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Engineering Apollo

Crimson Team Final Report

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List of Acronyms

BIT…………………………………… Built in Test
CEV………………………………...Crew Exploration Vehicle
CommPro………………………….. Communications Procedure Crewmember
CRM………………………………. Crew Resource Management
CTE……………………………..….. Coefficient of Thermal Expansion
DSN……………………………….. Deep Space Network
ECL………………………………... Electronic Checklist
ESAS………………………………Exploration Systems Architecture Study
FAF………………………………... Final Approach Fix
GRC……………………………….. Glenn Research Center
HDA………………………………..Hazard Detection Avoidance
HF…………………………………. Human Factors
HGA………………………………..High Gain Antenna
IHASM……………………………..Intelligent Health and Safety Monitoring System
LIDAR…………………………….. Laser Imaging Detection and Ranging
LLTV………………………………. Lunar Landing Training Vehicle
LM…………………………………. Lunar Module (Apollo)
LOI………………………………... Lunar Orbit Insertion
LOX……………………………….. Liquid Oxygen
LP…………………………………..Landing Pilot
LPD………………………………...Landing Point Designator
LRO……………………………….. Lunar Reconnaissance Orbiter
LSAM……………………………....Lunar Surface Access Module
MBS……………………………….. Motion Based Simulator
MC……………………………….....Mission Commander
MCC………………………………..Mission Control Center
NAFCOM…………………………..NASA Air Force Cost Model
NTO/MMH…………………………Nitrogen Tetroxide/Monomethyl Hydrazine
OLW……………………………......Optimum Level Workload
PCHM………………………………Propulsion Control Health Monitoring
PDI………………………………….Powered Descent Initiation
RCS…………………………………Reaction Control System
SP………………………………….. Systems Pilot
VTOL………………………………. Vertical Takeoff and Landing

Introduction

At 22:54:37 UTC on 14 December 1972, the Apollo 17 Lunar Module, *Challenger*, lifted off from the surface of the moon. That was the last time humans visited the surface of the moon, or of any solar system body other than Earth. [1] After the termination of the Apollo program the U.S. concentrated its human space flight efforts on programs that remained in orbit around the Earth. Although there have been critics of the decision to abandon manned exploration of deep space, the policy held until recently. The event that brought exploration back into the forefront of human space flight was the tragic loss of the Space Shuttle *Columbia* on February 1, 2003. The Report of the Columbia Accident Investigation Board identified as one of the organizational causes of the accident, the "…lack of an agreed national vision for human space flight." [2]

In response to this deficiency the president set out a new vision for space exploration, in which he stated as one of the primary goals, "America will return to the Moon as early as 2015 and no later than 2020 and use it as a stepping stone for more ambitious missions." [3] Congress funded this vision in its 2005 NASA Authorization Act, and directed that, "The Administrator shall establish a program to develop a sustained human presence on the Moon, including a robust precursor program, to promote exploration, science, commerce, and United States preeminence in space, and as a stepping-stone to future exploration of Mars and other destinations. [4]

The decision to return to the moon was presented and justified in language that was as much emotional and political as it was rational in its reaction to the Columbia accident:

> Mankind is drawn to the heavens for the same reason we were once drawn into unknown lands and across the open sea. We choose to explore space because doing so improves our lives, and lifts our national spirit. So let us continue the journey. [5]

President George W. Bush's words evoke emotional and political reactions from across the spectrum, but despite any individual personal reaction, they are relevant because they have prompted policy, but more importantly the American public has accepted that policy. According to NASA, "In a Gallup poll, 68% of those surveyed support the new plan to return to the moon, then travel to Mars and beyond." [6] In a nation as diverse as ours, when over two thirds of the people agree on such a policy, it is clearly more than a political issue.

It is in this context that MIT's Team Crimson was tasked to present a study of the future lunar landing. Accordingly, this study will present a technical assessment of the engineering problem, while taking into account the larger social and political considerations raised above. The study will show that Team Crimson's plan not only meets the technical goal of enabling a sustained human presence on the Moon, but will also satisfy the political goals of promoting commerce and maintaining United States preeminence in space, as well as the goals of society including exploration that will further scientific knowledge and "lift our national spirit" by fulfilling the innate human need to explore.

Scope

The Team Crimson study for the lunar landing will begin immediately after Lunar Surface Access Module (LSAM) separation from the Crew Exploration Vehicle (CEV), and terminate after lunar landing and main engine shutdown or abort. It will also address relevant support functions, such as crew training, mission control, and communications support.

Goals

Unstated in the New Vision for Space Exploration are some inherent requirements of any plan to return humans to the moon. The tragedies of the space shuttle Columbia, Challenger, and Apollo 1 have highlighted the need to compensate for the dangers of human spaceflight. Also, budget constraints will be a reality during this program. Unlike the Apollo program, where the nation invested large sums of money into a big push to land on the moon, followed by budget cuts and program dismantlement, this program will need to be consistently compatible with budget limitations over a long period of time. Finally, related to safety and cost is the need to develop a program that will not be hampered by inconsistent or unreliable equipment or procedures. This will not only result in a safer program, but will help it to stay on schedule and within its budget. As a result, Team Crimson has established the following program goals. The program will be safe, reliable, precise, cost effective, and sustainable.

Assumptions

In order to consider only the lunar landing portion of the program, some assumptions about the overall program must be made. First, the mission is assumed to have a crew of four that will stay on the moon for seven days. To make this possible a habitation module will already be on the lunar surface adjacent to the planned landing site. A previous unmanned mission will preposition the habitation module. Other unmanned missions will also precede the manned mission, including the Lunar Reconnaissance Orbiter (LRO), which will provide detailed terrain data for use in navigation of the manned mission.

A further assumption is that the landing site will be at the south pole of the moon, near the edge of the Shackleton Crater. There are several reasons for choosing this site, including the following characteristics. This site receives sunlight during a very high percentage of the time, which allows for consistent use of solar panels for power generation, as well as increased light conditions for lunar surface operations. Because of the lower sun angle, the temperatures at the proposed landing site are more moderate than locations in more direct sunlight or in shade for extended periods. It also offers exciting opportunities for exploration. Besides the interesting terrain associated with large craters, there is evidence that water or other interesting geological features may exist there, which could be a factor in using the moon as a jumping off point for future interplanetary missions.

Finally, the CEV will be uninhabited while the crew is on the moon. This is a major difference from the Apollo program, where an astronaut stayed in lunar orbit in the Command Service Module. The Team Crimson plan has no requirement for human control of the CEV.

These overall program assumptions are consistent with the current NASA plan. Team Crimson has come to the same conclusions for many of the same reasons, the most important of which are detailed here. Further assumptions regarding specifics of the program will be addressed within this report in the applicable sections.

Lunar Landing Procedure Overview

Based on the overwhelming success of the Apollo program, the only program that has ever succeeded in landing humans on the moon and returning them safely to Earth, Team Crimson began this study using the Apollo procedure as a baseline. For comparison purposes, a brief overview of the Apollo procedure is included. [7]

The Apollo Lunar Landing Procedure

Apollo used a four phased procedure. The Lunar Module (LM) started in a 60 nautical mile (NM) parking orbit (deposited by the CSM). It conducted a Hohmann-type transfer to shift to an altitude of 50,000 feet above the lunar surface. At the calculated position, approximately

250 NM from the touchdown point, the landing procedure began with the powered descent initiation (PDI).

Phase 1 – Braking Phase. Program P63 ran, igniting the main engine for the braking phase. This decreased horizontal velocity over the surface of the moon, as well as allowing it to lose altitude. The target was a point called “High Gate” approximately 7000 feet above the lunar surface, and 4.5 NM horizontal distance from the landing site. During the braking phase the radar altimeter began tracking the lunar surface (~39,000 feet).

Phase 2 – Approach Phase. At High Gate the LM rotated so the astronauts could visually acquire the landing site. The 7000 foot altitude at High Gate prevented an optimal approach trajectory. At High Gate the LM transitioned to a series of guidance programs (P64 – P67) which allowed the LM to move to the designated landing spot using the Landing Point Designator (LPD) inscribed on the window of the LM, in conjunction with output from the computer which was verbally given to the astronaut controlling the craft. This phase ended at a point called “Low Gate.”

Phase 3 – Landing Phase. The landing phase began at Low Gate, an altitude of approximately 500 feet and a horizontal distance from the planned landing site of 2000 feet. This allowed the crew to locate a suitable landing site and maneuver the LM to the site for landing.

Phase 4 – Engine Shutdown Phase. When the probes attached to the LM’s legs contacted the ground, the engine shutdown. The astronauts completed the shutdown checklists.

Team Crimson Lunar Landing Procedure

The Team Crimson procedure is designed to leverage increases in technology and experience to yield a more capable and efficient landing procedure. It will be conducted in three phases, versus Apollo’s four. It will begin at a parking orbit of 100 km (~60 miles). [8] Due to better lunar terrain data and more precise navigation the LSAM will begin its PDI from an altitude of 10 km (~30,000 feet). Another improvement over Apollo, made possible by improvements in computer technology, is that the guidance and control will be a continuous program and will eliminate the rigid breaks in programs used by Apollo. Furthermore it will allow for continuous diagnostic tests to run in the background, and improved displays and electronic checklists will increase efficiency and effectiveness of the crew. This will allow mission control to assume the reduced role of passive monitoring of the landing operation under normal conditions. Finally, improvements in the spacecraft design, including composite materials, propulsion, and fuels will allow the Team Crimson landing procedure to drastically increase its payload capacity, and the percent of its weight dedicated to payload.

Phase 1 – Powered Descent Phase. At the initial altitude of 10 km (~30,000 feet), the guidance computer will command PDI at the position that will provide the most efficient trajectory, as calculated by the guidance computer. This powered descent phase will replace the braking phase and approach phase of the Apollo procedure. Instead of ending at a High Gate point this phase will end at a point designated as the Final Approach Fix (FAF), with an altitude of 100 m (~300 feet, vs. ~500 feet for Apollo). Video cameras and LIDAR / radar imaging, which will be discussed in detail later, will provide real time displays to the crew so no inefficient maneuvering will need to be done to provide visual acquisition of the landing site. Video displays will be positioned so that transition from video to direct visual tracking of the landing site will be smooth. This, and all other phases of the landing procedure, will be automated requiring no pilot input under normal conditions. Precision navigation will be provided using updated inertial guidance. LIDAR / radar imagery will be used to update the inertial guidance system. This will be compared with stored terrain data acquired on previous reconnaissance missions. Mission control will monitor the approach and landing via telemetry, but will not be required to provide input.

Phase 2 – Final Approach Phase. Upon reaching the FAF the LSAM will pitch to a vertical attitude for the final descent to landing. Updated automated guidance and control will allow for a more efficient decent to a precise landing spot, further decreasing fuel requirements. The “landing pilot” (the names and roles of each crewmember will be discussed in detail later) will monitor the approach and landing visually and be ready to take control and land manually, in the event of malfunction. Specific instrumentation and video displays will be discussed later.

Phase 3 – Engine Shutdown Phase. Upon touchdown the computer will perform all shutdown procedures except those involving the crew, such as unstrapping. Figure 1 gives a visual comparison of the two procedures.

