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The design of controls for NASA's Orion Crew Exploration Vehicle

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Abstract

Little interplanetary vehicle design work has been done in the 40 years since the Apollo capsule first flew in 1968. The Orion Crew Exploration Vehicle (CEV) is now in the beginning of its design process. Orion will be similar in shape to the Apollo spacecraft, but significantly larger. With a diameter of about five meters, Orion should have about 2.5 times the habitable volume of Apollo. The Apollo capsule was designed to fit three very closely spaced astronauts for round trip missions to the Moon. Orion's larger size will allow it to accommodate four crewmembers on lunar missions, and six on missions to the International Space Station.

Many new human factors issues will need to be addressed. For example, the Orion CEV will be subject to higher G forces and interior vibration levels during launch than the current Space Shuttle. Thus, the crewstation will need to be designed to address the control limitations imposed by having restrained astronauts in a more challenging physical environment. Unlike the Shuttle flight deck, Orion will have a limited number of buttons, switches and dials. Instead, Orion's operators will monitor and command the vehicle's systems via graphics-based displays not unlike those of modern flight decks. As this would imply, the design of Orion's displays and controls places an increased emphasis on human-computer interaction and usability.

Introduction

NASA's Constellation Program intends to return humans to the moon by 2020, followed by exploration to Mars and beyond. The Orion Crew Exploration Vehicle (CEV) will serve as the primary vehicle for transporting the crew. It will be capable of carrying crews to the International Space Station (ISS), rendezvousing with a lunar lander module, carrying crews to the moon and beyond, and serving as the Earth re-entry vehicle (NASA, 2008). Orion is a capsule-type vehicle similar to, but significantly larger than, Apollo. The Apollo capsule was designed to fit three very closely spaced astronauts (see Figure 1a) on round trip missions to the moon. Orion will carry six astronauts during low earth orbit missions such as those to the ISS (see Figure 1b), and four astronauts on lunar missions. Unlike its Apollo predecessor, Orion will have an autonomous mode, thereby allowing all crewmembers to descend to the lunar surface.

Many new human factors issues will need to be addressed. For example, the Orion CEV will be subject to higher G forces and interior vibration levels during launch than those subjected by the current Space Shuttle. Thus, the Orion crewstation will need to address the control limitations imposed by the resulting astronaut restraints.

Unlike the Shuttle, which relies heavily on ground-based mission control to monitor and command a majority of the Shuttle's systems, Orion places an emphasis on onboard automation and control via crewmembers. Orion will be equipped with a modern 'glass cockpit' that will allow the operators to command and control all of the vehicle's systems from one of two operator stations. The importance of human factors is reflected in the fact that NASA, for the first time, has mandated usability and workload criteria within vehicle design requirements. As a result, human factors engineers are heavily involved in every aspect of Orion displays and controls design.

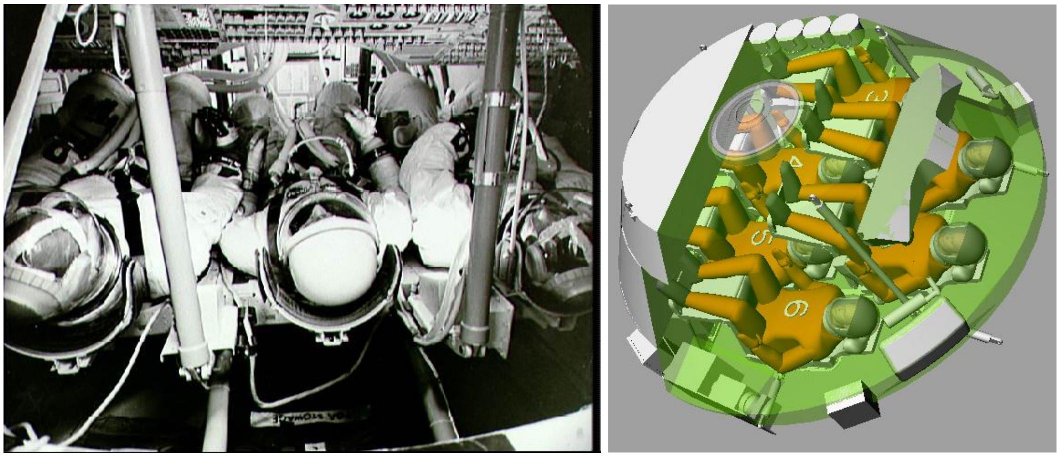


Figure 1. (a) Apollo capsule with a crew of three, (b) Orion capsule with a crew of six.

Human-Centered Design Process

The iterative human-centered design process for determining CEV crew console layout requirements is illustrated in Figure 2. We discuss some of the Mission and Function Analyses performed in more detail below.

