

Realizing a Spacesuit Compatible Augmented Reality System to Meet the Work Needs of Future Human Spaceflight Exploration

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In this paper, we identify the broad range of challenges associated with creating an augmented reality for future spaceflight missions. The challenges were framed within a sociotechnical framework to explore how an imagined augmented reality system might one day help crew cope with future exploration mission demands. Key challenges include an augmented reality system cannot simply be designed to help a single suited astronaut and must enable the broader mission team. There exists a host of optical, compute, and control technical challenges that must be simultaneously addressed while the work domain itself is in development. There exist limited methods to help cope with the envisioned world problem; however, we emphasize a few strategies to articulate work design assumptions and host this detail in a transparent fashion. Finally, we note the broader organizational constraints that shape the creation of such novel technology for spaceflight. By addressing these broad range of challenges directly, early in the design and development process, key trade-offs can be considered and fundamental concerns within the community can be addressed to yield desired mission outcomes.

I. Nomenclature

AR	=	augmented reality
b	=	eye box size
Joint AR	=	Joint Augmented Reality Visual Informatics System
MCC	=	Mission Control Center
PPI	=	pixel per inch
r	=	eye relief
s	=	optical surface size
v	=	field of view
xEVA	=	exploration extravehicular activity

II. Introduction

NASA plans to return to the moon in the coming years with the goal of establishing a sustainable human presence on the lunar surface and beyond [1]. This campaign has an inherent goal of enabling crew to become less reliant on Earth-based mission support and to become more self-reliant on local assets and resources which is often referred to as enabling *crew autonomy* or more broadly enabling Earth-independent missions [2]. Earth independence implies that the crew and their local assets have the capacity to live, work, and survive for long duration without intervention

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from Earth-based mission support or resources. One assumption with this goal is that crew autonomy systems will be sent with the crew to help them cope with all the demands of the mission. But what does crew autonomy mean and is autonomy as a concept sufficient to achieve such an ambitious goal given its prevalent limitations [3]?

NASA is dedicating efforts to building new technologies that enable autonomous capabilities for future human and robotic missions [4, 5]. These tech-centric initiatives include but are not limited to augmented mobility, manipulation, situation awareness and multi-agent operations and human system interaction [5]. While these efforts are necessary, they are not sufficient to create the envisioned work domain of future missions. We assert in this paper that achieving Earth independence must involve not only the development of novel technological systems, but also the deliberate design of the work domain itself to best situate these capabilities within the broader work system. We propose shifting the focus away from building autonomous systems directly and prioritize enabling a broader view of *crew autonomy* which we define in this paper as *the capacity of the crew to make an informed decision*. The anticipated decisions crew might face in future missions must be deliberately designed along with how underlying information necessary to make such decisions will be made available. This vantage point shifts the expectation from building automated systems with the hope that they provide useful capabilities to enabling desired decision support that we *hypothesize* will be valued by workers in their situated work to achieve desired performance outcomes.

In this paper, we built upon a sociotechnical system lens to help envision future Earth-independent extravehicular activity (EVA) operations [6–10]. The Joint Augmented Reality Visual Informatics System (Joint AR) project at NASA Johnson Space Center aims to create an augmented reality system that is compatible with a lunar surface spacesuit to support the Artemis missions and beyond by providing crew with information that addresses their work-driven needs throughout EVA operations. We outline in this paper the envisioned work domain by decomposing it into the key aspects of the sociotechnical system: the technologies, the workers, the organizational and environmental contexts, and the relevant challenges associated with realizing an augmented reality system in future spaceflight.

Our intention in discussing these challenges is to help outline the scope and scale of the problems that exist with realizing an augmented reality solution within the EVA work domain. All too often, novel technology development is pursued in a vacuum, isolated from the real work demands it is intended to support [9]. The concepts highlighted in this paper such as the envisioned world problem, crew autonomy, function allocation, work domain development, and augmented reality must continue to be addressed, refined, and researched among the broader community of technologists, academics, and spaceflight industry. We acknowledge that this paper cannot address all the questions or concerns raised with building a work domain that has never existed; however, there is value in appropriately scoping the problem to more directly address the complexities that exist to increase the likelihood of successfully fielding desirable and successful future human spaceflight systems.

III. Defining an Envisioned System

The Joint AR project implemented a complex sociotechnical system view, as defined within the fields of cognitive systems engineering [11] in a similar approach to previous research in EVA work domain development [9]. Figure 1 shows the Joint AR system, which is comprised of the workers, interacting with technologies present in the workspace that is governed more broadly by organizational and environmental constraints. Instead of simply focusing on building a suit-compatible AR device, this sociotechnical framing focuses on answering how might this entire set of interrelated domain elements collectively perform work to achieve overall system outcomes. There exists a set of workers (suited, unsuited crew, and remote flight controllers) who, together, perform work using a set of technologies available to them (e.g. a novel AR system among a vast array of other mission assets) within the organizational (e.g. NASA and private industry companies) and environmental contexts (e.g. Earth and mission destinations such as the lunar surface) of the mission to achieve desired mission goals (e.g. scientific exploration and pioneering engineering during EVA operations).

Central to this work domain framing is the need for simultaneous advancement and definition of each of these system elements. The definition of the intended system work goals must be made in concert with the anticipated people involved, the assumptions and goals of the mission, and the proposed technologies available all at once to grapple with the interrelated complexities that will inevitably manifest [9, 12]. In other words, the envisioned future we imagine and propose must resonate and align with the broader organization and the hypothesized technology capabilities must match with people's expectations to achieve desired overall system performance.