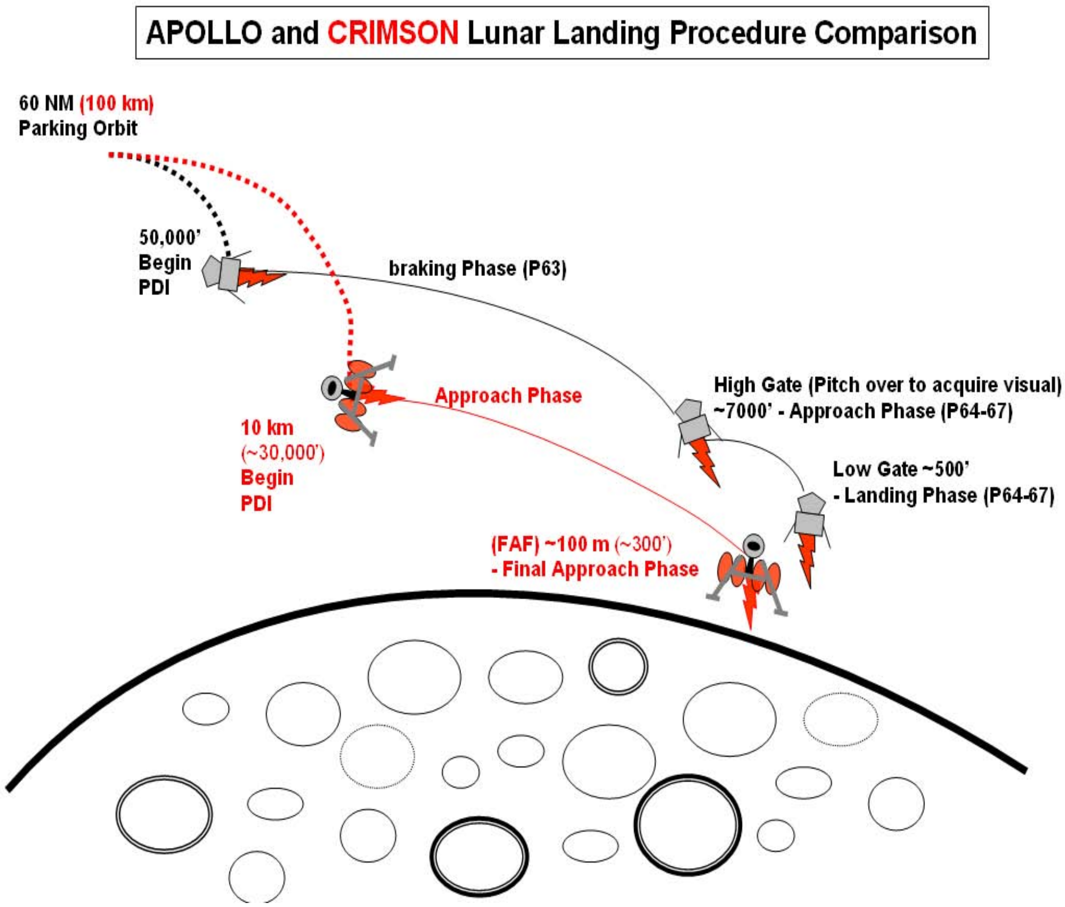

Figure 1- Comparison between the Apollo lunar landing (black) and the Team Crimson lunar landing (red)

Baseline Lunar Architecture: ESAS LSAM

A new vision for space exploration means a complete overhaul of the design of the lunar lander from its original inception over 40 years ago. Now, the lander must be designed with a maximum payload to allow a greater number of sustainable components and experiments to further knowledge of the lunar environment and, ultimately, space exploration. The design of the Crimson LSAM is in many ways different from the Apollo lunar lander, as it incorporates many different kinds of new technology, ranging from propellant to structure. Different designs were considered as a baseline for the Crimson LSAM; the team decided to baseline its design from the minimized ascent conceptual design presented in the November 2005 NASA Exploration Systems Architecture Study (ESAS) final architecture report. This report reflects results of a 90-day study from May through July, with intentions to "define the top-level requirements and configurations for crew and cargo launch systems to support the lunar and Mars exploration programs [14]." Team Crimson decided to model the lander after a conceptual design that the ESAS report did not ultimately recommend. Therefore, although the overall lander height and mass Team Crimson proposes are not very different from the one proposed in the ESAS report, there are significant differences in most of the lunar architecture components, as illustrated in Figure 2 below.

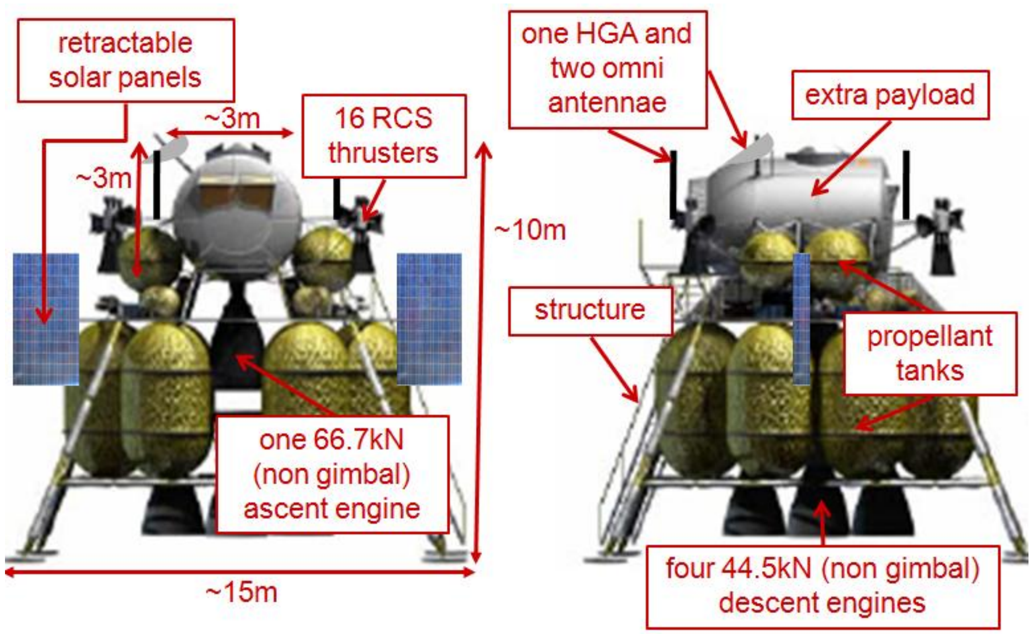

Figure 2 - LSAM Architecture

The LSAM is certainly larger than the Apollo LM, reaching approximately ten meters in height and fifteen meters across its base, with a four to four-and-a-half meter descent stage propellant tank height. The ascent stage, meant to be minimized, is approximately three meters in height.

Almost all of the components that make up the LSAM architecture utilize new technology that was not available during the Apollo missions. These components will be written about in greater detail later in this subsection. This section will discuss new propellants used in the descent and ascent main engines, as well as a four-quad system of independently throttleable reaction control system (RCS) thrusters to ease the control system of the LSAM. One high gain antenna (HGA) and two omni antennae are used to communicate within the LSAM and back to Earth, and the combination of retractable solar paneling and batteries provide the LSAM power.

Finally, composite materials are used to provide a strong LSAM structure without increasing its mass. These systems are used interchangeably in order to provide the LSAM with a payload nearly five times as large as Apollo's payload. The bottom line, therefore, is that the new technology utilized in this design allows for a larger payload to sustain operations on the moon. This payload will allow the United States to take a giant step forward in space exploration as more experiments to better understand the lunar environment can now be performed in a shorter amount of time and taxpayer dollars, thus meeting the team's goals and fulfilling the new vision for space exploration.

Initial Mass Estimate

Our design goal of maximized descent stage payload mass was pursued by taking off masses from each structural component and counting the reduced masses as additional payload mass. Normally, mass estimate of a spacecraft structure is based on mass and volume requirements of the payload. However, in this design process, maximization of the payload mass was desired, and thus the initial reference mass was the total lunar module mass (decent +ascent stages), ~49,000kg, calculated assuming the launch vehicle and trajectories mentioned above in the section titled Baseline Lunar Architecture. Heavily based on ESAS LSAM design, the minimized ascent stage mass was estimated as ~8,000kg, assuming 0kg of non-human cargo [22], leaving the total descent stage mass as ~41,000kg. With the lunar landing trajectories to be described in the Trajectory and Approach section below, the descent stage propellant was estimated as 30,000 kg (~71% of the total descent stage mass). This propellant mass fraction to the total mass was decreased compared to the Apollo descent stage (8165kg, ~80% of the total descent stage mass) with our much steeper landing trajectory (see Trajectory and Approach) [22]. To further increase the payload mass, more masses should be taken off from other components, and thus it was important to study mass fraction of each component. The mass breakdown of the

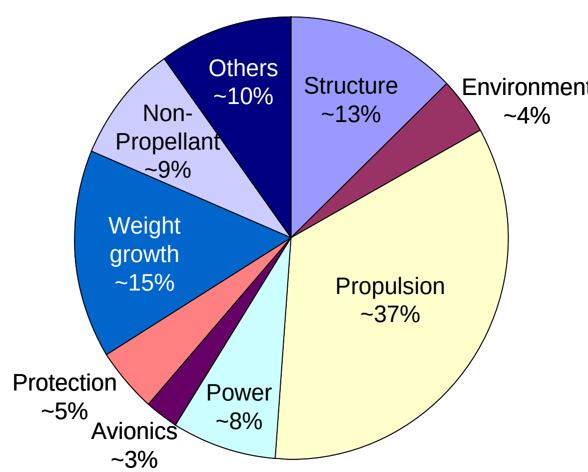

Figure 3 - Mass breakdown of LSAM descent stage dry mass [22].

LSAM is shown in Figure 3 [22]. Two distinct fractions are structure and propulsion components that account for 13% and 37% respectively. Considering these components are mostly structural to support the massive lunar module, usage of stiffer but lighter materials substituting traditional structural materials was suggested later in the Structures section below. Other large fraction components, such as weight growth, non-propellant (cooling waters etc.), or power, are harder to modify: the total mass that decides the weight growth is set to optimize the payload mass, and because the electronics device masses that largely decide non-propellant and power components are already optimized over 40 years since the Apollo project, along with their precision. In the following section, individual components of the structure will be discussed in details focusing on their mass as well as their reliability and sustainability.

Components of the Lunar Modules

Propulsion

Team Crimson designed the LSAM with a very innovative propulsion system. From the propellant type to the concept of independently throttleable RCS thrusters, Team Crimson is at the cutting edge of space propulsion technology. The overall descent and ascent stage propellant options are listed below.

Table 1 - Propellant Choices

	Descent Stage	**Ascent Stage**
Main Engine Quantity/Thrust	4 / 66.7kN	1 / 44.5kN
Propellant	Pump-fed LOX/H2	Pressure-fed LOX/CH4
Mass Estimate	~ 29,500 kg	~ 3,500 kg

According to the ESAS report, the combination of the above thrust and propellant used will sufficiently meet (and exceed) the delta-V necessary to land on the lunar surface and propel itself for redocking. The combination above for the ascent stage can perform up to 1,866 m/s of main engine. The descent stage combination can perform up to 1,100 m/s of lunar orbit insertion (LOI) delta-V while still attached to the CEV and can perform up to 1,900 m/s of delta-V as it descends to the surface [14].

The LOX/H_2 propellant was chosen for its great performance and reasonable cost, and is also the current choice for NASA's next lunar LSAM. It shows superiority over the propellants used for the Apollo LSAM's descent stage, as its specific impulse is significantly higher than even the LOX/CH_4 propellant chosen for the ascent stage [15]. The propellant is fed through RL-10 descent stage engines. These engines were chosen because they have already proven themselves as throttleable engines that can produce the high thrust numbers necessary to land such a fairly weighty LSAM.

The LOX/CH_4 propellant for the ascent stage was chosen for a number of reasons, ranging from reliability to best integration with the throttleable RCS system (to be discussed later in the paper). Although it has a lower specific impulse than its main competitor, LOX/H_2, the impulse is still fairly high, at 374 seconds [15], and its impulse is certainly higher than other storable propellants (another close competitor was nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) with a specific impulse of 340 seconds [16]). However, one of Team Crimson's project objectives is to maximize payload to the moon, which ultimately means minimizing the ascent stage to the greatest degree possible. For this reason, LOX/CH_4 was the clear winner over the LOX/H_2 propellant: this newest liquid rocket propellant boasts a bulk density of $800 kg/m^3$, compared to LOX/H_2's bulk density of $360 kg/m^3$ [15]; LOX/CH_4 can therefore package nearly 2¼ times more propellant than LOX/H_2 using the same amount of space. This observation was confirmed in an analysis performed by the NASA Glenn Research Center (GRC). The GRC performed a study on the overall mass and power extraction for various propellants (such as LOX/CH_4, LOX/H_2, and MMH/NTO) and the LOX/CH_4 propellant had the lightest mass system [14]. Finally, the LOX/CH_4 propellant has a higher reliability than the LOX/H_2 propellant for the RL-10 engine family: 0.997 to 0.996, respectively [17, Figure 64].

The independently throttleable RCS system also had a significant influence on the type of propellant choice to use for the ascent stage. Besides its non-toxic and non-corrosive properties, CH_4 also has a high boiling temperature (110K, compared to liquid hydrogen's 20K boiling point [15]). This is crucial to its use in the RCS system, as the thrusters will need to be actively cooled because of their continual use. A higher boiling point will help alleviate this risk in the RCS design. Additionally, this propellant use in the RCS system has a higher reliability than using a similarly-fed LOX/H_2 propellant: 0.998 to 0.995, respectively [17, Figure 69].

