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Trades, Architecture, and Design of the Joint Augmented Reality Visual Informatics System (Joint AR) Product

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Future expeditions will enable exploration and study of the planetary surfaces of the Moon and Mars by performing extravehicular activity (EVA) operations. Present-day International Space Station (ISS) EVA operations require an intricate choreography of crew, space suits, tools, systems, and flight teams to plan, train, and execute with limited advanced informatics. In this paper, the Joint Augmented Reality Visual Informatics System (Joint AR) project team at NASA Johnson Space Center (JSC) characterizes the design space for developing a modular augmented reality (AR) device for a spacesuit form factor that can support crew decision-making for EVA. The Joint AR product was defined via trade studies and market analysis of previous EVA display efforts, various AR components such as optics, commercial AR systems, light engines, data interfaces, and graphics engine software. This paper outlines the defining architectural design decisions, including safety criticality considerations, interfaces, and computer architectures. The outcomes of these studies result in a prototype design which is defined here as the Joint AR product. This work aims to enable a community-wide discussion toward realizing necessary suit-compatible AR features and capabilities for future missions.

Nomenclature

API	=	application programming interface
AR	=	augmented reality
ARGOS	=	Active Response Gravity Offload System
cFS	=	Core Flight Software
CLPS	=	Commercial Lunar Payload Services
COTS	=	commercial-off-the-shelf

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CPU	=	central processing unit
DSEE	=	destructive single event effects
EPG	=	environmental pressure garment
EVA	=	extravehicular activity
GFE	=	government furnished equipment
GPU	=	graphics processing unit
HITL	=	human-in-the-loop
HIVE	=	Human Integrated Vehicles and Environments Lab
HLS	=	Human Landing System
HPSC	=	High Performance Space Computer
HUD	=	heads-up display
ISS	=	International Space Station
IRCD	=	Interface Requirements Control Document
ISP	=	integrated solution provider
IVA	=	intravehicular activity
JETT	=	Joint EVA Test Team
Joint AR	=	Joint Augmented Reality Visual Informatics System
KLM	=	Keystroke-Level Model
LCD	=	liquid crystal display
LED	=	light emitting diode
LunaNET	=	Lunar Network
OEM	=	original equipment manufacturer
OLED	=	organic light emitting diode
ORU	=	orbital replacement unit
RFI	=	request for information
RFP	=	request for proposals
SEFI	=	single event functional interrupt
SEU	=	single event upset
TID	=	total ionizing dose
TLX	=	Task Load Index
TRL	=	Technology Readiness Level
UI	=	user interface
VR	=	virtual reality
xEMU	=	Exploration Extravehicular Mobility Unit
xEVA	=	Exploration Extravehicular Activity
xEVAS	=	Exploration Extravehicular Activity Services
xINFO	=	xEMU Informatics Subsystem

I. Introduction

THE future of human spaceflight is being driven by NASA's Artemis Campaign Development which involves the close choreography of multiple industry vendors at every stage of spaceflight operations- from launch, surface exploration, to re-entry. Contractual mechanisms are being created and solicited by NASA to industry vendors such as Human Landing System (HLS) services development,[1] Exploration Extravehicular Activity Services (xEVAS),[2] Commercial Lunar Payload Services (CLPS),[3] and Lunar Network (LunaNET)[4] to enable a sustained human presence on the lunar surface. Within this integrated industry-government model, future human spaceflight will depend even more on distributed assets, vehicles, and payloads with the need to have digital data span across assets for local crew consumption and utilization. This complex human-machine teaming scenario will require all agents in an EVA, utilizing assets from both NASA and industry vendors, to have shared situation awareness via distributed display hardware and translatable data visualization via software.[5]

Today, displays are a ubiquitous component of everyday life. Modern-day cell phones and computers, continuously receive, generate, and relay useful information to end users. Leveraging many aspects of modern computing, display systems rely on heterogeneous architectures and advanced graphics engines to process and render digital content. Additionally, software frameworks and application programming interfaces (APIs) enable development of applications featuring user interfaces (UIs) that seamlessly and effectively covey information to users.

However, traditional Earth-based displays rely on highly-optimized, non safety-critical software and the latest commercial-off-the-self (COTS) hardware, both of which pose a high risk of malfunction or failure when operating in the lunar and deep space environments.[6,7] These harsh environments introduce challenges relating to extreme thermal conditions and cosmic radiation that will quickly degrade critical display elements such as processors, light engines, and other small electronic components.[8] Therefore, there is a need for the intentional design for a radiation tolerant, safety critical architecture to support sustained informatics displays to meet the needs for deep space missions.

Among the variety of space vehicles anticipated in Artemis, spacesuits play a unique role in this informatics and data ecosystem. Crew are highly confined and ultimately dependent on the spacesuit to perform any activities outside of a host vehicle. In this capacity, the suit offers a potentially consistent, centralized, and seamless access point for crew to consume and interact with data via a custom suit-mounted display, otherwise known to the extravehicular activity (EVA) community as EVA *informatics*. To address this need of enabling crew displays in deep-space settings, the Joint Augmented Reality Visual Informatics System (Joint AR) project has developed a modular display and control system with the capacity to become safety critical, fault-tolerant, and flight certifiable within a spacesuit form factor. As the name implies, Joint AR explores how a near-eye augmented reality display might be fielded as a centralized information display upon which crew can make mission decisions while performing EVA.

This paper outlines the design decisions, architecture studies, and market analyses conducted between 2018-2023 for the Joint AR project. In doing so, this paper describes important trade space dimensions and corresponding insights gleaned from attempting to realize a spacesuit compatible AR display that supports the work context of EVA operations. It is important to note that this paper does not offer a definite flight design solution, but rather unpacks the trades and choices made to inform component selection of prototype suit hardware. The trades have also informed software products which are positioned to meet safety critical and radiation tolerant needs. Coupled to both the hardware and software trade spaces is the underlying ground support products needed to support envisioned EVA work demands for Mission Control and the intravehicular activity (IVA) crewmembers. Those products are not outlined within the scope of this paper. The hardware and software design presented in this paper is a snapshot of progress made between Fall 2019 through Spring 2023.