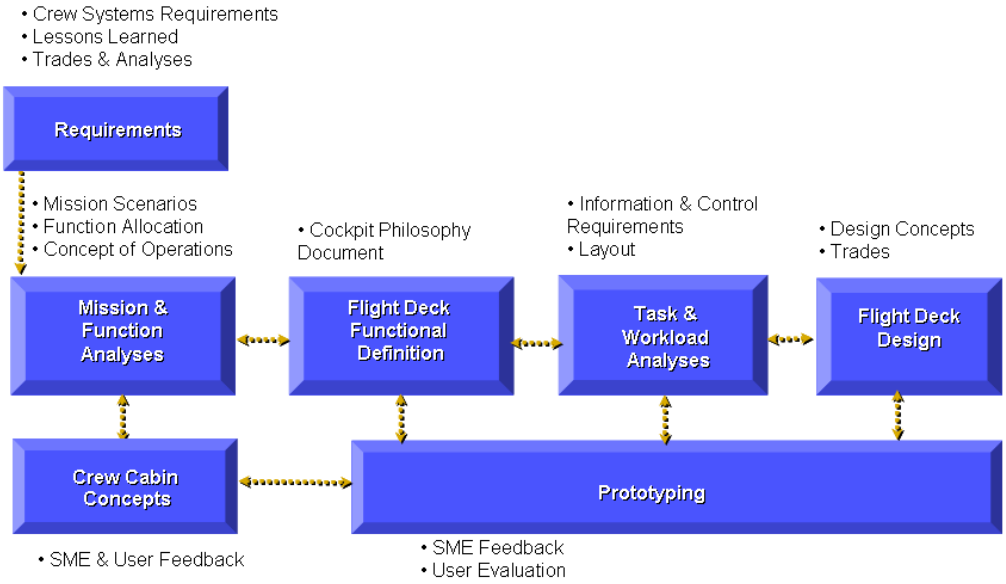


Figure 2. Crew Console Layout Methodology.

The CEV Mission Operations Working Group defined a relevant set of mission scenarios and critical mission elements, so that all teams were using common terminology. These were then used to define initial operational requirements that started at a general (qualitative) level and progressed to a more specific level.

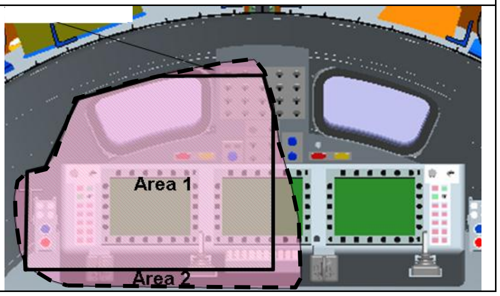
Derive Functions (Function List). The displays and controls layout design process began by deriving the CEV function list. The primary source of function data was the CEV Concept of Operations document. Further functions were uncovered by examining Space Shuttle (current technology and procedures) and Apollo (similarity to interplanetary mission and vehicle type) records to determine the set of functions that have traditionally been needed for accomplishing similar mission sequences (e.g., launch, entry into orbit, docking, undocking, de-orbit, landing). The original list of functions is now included in a Master Task List that is a living document.

Functional Flow Block Diagrams. Block diagrams were developed for each mission phase. Initial concentration was on International Space Station (ISS) missions. The diagrams served two main purposes: matching functions to a timeline, and establishing parallel and sequential activities. Time tagging provided input to decisions on accessing displays and controls for task completion. Parallel activities indicate a need for simultaneous displays and non-shared controls.

Display and Control Area Allocation

Display and control area allocation was conducted using the Function Allocation Matrix Tool (FAMT) and related human-centered design processes to address how to systematically assign display and control functionality throughout the cockpit. The FAMT produced a significance score for every operator task (between 4 and 20), based on four criteria: hazard criticality, direct control of spacecraft, operational criticality, and frequency of use. For a detailed description of the FAMT process, see Olofinboba, et al., (2008). The significance score was then used to rank the various information and control needs and thus where each should be placed relative to the resting line-of-sight in a microgravity environment following standard human factors engineering protocol. A high significance score indicates a function with very high potential workload, meaning displays and controls should be placed for maximum ease of use. A low score indicates that placement in a less accessible area may be acceptable (see Table 1).

Table 1. Display and control requirements for each Area.

Required Access Level	Display Access Requirements	Control Access Requirements	Access areas defined by HSIR minimum female reach
Area 1, FAMT = 16-20: defined by operator primary eye rotation range and reach envelope.	No head motion required.	Little arm motion is required.	
Area 2, FAMT = 11-15: represents display/control area shared between the two operators.	Field of view may require head motion.	May require substantial arm motion.	
Area 3 FAMT <= 10: represents areas that are at the edges of the field of view and reach envelope.	May be towards limits of field of view with head movement.	May require substantial arm and body motion.	