Perhaps the most innovative, but riskiest, component of Team Crimson's propulsion design is the design of the RCS system. This LSAM utilizes sixteen independently throttleable RCS thrusters in an effort to improve the control system and decrease mechanical complexity. There are three main reasons why this innovative concept is utilized:

1. The control system will now be able to respond to error as necessary
2. The control system will be able to scale gains as a result of the instantaneously changing LSAM mass
3. Gimbal elimination results in a structural mass savings for, and smaller structural stress placed on, the LSAM

This section discusses the above three advantages in detail. It also discusses the current status of the technology, as it is currently not available in production today.

Error Response: Using a fixed position main engine in concert with throttleable RCS thrusters allows the main engine to be used for large trajectory corrections and reserves the RCS system for orientation correction. Due to the magnitude of the main engine impulses, it would be difficult to use the main engine to make small corrections without inducing new error. By using a throttleable RCS system, the control system will be able to correct for current error in a continuous manner as opposed to an impulsive manner. This ability will make the controller more robust to error which will improve landing accuracy and help ensure Team Crimson's goals regarding landing precision.

Continuous Scaling of Gains: The control system is designed such that system gains will continually be scaled based upon system feedback. A throttleable RCS system that can respond to feedback by simply changing the gains will be more responsive than one that must respond to feedback by issuing new commands as in the case of a throttleable main engine.

Structural Mass Savings: According to a technical memorandum NASA published during the days of Apollo, each RL-10 descent engine's gimbal system has a mass of about 33 kg (approximately twenty-five percent of the engine's 131 kg dry mass) [18]. Removing this system entirely from the Team Crimson LSAM frees up 132 kg of mass. Additionally, elimination of the gimbaling system from the ascent main engine will also free up additional mass (scaled proportionately to the RL-10 engine based on thrust alone, the gimabling system of the ascent engine therefore has a mass of 22 kg). Elimination of the entire gimabling system therefore frees up over 150 kg. This also significantly reduces the structural stress of the LSAM due to its now less impulsive state. A twenty-five percent decrease in structural mass is proportional to that amount of loss in force on the LSAM. Simply put, stress is proportional to force, so it will experience an equivalent amount of structural relaxation.

This technology is not yet available for the next manned lunar landing mission, but Team Crimson has taken great thought in how such a system would perform. As mentioned earlier, the use of LOX/CH4 as the RCS propellant allows for higher reliability of the system as well as less insulation necessary to continually cool the system due to its high boiling point. The propellant would be fed through a Rockwell SE8 family engine. This engine was chosen because it has, in its design, an ablative cooling method [16] where cooler gases flow over the engine wall surface and lower the boundary layer temperature to help cool the system. This technology has actually been proven effective as it was used for the Apollo command module thrusters. The system would also have to utilize some sort of active control of combustion instabilities, which is already feasible on small engines [19]. According to Frank Lastrina, design engineer of aircraft engine combustion modules at General Electric Aircraft Engines in Lynn, MA, this sort of control would utilize "an AC fuel oscillation on the DC fuel flow with the intent to have the fuel flow oscillation and the heat release associated with it, out of phase with the pressure oscillation. This theoretically would cancel out the base instability" [20].

Since the days of Apollo, throttleable engine technology has been used more and more often, thus improving its reliability. Keep in mind also that the first time these throttleable engines were used on an LSAM, they performed without fail (during the Apollo moon missions). The concept is tried and true. Forty years later, it is possible to take this technology to the next level and develop it for use on RCS thrusters. The combination of LOX/CH_4 and the Rockwell SE8 engine make this concept all the more possible. Throttleable engines have proven their worth as evidenced in the Apollo missions, and the active controlling necessary to turn this developmental technology into production technology have already been utilized in small engines. A study into throttleable engines for a larger thrust range were also studied in 1993 [21] but unfortunately the study was cut short due to funding termination. Yet the conclusive results of the study thus far indicated that, although there is no performance advantage to such a system compared to pulsing engines, there is also no performance disadvantage. For all the reasons mentioned in this paragraph as well as having a comfortable ten-year timeframe to develop the technology, Team Crimson highly recommends further study into this innovative concept as its payoffs would be tremendous in terms of control and structure mechanics. The United States would be the first nation to produce this new space technology; it would help meet the goal to firmly establish the nation's preeminence in space.

Communication

The radio communications equipment carried by the LSAM will be based chiefly on the following principles: Compatibility with existing NASA communications infrastructure and ability to handle a higher data rate than the communications hardware onboard the Apollo LM.

LRO's need for high data rate transmission prompted NASA to construct a new 18-meter parabolic antenna at White Sands, NM (station WS1) [56]. This antenna is designed primarily to support LRO's S- and Ka-band command, telemetry, and data requirements, as well as to augment the Deep Space Network (DSN) when not being used for LRO support. By specifying the LSAM's radio loadout to be compatible with this station, we will also ensure that the communications architecture will also be compatible with the 26-meter (and larger) dishes of the DSN, which were built for Apollo. Utilizing this existing infrastructure will negate the need to invest large amounts of money in new ground antennae.

Onboard the LSAM, there will be one 1.25-meter parabolic dish antenna (mounted on top of the ascent stage), and two low-gain omni antennas (one on either end of the ascent stage), all driven by a 50 watt transmitter feeding a three-way multiplexer (allowing simultaneous transmission on all three antennae, though not at full data rate). Like LRO and the Space Shuttle, low-data-rate communications will be on the S-band (~2.4GHz), and high-data-rate one-way transmissions will be on the Ka-band (~20GHz). Use of these bands, in particular, serves to further ground our communications architecture in existing, well-known, reliable hardware.

The dish antenna is sized to allow a 100Mbps data connection to the 18-meter WS1 antenna [21, Section 13.3]. This data rate will allow a single high-quality broadcast video channel (94.5 Mbps), as well as 5.5 Mbps of buffer [31, Section 13.2], which may be used to downlink a variety of other data (digital photos, science data, etc.). Having this high-quality video channel will greatly support the mission goal of "lift[ing] the national spirit", as a major aspect of obtaining public support is providing engaging visual material of the mission.

As a result of this design point for the dish antenna size, it is also large enough to support the required 192kbps data uplink/downlink rate required for 2 voice channels, and 1 telemetry and command channel (3 channels at 64kbps each) [31, Section 13.2]. While two voice channels are required more for extra vehicular activity (EVA) activity than the actual landing, it is important to take into consideration this down-mission requirement, as it affects hardware design for items used during the landing itself.

Navigation

A set of navigation tools for our lunar module design include gyroscopes, star finder, LIDAR, radar altimeter, and accelerometer. The latter three devices will be used intensively for landing operation. The selection criteria of these devices will be explained in the Trajectory and Approach sections below. To ensure safe landing from ~100km lunar orbit, improved lateral accuracy (~10-100m) and high vertical accuracy were required. As briefly mentioned above, the navigation devices were improved in precision, and were miniaturized for the past space projects such as Clementine multi-spectral lunar imaging mission or Hubble telescope mission. Those commercially available products are light. For example, a star tracker [23] and an accelerometer [24] weigh less than ~1kg respectively, and a gyroscope [25] weighs ~20kg. Radar altimeter and LIDAR devices have been improved also through space missions since the Apollo time, including missions to obtain lunar surface topography such as Clementine (1994-) [26] or earth-based interferometry (1997-) [27]. While satisfying the resolution requirements specified above, the LIDAR used for the Celmentine mission [28] weighs ~7kg. The radar altimeter used for GEOSAT weighs ~25kg [29] with precision of 0.035m, compared to the radar altimeter used in Apollo landing with ~19kg but with precision of 10m [30].

Table 2- Comparison between possible space structural materials in terms of specific strength and CTE [31, 32].

	Al (2219-T851)	**Steel (17-4PH H1150z)**	**Titanium (Ti-6Al-4V)**	**Composite (P100/6061Al)**
Ultimate tensile stress/ density [kPa/(kg/m^3)]	**147.4**	**109.4**	**203.2**	**362.0**
CTE [10^{-6} /K]	**22.1**	**11.2**	**8.8**	**-0.49**

Structures

New material was sought to replace the traditional metals in the structure and propulsion (propellant tanks etc.) components. These components are required to be strong enough to carry the spacecraft/propulsion masses through accelerations/impacts during launch and landing. To effectively compare the performance of materials, two parameters were chosen: ratio of strength to density, and coefficient of thermal expansion (CTE). High strength to density ratio is desired

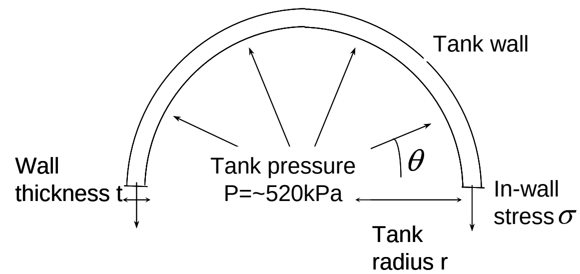

Figure 4 - Schematics showing equilibrium between propellant pressure and in-wall stresses.

for strong but light structure, and low thermal coefficient of expansion is the key to minimize the structural fatigue on the lunar surface with high temperature variation. Four materials are compared for their performances in Table 2 [31, 32]. Aluminum and steel are two often used materials in the structure, but they are not optimal since the CTE of aluminum is high and steel is heavy. Titanium (Ti) gives better performances than these two metals, but the cost is high. At the very right of the column is a metal-matrix composite that consists of P100 graphite fibers and 6061 aluminum matrix. The composite's specific strength is almost twice that of titanium with its fiber reinforcements. Unlike polymer-matrix composites, these materials will endure manufacture/assemble process including joints taking advantage of ductile and strong metal matrix. The CTE is almost negligible, incorporating two different CTEs of the metal and the fiber. The composite P100/6061Al has been employed as antenna booms in the Hubble Space Telescope structure, and confirmed to be space-qualified [32].

Mass saving by substituting the current Al with this composite was preliminary estimated as following. Since the composites have higher strength in tension, the composite was employed in propellant tanks (1m radius, 4.5m height). The tank walls will always experience tension due to the inside pressure (75psi = ~520kPa [22]). Required thickness to hold the pressure was calculated by equating the in-wall stresses (as the tensile yield stress with safety factor of 1.5) with the inside pressure as shown in Figure 4:

$$\int_0^{\pi} pr\sin\theta d\theta = 2t\left(\sigma_{yield}/1.5\right)$$

The total mass of the 8 tanks are calculated as ~600kg with Al, while that for the metal-matrix composite was ~240kg decreased by ~60%. Assuming that one-third of the structure should be replaced with this composite, with the rest left as the current metal for joint strength, manufacturing, or cost performance, the mass reduction in the structural/propulsion components was estimated as ~-20% of each component.

Other Systems

In addition to the listed components above, further investigations on other components such as thermal management or power will be appropriately pursued for the descent stage to stay functional for long on the lunar surface. As for thermal components, extra care to keep the devices' operation temperature of 5-25^{o}C will be taken with proper (possibly active) shielding from heat sources such as solar radiation, reflections from Sun/Moon/Earth, and energy from electrical devices on board [31]. As for the power, combination of battery and solar panels will be employed for sustainable supply and storage on the lunar surface.

Improvements from Apollo Structure

The mass estimate and payload mass were re-estimated accordingly with the studies shown above based on the assumptions, LSAM [22], and some historical data [31] (see Appendix B for details). The propellant and payload masses and their fractions to their total descent stage mass are shown in Table 3, and compared with those of Apollo [33]. The total payload mass was increased by ~470%, and the mass fraction of the payload to the total descent stage mass increased from 9% to 13%. The total payload mass was estimated as 5211kg.

Table 3 - Comparison of the propellant and payload masses and their fractions to the total mass of Apollo and Crimson descent stage.

	Apollo (14,690 kg)		**Crimson (49,100 kg)**	
	Mass	**Mass Fraction**	**41,347kg**	**Mass Fraction**
Propellant	8,165 kg	81%	~29,537 kg	71%
Payload	907 kg	9%	~5,211 kg	13 %

Guidance, Navigation, and Control

For the Apollo missions, it could well be argued that the most difficult aspect of the landing was precision. In the Apollo project, the landing trajectory was dictated by the pilot's need to have a visual of the landing location. This constraint and limited knowledge of the topography of the moon resulted in successful, but imprecise landings. While the guidance computer and software developed for Apollo was in every way revolutionary, technological advances since then will make it possible to develop a navigation and guidance system that can ensure a safe, reliable, and precise landing.