II. Engineering Assumptions

The Joint AR project began in 2019 as the Informatics (xINFO) Displays and Controls component of the Exploration Extravehicular Mobility Unit (xEMU) project. The team based iterative design and development activities off an overarching set of system assumptions as shown in Table 1. These assumptions were compiled from heritage xEMU government furnished equipment (GFE) project[9] documents (prior to the xEVAS contract release), EVA operations and engineering stakeholder discussions, technical presentations with community feedback, and subsequent xEVAS contract requirements. Important to note here is that the Joint AR project scope span both the xEMU GFE project and the corresponding xEVAS contract.

Table 1. Joint AR Engineering Assumptions

1.	The xEMU shall be the reference design to baseline trades and decision matrices.
2.	Crew shall not have anything mounted to the head within the spacesuit
3.	The display system shall be modular for any suit configuration
4.	Compute hardware and software shall support Class A safety critical features
5.	Hardware and software shall incorporate radiation and fault-tolerant strategies
6.	Software shall be compute hardware agnostic
7.	Software shall be operating system agnostic
8.	System shall rely solely on onboard compute capabilities (i.e., no cloud computing available)
9.	System shall be capable of augmenting core capabilities by visualizing data from other assets
10.	Software shall be low compute
11.	Software shall be performant for modern display rendering needs

In context to the recent xEVAS requirements, Table 2 shows a side by side comparison of the xEVA Concept of Operations (EVA-EXP-0042)[10] and the xEVAS Information System Requirement (RQMT-065).[2] The Concept of Operations document provides a vision of what might be worthwhile fielding in a future EVA scenario and the corresponding xEVAS requirement depicts what the xEVAS vendors will be expected to deliver. This visual depiction is intended to share what the Joint AR team primarily scoped to drive the display functions and how they may be translated for future xEVAS-related use-cases. The Joint AR software focuses on each of the EVA-EXP-0042 requirements as a separate function and application (or “app”) within the display.

Table 2. Concept of Operations and Requirements Mapping

Exploration EVA System Concept of Operations (EVA-EXP-0042)		**xEVAS Contract Requirement: Information System (RQMT-065)** *Applicability: ISS or Artemis (or Both)* *The xEVA System shall provide an EVA information system and graphical display with the following key information to the suited crew member.*	
ID	**Description**	**ID**	**Description**
1	Suit systems monitoring and consumables displays Consumables calculation	A	Consumable monitoring and display (Both)
2	Procedure and cue card viewing	B	Procedure viewer (Both)
3	Viewing of diagrams, photographs, annotated images, and videos	C	Display of photo imagery and graphics (Artemis required, ISS goal)
4	View timeline status, including time ahead/behind and consumables margin	D	Timeline viewer (Artemis)
	----	E	Data storage (Artemis)
5	Text communication from both MCC and an IV	F	Display for send/receive of text messaging (Artemis)
6	Verifying helmet camera video framing and quality	G	Camera viewfinder (Artemis required, ISS goal)
	----	H	Recording of crew audio/video/still image field notes (Artemis)
7	Navigation and tracking	I	Map display, which includes EVA crewmember position and supports real-time navigation (Artemis Only)
	----	J	Communication of relevant biomedical information. (Artemis required, ISS goal)
8	Ability to receive near real-time updates and content from MCC during the EVA		----
9	Augmented reality graphics and cues		----
10	Interface with and transmission of scientific instrument, sensor, and camera		----

Given the discrepancy in requirements applicability, some discussion is warranted. Functional requirements which the Joint AR team *pursued* and are not included within xEVAS include: ID 8) the ability to receive real-time updates from mission control, ID 9) augmented reality graphics and cues, and ID 10) interface capabilities with science instruments and cameras.

While the spacesuit may be physically perceived as a single-user vehicle, the system is a multi-agent data ecosystem which incorporates communication between the Mission Control Center (MCC), intravehicular (IV) crew members, and the EVA crewmember. In current day EVA, MCC is the primary, live audio instruction for crew. MCC providing near live-time updates is an assumed responsibility of the EVA workflow. To deviate from ID 8 is a shift in EVA workflow dynamics given an informatics display is a critical element of an EVA. MCC control schemes for the Joint AR design are captured in this paper under control modes in section IV. As it pertains to AR, the project team chose to address augmented reality graphics and cues from a hardware and software implementation approach. ID 9 may be interpreted in multiple ways. First, as a heads-up display (HUD) optical form factor – this is a function of the hardware and display optics. Secondly, as the ability to superimpose a digital image onto the real world, otherwise known as *registered* AR – this is a function of the software application and sensors. These optical hardware and digital software approaches are related, but mutually exclusive. For example, the automotive industry has designed windshield HUDs that show speed limits which do not have “registration” or sensing needs tied to the real-world environment. Conversely, modern two-dimensional displays like cell phones demonstrate registered AR by use of social media filters or games like Pokémon Go where the phone cameras sense the real world and superimpose digital elements accordingly. Registration gives the user ability to infer new information about the perceived world, while a near-eye or HUD form factor enables the user to ingest information at a glance without diverting visual attention from the task at hand – innately valuable during high workload task scenarios such as long duration EVA. In the scope of this work, Joint AR chose both the AR optical display form factor and registered AR software as it targets the highest value proposition to enable a hands-free, near-eye display to ingest information efficiently. Regarding interfacing with instruments and tools, the paper discusses the necessity for tool port interfaces and the implication to data rates and design decisions to avionics in section V.

The requirements leveraged on xEVAS and not within the Joint AR project include ID E) data storage, and ID J) communication of biomedical data. Data storage was a subsystem-level requirement was not deemed a responsibility of the displays & controls component. Architecturally, the Joint AR team is a component-level implementation of the larger xEMU Informatics (xINFO) subsystem. xINFO housed the EV-702 which was the primary compute, radio, and avionics. Another unmatched criterion, biomedical data, while valuable to flight controllers, is still in early stages of developing crew-facing front end display needs. Also, personal biomedical data is protected information and requires increased security of data handling. Other features such as consumable monitoring and procedures have a primary system called the Display and Control Unit (DCU) and paper cuff checklist to meet the criticality needs of these features.

