

Considerations for Implementing Voice- Controlled Spacecraft Systems through a Human-Centered Design Approach

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Abstract

As computational power and speech recognition algorithms improve, the consumer market will see better-performing speech recognition applications. The cell phone and Internet-related service industry have further enhanced speech recognition applications using artificial intelligence and statistical data-mining techniques. These improvements to speech recognition technology (SRT) may one day help astronauts on future deep space human missions that require control of complex spacecraft systems or spacesuit applications by voice. Though SRT and more advanced speech recognition techniques show promise, use of this technology for a space application such as vehicle/habitat/spacesuit requires careful considerations. There are still recognition challenges to overcome such as background noise, human speech variability, and task loading. However, implemented correctly, a voice-controlled spacecraft system (VCSS) can provide a useful, natural and efficient form of human-machine communications during complex tasks such as when the hands and eyes are busy or as an aid for vehicle situational awareness inquiries or collaborative human-robot tasks.

This document provides considerations and guidance for the use of SRT in VCSS applications for space missions, specifically in command-and-control (C2) applications where the commanding is user-initiated. First, current SRT limitations as known at the time of this report are given. Then, highlights of SRT used in the space program provide the reader with a history of some of the human spaceflight applications and research. Next, an overview of the speech production process and the intrinsic variations of speech are provided. Finally, general guidance and considerations are given for development of a VCSS using a human-centered design approach for space applications that includes vocabulary selection and performance testing, as well as VCSS considerations for C2 dialogue management design, feedback, error handling, and evaluation/usability testing.

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Table of Contents

1.	Introduction	1
2.	Definitions	2
2.1	Command and Control (C2)	2
2.2	Confusability Matrix.....	2
2.3	Command and Control (C2) dialogue management	2
2.4	Speech Recognition Grammar.....	2
2.5	Human-Centered Design (HCD)	2
2.6	Phonemes.....	3
2.7	Recognition Errors (RE).....	3
2.8	State Node	3
2.9	User-Initiated Dialogue	3
2.10	Voice-Controlled Spacecraft Systems (VCSS)	3
3.	SRT Limitations	3
4.	Brief History of Speech Recognition in the Space Program	4
4.1	Ground Investigations.....	4
4.1.1	Feasibility of Controlling the Space Shuttle Video System by Voice	4
4.1.2	EVA Voice-Activated Information System.....	4
4.1.3	Speech Recognition at Reduced Pressures	4
4.2	Space Flight Demonstrations and Experiments.....	5
4.2.1	STS-41 Voice Command System Flight Experiment	5
4.2.2	Detailed Test Objective 675 “Voice Control of the Shuttle CCTV System	5
4.2.3	Flight Experiment Command Word Selection	6
5.	Speech Variations.....	7
5.1	Human Intrinsic Speech Variations.....	7
5.2	Factors Affecting Speech in Space	8
6.	VCSS Development Considerations.....	8
6.1	Human-Centered Design (HCD) and the Development Process	8
6.1.1	HCD design process planning	9
6.1.2	Context-of-use	10
6.1.3	Usage Requirements & Specifications	10
6.1.4	Design Solution	10
6.2	Vocabulary Selection.....	11
6.2.1	Task-Relevant Vocabulary	11

6.2.2	Vocabulary Phonetic Features	11
6.2.3	Vocabulary Confusability Performance Testing.....	12
6.3	C2 Dialogue Design.....	13
6.3.1	C2 Dialogue Structure	13
6.3.2	VCSS Activation and Readiness	14
6.3.3	VCSS Deactivation.....	14
6.3.4	Common Transition Command and Query Words	15
6.3.5	Alternate Transition Command Words.....	15
6.3.6	Guidance on Task Feedback.....	15
6.4	Handling Recognition Errors.....	15
6.4.1	Substitution Error	16
6.4.2	Rejection Error	16
6.4.4	Deletion Error	16
6.4.5	Insertion Error.....	16
6.4.6	Spoke-too-Soon Error.....	17
6.5	Usability Evaluation and Testing	17
6.5.1	Test Planning and Scheduling	17
6.5.2	Performance Metrics.....	17
6.5.3	Test Facilities.....	17
7.0	Conclusion.....	18
	Acronym List.....	19
	References	20

List of Figures

Figure 1	Voice Production (<i>Johns Hopkins Voice Center</i>)	7
Figure 2	NASA Life-Cycle Phases with Project Milestones.....	9
Figure 3.	Human-Centered Design Process.....	9
Figure 4	VCSS Design & Development Process Venn Diagram	10
Figure 5	STS-78 Voice Command System Dialogue Structure	14

List of Tables

Table 1	Voice Command System Vocabulary.....	6
Table 2.	Vocabulary Confusability Matrix	12
Table 3	Recognition Performance Scoring Calculations	13

1. Introduction

Since the first commercial use of speech recognition technology (SRT) in the 1980s—primarily in the telephone industry—SRT and voice-controlled spacecraft systems (VCSS) have improved concerning speaker recognition performance and dialogue design. Today, many commercial industries including banking, airline reservations, medical, automotive, and legal (to name a few) use SRT. The iPhone industry has advanced human-computer interface (HCI) dialogue development using artificial intelligence (AI) and natural language processing (NLP). It will soon become people's chief means of interacting with computing devices and systems. For future space missions, these advancements may one day help astronauts control complex spacecraft systems, information storage and retrieval, or spacesuit interaction by voice [6].

Currently, more than 50 people in the Mission Control Center (MCC) support the operation of the Space Station. They serve as an extra pair of eyes to the astronaut overseeing the numerous station systems and handling emergencies. As humanity advances farther from Earth, the round-trip communication delays between Earth and the spacecraft increases, requiring more onboard MCC functionality to maintain and control the vehicle. Hence, deep space missions to Mars and beyond will place challenging constraints on the crew which will demand an efficient and effective HCI to control a highly complex vehicle/habitat system. NASA Human Research Program (HRP) has identified inadequate HCI as a risk for future missions. New tools and procedures to aid the crew in operating a complex spacecraft will be required.

Though SRT has come a long way, it still struggles with challenges such as background noise and human speech variability that is influenced by task loading and the user's psychological and physiological health. SRT recognizes the words spoken but lacks an understanding of the meaning of the words. The responsibility for interpreting the users meaning lies with the VCSS application dialogue between the user and the machine. However, the machine-understanding dialogue is still a long way from understanding the speaker's intended meaning. Incorrectly recognized words are treated cautiously as the system could branch into a wrong part of the application software code furthering the likelihood of more recognition errors. Implemented correctly, VCSS in a data entry application permits increased machine or system operator efficiency with a high level of recovering from recognition errors (RE). If incorrectly developed, the task workload can increase resulting in potentially more errors, therefore making it unacceptable to the user.

There are numerous published reports, masters' / doctoral thesis, and presentations on the development and implementation of SRT applications. The majority of these documents focus on commercial, aviation, or automotive applications rather than spaceflight. The few industry standards in the military [16] and the automotive industry provide some design guidelines that may be applicable for space applications. However, the space environment is different from any of these industries. NASA has provided some guidance on applying speech recognition [17] but lacks in details.