Three areas need to be addressed in order to ensure a precision landing. The first of these is navigation. A precision landing not only requires that the landing location is known, but also that the position of the spacecraft is known. Since the spacecraft position is constantly changing, a system needed to be developed that would be both quick and accurate. The other two areas of interest are guidance and control. Once the current position and desired landing location of the spacecraft is known, an optimal trajectory needs to be calculated. In order to orient the spacecraft with the desired trajectory, a controller needs to determine what the corresponding main engine and RCS thruster settings should be. Since each of these subsystems relies on information from the others, they also had to be designed such that they could communicate with one another.

The combined guidance, navigation, and control system was developed based on the concept of state space design. Using this method, the spacecraft dynamics were described using a position state vector and an orientation state vector. The position state vector consisted of the latitude, longitude, and attitude of the spacecraft and the velocity components in the three body axes directions. The orientation state vector consisted of the attitude orientations and angular rates of the vehicle. Each of the three independent subsystems are able to perform their respective tasks and communicate to the other subsystems using the two state vectors. By working together, these subsystems then create an overall system that is constantly monitoring and adjusting the position and trajectory of the spacecraft to ensure a precise landing. A graphical overview of the guidance, navigation, and control system can be seen below.

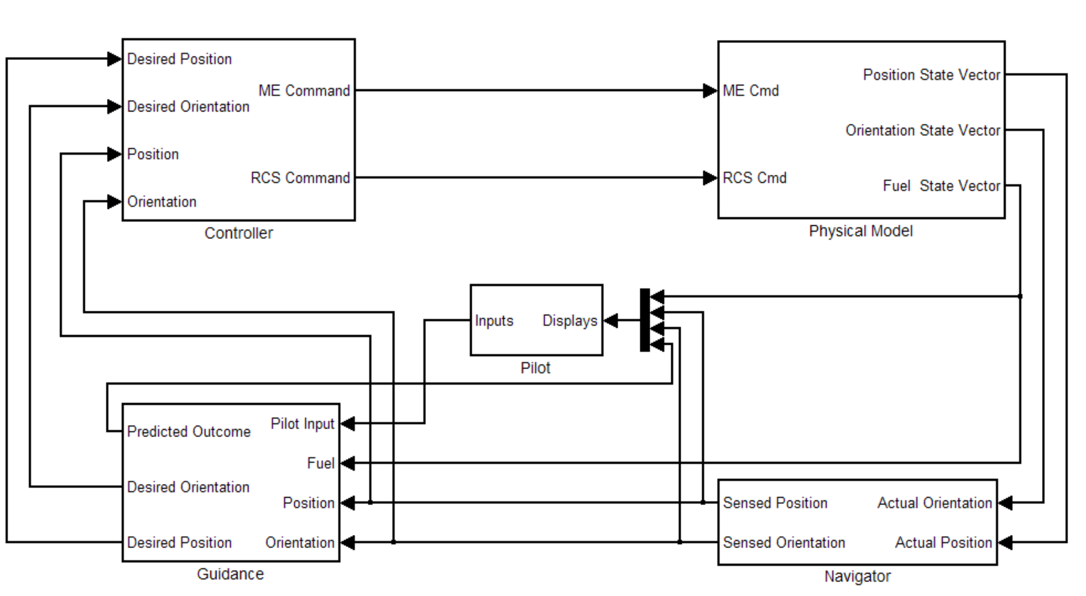

Figure 5 - Guidance, Navigation and Control System Overview

It is important to take note of the center pilot block. While the system was designed to be completely autonomous, it was also realized that in certain circumstances it may be desirable and/or necessary to have pilot input. For example, a pilot may decide that a landing location is unsuitable due to rugged terrain, and therefore would need to change the landing location. Therefore, the system also has the ability to incorporate a human in the navigation and landing process.

A system that can be both autonomous and manually controlled provides many advantages. An autonomous landing will be crucial to a sustainable presence on the moon or Mars for that matter. In order for habitations to be built and maintained many supplies will be necessary. An autonomous landing capability will permit cargo vehicles to land without having a dependency on human/pilot availability. The human absence will allocate more room for cargo which will result in cost savings in the long run. However, having a pilot when necessary or desired will allow humankind to become part of the space exploration process which will not only lift national spirit, but also enhance the thirst for greater scientific understanding and more technological advancements.

Navigation

The state vectors used in the guidance and control software are provided by a combination of sensor measurements. Ring-laser gyroscopes and solid state accelerometers will measure angular rates and vehicle velocities respectively. An autonomous star finder will be used in determining orientation and position. Radar and LIDAR will also be used in determining position and velocity. More than one sensor will be used when determining a certain parameter to provide redundancy and accuracy. For example, accelerometer measurements will become inaccurate due to drift rates. This will result in errors in the sensed position of the spacecraft, but these errors can be corrected through the use of multiple sensors. In regions where LIDAR is known to be extremely accurate, the position of the spacecraft based upon LIDAR measurements can be compared to those from the accelerometer to determine possible errors due to drift and appropriate adjustments can be made to correct for this error. In order to compensate for the limitations of each sensor, filtering is also used on all of the devices. From the combination of all sensor measurements, new position and orientation state vectors are calculated and then fed into the guidance system. An overview of the navigation system architecture is included below.

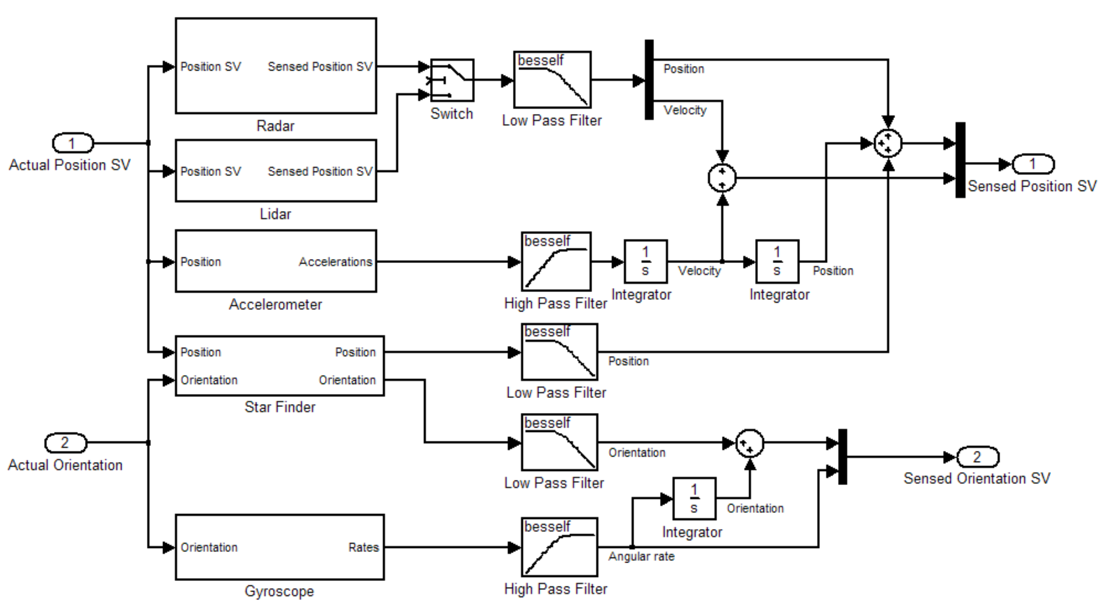

Figure 6 - Navigation System Overview

Guidance

The guidance system uses real-time state information to generate a plan for the remainder of the landing phase. The system contains a set of commands to provide a fuel optimal descent trajectory for the spacecraft. Every several seconds, the guidance computer uses a model of the physical system to predict the future path and end state of the vehicle based upon the forces and moments acting on it. This information is fed into a decision matrix which evaluates whether the commands provide the most efficient solution. If the commands do not provide the most efficient solution, then they are re-evaluated. Otherwise, the commands are passed to the controller. An overview of the guidance system is shown below.

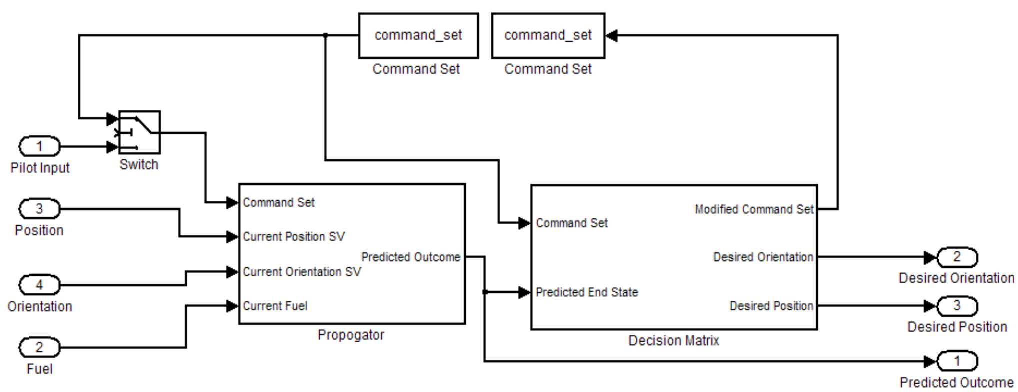

Figure 7 - Guidance System Overview

Controller

The controller compares the position and state vectors from the navigation block with those from the guidance block and determines what the corresponding main engine and RCS thruster commands need to be in order to reach the desired position. For example, if the actual altitude of the spacecraft is lower than what is desired in order to reach the landing position, the controller can signal the main engine to provide more thrust in order to increase altitude. The main engine will be used to provide major course correction and changes to the trajectory. The RCS system will be entirely responsible for changes in orientation and may be used as a fine adjustment to position and trajectory when required, or when small changes in trajectory must be made without changing the orientation of the vehicle, as in the final landing phase. Feedback is used to adjust controller gains and maintain an active model of the system response. An overview of the controller is shown below.

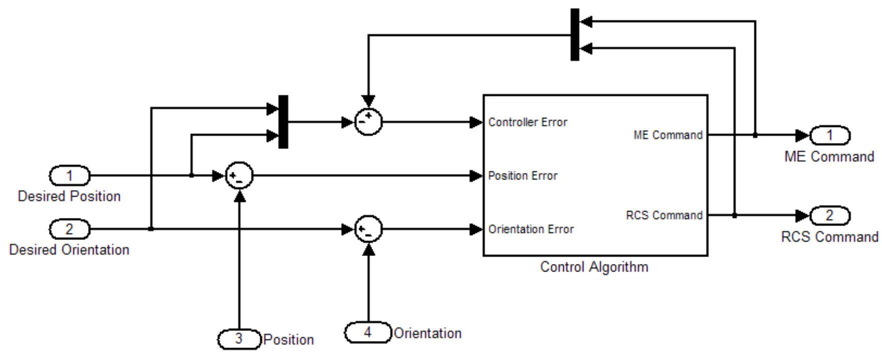

Figure 8 - Control System Overview

More thorough topographical information and advances in both hardware and software capabilities since the days of Apollo will make it possible to develop a high-speed, real-time, reliable, and robust guidance, navigation, and control system that can ensure precise and efficient landing operations regardless of initial starting conditions or unforeseen events that may necessitate sudden changes to be made in the landing location or trajectory.

Human presence on the moon offers numerous opportunities for scientific exploration and discovery. While much of this was able to be accomplished during the Apollo missions, the radius of exploration was limited by where the astronauts could land and how far away they could venture from the lunar lander. A more precise guidance, navigation, and control system will expand the arena of exploration by allowing the astronauts to land in new places that were previously unfeasible due the imprecise nature of the guidance system. The sustainability of the lunar program will be eased by the fact that all of the hardware and software needed for this system has already been developed. Similarly, there will also be minimal cost associated with development and with software verification and validation. The fine-tuning of this system throughout the lunar landing project will help the United States be better prepared to venture to places in the vast frontier of space that will require even greater autonomy and precision.

