDR, LMP and CapCom during the three landing phases, as described above. Exchanges spoken by the CMP comprised less than 0.5% of all exchanges throughout this period, and were thus excluded from the analysis. Once the exchanges were classified (as described below), relevant statistical tests were applied in order to determine which crewmember role spoke the most across the three landing phases, as well as which context was the most important for the different phases.

For each exchange, the speaker (CDR, LMP or CapCom) and the phase in which the exchange occurred (PDI, P64 or P66) were noted. Each exchange was classified into one of seven context categories (Table 1). The first four classifications (Schedule, Vehicle/Mission Status, Vehicle Position, and Off-Nominal) categorized exchanges containing critical quantitative information, whereas the last three classifications (Personal, Acknowledgment and Miscommunication) categorized qualitative exchanges. The quantitative categories were selected since they encompass specific pieces of numerically-based information that astronauts were seeking in order to maintain the Lunar Module in a safe operating envelope.

However, as in any team environment, a significant portion of Apollo communications were qualitative, such as clarification of transmissions and social interactions, so these were also captured. Analysis of quantitative communications can directly translate into information requirements (e.g., continued requests for altitude data indicate the need to better present this information to the relevant stakeholder). However, qualitative communications can also provide insight to the contribution of communications to overall workload, as well as to discrepancies in shared mental models (i.e., confusion over specific pieces of information that cause significant discussion). Thus, qualitative communication content analysis can further elucidate the overall team functions that need to be supported, which cannot be gleaned by simple individual quantitative transmission analysis.

[INSERT TABLE 1 HERE]

The classification of exchanges across the seven categories was performed separately by two individuals with an intra-class correlation of .964. Then, a statistical analysis using the context categories of Table 1 was performed on the voice exchanges of each crewmember (CDR, LMP, CapCom) during each phase (PDI, P64, P66), for a total of nine crewmember-phase combinations.

For each combination of role and phase, the number of exchanges by context was analyzed using the non-parametric Kruskal-Wallis test, since the majority of data violated the normality and homoscedasticity assumptions of parametric tests. Mann-Whitney U tests were then performed to compare significant Kruskal-Wallis results. A total of 895 voice exchanges across the six Apollo lunar landing missions were analyzed (Figure 2). In all cases, $\alpha = 0.05$, unless otherwise stated.

Results

The content analysis was initially performed in two ways. First, the absolute number of exchanges for each phase-crewmember combination was analyzed without accounting for the differences in phase duration across the six different Apollo missions. The analysis was then repeated with the number of exchanges normalized to account for the variation in phase duration across different missions, phases, and crew. The two methods yielded very similar results: 94% of the Kruskal-Wallis rankings calculated using the absolute data were identical to those from normalized data. Even in the 6% of cases where rankings were not identical, the difference between the results for the two data sets was minor in that only two context categories either switched adjacent rankings (e.g., from 2nd and 3rd to 3rd and 2nd) or had equal rankings instead of ordered rankings (e.g., both equal to 5th instead of 5th and 6th). Furthermore, the rate at which voice communications occurred, measured in number of exchanges per minute, was not significantly different across phases (Kruskal-Wallis p = 0.166), nor across missions (Kruskal-Wallis p = 0.623). As such, only results from the absolute data are presented hereafter.

During PDI

Crewmember role was significant (Kruskal-Wallis p = 0.021), driven primarily by the CapCom's significantly reduced communication role. The CapCom spoke less frequently than the CDR and LMP (24%, or 144 out of 594 exchanges, Mann-Whitney $p < 0.026$ for all pairwise comparisons between the CapCom and other crewmembers; Figure 3a). In contrast, the frequency with which the CDR spoke was not significantly different from that of the LMP.