Design and use of this technology for space applications, such as vehicle/habitat/spacesuit, require careful considerations, particularly when it comes to user satisfaction and safety. Typically, a VCSS is suitable where the crews' hands and/or eyes are busy performing another task. Thus, a VCSS provides a "third pair" of hands to the crewmember via spoken commands. In case speech recognition performance and/or reliability degrades in safety-critical applications, an alternative means of controlling the task must be available. Additionally, current space radiation-hardened processors may be sufficient for C2 space applications, which typically require smaller vocabularies and recognition algorithms, but not NLP conversational systems applications where several high-performance general-purpose graphics processing units are working in unison.

This document provides considerations and guidance in developing a VCSS for space applications. Specifically, it addresses C2 dialogue applications associated with controlling a subsystem by voice (such as a camera or a robot system), dictation, or retrieving information such as system status or data files. In C2 applications, the user initiates the dialogue (user-initiated) rather than the machine (computer-initiated). First, current SRT limitations as known at the time of this report are given. Then, highlights of SRT used in the space program provide the reader with a history of some of the applications used in space research. Next, an overview of the speech production process and the intrinsic variations of speech are provided. Then, general VCSS development guidance using a human-centered design approach is given. Finally, considerations for vocabulary selection, C2 dialogue, feedback, error handling, and evaluation/usability testing are discussed.

2. Definitions

2.1 Command and Control (C2)

Dialogue style that is user-initiated where the user is the decision-maker that commands and directs the application. In this C2 dialogue, the machine is passive but responsive to the commands. Note: This type of C2 machine conversation is also useful for searching, limited menu-driven applications, and limited natural language processing (NLP).

2.2 Confusability Matrix

A tool used in performing a speech-recognition engine vocabulary performance test. The number of spoken words in the vocabulary that are correctly recognized or confused with another word in the vocabulary is recorded in the matrix. Example: For a vocabulary of 10 words each spoken 5 times, a perfect score of 5 in each of the diagonal cells would be recorded. See Table 2 for an example of a confusability matrix.

2.3 Command and Control (C2) dialogue management

The interaction flow structure of the application that enables the user to accomplish the task. Based on the word/phrase recognized and confidence scoring, the C2 dialogue management orchestrates the commanding and feedback to the user comprised of prompts (tones or voice) as well as handling errors.

2.4 Speech Recognition Grammar

A set of word pattern rules that restricts word/phrase choices during the speech recognition process. It tells the dialogue manager what to expect the human to say.

2.5 Human-Centered Design (HCD)

The human-centered design process incorporates the user's perspective into the hardware/software development process to achieve a usable and acceptable system.

2.6 Phonemes

The smallest sound unit in a language that conveys a distinct meaning such as /s/ in “stop.” Phonemes are language specific. They can vary in pronunciation from word to word such as /t/ in “tip,” “stick,” and “water.”

2.7 Recognition Errors (RE)

Errors in a speech recognition system where the system misrecognized a legal spoken word for another, omitted the spoken word or rejected the command word.

2.8 State Node

A node containing a subset of a task vocabulary. Each state node has transition command words to transition into that state from another state and transition out to another state.

2.9 User-Initiated Dialogue

In C2 applications, the user gives direct commands to the system. Typically, this dialogue approach works best in complex task applications. Through restricted vocabulary, it provides a higher degree of determinism compared to natural language processing where the user may say something that is not recognized/understood by the system and result in the system taking the user to an undesired state in the application.

2.10 Voice-Controlled Spacecraft Systems (VCSS)

A system typically comprised of a voice input microphone system, the speech recognition engine, the dialogue management that orchestrates the interaction between the user and the machine, and an output system to provide visual or annunciated auditory feedback to the user in addition to required output to the task application.

3. SRT Limitations

Several challenges exist for applying SRT to deep space human missions. High-performance computing platforms such as used for terrestrial application are not suitable for deep space applications. Unlike low-earth orbit where the Earth’s magnetic field provides considerable protection of a spacecraft and its electronics from damaging radiation, outside the magnetic field the radiation is much more severe [9]. The galactic radiation can cause electronics (if not designed for the deep-space environment) to experience single event effects such as functional interrupts resulting in an abrupt halt to operations and possibly catastrophic failures.

Environmental noise plays a significant role in speech recognition performance, specifically how well the system recognizes speech in the presence of stationary and non-stationary noise. Current technology does well when the signal-to-noise ratio (SNR) is better than 25 dB such as in an office environment. However, a low SNR causes poor recognition results [2]. The combination of enormous reverb such as in a spacesuit and both stationary and non-stationary noise (such as pumps kicking on and off) poses challenges for SRT in space applications. Use of deep neural networks to predict the acoustic/noise environment has shown promising results [8].

Natural language processing (NLP) is still maturing. It still struggles with correctly parsing a sentence and understand its meaning. Therefore, it will not be considered in this paper. (Note: The amount of

hardware and software necessary for NLP would place a significant burden on a spacecraft's size, weight, and power constraints. For example, Apple's Siri uses the iCloud and several servers for its speech recognition function.). Even in human-to-human communications, there are misunderstandings in what was said. Factors such as prosody of the speech indicate grammatical structures and stress of a word which suggests importance in the sentence. The ambiguity of the English language is also another challenge. Homophones (words that sound the same but have a different meaning) can confuse the NLP application. Similarly, word boundary ambiguity recognition can pose speech recognition difficulties (e.g., recognize speech vs. wreak an ice beach) [1].

4. Brief History of Speech Recognition in the Space Program

NASA has been involved in SRT for space applications for quite some time for both spacecraft and ground operations. A few SRT investigations have been performed in an operational environment. All experiments have been in the form of C2 applications and dictation. What follows is a summary of some SRT investigations and demonstrations that have occurred in the space program.

4.1 Ground Investigations

4.1.1 Feasibility of Controlling the Space Shuttle Video System by Voice

In the late 70s, the Jet Propulsion Laboratory (JPL) developed a prototype voice controller to manipulate the Space Shuttle Closed Circuit Television (CCTV) System. It provided an opportunity to investigate the potential of the technology to improve the performance of the Space Shuttle remote manipulator system (RMS) operations [10]. Several successful ground tests occurred at the JSC Manipulator Development Facility to perform berthing, maneuvering, and deploying a simulated science payload in the Shuttle payload bay. The conclusion was that a voice-controlled system would help reduce space shuttle robotic operations workload. [4]

4.1.2 EVA Voice-Activated Information System

In 1990, a voice-activated information system was developed to control a heads-up display on a prototype EVA suit. The system was designed to assess the effectiveness of a voice-activated heads-up display as compared to a manual/electronic wrist-worn or "cuff" checklist during EVA operations. The issue with a manual cuff checklist is that the wrist is not always in the best position to read a page. Also, at least one hand is required to turn the pages. Electronic cuff-mounted checklists have issues with size and displaying data in the presence of sunlight. The voice system was termed an improvement over the manual/electronic cuff checklist allowing both hands on the job while moving through procedures by voice. However, there was an issue with disruptions between the voice communication with the ground and other astronauts versus communication with the SRT [5].