Trajectory and Approach

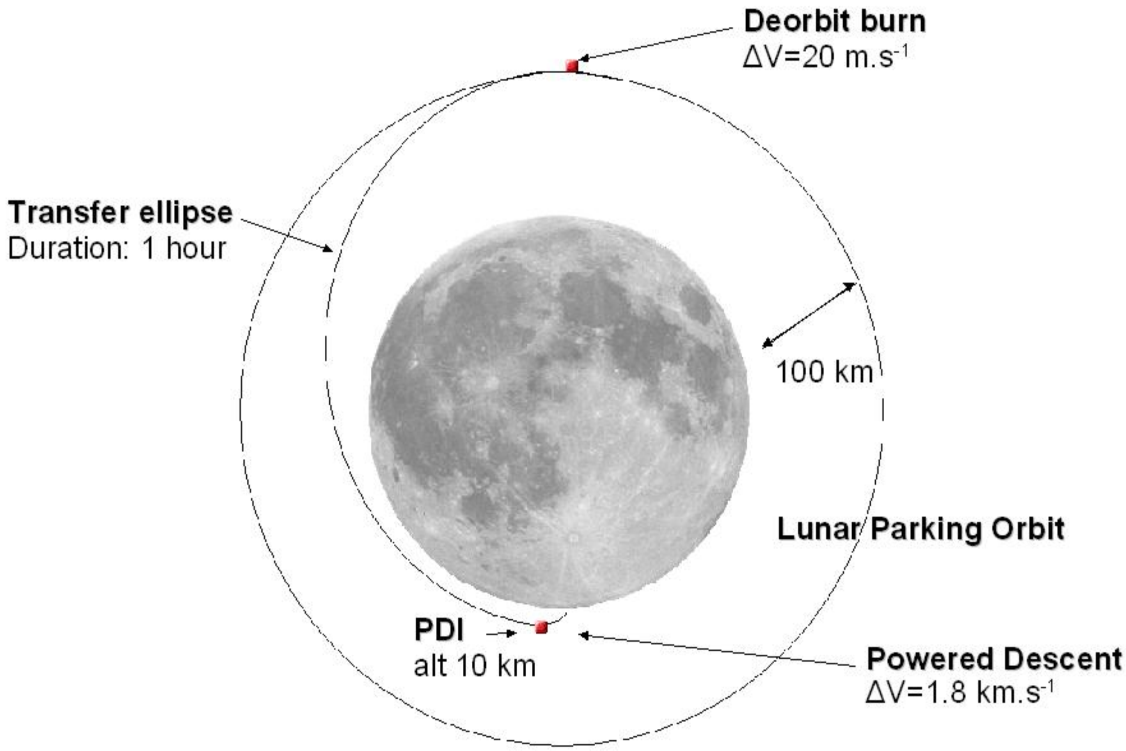

Figure 9 - Orbital Trajectory

The lunar parking orbit is a phase when previous navigation errors are canceled. All systems can be checked before deorbit burn. Using ground telemetry and/or start tracking, initial measurements could be taken in order to refine computer estimation of location with respect to the lunar features. Any problem or uncertainty would be much harder to account for in a direct descent from interplanetary transfer orbit.

At a location close to above the North pole, a deorbit burn places the Lunar Lander on an elliptical trajectory with a perilune 10 kilometers above the South Pole where PDI is to occur.

One important event before PDI is the moment when the lander acknowledges where it is with respect to lunar features. Recent missions such as Clementine [52] have shown that LIDAR technology will allow the lander to acquire this information before PDI. Using the 10-meter precision LRO maps, the computer will recalculate the 3D trajectory. Doing this so early in the trajectory will allow this recalculation to have a limited impact (if any) on fuel consumption. For example, if the computer realizes that the trajectory is short, it will initiate powered descent later. This would be impossible with radar technology. Even using centimeter wavelengths, the size of the dish would have to be superior than 10 meters in order to have a 10 meter precision at a 10 kilometer altitude. Indeed, lambda/Diameter < 10^{-3}.

The precision that was achieved in the Apollo 12 mission, the progress that has been made in control theory and the increased knowledge that we have of the topographic and gravitational environment around the moon thanks to the LRO mission leads us to think that achieving 10 meter accuracy automatic landing is easily achievable.

The LRO mission is expected to bring sub-meter resolution maps of the landing area near the rim of the Shackleton crater. Between the altitudes of 200 meters and 30 meters, the LIDAR and cameras will establish where the hazards such as boulders, small craters and previous landed infrastructures are with a 10 centimeter resolution.

Using this assessment the computer will designate a landing site inside a safety circle with a 10 meter diameter which will contain no hazard. The pilot will be able to confirm the site or choose a new one. The order of magnitude of the distance between two landing zones will be 10 meters.

The rest of the trajectory is a totally automated vertical descent, except for the potential correction. At an altitude of 30 meters, the lander will be above the safety circle. From there, during the last 15 seconds, hazards such as small craters (that would be outside our safety circle anyways) will not be visible anymore. Indeed, Apollo 11 and 12 both witnessed the "first signs of dust at about 120 feet [or 36.5 meter] altitude."[53]. Apollo 11 could actually see features until the last moment, whereas during the Apollo 12 mission the features disappeared completely at an altitude of 12 meters. Taking the rather conservative height of 30 meters for feature disappearance still does not have any impact on the safety of the landing. If future LIDAR missions continue to be successful, the cost and weight of an additional radar would not be worth the redundancy and safety that it could provide.

Human Factors

The social, political, and engineering environments of today form a context for lunar lander designs, and the legacy from Apollo will inevitably play a role in design decisions. Although the original Apollo missions did contain some automation, the main design decision for the next generation lunar lander Human Factors (HF) systems is the role of the computer as a fifth crew member. Advances in automated systems have made them more robust, and thus has lead to greater reliance on and trust in automated systems. Although there has been a heritage of manual control of spacecraft up through the Space Shuttle program, these traditions have begun to phase out with the continual operations on the International Space Station, and will continue to do so with the introduction of the Crew Exploration Vehicle's Apollo-style re-entry. With the continued increase in automated systems in flight and spaceflight regimes, astronauts flying the lunar lander in 2020 will be very well acquainted with automated systems, as they will have interacted with automated systems in various applications over the first part of the millennium. By having automation as a fifth crew member who is primarily in charge of the lunar landing, the crew will experience less workload during the landing, and there will be more flexibility for human crew to have diverse non-pilot backgrounds. Thus, scientists, engineers, and others may go to the moon and conduct research and exploration activities, thus being able to further scientific knowledge and exploration goals.

Automation

To understand how the human operator can best complement the lunar lander systems, automation levels for the design must first be selected. Automation here is defined as any function which a "system…accomplishes (partially or fully)…that was previously, or conceivably could be, carried out (partially or fully) by a human operator" [44]. To capitalize on the human operators' and computer's best attributes, Fitts' list notes that computers have larger capacities for information storage and excel at tasks requiring speed, consistency, and repetitive actions. In contrast humans have superior abilities to exercise creative reason and to perceive emergent events or patterns [46]. Tom Sheridan diagrammed various levels of human and computer interactions with manual control at one extreme and full autonomy at the other. The ideal compromise for the lunar lander is supervisory control, where the best attributes of humans and computers are utilized [44].

In addition the optimal level of workload must be considered when designing for a human in a supervisory control role. The desire is to keep a human at the peak of the Yerkes-Dodson curve [49] as illustrated in Figure 10. The left side of the curve illustrates a control system where the astronauts are under-utilized and bored. On the right side of the curve, the astronauts are oversaturated with the events of the system and ineffective in working with the lunar lander. Since performance declines on either side, the center marks a balanced workload amount for maintaining good situational awareness of the vehicle and mission state throughout the landing.

Images removed due to copyright restrictions.

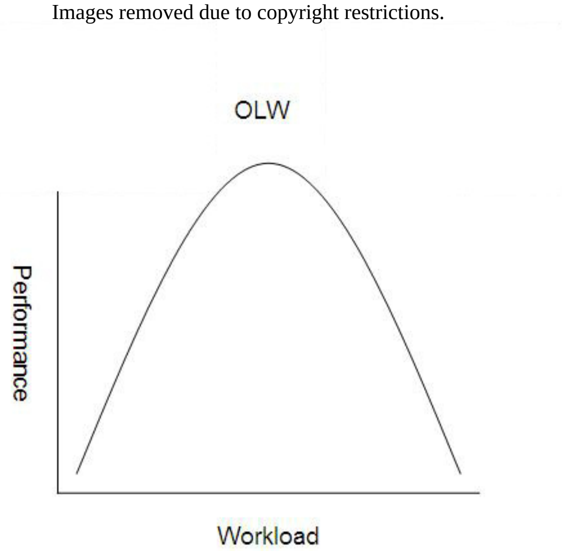

Figure 10 - Yerkes-Dodson curve and Apollo comic illustrating the two extremes of possible astronaut involvement in controlling a space capsule.

A human operator cycles through four actions in a supervisory control situation: acquiring information, analyzing the information, making a decision, and implementing the decision [48]. From Tom Sheridan's ten levels of automation, in Figure 11 [44], a level is chosen to be used within each of these actions. Often, multiple levels may be chosen for execution of specific conditions, but these classifications form the baseline design principles.

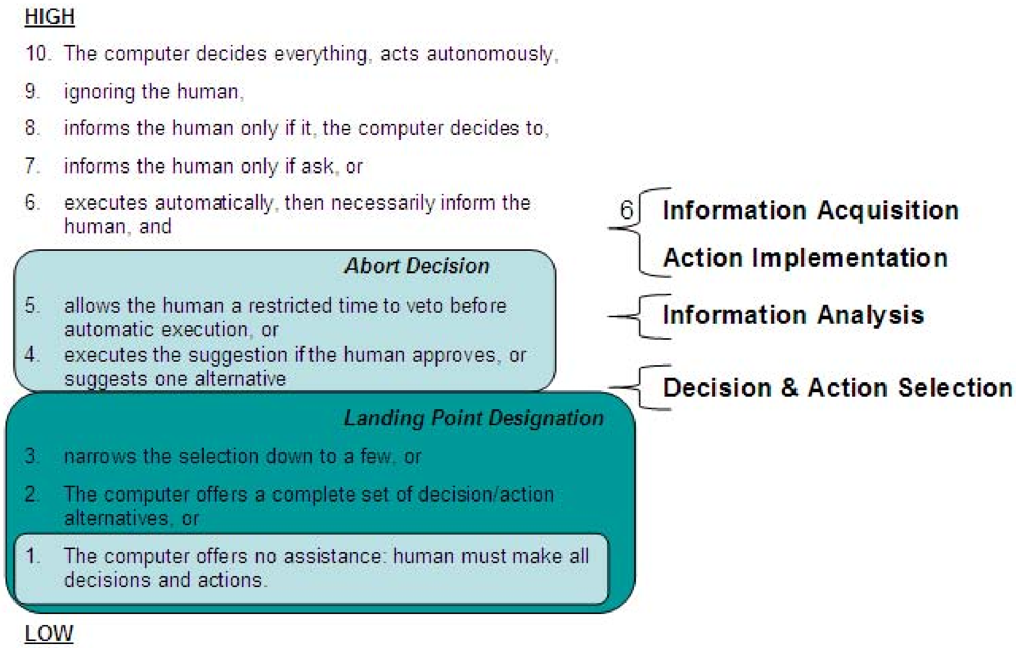

Figure 11 - Sheridan's 10 Levels of Automation of Decision [44] with the human functions and roles in landing the lunar lander.

For the design of the next lunar lander, information acquisition and decision implementation are both selected at level six; due to the attributes necessary to perform these actions, the computer greatly assists in gathering information about the current state of the lunar lander and executing a fuel efficient and safe flight profile. At the same time, the human(s) will continually monitor feedback from these actions to make sure the lunar lander remains within the safety envelope.

The human will play an integral role with the analysis and decision functions. Previous cognitive task analysis that drew upon extensive interviews, transcript analysis from the six moon landing missions, and decision ladder development revealed three key decisions that crews of the lunar lander can expect to make: (1) landing re-designation, (2) a final abort decision, and (3) a decision to use lower levels of automation during the landing phase [47]. The landing designation role of the human operators will start from Sheridan’s level three and vary down to level one. Early in the descent, real-time hazard detection and avoidance (HDA) will compute and offer alternative landing sites for operation evaluation and selection [39]. As the lunar lander pitches over for the last 100m of the descent, the operator will have the opportunity to move to automation level one or two if he or the HDA (respectively) detects hazards on the order of meters. For the abort decision, the human operators will primarily use Sheridan’s level four, as the computer can most quickly recognize unsafe internal faults with BIT and advise an abort that the human can then approve or disapprove. An overriding abort (level one) will also be available in an emergency situation where the human’s unique pattern-recognition and creative reasoning facilities allow him to diagnose something the computer has failed to identify. Further study must examine a scenario of crew incapacitation where the computer would need to make an abort decision that results after a set amount of time with no human inputs (level five). These chosen levels of automation form the basis for the HF components of the lunar lander design.