Pairwise context categories comparisons were then conducted for each of the three crewmember roles to determine dominant categories. The top three statistically significant context categories (as compared to the other contexts) for each crewmember across each phase are shown in Table 2 (if less than three categories are listed, only those that showed a statistical difference are included). In the PDI phase, the CDR discussed Vehicle/Mission Status significantly more frequently than any other context (Mann-Whitney p = 0.04 compared to Schedule, the second most frequently discussed context which was not statistically different from the remaining categories). The LMP discussed Vehicle/Mission Status, Vehicle Position, and Schedule significantly more frequently than other contexts (Mann-Whitney p = 0.041 between Schedule and Personal, the third and fourth most frequent contexts; Table 2). The most important contexts for the CapCom were Schedule (35% of all CapCom exchanges), Acknowledgment (30%) and Vehicle/Mission Status (18%). These were marginally more significant than other contexts (Mann-Whitney $p = 0.093$ between Vehicle/Mission Status and Vehicle Position, the third and fourth most frequently discussed contexts respectively.)

[INSERT TABLE 2 HERE]

During P64

As in the PDI phase, crewmember role significantly influenced the communication frequency (Kruskal-Wallis $p = 0.007$). The CapCom spoke significantly less frequently than either the CDR or LMP (11%, or 17 out of 155 exchanges, Mann-Whitney $p < 0.009$ for all pairwise comparisons between CapCom and other crewmembers; Figure 3b). As in the PDI stage, the frequency with which the CDR spoke was not significantly different from that of the LMP.

Within the context categories, the CDR discussed Vehicle Position, Personal, Acknowledgment, and Vehicle/Mission Status more frequently than other contexts (Kruskal-Wallis $p = 0.001$), but there was no significant difference in the pairwise frequencies of these four contexts (thus they were all discussed with the same frequency). In contrast, the LMP discussed Vehicle Position significantly more frequently than any other contexts (Kruskal-Wallis $p = 0.002$, Mann-Whitney p = 0.002 compared to Personal, the second most frequent context). The CapCom discussed Schedule and Acknowledgment more frequently than other contexts (Kruskal-Wallis $p < 0.0005$) except Off-Nominal, which was marginally significant (Mann Whitney comparison between Off-Nominal and Acknowledgment, $p < 0.093$; between Off-Nominal and Schedule $p = 0.009$).

During P66

Crewmember communications were significant across the P66 phase (Kruskal-Wallis $p = 0.001$), with the LMP speaking significantly more frequently (64%, or 94 out of 146 exchanges, Figure 3c) than both the CDR (Mann-Whitney p = 0.015) and the CapCom (Mann-Whitney p = 0.002).

As seen in Table 2, the most important contexts for the CDR were Vehicle/Mission Status (1st), Vehicle Position (2nd) and Acknowledgment (3rd) but these were only marginally more frequent than the other four contexts (Kruskal-Wallis $p = 0.008$; Mann-Whitney $p = 0.093$ between Vehicle/Mission Status and Schedule, the fourth most frequent context). In contrast, the LMP discussed two contexts significantly more than others (Kruskal-Wallis $p < 0.0005$): Vehicle Position (Mann-Whitney $p = 0.026$ compared to Vehicle/Mission Status, the second most frequent context) and Vehicle/Mission Status (Mann-Whitney $p = 0.004$ compared to Personal, the third most frequent context). The CapCom discussed Acknowledgment, Schedule and Vehicle/Mission Status significantly more frequently than other contexts (Kruskal-Wallis $p = 0.049$) except for Off-Nominal (Mann-Whitney $p = 0.18$ compared to Acknowledgment, the most frequent context).

The Most Predominant Context Categories

Inspection of Table 2 shows that of the originally identified seven categories, Vehicle/Mission Status, Vehicle Position, Acknowledgment, and Schedule accounted for the majority of the communications. Of particular note, three of these four categories represent quantitative categories, i.e., they include numeric information that the crew was seeking from the displays in order to maintain the lander in a safe operating envelope. Given that the acknowledgement category did not represent the conveyance of display-specific information, the other three most commonly occurring categories were examined more closely to discern any statistically significant trends.