4.1.3 Speech Recognition at Reduced Pressures

In 1993, the Crew and Thermal Systems Branch at JSC performed informal evaluation/experiment of speech recognition at reduced pressures. The evaluation/experiment occurred in the building 7, 11-foot vacuum facility. A speaker-dependent recognizer (called voice navigator) was used in the experiment to determine if recognition accuracy degraded due to lower EVA suit pressure. Test data showed that best recognition results (>92% accuracy) occurred when the system was trained with the person's voice in the system environmental pressure usage. Factors such as background suit noise and voice-communications bandwidth limitations did not affect recognition scoring.

4.2 Space Flight Demonstrations and Experiments

4.2.1 STS-41 Voice Command System Flight Experiment

The results of the JPL-developed voice control of the Shuttle CCTV system provided an opportunity for the Johnson Space Center to pursue development of a Voice Command System (VCS) flight experiment demonstration to control the Shuttle CCTV system—the first-ever control of a spacecraft system by voice [25]. The objective of the flight experiment on STS-41 was to collect baseline data on the effect of microgravity on speech production and recognition, as well as show the utility and operational effectiveness of controlling a spacecraft system by voice.

The system utilized a military speaker-dependent commercial recognizer developed by Spacecraft Incorporated out of Huntsville, Alabama. The unit included a commercial speaker-dependent recognizer made by Votan. The unit required capturing and storing into non-volatile memory command word templates used in the speech recognition process. At power-up, the astronauts had to identify themselves by speaking their name. The unit would then retrieve their templates from non-volatile memory.

The VCS paralleled the Shuttle CCTV switch panel that was comprised of 33 switches, both toggle and push button switches to control the cameras, monitors, and pan/tilt units. Twenty-three command words mimicked CCTV switch panel closures. Two command words, “stow cameras,” was used as a macro command that would configure all four payload cameras into their stow position.

Recognition accuracy of the command word templates captured on the ground dropped about 10% for one astronaut and about 30% for the other. Several factors played into the lower performance including microphone quality (used existing Shuttle headset) and the operational environment. However, both astronauts were highly successful in creating on-orbit voice templates and obtaining a recognition accuracy average of 97%. Both astronauts agreed that the system would be attractive for use during CCTV mission operations, especially macro commands.

4.2.2 Detailed Test Objective 675 “Voice Control of the Shuttle CCTV System

A follow-on flight of the VCS was approved for STS-78. STS-78 was a 16-day mission compared to the 5-day STS-41 mission that provided an opportunity to examine if a longer duration mission affects the speech process. Two astronauts used the system early, midway through and toward the end of the mission. Several modifications were made to the electronics in response to requests by the astronaut office to improve the VCS flown on STS-41. Most notably, the updated system included the use of adaptive speech recognition technology that was cutting-edge at the time. The recognizer outputted the top three words in the vocabulary it thinks was spoken along with confidence scores of each. For questionably recognized words, a query in the dialogue would invoke a “yes” and “no” response to determine what word was said by the astronaut to update the word template. The adaption feature would track changes to the astronaut’s voice. Other modifications included adding a microphone gain feature to help compensate for microphone placement, and four macro commands were incorporated in addition to the “stow cameras” macro from STS-41.

One additional feature added to the system was in-flight raw audio recordings of the two astronauts that used the system. These recordings were stored for ground analysis to determine if microgravity affected the speech process. Preflight audio samples were obtained from both astronauts. Post-flight speech analysis showed that one astronaut’s fundamental frequency changed much more than the other astronaut. In fact, on the 16th mission day, the astronaut had difficulty with speech recognition that may have been attributed to this frequency shift even though the pitch period remained steady.

Overall, the adaption feature worked reasonably well, providing average recognition accuracy for both astronauts of 90% throughout the mission. However, the VCS had limited capabilities in adjusting for placement of the microphone. One identified shortcoming was that the macros did not provide feedback to the astronauts, such as percent complete, nor did they provide the ability to stop/resume the macro. The cabin acoustics environment provided unique challenges as 95 dBspl audio messages were sometimes uplinked and the reverb in the cockpit confused the VCS. During pan/tilt commanding, the querying feature for questionable recognition interrupted the task and therefore is not recommended. Another astronaut observation was that speech recognition for continuous control, such as tracking a location on Earth with cameras, is difficult to do compared to the traditional method of using the switch panel [26]. As experience has shown, crew members will revert to the primary control system to which they are used to if an alternative method is not sufficiently accurate or usable [13].

4.2.3 Flight Experiment Command Word Selection

For both STS-41 and STS-78, the command words were nearly the same. The STS-78 crew modified some of the command words to make it easier for them to remember. Not all CCTV switch panel buttons were implemented, just the most commonly used ones. Macro commands were considered useful by both crews, which permitted one command word to cause a plurality of commands sent to the cameras. The table below shows the command words used that emulated the CCTV switch panel and unique commands. Note that the transition words “voice command” was spoken first and then within 2 seconds “activate” to put the system in the listening mode. If they did not speak activate within 2 seconds, a timer would time out, and the system would return to first listening for "voice command."

Table 1 Voice Command System Vocabulary

A7 Panel Commands	Purpose	VCS Unique Commands	Purpose
<i>Up/Tilt_Up</i>	Tilts camera up	<i>Confidence_Check</i>	Trains all words
<i>Down/Tilt_down</i>	Tilts camera down	<i>Query_Check</i>	Trains "Yes"/"No"
<i>Zoom_In/Close_Up</i>	Zooms camera in	<i>User_Setup</i>	Loads requested parameters
<i>Left/Pan_Left</i>	Pans camera left	<i>Setup</i>	Transition word
<i>Right/Pan_Right</i>	Pans camera right	<i>Voice Command</i>	Transition word
<i>Zoom_out</i>	Zooms camera out	<i>Activate</i>	Transition word
<i>Focus_near</i>	Focus camera near	<i>Stop/Halt/Whoa</i>	Stops camera/pan/tilt movements
<i>Focus_Far</i>	Focus camera far	<i>Macro</i>	Transition word
<i>Monitor_1</i>	Selects monitor 1	<i>Configure</i>	Transition word
<i>Monitor_2</i>	Select monitor 2	<i>Standby/Relax/ Go_To_Sleep</i>	Put VCS into non-listening
<i>Alpha</i>	Select camera A	<i>Move/Adjust</i>	Transition word
<i>Bravo</i>	Select camera B	<i>Macro_1</i>	Reserved
<i>Charlie</i>	Select camera C	<i>Macro_2</i>	Downlinks test pattern
<i>Delta</i>	Select camera D	<i>Macro_3</i>	Views earth using cameras A,D
<i>Middeck</i>	Select Middeck camera	<i>Macro_4</i>	Scans PLB port side w/cameras A/D
<i>FlightDeck</i>	Select Flightdeck camera	<i>Macro_5</i>	Scans PLB STBD side w/cameras C,D
<i>1_Left</i>	Select Monitor1 left side	<i>Calibrate</i>	All 4 PLB cameras placed into known position
<i>1_Right</i>	Select Monitor1 right side	<i>Stow_Cameras</i>	All 4 PLB cameras into ascent/reentry position
<i>2_Left</i>	Select Mon 2 left side	<i>Yes</i>	Query response for choosing <u>correct</u> word spoken
<i>2_Right</i>	Select Mon 2 right side	<i>No</i>	Query response for <u>not</u> choosing a word spoken
<i>Open_Iris</i>	Opens the camera iris	<i>1,-2,-3,-5,-10,15- degrees</i>	Number of degrees selected for a camera lens or pan/tilt movement command
<i>Close_Iris</i>	Closes the camera iris		
<i>Change_Rate</i>	Changes the pan/tilt rate		