For the CEV 604 configuration, we divided the workspace into three groupings based on anticipated access levels required by crewmembers. In all cases, it is important to remember that these rankings suggest the minimum acceptable locations. A display or control can always be placed in a higher ranked area if there is sufficient room.

Reach Envelopes

Reach envelopes were determined using ergonomic computer mannequins. Figure 3a shows the CEV 604 configuration thumb tip reach envelopes of the Human Systems Integration Requirements (HSIR) minimum female and maximum male body sizes. Shared controls were used wherever possible for the two operators. This configuration saved space and weight, while also supporting the customer goal of allowing operating crewmembers to view and confirm each other's operations. The CEV 604 reach analysis had shown that the shared controls were accessible to a HSIR minimum body size female operator (Figure 3b). As such, the layout only duplicated controls (at both operator workstations) that did not fit in the shared space or that might have immediate access requirements. An example of duplication was with the emergency re-entry pyro event controls (e.g., parachute deploy, hatch jettison).

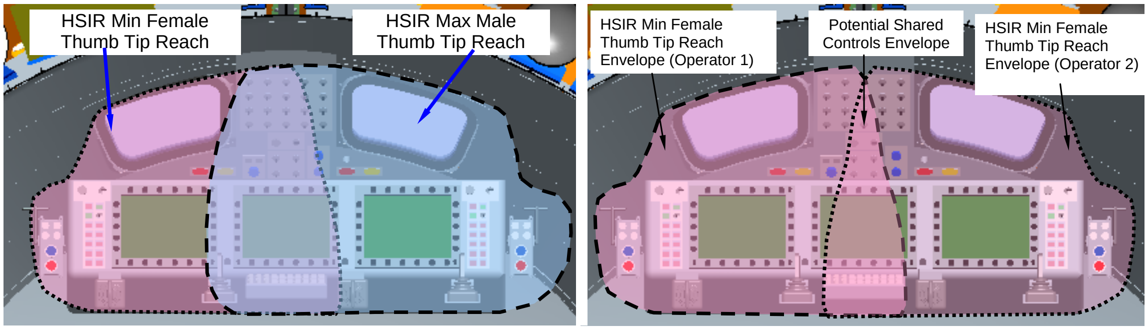


Figure 3. (a) Seated Thumb Tip Reach Envelope, (b) Potential Shared Controls Envelope.

Displays and Controls

To the astronaut, Orion's D&C panel will appear sparse compared to that of previous vehicles, as Orion will only have a fraction of the displays and controls found on the Shuttle or Apollo capsule. In the current configuration, Orion has two redundant operator stations. The instrument panel is equipped with three 13 x 10 inch LCD display units, compared to nine 8 x 8 inch display units found on Shuttle (see Figure 4). Each display unit will be configured to show up to two screens at a time. Every effort has been made to eliminate physical switches (button, dials, circuit breakers, etc.), with the exception of those that will be needed during emergency conditions. Operators have a rotational hand controller assigned to their right hand and a cursor control device assigned to their left hand. Translational hand controllers will be located on the outboard side of each station but they will only be used during orbital maneuvers.

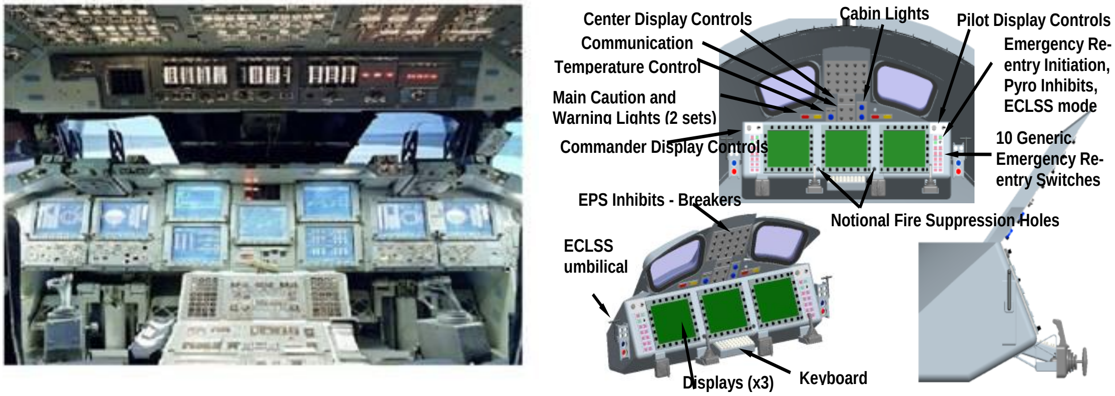


Figure 4. Crew console layout for the (a) Shuttle and (b) Orion (CEV 604).