Analysis of these three most predominant display-specific contexts (Vehicle/Mission Status, Schedule, and Vehicle Position) across the PDI phase showed that the CDR and LMP discussed Vehicle/Mission Status significantly more frequently than the CapCom (Kruskal-

Wallis $p = 0.004$, Mann-Whitney $p < 0.004$ for all pairwise comparisons between CapCom and other crewmembers). The LMP discussed Vehicle Position significantly more frequently than the CDR and CapCom (Kruskal-Wallis $p = 0.003$, Mann-Whitney $p < 0.041$ for all pairwise comparisons between LMP and other crewmembers. In contrast, there was no significant difference in the frequency with which the three personnel discussed Schedule. These rankings are represented in Table 3.

For P64, across the crewmembers, the CapCom discussed Schedule marginally more frequently than the CDR or LMP (Kruskal-Wallis $p = 0.052$, Mann-Whitney $p < 0.093$ for all pairwise comparisons between CapCom and other crewmembers.) The CDR discussed Vehicle/Mission Status marginally more frequently than the LMP or CapCom (Kruskal-Wallis $p = 0.005$, Mann-Whitney p < 0.132 for all pairwise comparisons between CDR and other crewmembers). The LMP discussed Vehicle Position significantly more frequently than the CDR or CapCom (Kruskal-Wallis $p = 0.001$, Mann-Whitney $p < 0.026$ for all pairwise comparisons between LMP and other crewmembers, Figure 3b and Table 3).

For P66, the CDR and LMP discussed Vehicle/Mission Status significantly more frequently than the CapCom (Kruskal-Wallis $p = 0.008$, Mann-Whitney $p < 0.041$ for all pairwise comparisons between CapCom and other crewmembers). As with P64, the LMP discussed Vehicle Position significantly more frequently than the CDR or CapCom (Kruskal-Wallis $p = 0.001$, Mann-Whitney $p < 0.004$ for all pairwise comparisons between LMP and other crewmembers, Figure 3c). As in the PDI phase, there was no significant difference in the frequency with which the three individuals discussed Schedule (Table 3).

[INSERT TABLE 3 HERE]

Discussion

This content analysis demonstrates that the context and frequency of the voice communications during the critical final minutes of the Apollo lunar descent and landing varied considerably by both crewmember and phase. It also demonstrates some consistent trends suggesting that changing future roles and function allocation could increase the efficiency and safety of precision landings in future vehicles.

During PDI and P66, the CDR and LMP both held a supervisory control role, primarily monitoring Vehicle/Mission Status. This suggests some redundancy in role allocation, and the content analysis reflects this by illustrating that the communications of the CDR and LMP were relatively similar in context and frequency (Figures 3a and 3c). However, one striking difference between the CDR and the LMP can be seen in Table 3, which demonstrates that across all three phases, the LMP held a vehicle position monitoring and callout role to support the CDR, who was assuming cognitively demanding, perceptually-based manual control of the spacecraft. The content analysis correspondingly shows that 71% of the LMP's exchanges in the higher workload P64 and P66 phases served the primary purpose of informing the CDR of Vehicle Position information, particularly altitude, descent rate, and projected landing site. During these final two phases, the CapCom (representing Mission Control) could not assist the crew in performing the critical task of finding a landing site, but did assist in reminding the crew of the planned Schedule.

Eliminating the necessity to call out cockpit information on the part of the LMP would thus considerably liberate the cognitive resources of the LMP. Moreover, as can be seen in Figure 3 and Table 2, the CDR incurred additional workload by having to acknowledge the LMP callouts, particularly in the highest workload phase of P66. This communication and cognitive overhead would disappear if cockpit information could be directly perceived by the CDR. Today, a head-up or helmet-mounted display could provide this capability by projecting cockpit information into the CDR's field of view. Unfortunately, this technology was not available during the time of Apollo, but a new precision landing head-up-display has been proposed to meet this need (Smith, Cummings, Forest, & Kessler, 2006), due in part to the findings of this study.