5. Speech Variations

The human speech process contains variations associated with fundamental physiological and/or psychological factors. These differences can be the result of intrinsic human variations, such as vocal tract cavity changes, and/or changes due to the environment, physical, and cognitive stresses.

5.1 Human Intrinsic Speech Variations

Speech recognition or a natural language understanding system will never achieve 100% recognition and understanding; Even humans cannot attain that. In fact, a speech recognition system is similar to a person with hearing problems such that hearing worsens with higher noise levels. The purpose of SRT is to detect and categorize a sound wave coming from a microphone into one of the basic units of speech, namely word comprised of phonemes. In the English language, there are about 40 phonemes while other languages have more or less. The challenge for the speech recognition system is to detect these phonemes, compare them against other similar phonemes using statistical models, and match them against a known library comprised of known words, phrases, and sentences.

Figure 1 shows the speech production vocal organs associated with the vocal tract. The lungs, diaphragm, and stomach serve as the air stream source through the larynx. The larynx includes the vocal cords that modulate the airflow from the lungs. This modulation creates a quasi-periodic pressure wave impulse with a specific frequency determined by muscle tension force and the mass and length of the vocal tract. These factors vary by age and gender. The vocal tract cavities filter the air stream between the glottis and the lips. The lips, tongue, and teeth further modify the air stream. The result is a sound wave emanating from the mouth as either voiced or unvoiced speech signal.

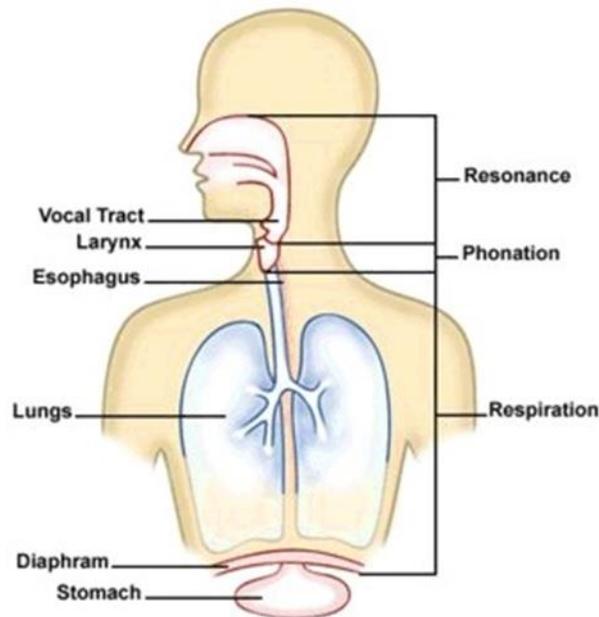


Figure 1 Voice Production (Johns Hopkins Voice Center)

Unvoiced speech is aperiodic with low energy compared to voiced speech. For voiced speech, both the vocal chords and the vocal tract are used. Consequently, voiced speech is periodic and is most important for intelligibility. The energy of voiced regions is an order of magnitude larger than of unvoiced regions [2]. An example of voiced speech would include the vowel sounds. Example of unvoiced would be like the consonants /p/, /s/, /t/, or /k/. Also, some nasal consonants such as /n/ and /m/ are not as energetic as

voiced sounds. This can pose a problem with SRT trying to determine the beginning of a word/phrase. The problem is further exasperated with speakers that are soft-spoken. For applications that use far-field microphones such as array microphones, background noise can worsen the issue, especially for unvoiced speech.

5.2 Factors Affecting Speech in Space

The spacecraft environment and the mission tasks present challenging problems for speech recognition. In addition to intrinsic speaker variations, the environment, physical, and cognitive stress in a space mission can further affect the speech process and recognition. For example, the microgravity environment causes no sinus drain and micro-gravity causes muscular atrophy that could alter the speech process.

To date, only a few experiments/investigations regarding the speech process in the space environment have occurred [7, 25, 26]. Spacecraft volume and layout affects the reverb of a speech signal which can cause smearing of the spoken words [14]. Spacecraft systems typically have loud uplink and/or caution and warning audio message capabilities that can leak into the microphone and corrupt speech recognition. A loud cabin environment can create a Lombard effect, causing the crewmember to speak loudly over the background chatter/noise [11]. EVA activities can put physical stress on the crewmember that can alter their breathing/speech. The same can occur with tasks that have a high cognitive workload [12]. In short, the many human intrinsic speech variations pose challenges for spacecraft applications using speech control and natural language processing. The next section provides design considerations to help mitigate these recognition challenges.

6. VCSS Development Considerations

Developing a VCSS involves several human factors engineering (HFE) fields including physiology, psychology, and linguistics. It also comprises computer science, electronics and acoustics engineering, and signal processing. Human-in-the-loop evaluation is also necessary to optimize/refine the system. Since astronauts are highly skilled with knowledge of the task through training, this report focuses on considerations for implementing a C2 interactive speech control system for space applications. Following a description of the Human-Centered Design (HCD) process recommended for development of a VCSS application, VCSS design guidance in vocabulary development, handling errors, dialogue design, and usability evaluation and testing are given.

6.1 Human-Centered Design (HCD) and the Development Process

Speech recognition applications can be quite human-machine interaction-intensive especially in a multi-modal application where both voice and another modality, such as gestures, is used. Developed incorrectly without factoring the human element can result in an unusable system. Therefore, as part of the systems engineering effort, an HCD process is the recommended development approach. The HCD approach ensures the VCSS meets requirements and crew acceptance of the system. Also, it is highly recommended that a human systems integration (HSI) practitioner participates in the development early in the project lifecycle to ensure the human element is factored into the design of the system. Key aspects of the human-centered effort are [18]:

- The design is based upon an explicit understanding of the crew, the task and the environments.
- The crew is involved throughout the design and development process.
- The design and requirements are refined by evaluation of the prototype system.
- The process is iterative.