A final discussion is warranted regarding safety. There are additional safety considerations when meeting the listed requirements. The NASA Software Engineering Requirements (NPR 7150.2D)[11] and NASA Software Assurance and Software Safety Standard (NASA-STD-8739.8B)[12] identify support of real-time navigation and crew-to-crew communication to require class A safety critical software (which infers parallel hardware safety criticality). While xEMU pre-defined the suit Informatics (xINFO) subsystem as a crit 3 subsystem, future work is needed to conduct safety assessments to reconcile the informatics display requirements with component-level safety criticality definition. It is inefficient to defer safety critical level of rigor in development responsibility for systems such as navigation, crew communication, and so forth because in principle, the lack of or erroneous execution of such functionality can threaten human life. For example, a navigation system showing erroneous data can cause life-critical traverses in high contrast lighting environments along lunar craters. If the system inspired confidence to travel a long way from the lander and then were to fail, astronauts might not be able to find their way back safety. From a crew communication perspective, undelivered messages could lead to confusion that could harm situational awareness and lead to a potentially deadly situation if the nature of the communications were to involve navigation or medical information, or the state of consumables. Deferring such responsibility would mean other systems would have to be developed to accommodate these functions, which would lead to increased weight, power consumption, development costs, decrease crew efficacy by having them learn and be reliant on multiple systems, and might risk the crew ignoring the system completely if it could not be relied on consistently.

III. System-Level Market Analysis

Thus far, this paper has discussed system assumptions and requirements. The remainder of this paper will discuss market trends and past informatics trade study efforts which informed design decisions. Given that the displays, AR, and VR markets are growing at an accelerated pace each year, thorough and often market analysis is a necessity to keep pace with industry efforts. The Joint AR team has utilized two market studies and one Request for Information (RFI), to gain current knowledge of the transforming optics, display, and software technology landscape.

A. 2018 Market Study

In 2018, prior to the start of the Joint AR project, the xEMU Informatics (xINFO) subsystem team ran a market study on medium eye relief AR systems. Yet2, a global innovation consulting company contracted through NASA's Center of Excellence for Collaborative Innovation (CoECI), conducted a market analysis of head-mounted and heads-up display technologies. Particularly, this study explored medium eye relief display technologies to find a solution provider who would be willing to partner with NASA for these purposes. The search identified 85 potential solution providers and presented the 39 most promising solution providers to NASA. Thirteen of these solution providers were categorized as "Highly Interesting", with six of those requested for an initial introductory call. In addition to these six introductory calls, it was recommended that NASA prioritize leads for demos and coordinate with procurement to receive test devices. Yet2 also recommended that NASA consider request for proposals (RFP) in the future, and potentially consult with the U.S. Army on mixed reality contracts.

B. 2022 Market Study

The 2022 AR Market Study was completed in March 2022. This market study focused deeper into the optical requirements, contacted, and analyzed 36 companies in the AR market to identify 22 parameters. The parameters included organizational details like country of origin (headquarters location), industry use cases, and whether the company is an original equipment manufacturer (OEM) or integrated solution provider (ISP). Technical specifications included: head mounted vs. non-head mounted distinction, ocularity, field of view, eye box, size, weight, power, brightness, performance in low and bright conditions, Technical Readiness Level (TRL), eye relief, prescription compatibility, duration of use, depth of field, transmissivity, color range, & ruggedness. Based on the results, the Joint AR team identified 7 high interest companies, 19 mid-range interest companies, and 4 low interest companies. Factors contributing to decision points included TRL, ease of partnership mechanisms, eye box, eye relief, and off-head compatibility.

C. Analysis of 2018 and 2022 Market Studies

The 2018 and 2022 market studies allowed the Joint AR team to understand the state of augmented reality and related optics solutions available in industry. The technology readiness of these commercial augmented reality solutions spanned from proof-of-concept components to consumer products accessible to the public. From the diverse set of industry products, key parameters such as eye box, field of view, eye relief, and brightness are specifically compared to identify areas of technological growth and stagnation. These basic parameters are readily available for most augmented reality devices, but more importantly, they were chosen because they inform the user's comfort and clarity in seeing the full display image. Table 3 shows the average values of the technical parameters for both existing and developing technology. The presented values for existing technology are far from the ideal conditions, given the constraints and geometry of the spacesuit and helmet bubble, but developing technologies show growth in each parameter besides diagonal field of view. A Request for Information (RFI) was formulated to further evaluate the feasibility of the proposed technical parameters and facilitate internal industry discussions to improve areas of the technology that may otherwise be stagnant.

Table 3. Summary of technical parameters for existing and developing AR optics technologies.

	Eye Box (mm)	Eye Relief (mm)	Diagonal Field of View (degrees)	Brightness (nits)
Existing Technology	12 x 8	27	38	2171
Developing Technology	17 x 23	128	36	9417
RFI	50 x 50	40-100	>30	1000

D. Request for Information (RFI)

Market analysis and previous NASA efforts combined leave a gap to be explored. To customize existing AR optical components into the helmet bubble geometry with the assumptions present within this paper, the Joint AR team solicited potential sources for a spacesuit AR display system from industry solution providers via a Request for Information (RFI). On December 9th, 2022, Joint AR released RFI 80GRC023R0002.[13] This document outlined key performance parameters which included eye box, field of view, eye relief, brightness, mass, and power. The solicitation requested focus areas for response which include how existing AR systems can be modified or scaled to meet the constraints of a helmet bubble, how technologies have potential to meet key optical requirements and their associated costs to reach TRL 6, feedback on given requirements, and environmental qualification potential for proposed AR systems. Results gathered on March 17th, 2023, showed the following:

There were 14 submissions to the RFI with potential paths to enable a TRL 6 spacesuit augmented reality solution meeting the Joint AR requirements. Most systems started around TRL 4, with custom modifications to meet the challenging curvature of the helmet bubble while preserving eye box and brightness requirements. Factors toward favorable proposals include addressing the vergence accommodation conflict for long term wear as well as strong considerations toward the environmental factors. With a multi-step iterative design approach partnering directly with the AR industry, a Joint AR system design is considered achievable in a 1–2-year period per industry proposals.