EVA, as a work domain, has been a focus of study in recent years to identify the inherent constraints and necessary structural changes that the domain will need to accommodate to achieve more Earth independent capabilities [7]. These previous efforts focused on distilling domain constraints, prototyping and testing decision supports systems for non-suited crew members in future EVA work settings [8, 10]. Additionally, investigations into a visual display system

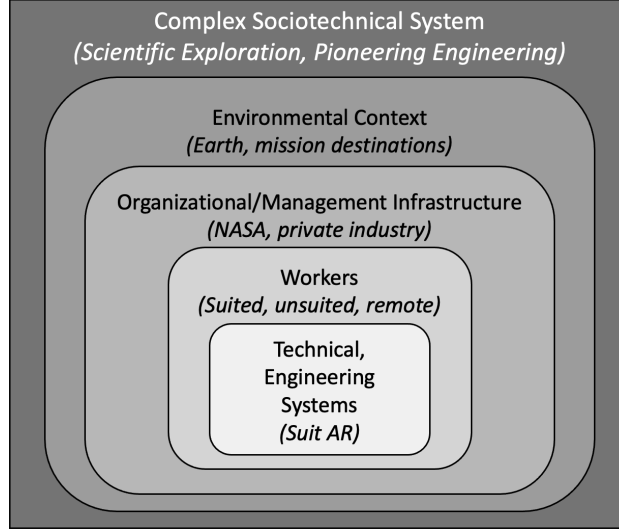


Fig. 1 Complex sociotechnical system layers with italicized emphasis on the components relevant for Artemis with envisioned augmented reality technology (structure adapted from [11])

in the form of augmented reality indicated promise to enhance task performance, workload, and situational awareness of suited crew members [13]. We expand on these previous works to include what it might mean to afford decision support directly to the suited crew member via a suit compatible AR device. In in doing so, our proposed AR solution might one day enable an entirely new medium of access to information and mode of control within the EVA work domain, thereby fundamentally changing the field of practice. The remainder of this paper focuses on the challenges present in building an AR system. The potential solutions created by the Joint AR project will be a subject of future papers.

IV. Defining the Workers

The ironic aspect of attempting to build an AR system for a suited astronaut is that the suited astronaut is not the only user the AR system must support. Figure 2 shows a depiction of the envisioned domain, annotated with Joint AR technology and workers, annotated within the latest NASA concept of operations for exploration EVA [14]. Multiple actors exist within the domain who collectively work together to accomplish EVA goals (see Refs: [6, 8] for examples of present-day ISS EVA operations). Suited astronauts perform EVA in pairs, so there are really two suited astronauts during operations at any given time, each with their own envisioned AR system that must support their own individual needs as well as their grouped needs. Additionally, there may or may not be local intravehicular crew who may provide EVA support (e.g., crew that remain inside the lander or rover), and there will be a large team of remote flight support workers (e.g., Mission Control Center (MCC) in Houston).

Human spaceflight operations is a team effort and therefore an AR system cannot simply be designed with a single suited astronaut in mind. Specific functionality and features must be thought about collectively within this team of people and how the relationships between these workers are structured, particularly via the new data connections and interactions provided by a novel AR device. Augmented reality has the possibility to enable an entirely new medium of access to information and mode of control within the EVA work domain. If this potential is to be realized, how each member of the flight team accesses, interacts with, and makes decisions collaboratively must be addressed.

V. Defining the Technology

The AR industry has seen massive investment and advancement in recent decades, so much so that it is no longer considered a technology hype, as defined by that Gartner hype cycle [15]. Numerous professional societies have dedicated tracks to the discussion, promotion, and advancement of the AR industry (see [16, 17] as examples) and AR is projected to be a trillion-dollar enterprise across various industries such as product and services development, healthcare, training, process improvements and retail [18]. Furthermore, a variety of industry standards now exist to help frame the characteristics of AR technology such as optics requirements [19–22], optic metrology [23–27], and

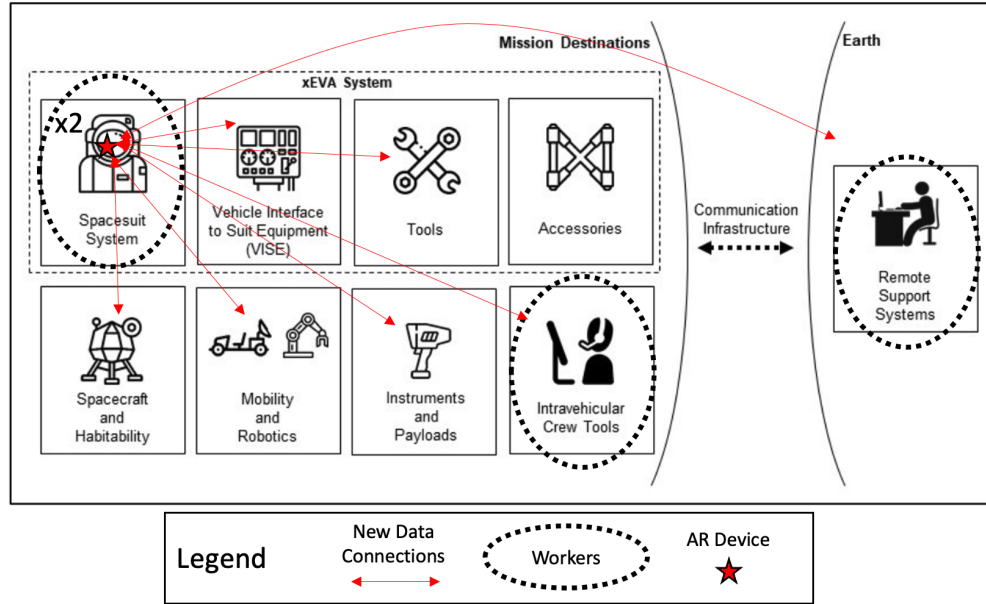


Fig. 2 Joint AR system elements aligned with the Exploration EVA Concept of Operations (adapted from Ref: [14])

controls [28]. These advancements warranted a close examination by the Joint AR project to the applicability of AR technology toward supporting human spaceflight.

The Joint AR project conducted a multifaceted evaluation of the commercial AR market. Two separate Yet2 market studies (2018 and 2021) were completed as well as team attendance to multiple international AR conferences to demo, discuss and understand current AR devices [29]. Additionally, an internal procurement and evaluation campaign of commercially available devices was performed. From these efforts, the Joint AR project identified two broad technological challenges associated with applying the present-day commercial AR technology with human spaceflight EVA operations. There exists a novel optics challenge associated with rendering AR content via a transparent medium to a suited crew member that the private sector is not actively addressing. There additionally exists challenges associated with enabling the necessary AR compute and control capabilities on a spacesuit platform. The remainder of this section describes these various challenges in more detail.