Crew Roles

During the first lunar landing, Neil Armstrong and Buzz Aldrin experienced high workload due to computer supervision, landing site re-designation tasks, manual flight control, and communications [41]. In order to prevent high workload during landing and advanced lunar surface scientific exploration, four people, rather than two, will land on the moon to conduct near 24-hour operations. To mitigate the high workload of the landing, responsibilities that were divided between two Apollo astronauts will now be divided between four human crewmembers and the "silent" fifth crew member, namely the computer. The roles of the landing astronauts are Landing Pilot (LP), Systems Pilot (SP), Mission Commander (MC), and Communications and Procedures (CommPro). These positions are updated decompositions of the Commander and Lunar Module Pilot roles that existed in Apollo.

The LP shares authority of landing operations with the SP, but the LP will focus outside of the cockpit while the SP focuses inside. In terms of the aforementioned three key decisions, the LP's main responsibility is to monitor the lunar surface for hazards through a window or a video display, and perform landing site re-designation with a hand controller if necessary. During Apollo, commanders, who were responsible for landing site re-designation, were required to fly helicopters for 200 hours before they were allowed to train in the Lunar Lander Training Vehicle (LLTV) [40]. Because vertical landing and take off (VTOL) aircraft, such as Harrier jets and helicopters, are the terrestrial vehicles most similar to the lunar lander, the LP should have extensive background in piloting VTOL aircraft.

The SP's responsibility is to supervise and interact with the semi-automated landing system, ensuring that the computer is executing the landing correctly. The SP will supervise displays pertaining to the computer and other lander systems, and under nominal operations the SP will be in control of the landing. Should the high-level automation malfunction, the crew will shift to lower levels of automation with higher reliance of information from outside the cockpit. The SP should have an engineering background with extensive experience in supervising complex or automated systems; a good SP candidate could be an air traffic controller familiar with monitoring multiple entities in a time-critical situation [42].

The MC commands the entire lunar mission, but during the landing phase, the LP and SP have primary authority over landing operations. Although the MC plays a minimal role in the landing phase, he is integral as the commander of the lunar operations once the crew is on the lunar surface. Shared leadership allows the crew to further specialize in their respective areas and will reduce overall training time. During the landing, the MC will have access to composite information garnered from other crew members to provide him with a global awareness of the landing operations. With this system-wide view, he or she will aid the LP and SP should an off-nominal event occur. Because workload skyrockets (pun intended) during anomalies, the MC can perform fault diagnosis, a former mission control responsibility, to reduce the pilots' workload.

The MC should have previous experience in leading small teams, preferably in technical or scientific projects, and possess management and technical skills to lead the crew in achieving scientific and mission objectives.

CommPro (for Communications and Procedures) is responsible for communicating with mission control and ensuring that landing procedures are being followed correctly. With a designated crewmember as the spacecraft communicator, the two pilots and MC can better focus on the landing task. Additionally CommPro may perform tasks unrelated to other crew roles that require attention, such as data transmission or receipt. CommPro should exhibit excellent communication skills, and should either be a field scientist who will do research on the lunar surface or a family-practice or emergency-room doctor, especially if the lunar surface stay will be of long duration.

Because crew members will have defined responsibilities and tasks during the lunar landing, real-time crew coordination should not pose any overhead on the completion of the landing task. Additionally, crew coordination between the humans and the computer will be emphasized throughout training, to be discussed later in this paper.

Interfaces

Unquestionably, Apollo-era technology is insufficient for supervisory control of the advanced systems on lunar lander; the dials and gages of the Apollo LM (Figure 16 & Figure 17 in Appendix A) will be replaced by a glass cockpit design incorporating LCD technology. These displays can utilize the best characteristics of the popular Avidyne and the Garmin G1000 glass cockpits, or the more expensive Chelton Flight-Logic EFIS with its highway-in-the-sky (HITS) capabilities [35]. With established crew roles and an understanding of the human computer interactions, the next step is to explore what information each crew member needs to fulfill his or her duties.

An initial H-SI concept was conceived as part of the Lunar Access Project [37]; this concept is in Figure 18 in Appendix A. However, these displays were designed before analysis was performed on the levels of automation and crew role. In particular, this design fails to provide the decision aids required for the level four landing redesignation, where the computer presents alternative landing sites to the operators. The H-SI design report itself also lists numerous unresolved issues with the design, most obviously the use of a profile view that lacks lateral error tracking and fails to provide horizontal situational awareness [36].

Rather than immediately creating sample displays, effort was directed into studying the requirements of each crew member based on role and task. Cognitive models comparing the Apollo lunar module cognitive process and interface with a parallel process using Sheridan's fourth level of automation were used. The cognitive model is also based on conclusions from a crew task model that estimated landing site redesignation to take 12-29 seconds [50].

From the crew role divisions, the LP and SP are in charge of the redesignation decision. The far left display in Figure 12 illustrates a window with substantial visual augmentation. The "window" could be either an actual window (used after pitchover) or an external camera (used pre-pitchover depending on its orientation, maneuverability, and acuity) that will be compared to the display to the immediate right. This display shows what the radar and pre-loaded maps project should be outside the lander. This combination of displays will allow the LP to determine if the lander is on a safe trajectory and is landing in the desired location, in addition to verifying the expected surface features or cross-checking unclear features in the window. The south-pole landing sight will have the most daylight hours, but the sun will be at a very low angle in the sky. Poor visual perception and acuity due to the dim light can be mitigated by integrating night vision technology with a camera so that any existing sun or star light can be maximized for the imagery. This can either be done directly on the synthetic vision display or can be transferred to a helmet mounted display in the case that an actual window is provided. Interviews with multiple military helicopter pilots with numerous hours in similar lighting conditions in a desert-like environment confirm the usefulness and capability of this technology for this environment [51].

An instrument focused operator, the SP will use the far right display in Figure 12 as a way to monitor the state of the automation and vehicle systems. Apollo lunar landing communication transcripts reveal that vehicle position was the primary focus during the final phase of flight in addition to the aforementioned three key decisions [47]. Importantly, the two displays to its left will allow the SP to perform early landing site redesignation and to project the lander's future state. The displays will decouple the trajectory to allow the SP to see the landing area from a top-down view and to provide a state vector to check the lander's current projected trajectory and other possible trajectories against an established safety envelope. The decision aids for landing site redesignation will likely be incorporated into the top-down view of the landing area. Figure 12 below illustrates the primary display configuration for the LP and SP.

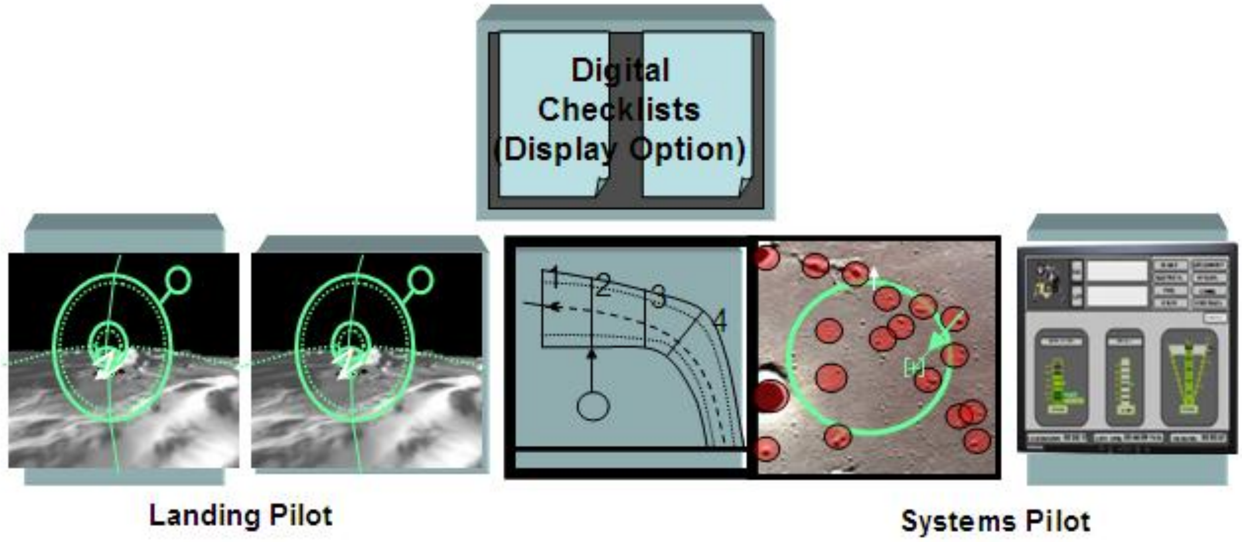

Figure 12 - Cockpit configuration of displays for the landing pilot (left seat) and systems pilot (right seat).

The MC will need to have flexible displays with the ability to view either the LP's or SP's displays in addition to a three-dimensional viewpoint with rotational, panning and zooming options controlled by bezel buttons that allow the operator to brace his hand against the displays side. This three-dimensional view will offer vertical and horizontal error tracking, and the ability to access specific data points that the computer is acquiring about the current lander's state to determine whether it is staying within the safety envelope. He or she should have three glass displays to cycle through the various displays or checklists in performing their role of supporting the LP or SP. The MC could also be provided with voice recognition software to call a computer-initiated abort (Sheridan's level 5) in various extreme scenarios involving crew incapacitation. A code word might be selected that has no meaning in English or any other language to trigger such an abort, but it is noted that such a system would require high reliability to be acceptable in a safety-critical environment such as the lunar landing. Requiring the ability to communicate with mission control, the CommPro will require displays to communicate over a radio or chat with mission control. Touch screens are not considered for any of the interfaces because of the NASA requirement to remain suited during descent and the potential unreliability during such a critical mission phase.

Training

The main objective for lunar landing training is to train crew and automation together as a system and team. This method will facilitate a smooth landing involving proper interactions between crew members and the lunar lander's automated systems.

Initial training will consist of lander system familiarization courses, providing all crew members with a basic understanding of the lander and its functionality, and emphasizing the role of the computer and automated systems. In addition, crew will receive individualized instruction specific to crew roles that will eventually transition to full-crew training to address crew coordination and crew resource management (CRM). This transition is similar to training provided to airline pilots [34]. As a full crew, the astronauts should initially complete mission simulations involving purely nominal conditions and progress to simulations containing anomalies, failures, and emergencies, to prepare for dealing with unexpected events. Similar to Apollo, final training should include integrated simulations with mission control [43], to practice interactions between the crew with the ground support team and to become accustomed to the time delay associated with earth-moon communications. However, with minimal crew-mission control interaction during landing operations, more emphasis should be placed on the separate training of the crew.

A variety of simulators, including fixed-base, motion-base, and flight, will facilitate crew training. Similar to Apollo, a procedure, or part task trainer, will allow the crew to practice landing operations, including how to use the cockpit displays and affordances to complete their tasks and uphold their responsibilities. This type of simulator is fixed-base and can be used for individual or team training, in the latter case allowing crew to practice interactions with one another other and the automation.

A motion-based simulator (MBS), similar to that used in the Space Shuttle Program [36], will be used for advanced lunar landing training and integrated simulations with mission control, as it combines many elements together to simulate a real landing. An MBS can simulate the otolith response to one-sixth gravity by tilting in three axes, effectively simulating the landing phase. In addition, the moon's surface will be projected in a window screen for the landing pilot, while all other crewmembers will have their displays populated with simulated landing information. The most important part of the MBS will be its ability to show the crew exactly what they will see during landing operations, from data displays to the lunar surface outside the window. This information is even more integral to the landing than the experience of one-sixth gravity that the simulator will provide.

Aircraft-based training will provide realistic landing experience, exposing crewmembers to working with and trusting the automation's performance in a realistic setting. Currently, a modified gulf stream is used to simulate shuttle landings and provide training to shuttle astronauts [36], but helicopters are better analogies to the lunar lander. Armstrong once stated that helicopter training "was valuable to understand the trajectories, visual fields, and rates of motion" [41]. Because lunar landing tasks will be mostly automated, a helicopter modified to contain lunar lander displays, controls, and automation could allow crewmembers to perform similar landing tasks in terms of supervision and re-designation. This training will fortify trust between human crew and the "fifth crewmember", the computer, and provide practice in pilot-automation interaction. Ideally, the whole crew should participate in aircraft-based training, but if not possible due to space constraints, this training should be mandatory for the LP and SP.