IV. Controls Trade Space

Given the optical design form factor and system level design is possible via one of the aforementioned partnership mechanisms, this section shifts focus to the possible technologies analyzed and test methods for controlling a suit mounted display. A primary design philosophy regarding Joint AR control modes is "time spent controlling the display is time spent not doing the EVA task". Facilitating crew productivity requires careful attention to the end user, their context, and the variety of tasks they may be expected to execute with help from the Joint AR system. Many methods were used to explore the controls space, including a trade study to establish assumptions, performance modeling to predict and compare control modes, metrics to prioritize human-in-the-loop (HITL) test objectives, and human-in-the-loop testing to refine the hardware. Each method, discussed below, provided a unique contribution to guide development toward the current Joint AR controls solution.

Testing pulls on human factors concepts from previous NASA informatics studies, including how often a user must reference a crew display, how long the user spends looking at the display, readability, distracting features, ease of use, and field of view. The team has utilized various human factors metrics as initial forays into verifying functionality and usability of the displays. Some of these metrics include the Adjective Rating Scale,[14] NASA Task Load Index (TLX),[15] Cooper-Harper rating scale,[16] Likert Scale,[17] think-aloud protocols,[18] and the System Usability Scale.[19] As the team approaches further verification and validation exercises, more of these will be utilized.

E. Priority of Metrics

Joint AR was posed with solving a challenging problem space to design controls hardware. In 2019, when the team began development, the xEMU project design progression was baselined. To add hardware to the suit, the displays and controls component needed to minimally impact pre-existing designs. This drove desirements for the Joint AR product to take a modular, “plug-and-play” approach and have minimally invasive design impacts, thus driving much of the controls trade space scoping. This was due to the maturity of the spacesuit design and desire to be a plug-and-play device rather than affect the central architecture. Secondly, the suit gloves and challenging dexterity and ambulation environment, introduce the need for iterative, and thorough user testing. Separate trades and human-in-the-loop testing were conducted to assess controls design for usability. This second approach outlined assumptions for a first version of control mechanisms, upon incorporating HITL testing with the control methods. This mentality shifted with emphasis on what is best for the user, not what is least impactful to the program. User-centric design choices and the ability to stay modular and minimally impactful to the suit pose contradicting goals, yet the Joint AR product found middle ground in developing the physical hand controller, voice control, and full MCC or “remote” control capabilities.

F. Controls Trade Study

The initial controls trade study evaluated 26 design solutions that were to be mounted outside of the suit and less than two pounds mass. Control options spanned touch screen, gesture control, voice, wearable strain gages, pressure sensors, switches, and keypads to name a few. It considered the control mode to be primarily for menu navigation, and additional control mode was considered for powering the system on and off. The controls evaluation was focused on how to be minimally impactful to the existing NASA design for the spacesuit. Table 4 outlines the primary design criteria which scoped the premise of the initial trade study.

Table 4. Trade study design criteria and corresponding targets.

Design metrics	Target to metrics
Controls size, weight, power	minimize
Breadth of options to suit user	maximize
Physical usability - suited hand/suited user	maximize
Menu usability – navigating the menu structure	maximize
Development effort	minimize
Impact to xINFO design	minimize
Impact to PGS design	minimize
Impact to EVA workflow	minimize

Designs were then evaluated for each criterion on a 1-9 scale and multiplied by the category weight to give a weighted evaluation score. A baseline of MCC full remote control was evaluated and scored highly on the selected design criteria. Only one control mode scored above the baseline consideration. Rigid voice control was beneficial due to not requiring any additional hardware and providing the user with a large breadth of options. Known limitations for rigid voice control were interference with MCC audio communication, noisy audio environment within the suit, and increased software development effort. These factors are a carried risk for the Joint AR project team. We recommend a thorough communication traffic analysis as forward work if implementing voice control. Below the baseline, but within 5% of the score was a two/three position momentary switch near the helmet. This was considered minimal weight and impact to design, due to similarity with the suit lighting control. Three more choices rated within 10% of the baseline – voice control conversational, two/three position momentary switch routed under the environmental pressure garment (EPG), and switch combo near the helmet. Voice control conversational would reduce complexity in training the user on specific phrases but would require additional computing capabilities to be added.

Two/three position momentary switch routed under EPG would be much less strain on the user to reach the control but adds weight to the system. A switch combo near the helmet would provide additional options of control to the user but would have a large impact to the helmet lighting band design. It is of note that pushbuttons were not incorporated due to a lack of heritage flight hardware and hermetically sealed component selection options *at the time of this study*. This quickly changed as heritage Orion vehicle hand controller design and hermetically sealed pushbuttons emerged. Switches and pushbuttons became two options in the design space for Joint AR. Today, Joint AR has three modes of control: MCC remote control as the primary, baseline control method, a physical hand controller, and rigid voice control. This was the baseline assumption for control mechanisms before moving into human-in-the-loop testing.

G. Quantifying Metrics of a Controls System and Iterative Testing

Although there are many important dimensions related to human-system performance (e.g., time, accuracy, usability, learnability, workload), not all can be assessed at once and many cannot be investigated early in the design process. With many control modes under consideration, the team began by performing baseline efficiency comparisons between modes, expanding on the traditional operators within the Keystroke-Level Model.[20] The KLM model predictions and metrics, defined below, assisted with the selection of more promising control methods. After narrowing the scope of the controls space, the team iteratively increased the fidelity and refined the ergonomics of the physical controller using a series of human-in-the-loop tests.