A. Novel Optics Challenge

The Joint AR project framed the novel optics challenge by adapting standards as shown in Figure 3 to emphasize the application, environmental interface, human physical interface, and human optical interface levels [19]. Within this classification, the Joint AR project pursued the development of a see-through transparent AR device, that was unregistered, attached exclusively to the helmet/suit (i.e., no body worn components), that was monocular. This specific AR system was hypothesized to provide a faster path towards a flight solution, with the expectation that a more capable system could be fielded in subsequent iterations.

Application-level challenges focus on the impact of whether the AR display is a see-through or non-see through medium. Suit helmet bubble substrates already have transparency requirements that must be met to ensure adequate visual ability of the crew member. The suit helmet assembly also provides other optical mitigation methods to help the crew member handle the extreme lighting conditions of the lunar surface (e.g., gold-foil visor and opaque sun shields). Each of these additional components alter the opacity of the field of view of the crew member that also must not conflict with a transparent AR device. Non-see-through displays were not desired as part of the Joint AR project due to the inherent reduction in field of view of the crew member. A see-through display was hypothesized to offer a more tractable long-term solution that could be reconciled with the helmet bubble and visor assembly.

The environmental interface level focuses on whether the AR device is registered or nonregistered [30]. Registration is achieved when digital content on the AR display is ‘anchored’ to real world objects. Nonregistered information is simply digital content on the display that has no spatial relationship with the real world. Enabling registration requires

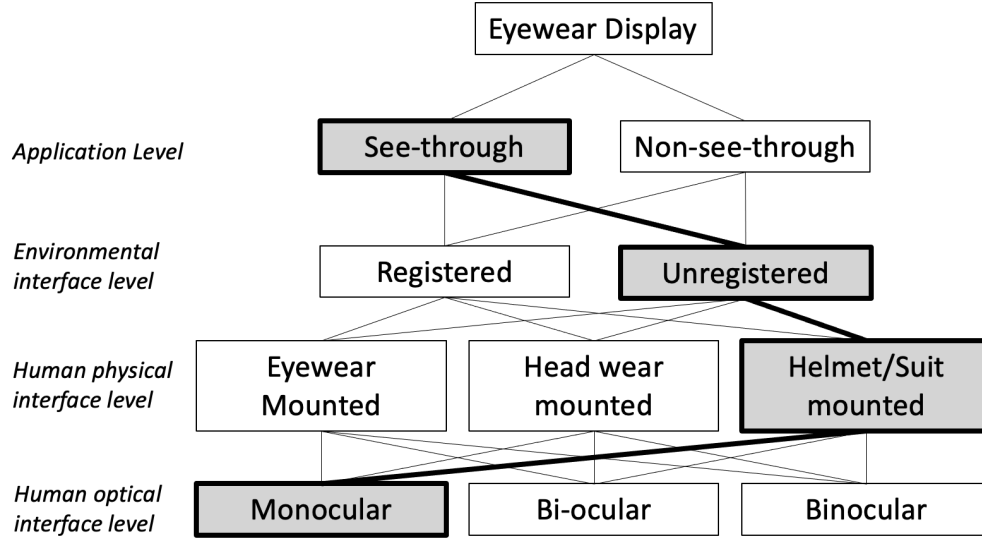


Fig. 3 Joint AR technology classification adapted from Ref: [19] with bold boxes and lines indicating the specific characteristics under investigation.

a host of additional sensors and data fusion computing to align digital content with the real world. HoloLens 2 is an example of a registered AR device which performs head tracking with 4 visible light cameras, eye tracking with 2 Infrared (IR) cameras, depth estimation using 1-MP time-of-flight depth sensor inertial measurement unit (IMU) for accelerometer, gyroscope, magnetometer measurements, and a camera with 8-MP stills, 1080p30 video capability [31]. These registration enabling sensors all require additional mass, power, and compute resources beyond the display rendering resources which leads to a bulkier overall system. The Joint AR project deemed these additional registration demands to be too high as a first-generation solution, therefore an unregistered AR system was hypothesized to be more favorable in the near-term.

The human physical interface level poses a host of challenges within a spacesuit context. EVA is a physically demanding experience, in part due to the physical interactions and demands the spacesuit itself places on the crew member. The physical volume within the helmet bubble is confined and is occupied by various devices such as a drink bag straw, Valsalva device, audio mics and speakers, perspiration/water management fabric, and possibly traditional eyeglasses. Furthermore, the internal atmospheric environment may be up to 100% oxygen in composition, therefore demanding all electronics inside the suit to adhered to strict anti-flammable environmental standards (see [32] as an example). To the best of our knowledge, there does not exist any AR systems rated to these environmental standards or devices that have proven all-day wearable comfort (8+ hours of continuous use). Given these challenges associated with existing within the spacesuit, the Joint AR team prioritized exploring a solution that involved mounting an AR solution to the helmet. In doing so, we traded in the near-term the demands of certifying AR electronics and possibly adopting/adapting an existing eyewear or head mounted AR solution for designing a novel mounted AR optics solution that integrates with the helmet bubble. Some anticipated advantages of this solution were improved physical comfort and reduced sweat accumulation by eliminating physical contact with the crew member as well as easier servicing and cable interfacing due to the potential for the image source and electronics to be externally accessible.

The human optical interface challenges are dependent on the type of ocularity of the AR display. One prevailing AR industry challenge is the vergence and accommodation conflict (VAC) affiliated when we attempt to perceive depth in the virtual content and the real world [33]. VAC stems from when eyes are rotating to look at the same object (vergence) and pupils are focusing on the object (accommodation) and these processes become misaligned, leading to discomfort [34]. VAC is non-linearly tied to the difference in distance the apparent image distance and the real-world object actual distance, the SPIE society [35] recommends an apparent image distance of 2 meters as a compromise when using AR with a large range of real-world scene object distances. Currently the AR market has few architectures that enable more than one or two apparent image distances or appropriately address focus/blur/visual cues amongst multiple image planes. Challenges also arise in the distortion of the user's real-world view when reducing the virtual image distance from infinity to 2 meters when adding push/pull lenses. Given the emphasis of the Joint AR system to be unobtrusive to the

user's field of view, efforts have not included optical correction of virtual image distance, but further investigation is required to address discomfort associated with VAC.