The Role of Mission Control

During the Apollo Program, Mission Control played a dominant role in every phase of the mission. The astronauts could not monitor all of the vehicle systems, so it fell to Mission Control to assess the spacecraft's status. In the Crimson Program, with better computer systems and a larger crew, the astronauts will have much more information about the vehicle's status and a greater ability to diagnose problems.

In such a system, the role of Mission Control during the landing phase becomes that of passive monitors. They will monitor all of the systems and be prepared to assist the crew if a problem should arise. Nevertheless, in a nominal flight the crew should be autonomous from Earth. At lunar distances the communications delay is noticeable, yet obviously not detrimental to flight monitoring from Earth. In a mission to Mars, however, the delay is substantial enough that the astronauts cannot rely on Mission Control to diagnose problems, they must be autonomous.

For the lunar landings, Mission Control will still be utilized to monitor the systems and diagnose any problems that the computer fails to recognize or to suggest alternate solutions to problems. The flight controllers will have instant access to the specialist in each system to help diagnose catastrophic systems failures. These specialists need not be in the same location as the lead controllers, they only need to be available via telephone or internet connection.

Mission Control will still play an important role in mission preparation and training. Currently "shuttle MCC workers only spend about 10 percent of their time controlling missions. Seventy-five percent of their time is spent planning and organizing, and 15 percent is devoted to their own training and education" [9]. As with Apollo, Shuttle, and Station, the controllers will be trained as experts in their specific systems. It will fall to the controllers to develop the procedures and checklists that the astronauts will use. The difference between previous operations and future ones is that those procedures will be carried onboard in the computers. In an emergency, the computer can diagnose the problem and recommend action. Concurrently, Mission Control will be monitoring the systems and will observe the computer recommendation. If the flight controllers disagree with the computer, they can instruct the crew to perform different actions.

A few of the Mission Control roles will not be accomplished onboard. For instance, the Flight Surgeon will not be duplicated by an onboard computer. The Flight Surgeon will be the primary source of medical advice and crew health monitoring during landing. This is because the professional judgment of a doctor is unnecessarily complicated to program into a computer. Medical emergencies will likely not be so time-critical that the transmission delay will be detrimental.

Abort Procedures

There are several situations that would require the lunar landing to be aborted. Some may be catastrophic, requiring immediate action, while some may result from a degradation of systems over a period of time. Regardless of the conditions requiring the abort, the LSAM will be in the abort envelope during the entire approach and landing procedure. The guidance, navigation, and control computer will continuously calculate an abort solution throughout the descent and landing. The actual mechanics of the abort will depend on the attitude, position, velocity, weight, fuel state, and condition of the LSAM at the time the abort is initiated. An explanation of the abort procedures for the different phases of the landing follows. Figure 13 provides a visual depiction of the abort procedures.

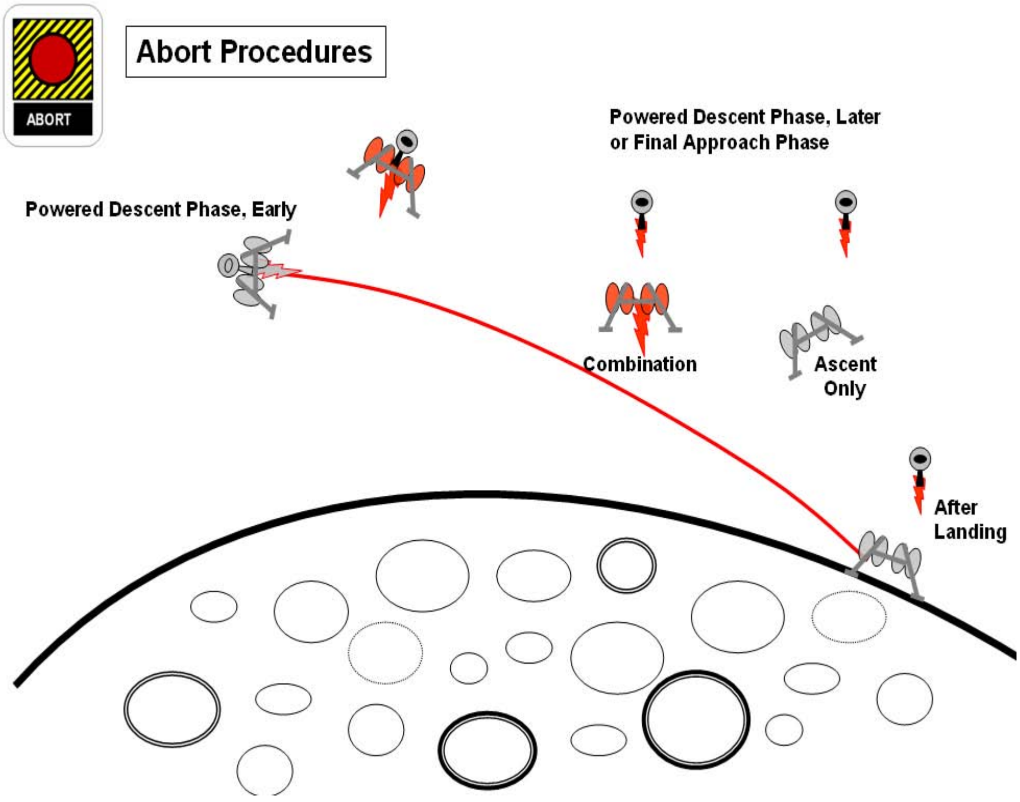

Figure 13 - Abort procedures for different phases of the lunar landing

Powered Descent Phase, Early – During the early part of the powered descent phase, the descent engine would be producing thrust in the opposite direction of travel in order to decrease velocity. The abort procedure would require maneuvering the spacecraft to align the thrust vector in the direction of travel in order to increase velocity. This would transfer it back to the CEV orbit for rendezvous based on the continuously updated abort solution.

Powered Descent Phase, Later or Final Approach Phase – During the later part of the powered descent phase, and during the final approach phase while the spacecraft is close to the lunar surface, the abort would be executed by applying thrust as required while changing the attitude to align the spacecraft with the trajectory that will return it to orbit to rendezvous with the CEV. While changing its attitude, the spacecraft will need to apply sufficient thrust to keep it from impacting the surface. Once aligned with the correct trajectory, the descent engine would increase to full throttle. If the descent engine were to exhaust its fuel, or if conditions dictate that a more efficient maneuver could be executed with the ascent portion alone, the spacecraft has an option to execute a combination abort. That is, the ascent engine would ignite, and the descent portion of the spacecraft would be ejected. The ascent module would return to orbit for rendezvous with the CEV. If the computer calculated that the most efficient way to abort was with the ascent stage alone, the ascent stage would immediately ignite, the descent stage would be ejected, and the ascent stage would execute the entire abort procedure.

After Landing – Once the spacecraft has landed and the descent engine has shutdown, there is a brief window when the craft could depart the lunar surface (ascent stage only) and still be able to rendezvous with the CEV without waiting for another orbital pass. In this case the ascent module would launch just as it would for a normal departure. A mode would be engaged that bypassed any nonessential procedures and expedited the liftoff.

Abort Initiation

Any member of the crew, or mission control can call an abort if they are the first to recognize conditions that require it. Due to the delayed arrival of spacecraft telemetry data at mission control, followed by the delayed arrival of the abort call back to the spacecraft (3 seconds plus mission controller reaction time), it is unlikely that mission control would be the first to detect abort conditions, but in that unlikely event, mission control could call the abort. Final abort authority rests with the landing pilot under normal conditions. The computer can also initiate an abort, but will alert the crew and allow a delay prior to initiation to allow the crew to override the decision if they deem an abort unnecessary.

The abort sequence will be initiated by either the landing pilot or the systems pilot. The abort button will be located between them and will initiate the appropriate sequence for the current abort solution at any point during the landing procedure. The abort solution will be constantly updated throughout the approach, landing, and immediately after the landing.

As subsystems are designed and developed, designers will establish procedures to correct systems problems, activate backup modes, implement workarounds, or otherwise enable the crew to continue the mission in the event of a malfunction. A malfunction will be detected by the computer diagnostic software and reported to the crew, or it may be detected by the crew. Regardless of how a malfunction is detected, the crew will execute the appropriate checklists. If system degradation continues and cannot be corrected by established normal or emergency procedures, and it is determined (either by the crew or the computer) that the mission cannot be continued, an abort will have to be initiated.

Another scenario is the occurrence of some drastic event, such as an onboard explosion, which would prevent a successful landing. In such a case the crew would initiate the abort in accordance with their critical action procedures. Even in the absence of established procedures, if at any time it is determined that the spacecraft is in a situation where mission safety is in jeopardy, even in the absence of equipment malfunction, an abort will be initiated.

Go/No Go Decision

In order to reduce the dependence on Mission Control and provide better monitoring of the health of onboard systems, continuous Built in Tests (BITs) are using. The need for a 100% Go/No Go decision from each station in Mission Control is no longer needed, the computer will continuously monitor the health of systems and provide immediate feedback to the crew and Mission Control, if a systems fails or degrades. Built in Tests are currently used in many aircraft today. The Glenn Research Center in Cleveland, Ohio is currently working on technologies that provide better Intelligent Health and Safety Monitoring (IHASM) and Propulsion Control and Health Monitoring (PCHM) for use in aviation [10].

The computer will present faults to the crew and Mission control as a warning, caution, or advisory. A warning is a problem that requires immediate action steps by the crew in order to prevent damage or loss of the spacecraft and crew. The computer will activate a warning light and associated audio. Once the crew acknowledges the warning by pressing the Warning Indicator Light, the audio will stop. However, the Warning Indicator Light will remain illuminated until appropriate action is taken in the form of an emergency procedure or abort. A caution is a problem that does not require immediate action by the crew but has the potential to cause an unsafe condition and elevate to a warning condition. The computer will activate a caution light and associated audio. The caution indicator operates the same way as the warning indicator. An advisory does not prevent a safe landing but only identifies a degraded system or improper switchology for the specific flight profile. The computer will activate an advisory to the two non-flight stations. As a result of categorizing faults, the crew should not experience any confusion for the severity of a system problem. The Airbus 340 currently utilizes this type of technology for its flight warning system [11]. Finally, a paper by J.E. Veitengruber of Boeing Commercial Airplane Company provides design guidance for this type of alerting system [12].

To further reduce the reliance on Mission Control, human memory, and heavy paper checklist and technical manuals, electronic checklist (ECL) will be utilized. The crew will not longer have to depend or wait on Mission Control to diagnosis problems. Similarly, crew members will quickly be able to backup required memorized emergency procedures with the appropriate ECL.

Advisory messages will be displayed to the non-flight stations. These crewmembers can access technical data in order to determine the systems affected. Knowing the systems affected and the level it is degraded will assist them in determining the overall effect of the fault. Similarly if the advisory is a switchology issue they can quick correct the fault. In the event of a caution the systems pilot will receive problem description with the ability to bring up more detailed technical data or corrective procedures. Additionally, if the systems pilot can pass cautions off to the two non-flight stations if the situation does not permit him to take action. Finally, in the event of a warning, the systems pilot will have the emergency procedure immediately pop up on their display. Barbara K. Burian's of the NASA Ames Research Center provides design guidance for electronic checklist in her paper titled "Design Guidance for Emergency and Abnormal Checklist in Aviation" [13].

Baseline Cost Estimate

While all the preceding sections detail a comprehensive plan of *how* we shall return to the moon, given the chance, we must consider if the prospect of a return of mankind to the lunar service has a reasonable likelihood of happening. Though many factors contribute to the feasibility of a sustained lunar program, one of the most major is public support of the endeavor, and one of the most key elements to maintaining broad public support over a long period of time is ensuring a relatively low cost for the program. Of course there are other issues that could derail a program, including a few single-point failures such as the prospect of a fatal tragedy in space, no program will literally even get off the ground unless it can be shown to be possible within NASA's means, and a budget that is unlikely to enjoy the more "blank check" Congressional support that bolstered NASA during the lead-up to its more halcyon Apollo days.