For flight systems, the NASA systems engineering process per NPR 7123 is used. Figure 2 shows an abbreviated NASA systems engineering project life-cycle phases along with key project milestone reviews. Most of the HCD occurs in the formulation phases leading up to critical design review. During the implementation phase, design evaluation becomes formal usability testing with the flight design as the system components are integrated with the rest of the system and requirements verified. Finally, system requirements validation to certify the system for flight is performed.

NASA Life-Cycle Phases	Approval for Formulation			Approval for Implementation		
Project Life-Cycle Phases	Pre-Phase A: Concept Studies	Phase A: Concept & Technology Development	Phase B: Preliminary Design & Technology Completion	Phase C: Final Design & Fabrication	Phase D: System Assembly, Integration & Test, Launch & checkout	
Human Spaceflight Project Life-Cycle Reviews		SRR SDR	PDR	CDR	SIR	Legend SRR-System Requirements Review SDR-System Definition Review PDR-Preliminary Design Review CDR-Critical Design Review SIR-System Integration Review

Figure 2 NASA Life-Cycle Phases with Project Milestones

HCD activities are part of the systems engineering process. Depending if the VCSS is a research/development project or a flight system, the process may differ. A key element of the HCD process is user evaluations that feed back into the development effort. Figure 3 shows the iterative HCD activities adopted from ISO standard 9241-210 [18].

The figure does not suggest a linear process but rather illustrates how each activity uses outputs from other activities. A short description of each activity follows.

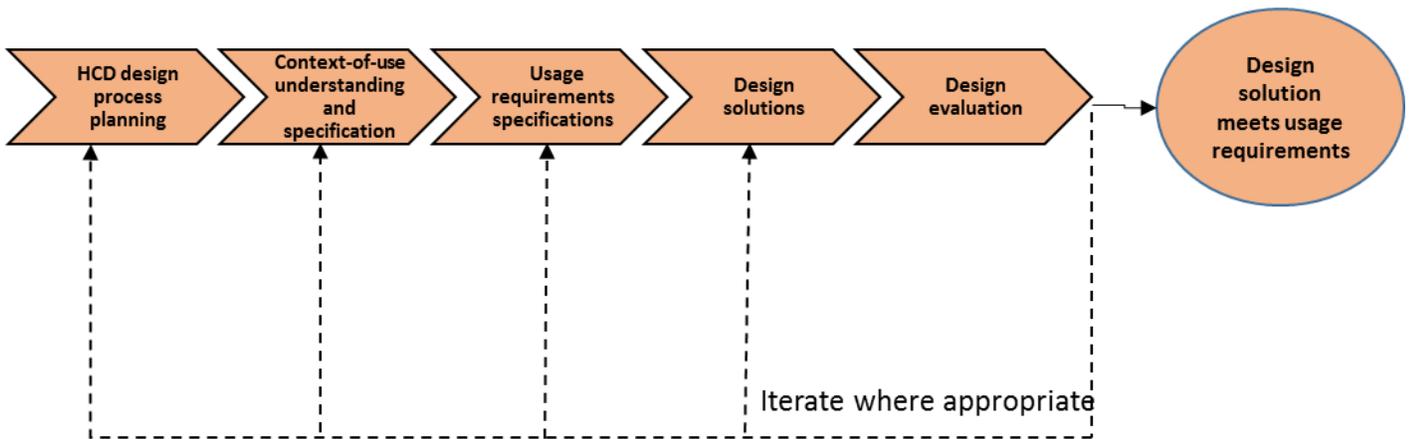


Figure 3. Human-Centered Design Process

6.1.1 HCD design process planning

This activity is ideally led by an HSI practitioner with the main objective of developing a HSI plan that integrates HCD into all phases of the VCSS project, as well as ensuring all HSI domains are addressed. The process includes requirements development, project resources, risk assessment, and scheduling of HCD activities that factor adequate time for evaluations and design iterations/optimization.

6.1.2 Context-of-use

The key activities include working with stakeholders to define the goals and tasks of the systems. HFE personnel are heavily involved in cognitive engineering assessment and analysis of the task, the crew, and system all working together. A concept of operations (ConOps) is used to define nominal and contingency use cases and task scenarios of what the user must do regarding actions and/or cognitive processes in the given environment to achieve the overall task. The use cases/scenarios help refine VCSS requirements as well as build the preliminary task vocabulary. They also help describe the task functions that need to be performed which defines the human-machine interaction behavior. As evaluations of the model (whether it is a wireframe, prototype or mockup) continue, feedback from the crew provides updates to the ConOps, scenarios, use-cases, VCSS requirements and design.

6.1.3 Usage Requirements & Specifications

Based on the task and functional analysis, usage requirements are developed along with the system requirements. Then decomposition of system requirements is performed to further define the VCSS. Many of the functional/sub-functional requirements are stated regarding performance such as time to perform a sub-task or speech recognition processing time (spoken utterance recognized to system output). Based on the functional requirements, a functional architecture is developed showing the functions and sub-functions. All requirements should be allocated to the functions/sub-functions of the VCSS. Also, requirements are allocated to either the hardware, software, or the user. In the design phase, the design is compared against the system requirements to assure compliance or to re-evaluate the design/requirements.

6.1.4 Design Solution

This activity focuses on creating a design that meets all requirements, both the functional and non-functional requirements (such as weight, power, and size). There are three main development activities involved to develop a VCSS, namely VCSS design, VCSS dialogue design, and Human Factors Engineering. All three are performed interactively. Figure 4 shows a Venn diagram of the three main development activities interacting to create and optimize the VCSS application. The acoustic environment is factored into all VCSS design considerations.