1. Keystroke-Level Model Analysis

The Keystroke-Level Model (KLM) was chosen because it provides a method for predicting the time required for an expert to accurately execute representative tasks by summing the durations of each of the primitive components, or *operators*, required for interaction using each control scheme before the system is fully specified. The original KLM model contains six operators (keystroke, pointing, drawing, homing, mental preparation, and system response time) and five heuristic rules for placement of the mental preparation operators.[20] The operators and rules in the model have subsequently been modified[21,22] and extended by other researchers for application to input methods beyond buttons and mice, including voice.[23] and gesture.[24,25] Along with the Not all input methods considered by the Joint AR team have published operator approximations, which necessitated data collection to capture time estimates for input using a dial (Microsoft Surface Dial), a flight-ready toggle switch (CH 8023), and flight-ready momentary pushbutton (Otto Pushbutton P3-90408). As an exploratory study, six participants practiced until proficient and for each input method and then, where appropriate, data was collected for sets of single actuations (e.g., single click), double actuations (e.g., double click), string of successive actuations, and homing, as actuating the controls may require movement of the arm and hand from a neutral position at the side rather than simply between input methods on a tabletop. Participants also completed a short task that incorporated each type of actuation for each input method with an interactive prototype display for the purpose of validating the model and execution times for each operator.

2. KLM Results

Results from this exploratory study suggested that, even though the pushbutton condition required an extra step of homing between two individual buttons to do the task, the momentary pushbutton provided a slight advantage over the toggle switch in that it required less time to actuate. Pushbutton times captured in the study were between the published typing rates for "good" and "average skilled" typists,[26] and even though the task was simple, the pushbutton style required more force than what is expected of a typical keyboard. The dial had the longest actuation times, especially for the first and last rotations within the string. The dial used had individual rotation segments marked, but did not have physical detents, so the increased times may indicate that more mental preparation was required to track the start and end of the string. However, the time to complete a string of actuations was much shorter than the other two input methods perhaps because actuation time was long enough to "absorb" the simple reaction time operators. The team took these preliminary results to generate the design for the physical hand controller, using a combination of a dial with physical detents and two momentary pushbuttons. It is important to note that while exploratory control comparison is helpful, it is only one method that can be used to determine the best Joint AR control solution. Making informed design decisions requires careful attention to the end user, the context, and the variety of tasks they may be expected to execute during an 8-hour time envelope. Control mode decisions must consider the impacts of hands-busy and eyes-busy situations, audio communication exchange, increased mental workload, and fatigue. The appropriateness of one control mode may not hold for all situations, which may indicate a multi-modal solution is most intuitive for various use cases.

Table 5. HITL testing criteria and corresponding targets.

Design metrics	Target to metrics
EV crew productivity (without any compromise to their safety)	maximize
Intuitiveness and ease of use to decrease training and mental workload	maximize
Number of discrete physical acts required by EV	minimize
Amount of time required to change from current state to desired state of Joint AR	minimize
Recovery time in cases of unintentional state changes	minimize
Interference with other means of communication (audio, video)	minimize
"Critical/priority" Joint AR content can be accessed via two EV-crew-accessible methods	verify (y/n)

A primary test space for the the Joint AR team to down-select controls is using the pressurized glovebox facility at NASA JSC. A series of glovebox tests included KLM analysis of individual control modes, and full control of a prototype Joint AR display using iterations of a physical hand controller. Testing showed that switches provide insufficient tactile feedback, require higher mental workload, and require fine motor movement that is not easily possible in a pressurized suited environment. Feedback on the switch concluded that it required effort to actuate, mapping the actuation method to the user interface was not intuitive, and it is difficult to actuate the switch away from the body. Feedback on the pushbutton concluded that inadvertent actuation was more likely to occur, it was difficult to position the hand to actuate the buttons without visual cues, mapping the actuation method to the user interface may take high mental workload to recall, the ring and pinky fingers do not have sufficient strength to quickly actuate the buttons, and the buttons have high dependency on dominant hand use.

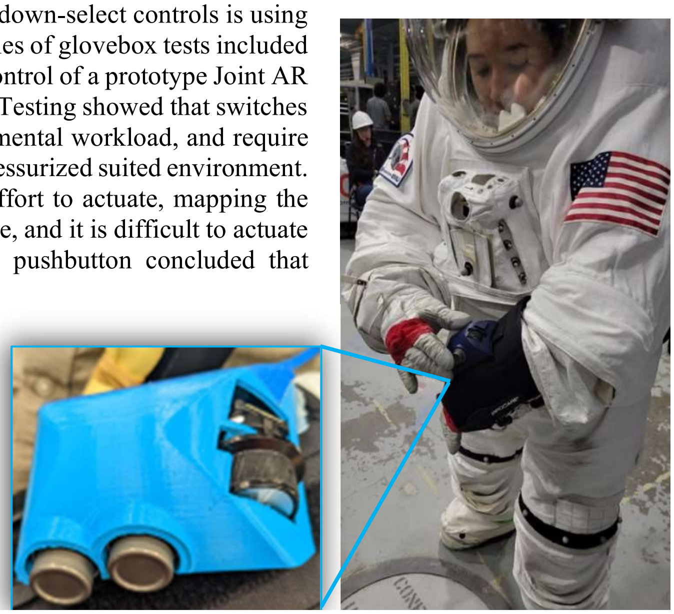

Figure 1. Design of the Joint AR physical hand controller represented on an xEMU pressurized suit fit check during ARGOS testing

Based on the KLM analysis and some iterative testing, the team proceeded to analyze the 2-pushbutton and dial combination in various hand controller housings and orientations the team completed 5-6 rounds of pressurized glovebox testing and settled on the design shown in Figure 1. This design leverages the least fatiguing physical actions such as pushing down on buttons with the pointer and middle finger and scrolling with the thumb in a left-right motion. This design underwent high fidelity testing in multiple test beds using methods outlined in Table 5. Figure 1 shows the first the hand controller in a pressurized xEMU test within the Active Response Gravity Offload System (ARGOS). The ARGOS fit check determined optimal placement along the arm for the controller based on reach and access of variously sized crewmembers. It was determined that wrist-mounted controls were best suited for adequate reach and fit. Fiscal year 2022 concluded with a full stack test that incorporated the controls system, display hardware, flight software, and graphics engine user interface into a 3D printed Hard Upper Torso (HUT) at the JSC Rock Yard. Subjects were required to take geology samples, traverse the field, and communicate with a MCC mockup of the Joint AR remote command software. Fiscal year 2023 test goals are centered around the navigation challenges from the Joint EVA Test Team lunar traverse testing (also known as JETT testing) at a remote EVA analog field test in Arizona. The team will be implementing the controller in further use case-based testing and continue to refine as needed with representative anthropometry and user tasks.