The content analysis also emphasizes that the CapCom's role was primarily to remind the crew of Schedule and to a lesser degree, Vehicle/Mission Status. This responsibility diminished as the descent and landing progressed. This reduction occurred not only because the CapCom spoke significantly less frequently than the flight crew, but also because many of the CapCom's exchanges were merely Acknowledgments to exchanges from the crew. Modern technology could provide the capability to automate the reminder functions, thus liberating the cognitive resources of the CapCom as well as the space-to-ground voice telemetry channels for higher level human supervisory control and mission management purposes. While the need for acknowledgment of communications is critical in any team environment to build and maintain shared situation awareness, it also introduces a cognitive overhead cost which could be eliminated if unnecessary communications between human team members were also eliminated.

While Table 2 demonstrates that the most frequent communications were based either on the need for specific quantitative display information or the need for acknowledgment, there was one qualitative context category that showed significance out of the top three context categories: Personal communication for the CDR in P64. Closer analysis of the transcripts revealed that the increase in CDR Personal communications during P64 occurred because the Lunar Module pitched over at the beginning of this phase to provide the CDR with his first view of the landing area. Several CDRs made repeated comments expressing their excitement about this initial view, and its similarity to pre-flight simulations. Given this trend across all the missions analyzed, one possible design outcome could be that as little information as possible should be conveyed at this transition point since it is an expected (and important) experience that could be distracting for a brief period of time.

Cockpit Design Implications

The role of the crew is central in the design of a manned (as well as an autonomous, unmanned) lunar lander because of the difficulties in maintaining situation awareness through remote displays. Why, when, and where the human contributes to a mission is inherently linked to the functional and design requirements. Moreover, which functions or subsets of functions should be allocated to humans and what should be allocated to automation remains a difficult design challenge for both space and aviation systems. The function allocation dilemma was one that Apollo engineers struggled with, as they debated whether to design a highly automated vehicle, requiring little reasoning or decision making on the part of the astronauts, or one with significant human input, which could result in a large number of tasks, resulting in possibly high mental and physical workload. This conundrum still exists today.

The resulting Apollo designs were largely driven by the technology available at that time, which resulted in very cumbersome, high workload displays that generally did not account for human cognitive needs. However, present-day technologies can and should be more accommodating to human cognition requirements, especially in light of the lessons learned from formalized cognitive systems engineering processes, which were not in existence at the time of Apollo. One of these formalized processes is the explicit development of functional and resultant display design requirements that support the human's role in the overall mission. While the establishment of functional and design requirements for complex systems is an established systems engineering methodology (Blanchard & Fabrycky, 1998), it has only been recognized in recent years that such a formal analytic approach should also be taken for the human-systems integration aspect (Booher, 2003; Chapanis, 1996), thus treating the human need for cognitive support *as important* as any other subsystem.

To this end in terms of designing the next generation lunar lander, this content analysis aided in identifying critical functional and display information requirements during the landing sequence by quantifying the context and frequency of voice communications during the actual Apollo lunar landing missions. In addition, this analysis provided important role allocation information for the astronauts and CapCom, and how they contributed to the overall functions of the mission. More specifically, this context analysis contributed to the development of the following functional requirements (Cummings, et al., 2005):

• *Astronauts/controllers should be constantly aware of vehicle endurance and position, both in time and space.* The content analysis clearly demonstrated the constant need for vehicle/mission status updates, as well as vehicle position across all three phases.

• *Software agents (e.g., on-screen smart checklists) must be provided to reduce astronaut/controller cognitive workload.* Since so much of the communication involved discussions and acknowledgements about the schedule, automated scheduling tools, the use of smart checklists could alleviate the human need to constantly remind the crew since contextual, event-driven reminders could be automated.

• *Provide advanced visualization tools (i.e., synthetic and predictive views) to enhance astronaut/controller situation awareness and reduce cognitive overhead.* The content analysis demonstrated the LMP's role as a human instantiation of a head-up display, which resulted in increased communication acknowledgment overhead for the CDR, who was actually controlling the lander. This could be alleviated by providing the required information *directly* to the CDR, instead of filtering it through the LMP. While this type of display would eliminate the need for the LMP in this phase for this task, this crewmember could then focus on other tasks such as the vehicle status and schedule monitoring, which would alleviate the need for such a close link to Mission Control (which will be discussed more in-depth in a subsequent section.)