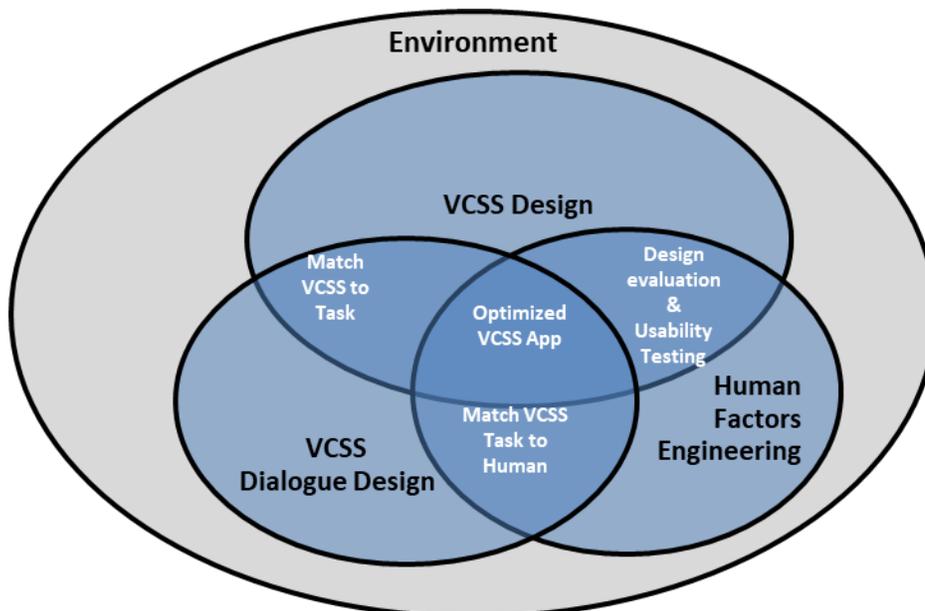


Figure 4 VCSS Design & Development Process Venn Diagram

The VCSS design effort develops the hardware and software/firmware necessary to support the task in the given environment. Optimization of the VCSS hardware/software to the task occurs between the VCSS design and the VCSS task design activities such as determining if a backup control is needed or type of feedback. Also, the speech recognition engine that will be used is selected (see confusability matrix testing). Based on the task use cases/scenarios, the C2 dialogue algorithm (see C2 Dialogue Design) is developed through the VCSS dialogue design and VCSS design efforts. As part of the VCSS design effort, the hardware computing platform is matched to the speech recognition engine selected for the task. The type of microphone (head-worn or array) and the front-end noise/echo suppression algorithm are developed as well. HFE works with the VCSS design engineers to develop and perform numerous evaluations and tests with the crew to optimize the VCSS design with the human regarding usability and crew acceptability. This optimization may include regarding minimal workload, response time, and intuitive C2 dialogue navigation. HFE also supports the development of the VCSS task and vocabulary selection to ensure an optimized VCSS experience for the user. Note that, depending on the phase of the project, there can be different levels of effort in these development activities.

6.2 Vocabulary Selection

Task vocabulary selection is both an art and a science. Words that sound similar to a human may be recognized differently by SRT. SRT statistical recognition algorithms can produce artifacts in the recognition process that may require replacing words that otherwise appear would be good candidates. (Note: It is highly recommended to engage the speech recognition vendor in the vocabulary selection process, particularly reporting issues encountered during the performance evaluation of the vocabulary. They have the tools to optimize recognition parameters.) The following are considerations in selecting the vocabulary.

6.2.1 Task-Relevant Vocabulary

Vocabulary selection is based on the functional requirements levied on the system and the system ConOps that spell out the end goal(s). From these two documents, use cases or scenarios drive task development that must meet the requirements and end goals. The vocabulary should be natural and reflect the task actions the system must do, e.g., command a camera pan/tilt unit should have the vocabulary words "pan" and "tilt" with the associated "left" "right," and "up/down" respectively. It should also be distinctive to minimized recognition errors. However, performance testing may determine that an alternate task vocabulary word(s) may be required.

6.2.2 Vocabulary Phonetic Features

During the selection of task-related vocabulary words, the design team should be aware of vocabulary phonetic features that could drive the use of specific vocabulary words [3]. Most words contain voiced and unvoiced consonants (or consonant pairs) that may determine the use of certain words. Voiced consonants such as /g/ in "good" or voice consonant pair /th/ as in "they" make sounds using the vibration of the vocal cords. Unvoiced consonants such as /p/ as in "put" or /t/ as in "ten" only use the teeth, tongue, and lips for the pronunciation.

Words that have low energy sounding consonants such as /s/ and /p/ in "stop" or nasal-sounding consonants such as /n/ or /m/ as in "none" or "more" can be troublesome. Like voiced consonants, vowel sounds use the vocal cords. Both produce more energy than unvoiced consonants. Also, be cautious of multi-syllable words that contain weak regions within the word such as "stop system" that contains a /p/ and an /s/ back-to-back in the middle of the word. Some recognizers may view this as silence. If the recognition engine/front-end microphone processing cannot compensate for the environment, task-related vocabulary word phonetic features will make the recognition more challenging.

6.2.3 Vocabulary Confusability Performance Testing

After the preliminary vocabulary selection, performance testing of the candidate(s) recognizer’s ability to recognize commands should be performed. Rather than depend on manufacturer performance data, the VCSS project should do an independent test. Typically, recognizer manufacturers will provide performance information about their product. However, most performance data occurs in a benign/controlled environment with trained speakers. The preference is to perform the test both in a benign and a simulated/actual environment. The benign environment test is performed first to baseline recognition performance and to understand the recognition engine's constraints and behavior response to spoken commands. Again, enlisting the services of the speech recognition engine vendor is highly recommended.

Standard recognizer performance testing does not exist. However, use of a confusability matrix (as shown in Table 2) helps determine which recognizer will provide the performance/features needed for the application. The test provides valuable information on how well the recognizer recognizes spoken in-vocabulary words(words part of the vocabulary) and how well it rejects out-of-vocabulary words (words not part of the vocabulary). Correct recognition responses occur down the diagonal part of the matrix. Substitution errors fall along the off-diagonal elements. Rejections and deletions can also be recorded on the table. The preference is for the vocabulary consist of words in a specific node (a subset of the entire vocabulary) as it is going to be used in an application. The matrix data also serves as reference data in an application to resolve recognition issues such as substitution errors within a state.

If rejection testing is done, the test should document the rejection threshold of the recognizer and the test set used (in and out-of-vocabulary words, coughs, filler words like “um,” ” ah,” etc.). It is highly recommended to repeat the test of the vocabulary enough times to make the data statistically significant. Note that the confusability matrix assumes that each command word is one utterance and not a sentence. Multi-word commands such as “go-to-sleep” or “ activate voice loops A and B” are considered one utterance.

Table 2. Vocabulary Confusability Matrix

		Actual Response				
		Word 1	Word 2	Word 3	Word 4	Word 5
Predicted Response	Word 1	x				
	Word 2		x			
	Word 3			x		
	Word 4				x	
	Word 5					x
	Word 5					

Several recognition performance metrics can be obtained from the test. Table 3 shows the scoring types to help in assessing a recognizer. Word Error Rate (WER) and Word Recognition Rate (WRR) are the common metrics used in scoring the performance of the recognizer when used in transcription/dictation since it measures the recognized word sequence against the spoken word sequence.

Table 3 Recognition Performance Scoring Calculations

Recognition Performance (%)	Calculation
Recognition Accuracy	$\frac{(\# \text{ Correct Words Recognized})}{(\# \text{ Test Words Spoken})} \times 100\%$
Insertion(I)	$\frac{(\# \text{ Insertion Words})}{(\# \text{ Test Words Spoken})} \times 100\%$
Substitution(S)	$\frac{(\# \text{ Substituted Words})}{(\# \text{ Test Words Spoken})} \times 100\%$
Deletion(D)	$\frac{(\# \text{ Deleted Words})}{(\# \text{ Test Words Spoken})} \times 100\%$
Rejection	$\frac{(\# \text{ Rejection Responses})}{(\# \text{ Test Words Spoken})} \times 100\%$
Word Error Rate (WER)	$100\% \times \frac{(S+D+I)}{(\# \text{ Test Words Spoken})}$
Word Recognition Rate	$1 - \text{WER}$
Command Accuracy	$\frac{(\# \text{ of commands correctly recognized and processed w/ correct feedback})}{\text{Total number of commands spoken}} \times 100\%$

As a cautionary note, in usability testing, command accuracy can be more important than recognition accuracy. It provides a measure of a performance metric of the system in the actual task environment. Note that both the correct command and correct system response must occur. The command was either successful (100%) or not (0%). Therefore, even though a recognizer scored high in recognition accuracy, it may fail to provide a suitable command accuracy [22].