In addition to the challenges associated with VAC, the commercial AR industry predominately focuses on two types of solutions – near to eye and far field displays, neither of which correspond to our helmet mounted context. Eye relief, defined as the distance from the eye pupil to the closest point of the AR display, is one way to characterize these solutions [33]. Near to eye displays (~10-40 mm eye relief distances) make up the bulk of commercial AR systems and are integrated with eyewear or are head born. Far field displays (>100 mm eye relief) are found in heads up displays in fighter jet and car cockpits. Suit helmet to eye distances (~40-100 mm) are not currently a commercially viable product, therefore limited investment has been made to-date to yielding a capable optics solution.

Many additional factors beyond eye relief play a central role in describing the optical properties of an AR display (see Ref [33] for a more complete summary). For the purposes of this paper, we highlight a simplified model of a transparent waveguide display as shown in Figure 4 and described in Eq. (1) [34].

$$s = b + 2r \tan(v/2) \quad (1)$$

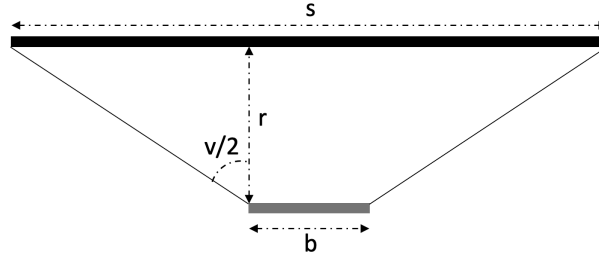


Fig. 4 Simplified AR waveguide display configuration that relates optical surface size (s), eye relief (r), eye box size (b) and field of view (v) [34]

Figure 5 shows a combination of the simplified waveguide model with a broader trade-space of pixel per inch (PPI) as a function of eye relief distances that span head born, helmet born, and off person, heads up, distances) (see Appendix for methods used to generate the plot). Plotted as grey-scale contours is the performance of human eye capability in units of arcmin (arcmin=1 is equivalent to 20/20 vision). Overlaid on this trade-space are the simplified model solutions generated from Eq. 1, assuming a constant eye box of 20 mm, to indicate the broader sweep of capabilities each optical solution might exhibit.

The commercial industry has made significant advancement on head born solutions which correspond to near to eye displays with viewing distances on the order of ~10-40 mm. The private sector is actively working towards resolution capabilities beyond that of the human eye (arcmin of 1 or better) (i.e. moving vertically upwards in Figure 5) in ever smaller head born form factors such as reading glasses. Non-head mounted solutions tend to towards large view distances such as those found in car heads-up displays or flat panel devices with view distances beyond 100mm. Suit helmet mounted solutions have a medium eye relief distance (~40-100mm) that currently has limited market potential (e.g., large eye box and medium eye relief distances), hence limited commercial investment and development.

Figure 5 shows some key challenges associated with realizing an AR display in a suit. Display pixel count must become exceedingly high to reach or exceed human vision, imposing very high demands on image source technology. Increasing FOV further exacerbates the needs for higher pixel count, but also necessitates a more complex solution beyond a flat panel waveguide in this example due to the excessive size of the planar optical surface required. Curved waveguides might offer some potential avenues to maintain a reasonable form factor while providing higher FOV capabilities, however, this technology is not yet proven. Increasing eye relief nonlinearly relates to decreases in PPI requirements, and this trend also depends on the FOV capability. Finally, increasing eye box (not shown in the graph) only exacerbates the trends discussed above, which will likely be a necessary component of the Joint AR system given the associated free movement of a suited astronaut's head within the helmet bubble.

The Joint AR system design goals prioritize increasing eye box size, brightness, and long duration comfort while minimizing mass and power for the system. Design challenges exist in ensuring a high brightness capable image source is paired with a large optical surface to enable a large eye box while maintaining considerations on VAC and obtrusiveness. The design is further challenged by the necessity for withstanding the spaceflight environment. Design