• *On-demand information access and sharing among crew members and mission Controllers.* This design intervention could further reduce the communication overhead imposed by the redundant communications between all three team members, as well as reduce the acknowledgement communications.

The resulting functional and design requirements led to the proposed design of a windowless cockpit for a future lunar lander consisting of three integrated synthetic displays (Cummings et al., 2005), discussed below (Figure 4):

1. Landing Zone display for visualizing the landing site and supervising the system's conduct of an automatic precision landing. This display also provides for manual intervention if necessary (Figure 4a).

2. Situation Awareness display for understanding vehicle position in both space and time, as well as in the sequence and schedule of events (Figure 4b).

3. System Status display for monitoring the vehicle systems in the event of an urgent or emergent condition that could threaten the safety of the lander during the landing sequence, as well as cause problems in the mission plan (Figure 4c).

The Landing Zone display was primarily developed to meet the advanced visualizations functional requirement, specified above. As seen in the content analysis, the primary role of the LMP during P64 and P66 was to call out cockpit information to the CDR as he focused his attention on the landscape outside the window. The proposed display in Figure 4a effectively eliminates the primary role of the LMP during these phases by integrating the outside view and critical landing information such that all of the information can be directly perceived by the crewmember responsible for choosing the landing site.

In terms of role and function allocation, as demonstrated in this content analysis, the CapCom's role in the landing sequence was relatively minor, particularly in the P64 and P66 stages. It primarily consisted of schedule reminders and acknowledgments to transmissions originating from the Lunar Module. The proposed Situation Awareness display (and the associated automation) provides this information to the crew in a manner that can be directly perceived and comprehended potentially more quickly than through voice communication, thus eliminating the need for the CapCom for schedule reminders. During the Apollo missions, the role of Mission Control during nominal operations was to provide information that could not be displayed onboard the Lunar Module due to both human and system limitations. For future missions, however, the eventual goal should be to become completely independent of Mission Control in order to enable decision-making to occur onboard the spacecraft. This ability to conduct operations without the link to Mission Control will be especially critical for deep-space missions where real-time voice communications may be unfeasible.

While the CapCom's (and thus Mission Control's) role during nominal landings was minimal, this analysis demonstrated that under off-nominal situations (i.e., when problems arise), Mission Control played a more central role. Thus, independence from Mission Control will only become possible through significant advances in health and status monitoring, particularly under off-nominal conditions. However, even in the present Space Shuttle displays which take on a greater degree of autonomy than Apollo missions, difficulties in using the Space Shuttle cockpit displays to identify and diagnose off-nominal situations have been documented (McCandless et al., 2005). In order to overcome these Apollo and Shuttle limitations, the System Status display of the proposed cockpit (Figure 4c) proposes a collaborative human-computer approach to health and status monitoring much like the astronaut-Mission Control relationship in the Apollo missions. Such an advanced, automated system would rely heavily on a significantly improved sensor suite as well as significant advances in predictive algorithms and software reliability.

Unlike the Apollo Lunar Module cockpit, which primarily consisted of electromechanical gauges, this suite of displays integrates landing information, system state information relative to position and time, and system status information. Since information within these three classifications is required to simultaneously conduct the supervisory control landing sequence, their perceptual proximity in a glass cockpit environment allows the information to be processed in parallel. Furthermore, such integrated displays have the potential to provide supra-normal acuity, wide field of view and reconfigurability for different flight phases and personal preferences.

However, such an advanced and futuristic design concept that dramatically changes the human-automation role allocation over that seen in Apollo could be controversial (Reichhardt, 2006). It is not uncommon for such advanced supervisory control systems, which represent a significant organizational and cultural paradigm shift, to meet some resistance, particularly when the importance of the human role could be seen as diminished (Sheridan, 2002). However, if NASA is going to achieve manned deep-space missions, or even landing on the dark side of the moon, such advanced supervisory control systems that reduce the reliance on Mission Control will be critical.