Command and control of Orion's avionics can be accomplished with traditional multi-function keys located around the perimeter of the display units. Although most modern flight decks are moving away from using multi-function keys, astronauts find them highly desirable for on-orbit use. Unfortunately, the geometry of the cockpit, specifically, the location of the seats relative to the instrument panel, prevents the operators from reaching most of the multi-function keys while the crew is suited, seated, and restrained. The location of the operators relative to the instrument panel is largely a result of functional requirements for impact attenuation as well as the ability to accommodate a wide variety of occupant anthropometry. These restraints are in effect during the most dynamic phases of flight (i.e., launch and entry), when access to the avionics can be most critical. A functional analysis of the user interface standards provided by NASA revealed the need for cursor control devices, which could interact with avionics during dynamic phases of flight when the crew is restrained and unable to access the multi-function keys.

Graphical User Interfaces

Instead of relying on physical switches distributed across a vast flight deck, an astronaut will be able to control all of the vehicle systems from a single operator station using 'virtual' switches displayed on Graphical User Interfaces (GUIs). The GUIs depict schematic models of the vehicle's systems which provide the astronaut with improved situational awareness of the system's health and status. It is also the goal that such GUIs will improve decision-making and reduce training time.

Interaction with Displays

Astronauts will be able to interact with Orion vehicle displays in multiple ways. Each display unit will provide hardware edge keys mounted on the display unit bezels which will allow direct access to individual displays. However, this method of interaction will likely not be possible during dynamic flight phases such as launch and entry. The gravitational and vibration forces placed on the astronaut during these phases, in addition to the crew's protective devices (e.g., suits, restraints), will limit the astronaut's reach and severely impede their reach accuracy, preventing them from directly interacting with the instrument panel. To address the need to interact with displays during dynamic flight, Orion will be equipped with a new user interface controller that will provide remote access to the displays similar to that of a cursor control device (CCD). The CCD will allow astronauts to be suited and restrained, and still interact with the displays. For more detail on the CCD design, see Hamblin, DeMers, & Olofinboba (2008).

Software Control

The approach was strongly biased towards use of 'soft' keys, accessible via either edge keys or a cursor control device (CCD) to select functions on computer displays, as opposed to having dedicated controls for each function. Generally, only dedicated controls were used for functions which were considered critical based on FAMT analysis (high significance score) and for which we believed an immediate response would be required (e.g., manual fire suppression). The goal was to improve accessibility of functions needed in an emergency. One exception to this rule was dedicated rotational and translational hand controllers due to expected crewmember experience, transfer of training, and initial subject matter expert feedback. Advantages to minimizing the number of dedicated controls include less wiring, which makes it simpler to do layout reconfiguration. This provides mission flexibility advantages. In addition, fewer controls save on cost (including certification cost), weight, and space requirements. There are also maintainability and upgradeability advantages with fewer hardware devices to service.

Flight Controls

Flight controls will appear very similar to those found on the Shuttle and Apollo. Each operator station will be equipped with a rotational hand controller and a translational hand controller. While the physical shape of the controllers will remain, both will receive upgraded electronics and will be optimized for the flight and orbital characteristics of Orion.

Control Spacing and Sizing

Design requirements for Orion's controls are unique in that they stipulate that astronauts must be able to interact with the controls while wearing pressurized space suits. This places special consideration on the design of the controls since they must be usable in ungloved, gloved, and pressurized glove conditions. Control spacing, control sizing, and appropriate device requirements were derived from applicable documents (e.g., Department of Defense, 1999; NASA, 2005). When spacing devices, minimum spacing requirements were generally not used. Specific guidance for gloved use was not always available and we wanted to ensure the ability to operate all controls when wearing pressurized and unpressurized gloves. Also, it was assumed that all control devices would be protected against inadvertent activation, e.g., barrier guards protect toggle switches, and lever lock switches are used wherever inadvertent action would be detrimental to flight operations or could damage equipment. Cover guards are used on switches where inadvertent actuation would be irreversible.

Conclusions

The design and testing of the Orion vehicle is one of the major human factors challenges facing us at the beginning of the 21st Century. The design task will involve the integration of state-of-the-art technology into a system that must be usable, extremely reliable, and fail-safe. Incorporating human engineering design principles from the earliest stages in the design of controls is an important step towards achieving this goal.

Acknowledgements

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