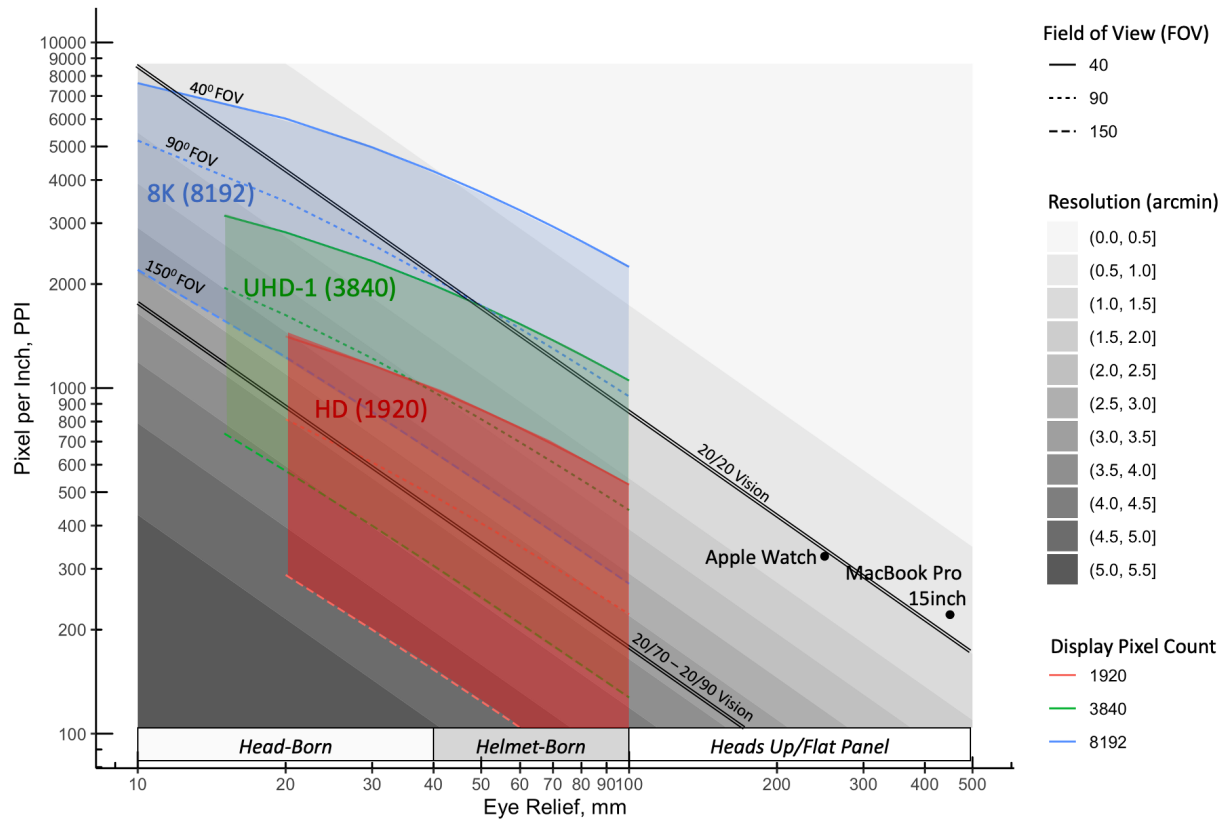


Fig. 5 Pixel per Inch (PPI) vs Eye Relief with contours of human eye resolution (arcmin) with AR display capabilities (assuming different simplified flat waveguides)

trade-offs are considered for a first iteration of the system, with additional technological advancement needed for meeting future needs of a more advanced AR system.

B. Suit Compatible Compute and Control Challenges

In addition to the novel optics challenge of rendering legible AR content to a suited crew member, the supporting compute and controls capabilities must also be enabled to achieve a useful AR system. As mentioned in the previous section, a non-registered capability was chosen to help reduce the overall compute and mass resources of the Joint AR system. However, even the compute resources required to render AR content can be demanding. A custom display engine was developed to render content at an acceptable level of performance in an embedded, safety-critical, radiation environment. The display engine is capable of using multiple graphics Application Programming Interfaces (APIs) to accommodate a range of potential hardware. It is tailor-made to support a low-power, low-overhead embedded hardware environment, supporting minimalist 2D textured sprites and ultra high quality text leveraging signed distance fields. The engine is capable of receiving data from multiple external sources via secure channels to drive dynamic content such as consumables quantity gauges and navigation state. It is developed with safety-critical applications in mind despite the use of GPU hardware by incorporating a generalized radiation tolerant render pipeline to mitigate the effects of cosmic rays on rendered output. Example techniques being explored include, but are not limited to, single-frame multi-rendering and averaging, spatial-temporal denoising, and custom texture formats with error correction channels. In the event of hard reset, the engine is capable of resuming state quickly to minimize downtime. By building a high-performance engine with build-in image correction, hot restarting, and decoupling from secure data sources, developers can focus on implementing advanced features with maximum reliability for safety-critical applications.

Controlling an AR display while in a spacesuit poses a host of challenges. The Joint AR team divided control into two broad categories: Crew *hands on hardware* control and *hands free* control. Hands on hardware control provides the crew member direct physical control using their hands on hardware such as switches, buttons, dials, piezoelectric

systems. These methods have challenges associated with attaching to the suit, wires and cables routing, environmental protection such as vacuum and dust tolerant, and being manipulated by pressurized gloves which offer limited dexterity, articulation, and tactile feedback. Hands free control methods include but are not limited to remote control, voice control, and gesture control. In addition to increased compute resources for hands free manipulation, they require a broader coupling of inputs from sensors and other users to enable (e.g. voice control must leverage and compute audio subsystem data, gesture control must leverage video inputs and remote control must interface with other users and software systems in a networked fashion). The Joint AR team has maintained an open trade-space of possible control methods and implemented a rapid prototyping and testing approach to help discover what combination of methods might be best situated to support future EVA operations.

In summary, simply getting legible AR content rendered to a suited crew member is non-trivial. This is further complicated by how crew might control the content to complete their work goals. The Joint AR project took the position that *time spent controlling an AR device is time not spent being productive during EVA*. An integrated, feasible solution will be discovered when we test these capabilities in the context of the work of future crew members as discussed in the next section.

VI. Defining the Sociotechnical System Work

A clear and agreed upon set of system work goals must be understood to evaluate the design and value proposition of a spacesuit augmented reality solution. To strive towards this understanding, the Joint AR team incrementally created EVA scenarios with varying degrees of complexity to help discover what specific work goals might be relevant for future operations. This effort adopted concepts from the envisioned world problem [9, 12, 36, 37] and function allocation [38] and combined them with the latest NASA published literature on lunar surface concept of operations [14]. The remainder of this section highlights this approach and discusses some of the ongoing challenges that remain.

As defined by Ref: [14] xEVA concept of operations, EVA tasks for exploration missions include “both engineering focused tasks for constructing and maintaining infrastructure and assets, as well as science-driven tasks for exploration of the natural environment.” More specifically, science tasks will “focus on evaluations and characterizations of the natural features of the destination. A variety of science-driven tasks will be conducted at any natural environment destination, including observations and imagery, acquisition of data, deployment, and retrieval of instruments, and acquiring physical samples for return to Earth. The science tasks may include the operation of novel EVA hardware and instruments. Sample acquisition will include loosely adhered particles (surface, regolith, float), rock chip samples broken from larger boulders or outcrops, subsurface samples exposed in trenches, samples from permanently shadowed regions (possibly including volatile samples requiring cold curation), and subsurface (core) samples. Science tasks will also involve deploying handheld instruments, larger stationary instrument packages, and instruments requiring prolonged astronaut or rover interaction [14, Section 4.1.5.2].”