Conclusion

As with all content analysis studies, this study is subject to a number of limitations. This content analysis provided limited insight into the workload or performance of the Apollo astronauts as there were no obvious metrics against which the results of the content analysis could be correlated. Previous content analysis studies in aerospace domains have used number of aircraft as a proxy for air traffic controller workload (Prinzo, 2003) and deviation from altitude, course, or time as a proxy for airline pilot performance (Cooke et al., 2003), but there are no analogous metrics for the Apollo lunar landings. Furthermore, it was difficult to subjectively estimate workload or performance by reading the transcripts. Several Apollo Commanders have cited P66 to be the most challenging phase of the landing (Cummings et al., 2005; Jones, 2006) but the context, tone and speech rate of their exchanges provide no direct indication of this. The fact that the CDR spoke significantly less frequently than the LMP only during the final P66 phase, but not during P64 or PDI, is only an indirect reflection of the CDR's high workload during this period.

While one advantage of using such a method is the ability to retrospectively capture cognitive functional and information requirements when subjects matter experts are no longer accessible, one question that such an analysis raises is whether the content analysis of such an older, less complex system can effectively contribute to a new, much more capable system? Such an analysis would really only be useful if the *functional* requirements for the older and newer systems are very similar, which is the case for the new lunar lander design. Despite the fact that proposed landings on the moon will occur 50 or more years after the initial landings, functionally the missions are nearly identical (Fuhrman et al, 2005). Both then and now, the displays must allow the crew the ability to monitor the status and position of the vehicle, track the mission progress, check it against the schedule, effect a safe landing, and respond to off-nominal problems. While these functions are identical between Apollo and the proposed lunar landings, which is why the content analysis of the Apollo transcripts is relevant, one significant change for the future will be the increasing application of supervisory control through advanced automation. However, as discussed previously, the use of more automation only changes the functional allocation, not the functions themselves.

In conclusion, the present study demonstrated the potential for content analysis to lead to human-automation design concepts through the generation of functional and information requirements, as exemplified through the analysis of voice transcripts of previous lunar landings which motivated the design of a futuristic lunar lander. As discussed previously, this application of content analysis to inform futuristic system design is valuable particularly when access to subject matter experts is limited or impossible, but is limited to those cases where the systems' functions have not changed in any significant manner. If system functions do not appreciably change between evolutionary (or even revolutionary) designs, this method could be applicable for generating requirements and improving the design of displays in a wide range of aviation fields, including military, space, and commercial applications.

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Table 1

Definition of Context Categories and Examples of Categorical Classification Exchanges

Context	Definition	Example
Schedule	Mission schedule, timing	"Falcon, Houston. You're Go at 2 minutes"
Vehicle / Mission Status	Status of spacecraft systems	"We're reading 87 and 85 in the fuel quantity"
Vehicle Position	Vehicle position, velocity or acceleration	"Altitude 4000 high. H-dot about 9 high"
Off-Nominal	Alarms or other emergency situations	"1201 alarm"
Miscommunication	Announcement of, and attempts to rectify, poor communications signals	"We've lost them. Tell them to go Aft Omni"
Acknowledgment	Reply to confirm that another statement has been received and understood	"OK"; "Copy that"
Personal	Non-task-related observations, humor, miscellaneous comments	"It's beautiful out here!"