6.3 C2 Dialogue Design

The C2 dialogue management gives the VCSS the behavior or “look and feels” of the interface to the user. A C2 dialogue is more user-driven, spending more time issuing commands and focused on completing complex tasks. A major goal of the dialogue is to ensure the task keeps moving forward and errors are mitigated. Even small amounts of errors due to failed recognitions can have a significant impact on time-critical applications [19]. Designed correctly, it will provide a high degree of user acceptability/usability. This requires a synergistic interaction between the user and the VCSS to accomplish the task in an efficient and effective manner. Situational awareness must also be a design consideration of the VCSS that contributes to what the user needs to perceive and understand as well as helping the user project the future state of the system. [15]

6.3.1 C2 Dialogue Structure

The overall C2 dialogue flow logic should be a deterministic state node machine to restrict the command words of the task and reduced recognition errors. The grammar and rules determine the flow logic of the interface. Each state node contains a sub-command word vocabulary relevant to the task for that state node. Transition in and out of each state node occurs through transition voice commands that are located in each state node to permit the user to transition to other state nodes. Within each state node, the user should be able to exit out of the application task and into a standby state node. An example of a dialogue structure is shown in Figure 5.

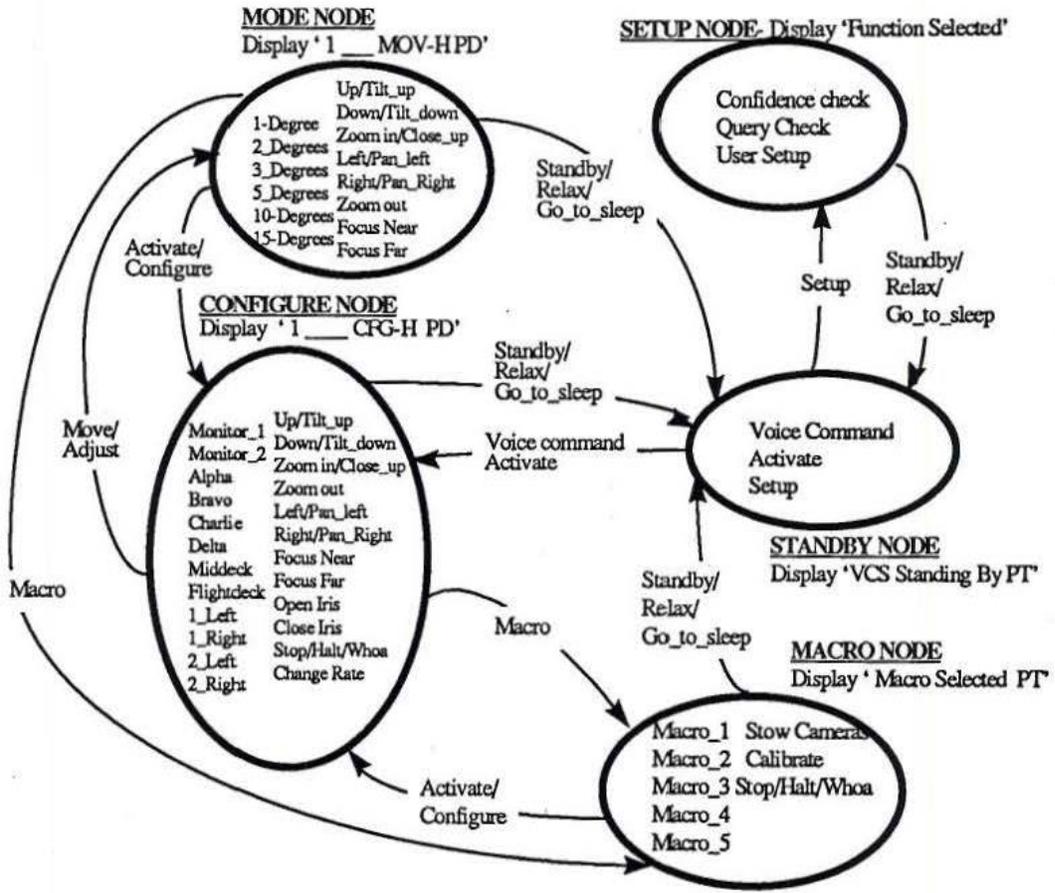


Figure 5 STS-78 Voice Command System Dialogue Structure

6.3.2 VCSS Activation and Readiness

Background noise and crew/mission control communication chatter could potentially inadvertently activate the system. Therefore, consider using an “arm and fire” command structure to ensure the system task C2 dialogue is reliably activated when needed. The “arm” command should be a robust word that causes the C2 dialogue to transition to a state node that awaits the “fire” command within a certain time period. If the “fire” command is not annunciated within the specified time, the system returns to listening for the “arm” command. Auditory or visual or both readiness indication should be provided to the user that the system is ready to accept voice commands. In case of background noise inadvertently triggering the recognizer, consider using a push-to-talk electrical switch. In addition, in the event an “arm-and-fire” commanding structure is not working well, consider providing a toggle switch to transition from standby to commanding the system.

6.3.3 VCSS Deactivation

Consider a means to deactivate the voice control of the task through a meaningful multi-syllable command word, distinct from the other vocabulary words. For gloved-box operations such as dictation/taking notes, consider a VCSS microphone input switch to disable the voice into the recognizer might need to be located inside the glove-box. When the user needs to speak to another crew member, s(he) can hit the switch to disable communications with the recognizer. Like activation, consider providing a toggle switch and associated feedback to transition to a standby/non-commanding mode.

6.3.4 Common Transition Command and Query Words

For C2 applications, being able to move to any of the state nodes is important. Therefore, state node transition command words and associated feedback prompts should be made available at each state node.

For applications that contain confirmation queries (Ex: Did you ask for system status?) or confirmation of executing a specific command (e.g., the system only expects a “yes” or “no,”), the system should have those command words available at each state node.

6.3.5 Alternate Transition Command Words

Consider an alternate set of command words/phrases that perform the same function as the primary command word vocabulary. This permits backup commands in case the primary commands are not working well for the user. For example, the command “standby” to place the system in a standby state node can also be accomplished with the command phrase “Go to sleep.”