The Joint AR team initially drafted a list of potentially useful AR capabilities that mapped directly to the aforementioned EXP-0042 task descriptions and existing xEMU requirements [39]. For example, we hypothesized the crew would want to see procedure steps and a navigation solution. However, this approach was too broad and vague. EVA is a complex and somewhat unpredictable series of events and proposing generic features did not align well with the anticipated variability of work demands the crew will need at different moments throughout the entirety of a hypothetical EVA. For example, there might be moments when the crew do not need to see a map but instead need a few procedure steps with an illustration. Do crew even really need to see a map at all? An alternate approach was needed.

A variety of more elaborate hypothetical narrative descriptions were composed to detail moments where decisions and actions were required and written in the first person from the crew perspective. These narratives not only told a story about what the crew were doing, they also provided insight into what they might be thinking and what information they might need to make decisions and perform actions. Throughout each narrative, individual descriptive statements were linked to hypothesized desires from the crew perspective. The following is an example narrative about two crew members, EV1 and EV2, about an opportunistic traverse to an unplanned destination.

On the traverse from Station 1 toward Station 2, EV1 spots something interesting in the distance. The features she sees do not show up in the orbital imagery map layer, so she has to estimate the location as relative to her position.¹ The feature is beyond a shadowed area, appearing to be approximately 300-400 meters away from the planned traverse path. Based on the topographic map, EV1 does not see evidence of any craters in the shadowed region between her and this new area of interest.² After conferring with the ground team on the remaining timeline and consumables, EV1 decides to take EV2 and investigate.³

In this example, the crew identified an opportunity to explore something that was not part of the original plan. The crew needed the distance to the feature of interest, how long it would take to get there, to determine whether it was feasible and safe to traverse there, and to estimate what impacts this deviation would have to the remaining plan. We captured these demands explicitly as a list of crew desires in the form of “I want to” statements, as shown below that are linked via the superscript citations in the narrative.

- 1) I want to know the location of an area I see as portrayed on a map (e.g. maybe an unplanned area of opportunistic investigation)
- 2) I want to know how to get to my next planned destination
 - Assume I know my location now
 - Translate a planned location from a map or other source (assuming you know where you want to go) to coordinates or relative location determination
 - Interpret that into heading, distance
 - Do I follow a direct path, or do I need to go left/right to avoid hazards?
- 3) I want to consider whether I should deviate from the next planned destination to visit an unplanned destination.
 - Assume I know my location now and how to get to my next planned destination
 - Translate what I see as an opportunistic unplanned destination into a location on the map
 - Analyze the impact of adding this destination (How far off the planned path does it take me? How long might this side trip take? Would taking this side trip result in needing to cut a priority objective later in the EVA timeline?)

The “I want to” statements created a way to build a common vision of what might be the essential support features of the AR system. It also provided a way to derive more specific assumptions and assertions about the state of being at that moment as denoted by the sub-bullets. For example, what might you already need to know prior to this moment? In this example, the AR system not only portrayed to the crew their position on a map, but it also enabled them to localize their position relative to features around them. The system showed potential hazards that might be in their path to a desired destination, and it suggested a safe path for the desired traverse. The system also provided an estimate of how long the side trip might take and how this decision could impact the remaining planned timeline. The Joint AR system provided the necessary information for both the crew and their broader team to make an informed decision together.

Another feature of these specific “I want to” crew perspectives is other members of the broader flight team can begin to evaluate where they might provide support functions. Not all capabilities must reside in the AR system itself. The organizational constraints of the work domain may demand a more distributed function allocation [38] among the flight team, thereby tying specific responsibility* and authority† to specific members and technologies within the flight team. We attempted to make it explicit who might have the responsibility and authority to take actions and make decisions to help have those deliberate design decisions earlier in the envisioning process. When we deliberately design the responsibility and authority for these types of decisions, it becomes possible to imagine how the crew might take on that responsibility and authority in conjunction with their AR system.

Table 1 shows a direct allocation of functions within an envisioned pioneering engineering task that involves bolt driving operations using a pistol grip tool (PGT). The EV crew has the authority to perform each action except for one – determining the final PGT setting, which is based on the outcome of the turn count of the previous step. This determination is made based on a data table prescribing different settings based on achieved turn count. In present day ISS conditions, the crew are not burdened with responsibility of knowing these details. The flight control team in the Mission Control Center (MCC) is ultimately responsible for the outcome of all actions and the crew are allocated the authority to act out each step. Table 1 shows how this function allocation could change with the addition of an AR system. Such a system could assist the crew in interpretation of the PGT setting decision data table and portray the correct choice in their field of view. In this work domain structure, the crew are granted authority to perform this action, thereby instilling in them the ability to have more crew autonomy. The crew, along with their locally sourced information, could be responsible for the outcome of the final three actions as indicated with the arrows that reallocate these elements of the work from MCC to crew.

This framing more specifically targets how we might one day enable crew autonomy by allowing the crew with their local assets such as an AR system to have the responsibility and authority to complete mission goals. To date, the Joint AR team has created 29 scenarios using this crew-perspective approach with function allocation detail to guide AR system scenario development. Across all these scenarios developed to-date is the reality that by shifting more and more

*Responsibility is defined here as a designation that is typically a legal or policy matter that assigns accountability to an agent for an action's outcome.

† Authority is defined here as the agent assigned to perform a certain action.

Table 1 Function allocation changes by an AR system for bolt driving operations. The Arrows indicate the specific reallocation of functions from MCC to EV1.

Actions	MCC		EV1	
	Responsibility	Authority	Responsibility	Authority
Identify Bolt	X			X
Congirgure PGT intial settings	X			X
Drive bolt to initial turns	X			X
Determine final PGT setting	X	X		
Set PGT final settings	X			X
Drive bolt to final torque	X			X

functions to crew, the total amount of work expected of them increases. The extent to which these new work expectations are achievable are a direct consequence of the capabilities of the supporting systems such as an envisioned AR system.

One additional dimension to scenario development the Joint AR team explored was emphasizing dynamic aspects of EVA operations. With a digital AR system, the crew are no longer constrained to a static set of information (i.e a paper cuff checklist). The use of position, navigation, and timing (PNT) data [40] or other system state information could be used to determine the crew position in real-time or share the system information when configurations change. The distance from the crew to another location can be calculated in real-time and portrayed to the crew. The current state of how much time the crew can continue EVA based on suit calculated information such as consumables and distance from the lander can constantly be updated and incorporated into decision moments. When decisions are made to alter the plan, the broader system can dynamically update the remaining timeline plan to reflect required revisions.