Table 2

Top Three Significant Context Categories by Crewmember and Phase

Phase		CDR	LMP	CapCom
	1	Vehicle/Mission Status	Vehicle/Mission Status	Schedule
PDI	2		Vehicle Position	Acknowledgment
	3		Schedule	Vehicle/Mission Status
	1	Vehicle Position	Vehicle Position	Schedule
P64	2	Personal & Acknowledgment		Acknowledgment
	3	Vehicle/Mission Status		
	1	Vehicle/Mission Status	Vehicle Position	Acknowledgment
P66	2	Vehicle Position	Vehicle/Mission Status	Schedule
	3	Acknowledgment		Vehicle/Mission Status

Table 3

Vehicle/Mission Status, Schedule, and Vehicle Position Communication Frequency

Phase	Vehicle/Mission Status	Schedule	Vehicle Position
PDI	CDR = LMP	CDR = LMP = CapCom	LMP
P64	CDR	CapCom	LMP
P66	CDR = LMP	CDR = LMP = CapCom	LMP

Figure Captions

Figure 1. The Apollo three phase landing sequence

Figure 2. Number of exchanges by Phase and Crewmember across the six Apollo lunar landing missions.

Figure 3. Exchange context by crewmember during (a) PDI, (b) P64, (c) P66, across the six Apollo lunar landing missions.

Figure 4. Proposed lunar lander displays: (a) Landing Zone, (b) Situation Awareness, (c) System Status.

Figure 1

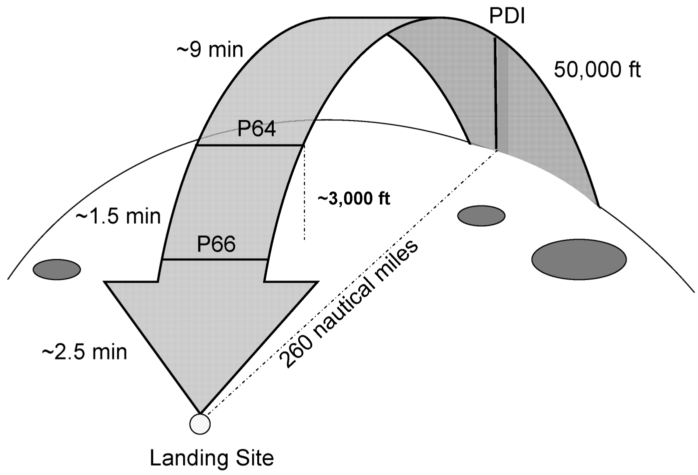
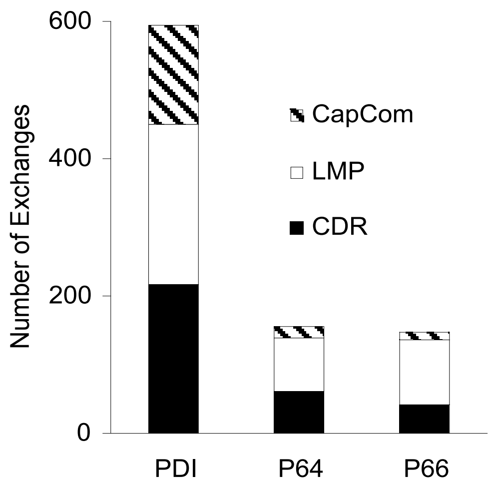


Figure 2



(Note: this Figure is intended to cover only 1 column in a 2-column page.)