V. Avionics and Software

As a spaceflight community, we have not flown modern displays on the lunar surface. With distributed assets, vehicles, data, and payloads across EVA tasks, it is necessary to have digital data be viewable across assets. A harmonious future digital environment is made possible by choosing and designing flexible, interoperable avionics and software architectures which withstand the radiation and thermally challenging environments. This next section outlines multiple trade spaces which defined the Joint AR avionics compatibility, display hardware choice, cabling interface, and the software architecture.

H. Radiation Tolerant Display Needs

While the compute avionics for Joint AR are subsystem-dependent, the team has kept a flexible, platform agonistic approach to enable plug-and-play into any suit computer and display avionics. However, the team has given much thought and partnership efforts toward radiation-tolerant compute research given the harsh environment of space poses significant challenges when deploying modern display technology. With an operating environment consisting of a cosmic radiant flux several times larger than LEO , the lunar surface represents the most challenging environmental conditions for human-consumable display technology to ever undertake.[27] Cosmic radiation can damage system components through cumulative and single-event effects, all of which must be sufficiently mitigated to meet mission lifetime requirements.[28] Moreover, displays are a unique subsystem of any spacecraft as they are only required for human spaceflight. Therefore, inclusion of a display is an indication of an elevated mission criticality. Avionic systems are able to meet critically by designing around radiation hardened and/or tolerant processors and components.[29]

Unfortunately, while these processing elements can withstand the necessary levels of radiation and corresponding effects, they struggle to deliver the computational throughput needed for modern graphics applications. Traditionally, a dedicated Graphics Processing Unit (GPU) handles the graphics workload. However, without commercially available rad-hard GPUs, system design is limited to vulnerable COTS GPUs. Alternative hardware accelerators were explored including radiation hardened FPGAs, but they have historically struggled to provide the framerates required and are difficult to develop towards. For this reason, the team elected to build towards a GPU-based system. To realize a GPU-based radiation-tolerant display system capable of advanced rendering, additional fault-mitigation is required.

Components are selected based on their ability to pass total ionizing dose (TID) testing. Criteria for passing TID testing is relative to radiation levels within the environment and time. A wide range of COTS GPUs are considered including devices from companies such as NVIDIA, AMD, and NXP. Once components are qualified and selected, a hybrid configuration of rad-hard and COTS components can be arranged for the avionics architecture. The rad-hard processor serves to facilitate graphics tasks to the COTS GPU while the GPU enables hardware acceleration for graphics applications. Supporting circuitry is required to mitigate destructive single-event effects (DSEEs) such as single-event latch-up (SEL). In addition to the aforementioned radiation effects, soft error or non-destructive single-event effects can alter application behavior (single-event upset - SEU) and device availability (single-event functional interrupt - SEFI). To address soft errors, software mitigation is employed in a variety of ways. For SEFIs, the COTS device can periodically communicate with the rad-hard processor that can issue reboot commands and serve as an emergency fallback rendering device upon the COTS device being interrupted. Middleware may also be used to provide operating system-level oversight including daemons to "rescue" stalled processes and the ability to switch context between devices. For SEUs, techniques such as use of Vulkan Safety-Critical graphics API drivers specifically engineered for fault tolerance, the development of rigorous radiation-tolerant rendering pipelines, custom error-checkable texture formats, offloading of a subset of tasks are all avenues that have been or are in development. Future innovations in rad-hard processing, such as the release of NASA's High-Performance Space Computer (HPSC) may help to alleviate need for some of these fault-mitigation technique or further improve performance.

I. Display Light Engine Trade Study & Radiation Test Results

Prior to choosing a light engine for the display system, the team evaluated ten options for micro displays. These options included a DLP (Digital Light Processing) projector, MicroOLED (Micro Organic Light-Emitting Diode), LCoS (Liquid Crystal on Silicon), OLED, flexible transparent OLED, flexible transparent LED (Light-Emitting Diode) display, LCD (Liquid Crystal Display), LED array, ePaper, and retinal projection. Among the ten, specifications for power draw, thermal range, schedule impacts, and pros and cons for design development were compared. The DLP projector was the primary contender as it met the thermal constraints of the lunar surface, had high TRL reference designs, was low power, small in size, and had heritage proton and heavy-ion radiation testing for Low Earth Orbit (LEO) conditions increasing confidence for survivability in lunar radiation environment. The results of this study informed selection to incorporate the DLP as the primary image source for the display optics as well as selection take the DLP projector to proton radiation testing in the xINFO subsystem radiation test in December 2019.

The DLP projector was tested at the chip level. First the DLP display controller (Texas Instruments (TI) I DLP3435), the LED driver (TI DLPA2005), digital micromirror device (TI DLP2010) were each tested to a 10-year equivalent dose. While the DLP3435 chip was under test, only one anomaly was reported. The image coming out of the projector went black. Current draw looked normal during the anomaly. Power to the board was toggled, and the projector resumed playing nominally. No unrecoverable failures were observed. While the DLPA2005 chip was under test, no anomalies occurred. The device reached the 10-year equivalent dose in a single run without any upsets. No unrecoverable failures were observed. While the DLP2010 chip was under test, one anomaly was reported. The HDMI input was temporarily lost. The display coming out of the projector briefly switched to the default splash screen that is displayed when there is no input. The screen may have temporarily gone black, but after about 5 seconds, the HDMI input was recovered automatically. The board was then manually power cycled to verify that there were no impacts on the ability to reboot the hardware. No unrecoverable failures were observed. Continued testing is required for heavy-ion and thermal analysis.