Table 2 shows a few examples of how dependencies on external data provided by additional sensors or other technology can be derived to support specific use cases. These examples are focused on the scenario of crew traversing from point A to point B according to the nominal plan. Besides the specific details in the “Required Sensors/Tech” column, it is assumed all rows in this table depend on access to PNT data for each suit. The first row identifies that with some fundamental PNT data, an AR system could present to the crew the desired heading and distance for their next traverse. This relieves the crew from having to review a paper top-down map and maintaining their own estimate of position to estimate orientation and distance to a target. In the second row, the AR system assists the crew with interpretation of hazards local to their position and in their planned path, providing first-person view indication of areas to avoid. The third row describes how an AR system could use as-performed traverse rates from an ongoing EVA, as compared to expected traverse rates used for the initial plan, to update the remaining timeline and prompt decision points based on the crew being ahead or behind the planned timeline. These few examples offer a multitude of more specific shifts in MCC and EV relationships based on who knows what and how might the team arrive at agreed upon decisions throughout the EVA.

The Joint AR team recorded and refined the scenarios within a NASA-internal MediaWiki platform which is being used by the broader NASA community in the scope of the Exploration EVA System [41–43]. The wiki enables any member of the community to document and refine the evolution of the con ops and hardware, organize test objectives and test events, and embolden transparent communication. The Joint AR team leveraged this collaborative resource to capture the iterative design processes described in this paper. The wiki is also used to document and organize test events and community demonstrations of the Joint AR system. By housing the team’s core knowledge in the same repository used by other organizations and projects supporting Exploration EVA, our assumptions are transparent and open to scrutiny. Discovery of disconnects between how individuals envision exploration EVA to happen based on real mission conditions is made possible by this collaborative approach.

Imagining and building a future domain that does not yet exist is a nontrivial problem. The problem itself stems from the underlying fact that creating new technologies for a work domain fundamentally transforms the field of practice within that domain in ways that are very difficult to predict, particularly for domains that do not yet exist [12]. Often, the unintended impacts of these new technologies are realized very late in the design process, resulting in few opportunities to correct the issues, and places the burden on the people within the system to overcome the limitations to still meet the desired system goals [9]. In some cases, the goals themselves become unintended or irrelevant to what the collective system should be accomplishing. Therefore, the Joint AR project is proactively imagining these future situations, exposing the assumptions that might be present and attempting to test these scenarios in prototyped environments.

Table 2 An example of deriving dependencies for dynamic content features.

Content Type	Inputs	Required Sensors/Tech	Outputs
Navigation	<i>PNT</i>	<i>Software</i>	Joint AR provides a heading compass with indication of actual heading and indication of target heading
	Location of crew	Calculation of crew position relative to target to determine desired heading	
	Location of target		
	Heading of crew		
Navigation	<i>PNT</i>		Joint AR indicates locations of keep-out zones (hazards, etc) in top-down maps as well as first-person POV registered AR. As crew traverse, EV crew see the keep-out-zone annotation/beacon in their FOV.
	Location of crew		
	<i>Map data</i>		
	Location of hazards		
Timeline Management	Duration of traverse	<i>Duration of traverse</i>	As crew traverse, Joint AR measures actual rate vs planned rate and reports performance. Joint AR updates timeline to show subsequent traverse durations based on realized rate. If traverse durations are longer than planned, Joint AR updates the timeline dropping stations based on priority.
		PNT (TBD) for start and end location determination	
	Time left for EVA	Timestamps at start and end used to calculate duration	
		<i>Timeline</i>	
		Logic to handle timeline modifications	

VII. Defining the Organizational Landscape

At present, the EVA community at NASA is undergoing a burgeoning surge of development which has major organizational challenges, particularly with regards to the spacesuit, the vehicles, and the broader ecosystem of data available in future missions. Philosophically, the Agency is approaching a business model to enable the growth of commercial aerospace companies via government contracts. In fiscal year 2022, NASA released a Request for Proposals (RFP) for the Exploration Extravehicular Activity Services (xEVAS) contract [39]. This contract outsources the spacesuit as an EVA service. Collins Aerospace and Axiom Space were chosen as the vendors and will deliver the Lunar spacesuit for future Artemis missions. Previously, the xEMU team, internal to NASA Johnson Space Center (JSC), was tasked with developing the spacesuit as a Government Furnished Equipment (GFE) project. The xEMU project enabled 5 years of technical development and was the culmination of 20+ years of research, development, verification/validation, and experience. The products of this work are available as a reference design, and it is necessary to handover this knowledge in an effective manner. Given these shifts in government and private procurement processes, the Joint AR project must now appropriately enable both NASA and private sector interests to enable a desirable AR system for future missions.

Apart from the contractual challenges, NASA is also establishing new programs to reflect Lunar and Martian mission objectives. The Exploration Systems Development Mission Directorate (ESDMD) was established in Spring 2022 and includes Orion, Space Launch System (SLS), Exploration Ground Systems, Gateway, Human Landing System (HLS), and xEVA and Human Surface Mobility (HSM) and Exploration Operations Program. While many of these programs are pre-existing and simply being relocated under a new umbrella directorate, xEVA, HSM, and Exploration Ops is the first EVA-specific and Artemis execution programs. This requires creating and staffing new positions and standing up mission directives, reallocating funding, technical gap identification, and risk assessments. Given these processes take time, it becomes even more imperative that continuity in mission assumptions and technology capabilities, particularly one as important and consequential as enabling crew autonomy.