6.3.6 Guidance on Task Feedback

User task feedback is critical to the success of a speech interface. For space applications, feedback also serves as a safety feature to allow recovery of an unsafe configuration or inadvertent command initiated by the user that could result in confusion if inadvertently taken to another state node. Feedback can be a visual display or an audible tone or speech message. Without feedback, the user may assume the spoken command was recognized and executed correctly. Lack of feedback can cause user frustration and errors. Factors such as consistency and length of the feedback also affect the user [20, 21]. The following guidance for C2 application feedback design should be considered:

- Provide a display to reduce task workload memory. The display provides a visual cue of what was heard, where the user is in the application, and any errors.
- Use short tones to convey quick feedback to the user. Each tone should be different. For example, a correct recognized command and an error tone should be different.
- Speech messages should be kept short and concise. Again, the focus is to keep the task completion moving forward at an acceptable rate.
- For commands that require more than a few seconds of wait time such as macro commands, the feedback should provide a periodic indication to the user that the command is in execution. For example, a display would provide a running tally of percent complete of a command.
- A mix of visual display and tones/messages is preferred in a task.
- Provide a mix of a tone and a speech message to aid the user in using the system.
- Since most recognizers need to indicate when they are ready to receive a spoken command (end-point detection), the system should provide a reminder to the user to speak after the tone.

6.4 Handling Recognition Errors

Despite good human factors design and the best SRT, there is a likelihood of recognition errors occurring during the use of the system, particularly in a noisy environment. Errors in an application can affect the user’s mental model that contributes to user frustration. This frustration can contribute to error amplification [3] where one error such as a state node error (in the wrong state node issuing commands from another state node) leads to subsequent recognition errors. Therefore, a VCSS should be designed to tolerate the various types of recognition errors that can occur.

Correcting and recovering from an error takes time away from completing the task while specific procedures in the task may not tolerate having to deal with correcting the error. A key aspect of the interface is how the system responds to human error [20]. The speech recognition C2 dialogue should ensure that the user speaks the correct command words in the correct state node. Also, prompts should guide the user when to begin speaking a command word. What follows are the various types of recognition errors that can occur that the designer should consider in a C2 application.

6.4.1 Substitution Error

Substitution error is an instance of an error in which one word in the command vocabulary is incorrectly recognized as another command word in the command vocabulary. For example, the user says "status," and the system recognizes "six."

Consider designing system feedback to catch the error and provide options to the user such as canceling the command. A substitution error cannot be detected by a recognition system. The best line of defense is to consider error reduction by design such as selection of a small and dissimilar vocabulary derived from the confusability matrix test for the given state node.

6.4.2 Rejection Error

Rejection error is an instance of an error due to either incorrectly spoken command utterance or background noise (correct rejection) or rejection of correctly spoken utterance (false rejection).

Consider prompting the user again to repeat the command. The assumption is that the system is listening for commands and the user is speaking to the system. Rejection errors can occur due to end-pointing parameters set incorrectly, background noise, strong dialect, or speaking to the crew or mission control while the system is listening. For the latter, the preference is to disable the recognizer. For adaptive recognizers, the system could return words it thinks it heard (top 2/3 based on confidence scores) and let the user pick. Then, the system would update the user template for that word.

6.4.4 Deletion Error

Deletion error is an instance when the system incorrectly omits a component of a valid command string and does not respond. For example, the user says, "Select camera alpha" and the system recognizes only "select camera."

Consider confirming the spoken string via feedback to catch deletion errors. The system could ask for repeat command, or the dialogue provides a different mix of command word/phrases that it will execute on. For example, in the above situation, the system would recognize "select camera" but would ask for which camera since that portion was not recognized.

6.4.5 Insertion Error

Insertion error is an instance of an error occurring due to either spurious noise or illegal utterance outside the vocabulary falsely accepted as a legal command word. For example, during high background noise levels the system captures what it thought was a valid command word. Alternatively, user speech disfluency (any of various breaks, irregularities within the English language, or meaningful non-verbal sound that occurs within the flow of otherwise fluent speech.) results in the recognizer detecting a valid spoken command.

Consider using a recognizer that contains different acoustic models to deal with the noise and provide a means to inhibit the recognizer when the user is not commanding the system. The system should also provide feedback to the user.

6.4.6 Spoke-too-Soon Error

Spoke-too-soon error is an instance when the user spoke before the system was ready or background noise was detected as speech. This usually happens when the user is not notified when to speak and/or the background noise levels are high.

Consider designing in a short prompt along with a tone or beep sound to indicate to the user the system is ready to accept a spoken command. Alternatively, a push-to-talk button could be used, particularly in noisy environments.

6.5 Usability Evaluation and Testing

Despite using the best human-centered design processes, there is still the likelihood that the VCSS design has flaws. Therefore, usability evaluation and tests are a vital part of the human-centered design process and are highly recommended during the development phase of the project [23]. This section provides usability evaluation and test considerations as part of the VCSS development and certification effort. Though the assessment and test can be time-consuming and expensive, the return on value has been shown to be as much as 25-35% improvement [24]. An HSI practitioner should lead usability evaluation and test development planning.

6.5.1 Test Planning and Scheduling

Test planning should begin early in the development lifecycle for both usability evaluation and testing. The development schedule should permit numerous evaluations and test sessions. Also, scheduling should allow enough time between evaluations and test to make changes based on an evaluation or test outcome. Usability evaluations are informal tests to evaluate candidate systems or continue to evolve a selected design after preliminary design review. After critical design review, plan on doing several crew evaluations in a high-fidelity environment to further refine the vocabulary and dialogue management. The final tests are usability run-for-the-record testing to verify/validate requirements.

6.5.2 Performance Metrics

VCSS performance metrics developed for the usability evaluation or testing should be observable and quantifiable. They should disclose the VCSS interface effectiveness (completing a task in a certain time), efficiency (effort required), and satisfaction (How happy was the user with the use of the system?) [22]. In addition, for a VCSS, how many errors that caused a loss of efficiency or task failure should be captured. Note that errors in speech recognition and C2 dialogue prompting/feedback should be uncoupled, i.e. tested independently, as excellent recognition with a poorly designed C2 dialogue could result in out-of-vocabulary words is no better than a poor performing recognizer hiding an effective C2 dialogue design [3].

6.5.3 Test Facilities

A usability lab should be available for performing usability evaluation and testing. The lab should be equipped with instruments and data capture devices that the HSI practitioner recommends for evaluating/test the VCSS. Early on, the VCSS is a prototype or engineering model. For usability testing to formally verify and validate requirements, the VCSS should be a flight equivalent unit or flight unit reserved for testing and the environment should be as close to the actual one as possible.

7.0 Conclusion

The guidelines and considerations presented here provide a project team with a systematic approach to developing a C2 speech application for space. Though speech recognition technology has improved considerably, for space applications it presents many mission challenges to overcome. However, a reliable and robust C2 VCSS is possible with a human-centered design process, iterative development usability evaluation/test, careful vocabulary selection, and dialogue management design and grammar rules.

Acronym List

C2-Command and Control

CCTV-Closed Circuit Television System

ConOps-Concept of Operations

HCD- Human-Centered Design

HCI- Human-Computer Interface

HRP-Human Research Program

HSI- Human Systems Integration

ISO- International Standardization Organization

JIT-Just-in-time

MCC-Mission Control Center

NPL- Natural Language Processing

NPU-Natural Language Understanding

RE- Recognition Errors

SRT-Speech Recognition Technology

STS- Space Transportation System

VCSS-Voice Controlled System

WER- Word Error Rate

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