J. Display Cabling and Interface Trade

To meet the requirements outlined in section III, a centralized suit display needs access to the relevant system and operational data and properly scarred interfaces. The project team prioritized the following data sources to correspond to the EVA-EXP-0042 features. Local *onboard data* sources prioritized include: 1) suit consumables, biomedical sensing, and telemetry, 2) suit mounted camera live and stored photos, 3) voice data from crew live and stored audio, 4) navigation and environmental sensing, and 5) suit tools telemetry. Local *lunar data* sources which include: 1) navigation and environmental sensing of both crew member(s) and other lunar assets, 2) handheld and other local camera sources, and 3) status and telemetry from other crew members and lunar assets. Of the *remote data* assets, the team scarred data interfaces for Mission Control procedures, maps, timelines, and messages.

The above may also be updated throughout the mission using MCC EVA software tools. Along with the ability for remote display control by MCC and giving MCC access to the Joint AR system state. It is imperative for and informatics system to have access to this data to meet the operational needs warranted by a crew member on the lunar surface. Awareness of self-status and other lunar assets status in the central Joint AR display solution enables the crew member to access the information they need to make real-time decisions during EVA operations.

Providing this data to the Joint AR system can be done locally on the suit and two main architectures were considered: integrated or via tool port. An integrated data path would have Joint AR software locally accessing shared memory of a shared processor with access to the relevant data. This option has power and mass saving benefits, but considerations need to be made toward criticality and requirements compatibility of such systems. Considerations for cabling on this option would primarily support a choice of DisplayPort between the suit processor and the display source – DisplayPort offers low power adapter chips with a small number of required pins for reduced mass with built into AUX channel for commanding and data transfer which was preferred when compared to HDMI and USB 2.0. A second option is a separate specialized processing system for the Joint AR system with access to all relevant data paths via a tool port. This option increases mass and power but offers a ‘plug-and-play’ option with an ease of adding the system to a pre-existing architecture. Considerations for cabling on this option would primarily support a choice of USB 3.0. A tool port option would be bandwidth limited, thus necessitating the suit processor to pre-process large data sets (such as audio/navigation) before sharing over the tool port. Other interfaces beyond DisplayPort, HDMI, and USB were considered, however these three were ranked higher due to ease of integration with existing xEMU architecture. An integrated architecture would provide the most flexibility for data access, which would benefit the data accessibility needs of the suited crew member display system as the complexity of Artemis missions increase. Details of Joint AR interface requirements may be found in the xEMU Interface Requirements Control Documents (IRCD).

K. User Interface Framework Trade

To develop safety critical software for a user to view on future EVA displays, it is necessary to define a safety critical framework for the development of user interfaces and display content. The team evaluated commercially available UI frameworks based on the following categories: License Cost, Performance (Speed), Safety Certification (DO-178), Ease of Learning, History of Production Use at NASA, Overall Complexity, Interoperability with NASA Technology (CFS, etc.), Feature Set (Solving Common Problems), Adaptability with Emerging Technology, Compatibility with Target Board (Zynq Ultrascale), GPU Requirement (High Score = Less work to run on CPU), NASA Certifiability, Multi-rate Rendering Capability, and Control of Framebuffers.

From this study, two UI safety critical frameworks known as IData (used currently in the Orion displays) and GL Studio were evaluated. GL Studio scored highly and was chosen as the development platform for the first two years of the Joint AR project. However, the team ended with building an internally built custom graphics engine known as STAR (Space Technology Application Renderer). This choice was motivated by a need for greater control of performance optimization in the embedded suit environment, flexibility to support multiple design paths with fluctuating availability of computing resources, and to incorporate a custom render pipeline supporting research and development of CPU and GPU software-level radiation hardening techniques. It also allowed the project to not become dependent on third parties to develop drivers or port functionality to alternative hardware platforms, and because it can be trimmed to support the minimum functionality needed for the mission and not serve as a general-purpose graphics engine, it is cheaper to flight certify. Today, the STAR graphics engine being developed with scarring to transition into a class A, safety critical product intended for vendors and the public to utilize for space-rated displays.

The STAR engine is developed internally within NASA. There are no external dependencies that have not or will not be open sourced by internal developers, other than the C standard library. The engine is developed using the C99 specification. It supports a platform abstraction layer to translate drawing commands into graphics API calls for Vulkan or potentially other graphics APIs and can run in both Windows and Linux. The engine can perform "hot reloading" despite being a non-interpreted language and can incorporate code changes without stopping execution (if data structure definitions do not change). The engine builds in a few seconds using a unity build, uses a custom build system built around the concepts of hot reloading and unity builds, and is very modular, built as a series of expandable and reusable plugins. Unlike traditional applications which link to engine libraries, the engine itself is the executable while applications are dynamically linked libraries. The engine can switch application libraries at runtime without stopping execution and can maintain individual application state, meaning the engine in its default state acts as an application switcher. This creates a smartphone like ecosystem without having to develop a custom operating system. STAR applications can communicate with other processes using shared memory infrastructure, literally chunks of RAM addresses which are readable and writeable by multiple processes, like STAR, and Core Flight Software. This allows other applications to act as data sources for commands, caution and warning telemetry, etc. While STAR maintains an independent state. This increases fault tolerance as either STAR or its data sources may suffer a soft radiation upset without compromising the other. It also ensures STAR can run at high processor priority and not be slowed down by less important applications when intensive rendering performance is required.