The majority of this paper emphasized the technical and work related challenges of envisioning an AR solution. However, when considering the organizational landscape, simply getting access to data may be critical challenge to overcome. Artemis will require creating a data ecosystem among the program offices and their products on the Lunar surface. This poses a unique communication network and systems engineering and integration (SE&I) challenge. A shared wireless communication and internet architecture will govern data transfer between all EVA and Lunar surface assets and allow for PNT data for navigation solutions. These architectures have yet to be established, and timelines to establish interface standards may not match needs for more mature product delivery timelines (e.g. – the spacesuit may be designed and manufactured before a communication architecture is defined). The Joint AR system aims to serve as a node within this ecosystem to display data from various assets beyond suit data (e.g. interface with tools, vehicles, and habitats). This forces the Joint AR system to emphasize extensibility (e.g. software API designs) to ingest and display

data from various sources, assuming the broader organizational infrastructure can serve the data in the first place.

VIII. Conclusion

In this paper, we reviewed the challenges associated with envisioning a spacesuit compatible AR solution within the context of future EVA operations. Of note, we recognize an AR solution is a particular technological hypothesis to enabling crew autonomy. To best situate our hypothesis that AR is indeed a valuable tool to enabling Earth-independent operations, we framed the challenges in the context of a sociotechnical system. In doing so, we more fully account for the work demands that exist and may one day exist so that an AR solution has the necessary capabilities to enable desired system performance.

Several topics were highlighted to emphasize the difficulties surrounding building a useful AR solution. First, building technology for a set of users that do not yet exist is incredibly difficult. The envisioned world problem is not solved, and the additional complexities with human–automation interaction further complicates the challenge. As a result, there is no simple solution to the problem of imagining the technology required for future work domains. A more dedicated effort from the research and commercial sectors on strategies to best wrangle with the multitude of factors that contribute to imagining the future is needed. Second, a seamless suit-integrated AR solution does not yet exist. This is particularly the case when attempting to construct a suit-mounted optics solution with a transparent AR display. The commercial sector prioritizes fundamentally different and distinct optics problems; therefore, substantial investment in medium eye relief optics solutions must be made. Third, the ability for the crew member to interact with and control an AR solution remains undetermined, particular when control is thought about in the context of the broader mission team. A multitude of possible options exist and it is likely necessary to promote a complimentary set of control inputs among the flight team to help the crew member cope with the dynamic nature of EVA operations. Finally, imagining future work and technological solutions are directly influenced by the organizational landscape within which this development takes place. Thus, it is imperative to be evermore transparent about the assumptions, anticipated work demands, and actual capabilities of an AR solution so that the broader community can contribute in the creation of the AR experience. In doing so, mismatches between stakeholder expectations about the work and technological capabilities can be caught and addressed early and often.

Appendix

Figure 6 shows the diagram and corresponding R-code used to generate data used to generate the contour plot in Figure 5. Also see NVIDIA Automotive Screen Density Calculator for an interactive calculation of relevant parameters.

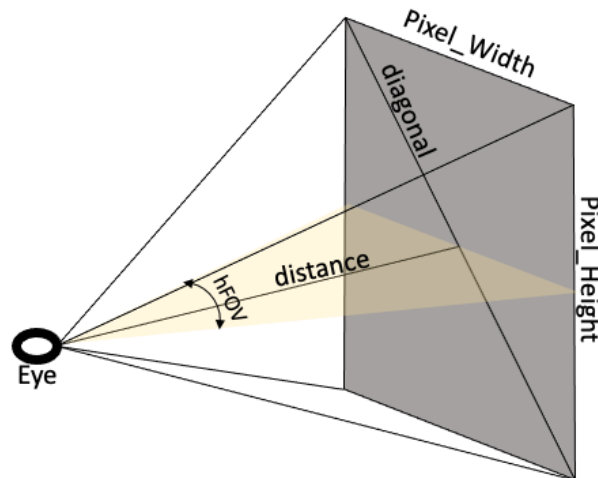


Fig. 6 Physical diagram relating eye distance and horizontal field of view to the size of flat display

```
diagonal <- seq(0.5,50,0.1)
distance <- seq(0.2,100,0.1)
```

```

Pix_Width <- 1920
Pix_Height <- 720
mat1 = matrix(, nrow = length(diagonal)*length(distance), ncol = 13)

index <- 1
for (i in 1:length(diagonal)) {
  for (j in 1:length(distance)) {
    # Diagonal
    mat1[index,1] <- diagonal[i]
    # Pixel Width
    mat1[index,2] <- Pix_Width
    # Pixel Height
    mat1[index,3] <- Pix_Height
    # Horizontal size (cm)
    H_size <- sqrt(diagonal[i]^2/((Pix_Height/Pix_Width)^2+1))
    mat1[index,4] <- H_size
    # Vertical size (cm)
    V_size <- sqrt(diagonal[i]^2-H_size^2)
    mat1[index,5] <- V_size
    # Pixel Per (cm)
    Pix_per_cm <- sqrt(Pix_Height^2+Pix_Width^2)/diagonal[i]
    mat1[index,6] <- Pix_per_cm
    # Distance (cm)
    mat1[index,7] <- distance[j]
    # Horizontal View Angle (deg)
    H_view_angle <- 2*(180/pi*atan((H_size/2)/(distance[j])))
    mat1[index,8] <- H_view_angle
    # Vertical View Angle (deg)
    V_view_angle <- 2*(180/pi*atan((V_size/2)/(distance[j])))
    mat1[index,9] <- V_view_angle
    # Pixel per Degree (PPD)
    Pix_per_deg <- Pix_Width/H_view_angle
    mat1[index,10] <- Pix_per_deg
    # Distance from Display (mm)
    Dist_mm <- distance[j]*10
    mat1[index,11] <- Dist_mm
    # Pixel per Inch (PPI)
    Pix_per_inch <- Pix_per_cm*2.54
    mat1[index,12] <- Pix_per_inch
    # Resolution (arcmin)
    Res <- 1/Pix_per_deg*60
    mat1[index,13] <- Res

    index <- index + 1
  }
}

df=as.data.frame(mat1)

colnames(df) <- c("Diagonal", "Pixel_Width","Pixel_Height", "Horizontal_Size",
"Vertical_Size", "Pix_per_cm","Dist_from_Display_cm", "Horizontal_View_Angle",
"Vertical_View_Angle","Pix_per_deg", "Dist_from_Display_mm", "Pixel_per_inch",
"Resolution")

```

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