With a clear interest in making both realistic and politically viable cost estimates (two qualities that are often at odds), a few attempts have been made to date to predict the ultimate cost of such an endeavor. Using the infrastructure and operational proposals put forth in NASA's Exploration Systems Architecture Study (ESAS), and the NASA and Air Force Cost Model (NAFCOM), preliminary figures have emerged as a starting point from which to converge upon the final bottom line. We are aided as well by a detailed study conducted by Georgia Tech and the National Institute of Aerospace, one that aims to further narrow the range of possible expected monetary commitment that a lunar landing would require. Of course, no projection a decade into the future will be bulletproof, and we expect the numbers to change in either direction as more development and production ramps up. The cost models are meant to be relatively conservative, and NAFCOM "assumes the historical levels of requirements changes, budget shortfalls, schedule slips, and technical problems." It also holds out hope for, but does not nearly count on, potential commercial services that may arise in the meantime to further aid in lowering the cost of exploration. Thus, these should not be considered pie-in-the-sky numbers that have been falsely deflated in order to be congressionally acceptable, but rather an honesty attempt at a first-order cost estimation for a long-term project that still possesses a certain level of uncertainty in several arenas.

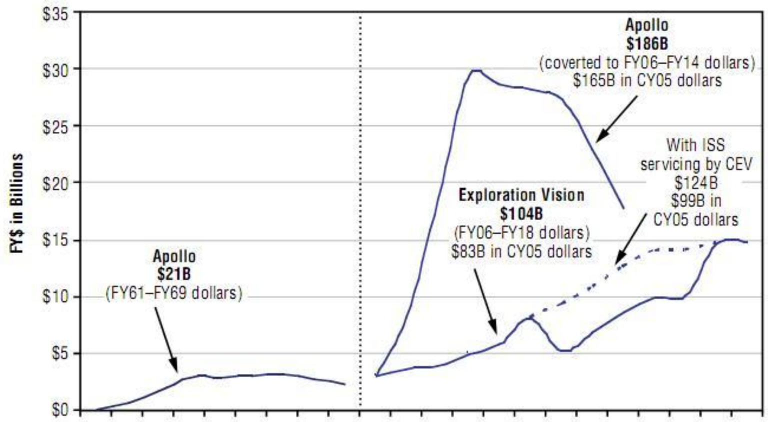

Figure 14 - Comparison of Apollo Costs to Exploration Vision

This cost estimate is only for the lunar landing itself, particularly for the LSAM. We choose this aspect of the mission as it fits within the scope of our project, as well as a microcosm for the program at large. Many of the aspects of the Crimson proposal that promise cost savings over Apollo in the LSAM and landing hold true across mission phases and indicate an overall ability to meet the financial goals set forth and necessary to ensure the program's long-term success.

Working with the earlier-stated assumption that there will be life support already waiting for the crew on the surface, the LSAM can be estimated to mass about 50,000kg. This is critical, as it allows a great flexibility in mission modes and is realistic about the difficult task of supporting the life safety of four astronauts for longer and longer periods of time. Georgia Tech has placed the cost of such a landing ranging from $26.2 - $31.1 billion. Using a conservative estimate, we can predict a rough figure of $600,000/kg landed on the lunar surface by the LSAM. While this may seem like a high number, compared with the general costs of the Apollo program, it is quite a bargain. This reduction in cost and improvement in capability is possible through technological upgrades since Apollo, and does not require any technological breakthroughs from the present day to the time in over a decade when mankind will return to our nearest celestial neighbor.

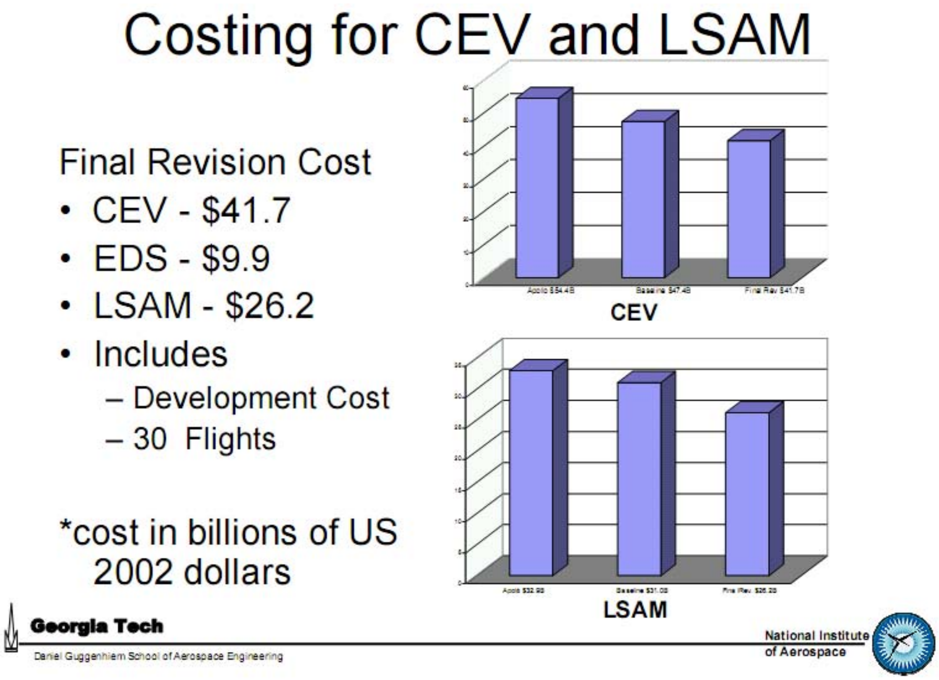

Figure 15 - Costs based on data from Georgia Tech.

<u>Conclusion</u>

Team Crimson has presented a plan to land on the moon that will make the New Vision for Space Exploration a reality. Drastic advancements in materials, rocket fuels, computer capability, guidance & control, sensors, instrumentation, and spacecraft design, as presented in this paper, will allow the team to improve on the successful Apollo program. These, together with the lessons learned from nearly forty years of human spaceflight since Apollo, and innovative initiatives in command & control and human factors considerations based on that experience, will work together for a lunar landing program that will be safe, reliable, precise, cost effective, and sustainable. This will be the first step toward sustained human presence on the Moon, and eventually missions to Mars. It will push the aerospace companies of America and collaborating nations past current technological horizons, which will promote commerce and maintain United States preeminence in space. Finally, Team Crimson's plan will again send humans to unknown and unexplored frontiers, increasing scientific knowledge and fulfilling the inherent need to explore, thus "lift[ing] our national spirit".

Appendix A: Human Factors

Figure 16 - Photograph of the "dials and gages" of the Apollo Lunar Module.

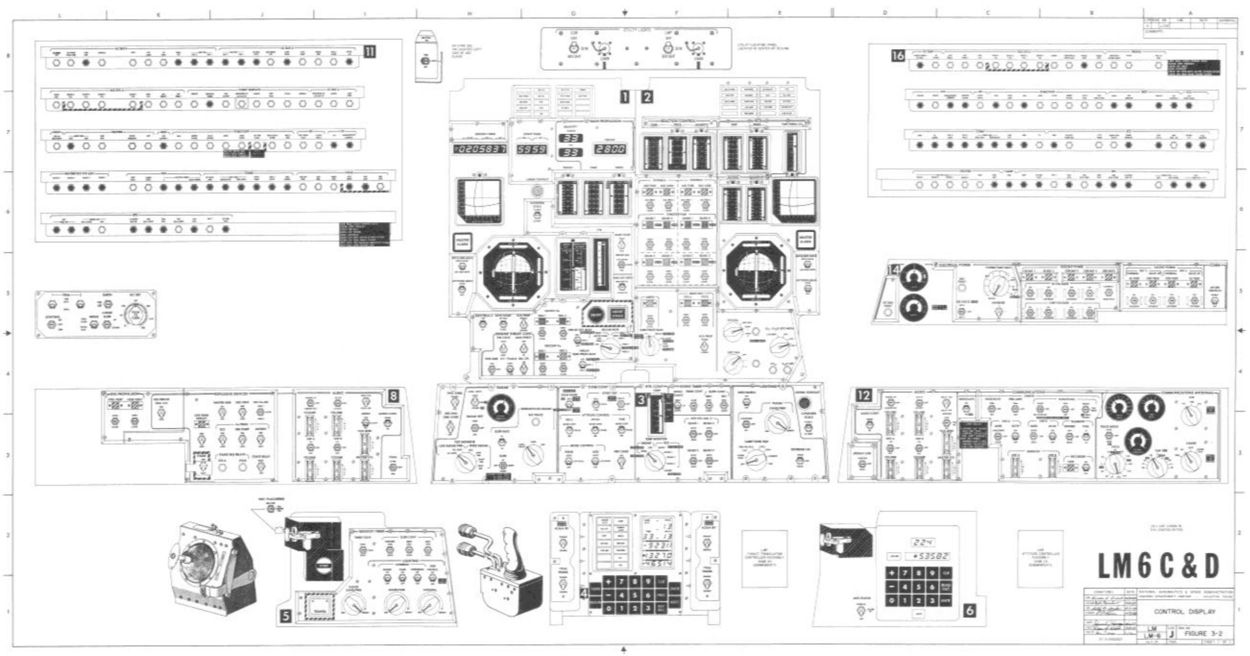

Figure 17 - Layout of the Apollo Lunar Module interfaces.

Courtesy of NASA.

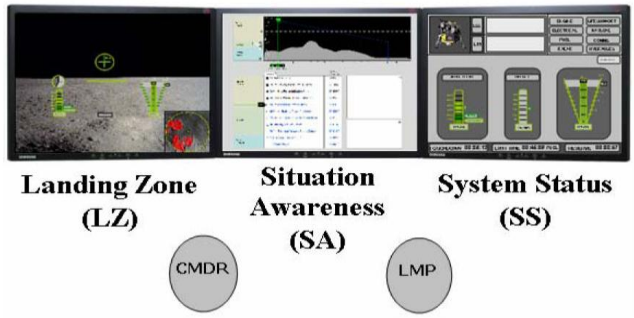

Figure 18 - Preliminary Lunar Access H-SI Concept

Audio alarm design recommendation

Sanders & McCormick (1993) recommendations that are applicable for the environment the lunar lander will be landing in are:

- Use frequencies between 200 and 5000 Hz, and preferably between 500 and 3000 Hz, because the ear is most sensitive to this middle range.
- Use a modulated signal (1 to 8 beeps per second, or warbling sounds varying from 1 to 3 times per second), since it is different enough from normal sounds to demand attention.
- Use signals with frequencies different from those that dominate any background noise, to minimize masking.
- If different warning signals are used to represent different conditions requiring different responses, each should be distinguishable from the others, and moderate-intensity signals should be used.
- Where feasible, use a separate communication system for warnings, such as loudspeakers, horns, or other devices not used for other purposes. (pg. 180)

Visual warning design recommendation

Here are Sanders & McCormick (1993) recommendations for visual warnings. "Do not use vague, ambiguous, or ill-defined terms; highly technical words or phrases; double negatives; or long grammatically complex phrasing" (pg. 683). Typically the warning should contain four critical elements:

1. Signal word: to convey the gravity of the risk, for example, "danger," "warning," "caution"
2. Hazard: the nature of the hazard
3. Consequences: what is likely to happen if the warning is not heeded
4. Instructions: appropriate behavior to reduce or eliminate the hazard (pg. 683)

An example is:

DANGER
HIGH VOLTAGE WIRES
CAN KILL
STAY AWAY (pg. 683)

Appendix B: Mass Breakdown

Revised mass breakdown of the descent stage of Crimson lunar module.

		Mass [kg]	Description
Propulsion		2003	[22]
	Tanks	1477	~5% of propellant weight [31]
	Thrusters	526	
	Lines, valves, fittings	8	[31]
Navigation		53	
	LIDAR	7	[28]
	Radar altimeter	25	[29]
	Accelerometer	1	[24]
	Gyroscopes	19	[24]
	Star Finder	1	[23]
Communications		35	
	Antennas	35	
Command + data handling		11	
	Command unit	5	[31]
	Pulse code modulation encoder	6	[31]
Thermal		512	2~5% of dry mass [31]
	Coating	472	4% of dry mass [31]
	Oven/heat pipes	40	[31]
Power: M		486	
	Solar Panel	196	17-47(25)W/kg [31]
	Battery	70	30-50W hr/kg for NiCd or NiH_2 [31]
	Controller	98	0.02kg/W
	Converter	122	0.025kg/W, 0.2P [31]
	Wiring	472	0.02-0.05P (losses) [31]
Structure		599	15-25% of dry mass [31]
Payload		5,210	~15-50% of dry mass [31]
Margin		2953	5~25% [31]
Propellant		29537	
	Velocity Correction and Control	22,721	
	Attitude Control	2525	
	Nominal	25,245	
	Margin	4249	10-25% of nominal [31]
	Residual	295	
Total Mass		41,347	[22]
Dry mass: Mdry		11,810	

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