VI. The Joint AR System Design Approach

Thus far, the trades landscape has been defined. Following these exploratory efforts, the final section of this paper defines the outcome of the design decisions as of May 2023. The prototype of the Joint AR system is intended to be an analog platform utilizing COTS components to emulate possibilities in a flight design. Components were chosen based off former trade study outcomes and to enable rapid iteration on the user experience. For example, COTS image source and optics components are used based on our trade studies recommendations but are not the custom solution required due to limited eye box, small form factor, and lack of vergence accommodation conflict (VAC) mitigation

Figure 2. The Joint AR system end-to-end components as tested via Joint AR avionics architect Tyler Garrett, and crewmembers Don Pettit and Kate Rubins (left to right)

solutions. Continued efforts and partnerships are required to field a flight-like, suited form factor display optics solution.

The 2023 system (as shown in Figure 2) is a suit mounted DLP projector light engine, with waveguide combiner, with COTS avionics, and three modes of control. The primary baseline control is full MCC control. The physical crew control is as mentioned earlier, is a wrist-mounted hand controller with two buttons and a dial. As a third mode of control, the user may also use voice recognition. The primary features of the display UI include navigation, photo view, and a customizable dashboard. The format of the display content is iterated upon based on crew testing feedback during simulated EVA traverses.

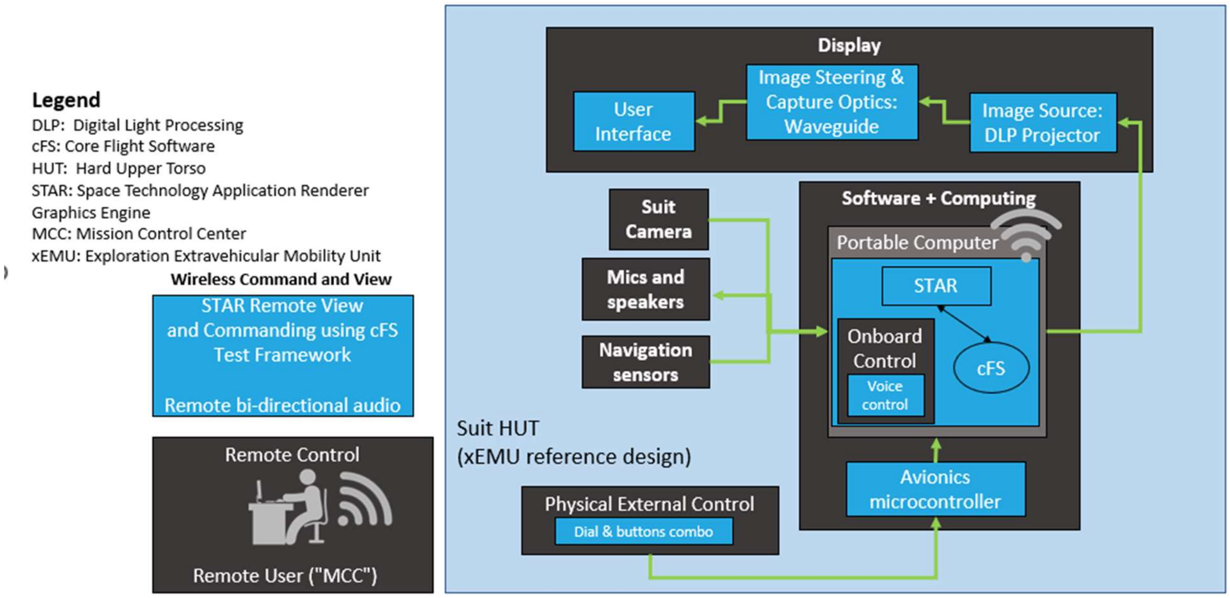

Figure 3. The Joint AR architecture diagram

The architecture diagram for Joint AR in Figure 3 shows the suit-mounted hardware and control methods. The display is comprised of the UI view and a passive waveguide optical element to guide the beam of light from a coupled DLP projector. This is mounted near the helmet bubble and placed near the user's eye within the small eye box of the COTS device. The waveguide location was chosen to emulate the field of view of what a custom optic could enable, while limited by the eye box of the device. A larger waveguide via a custom optics partnership, could increase the eye box and release the design from the near eye constraint. A larger waveguide would enable the software development to create the first-person user experience on a more similar vein to a future custom optics solution. The avionics on the suit include a portable computer (currently an off the shelf Intel NUC, but software in platform-agnostic) with the STAR engine software, voice control software, and Core Flight Software (cFS) sharing memory on the processor. A suit camera feed is also connected to the primary computer which feeds live imagery to the viewfinder and camera application. Finally, a microcontroller (an MSP430 with a rad-hard space rated version available) is used to interface the hand controller to the processor. MCC commands are wirelessly communicated via Wi-Fi protocol to the display system.

VII. Discussion and Conclusion

This paper covers contrasting area of topics which are critical elements to define a cross-disciplinary system design of a future centralized spacesuit display. Introducing a digital display element into the EVA workflow will transform modern day EVA operations and springboard crew autonomy capabilities. However, this transformative technology comes with many novel solution spaces. Over four years, the Joint AR project has researched, developed, and demonstrated an EVA suit display at a system technology readiness level (TRL) 5. The state of the Joint AR product as of May 2023 includes an xEMU configuration hard upper torso with a COTS monocle waveguide-projector optics display prototype, physical hand controller, voice control capabilities, and full MCC content control. The flight software and custom graphics engine has been written with upgrade capabilities to class A, crit 1 safety critical features. Forward work is required to conduct an initial assessment of system safety criticality, dust mitigation, software certification, and environmental testing for verification and validation activities. The design and component selection were driven via the aforementioned trade spaces and architecture considerations. From a market analysis standpoint, the AR market is one of the fastest growing businesses in technology today. We recommend keeping a close and thorough analysis of market trends on a bi-annual basis. Between 2018 and 2022, waveguides emerged as a potential technology to expand eye box and eye relief. This has greatly impacted the potential optical design solutions for a medium eye relief solution like what is needed within the xEMU helmet bubble reference design. Partnerships will be key to design to the latest, user-friendly optical specifications. The system design specifications must meet both user needs and environmental constraints of the harsh lunar and martian environments. We recommend taking a wholistic systems approach, ensuring avionics can meet the radiation conditions, and considering all possible agents, data sources, and users of a centralized suit display.

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