Figure 3

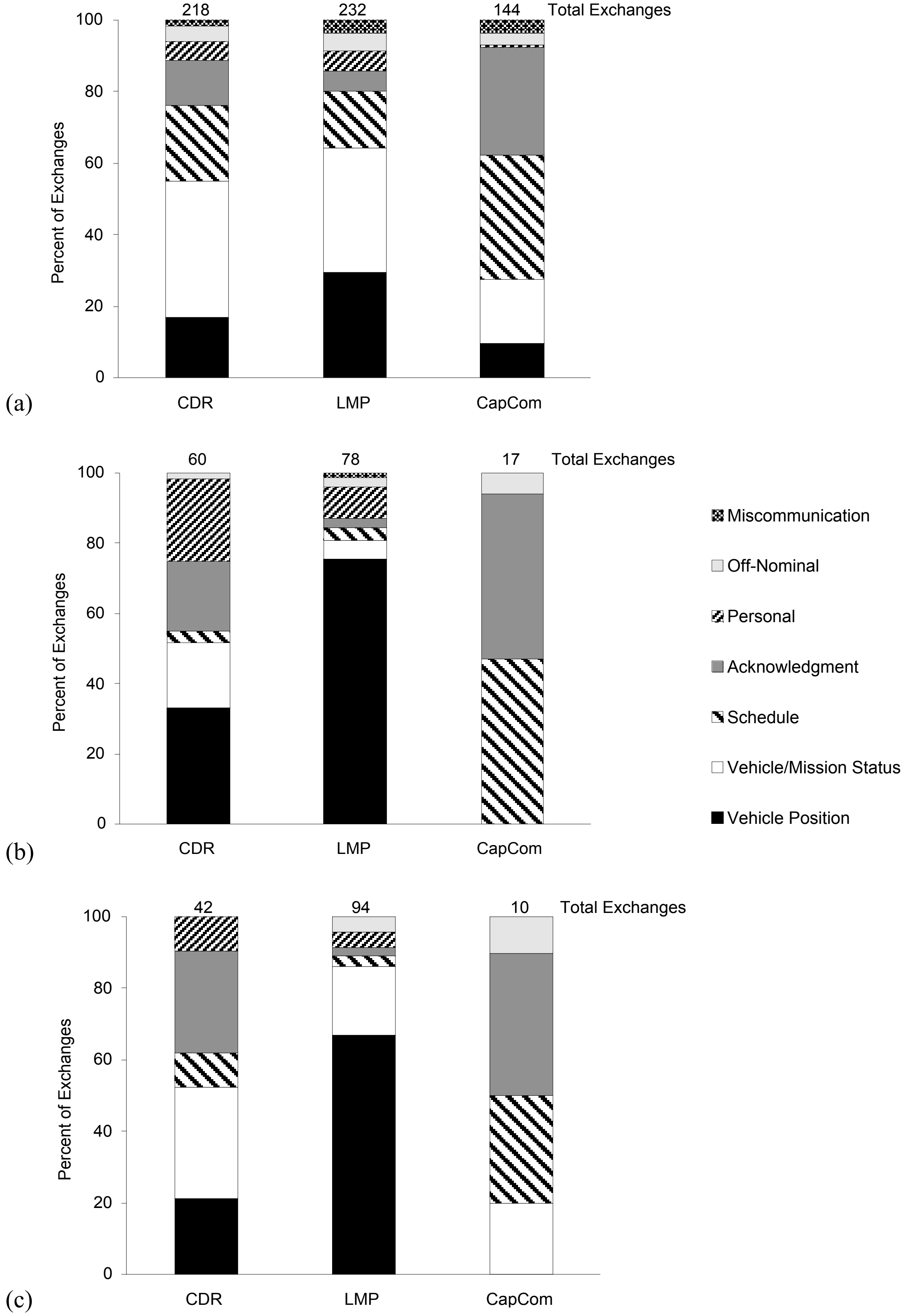


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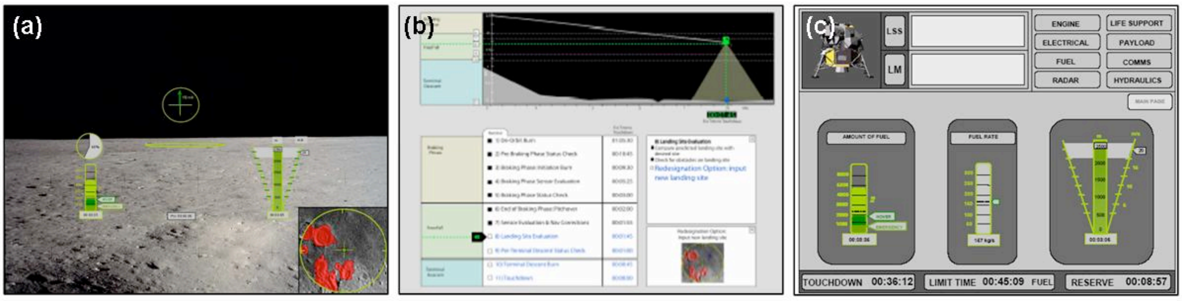
Figure 4



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