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Beyond Boundaries: Empowering Astronauts with Autonomous AI-driven Health Systems and On-the-Go Skills Mastery to Enhance Safety in High-risk Environments

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Abstract

As space missions extend beyond the Moon, astronauts face increased health risks including prolonged exposure to microgravity, communication delays, and psychological stress due to confinement, and isolation. The Canadian Space Agency's Health Beyond Initiative is working with other space agencies to address the paradigm shift in the delivery of medical operations with the new requirements of deep space missions. By leveraging advanced technology, this approach aims to drive innovation, enabling a paradigm shift in healthcare delivery and enhancing safety and efficiency, so astronauts can navigate challenges beyond Earth's boundaries with confidence. AI-driven health systems can offer continuous monitoring and real-time analysis of vital signs, predicting potential health issues before they become critical. By leveraging deep learning and large language models algorithms, these systems can provide personalized health recommendations, ensure optimal physical and mental well-being, while reducing anxiety and stress associated with clinical decision-making. AI-enabled health systems effectively support the human-in-the-loop ecosystem, demonstrating the harmonious interactions of humans and systems-of-systems to support timely and informed clinical decision-making. They offer invaluable insight into health data that are typically inaccessible due to lack of interoperability, data accessibility and integration and synchronization issues. To thrive in high-risk environments, astronauts are required to be adaptable, resilient, and proactive in health management. Therefore, having access to a suite of technologies supporting on-the-go skill mastery is of paramount importance. An example of such systems is the winner of Canadian Space Agency Deep Space Healthcare Challenge, EZResus application, developed to streamline information needed by emergency personnel in the critical first moments of resuscitation efforts. Likewise, effective knowledge transfer mechanisms ensure that astronauts can quickly assimilate critical information and apply it in high-pressure situations. It also offers an opportunity to master critical capabilities in augmented reality environments with the necessary support in place. Through a combination of real-time data processing, autonomous decision-making, and continuous skill enhancement, the autonomous AI-driven paradigm of medical operations not only supports astronaut well-being but also sets a precedent for future space exploration endeavours. While the intricacies of space medical operations may sound futuristic, many parallels can be drawn with terrestrial high-risk occupations, such as the military, first responders, and geographically isolated Canadian communities, where access to healthcare resources is limited. The intersection of terrestrial and space healthcare challenges is a high-potential area of collaboration to advance technological capabilities and provide opportunities for skill mastery, prior to deployment in deep space habitats, where the risk of failure has detrimental outcomes.

Keywords: AI, Support, Guidance, Stress, Health, Medicine, Emergency

Abbreviations

Augmented Reality (AR), Canadian Space Agency (CSA), Commercial Off-the-Shelf (COTS), Earth-Independent Medical Operations (EIMO), Electronic Health Record (EHR), International Space Station (ISS), Just-in-Time (JIT), Low-Earth Orbit (LEO), Mission Control Center (MCC), Mixed Reality (MR), Portable Document Format (PDF) Virtual Reality (VR)

1. Introduction

As human space exploration moves beyond low-Earth orbit (LEO), communication delays and limited evacuation capabilities will require the crew to detect, diagnose, and treat medical concerns autonomously [1]. Deep space expeditions including prospective missions to the Moon and Mars introduce a spectrum of challenges that exceed the current capabilities of conventional space medicine operations [1], [2]. Current medical operations on the International Space Station (ISS) rely heavily on real-time communication with mission control center (MCC) to support routine medical examinations. This model of care, however, is unsustainable for future deep space missions where communication delays and the inability to evacuate will demand greater crew medical autonomy [2]. While flight surgeons and ground experts will remain in the loop and continuously support astronauts, the lack of real-time communications will also transform their approach to providing healthcare support to the crew. The Health Beyond Initiative of the Canadian Space Agency (CSA) leads innovative work to help enable this paradigm shift in medical operations towards resilient, self-sufficient onboard healthcare systems and medical capabilities that empower astronauts to perform routine health examinations and treat medical conditions independently [2], [3]. This transition will also require addressing the psychological and cognitive demands placed on astronauts when they are expected to perform medical care under high-stakes, high-isolation conditions. This paper examines the growing need for autonomous medical operations in increasingly remote missions. It explores how AI-enabled on-the-go support and training can address performance challenges and skill degradation to better support astronauts' health and performance during long-duration missions.

2. Background

Space exploration pushes humanity to its absolute limits, as the exploration of the solar system expands outside of the LEO, venturing out to the Moon and beyond. Decades of successful space exploration aboard MIR and the ISS have provided a unique opportunity to investigate the capabilities and limits of the human body and mind, offering invaluable insights about overall health and physiological adaptation mechanisms. These insights have further contributed terrestrially to the study of aging, osteoporosis, rehabilitation treatments and other medical discoveries.

Human spaceflight comes with many physical and psychological challenges, necessitating a comprehensive and carefully crafted medical operations paradigm, to ensure astronaut health, mission success and safe return to Earth. To-date, astronaut health risks in LEO have been extensively studied [4], [5]. Psychological challenges, such as isolation and confinement as well as disrupted internal processes like circadian rhythms, have been linked to increased levels of stress, anxiety, sleep disturbances, as well as impacted team dynamics and overall astronaut performance [6]. These psychological stressors not only affect well-being, but also increase cognitive load, potentially impairing decision-making under pressure and increasing risk of medical errors. These stressors are going to significantly amplify, as humankind embarks on missions to the Moon and Mars. The heightened health risks of space exploration beyond LEO, including increased radiation exposure, prolonged microgravity exposure, and the inability to resupply or evacuate, all further exacerbated by periods of communication delays and blackouts, present critical challenges to astronaut health and mission success.

The paradigm of healthcare delivery in space is shaped by the unique constraints of the spaceflight environment, which are different from constraints in Earth-based healthcare systems. On Earth, healthcare systems in urban centres leverage abundant resources, facilities and a variety of medical experts for diagnosis and treatment of an array of medical conditions, mainly concerned with primary, rehabilitative and palliative care. In contrast, space healthcare must adapt to a hazardous space environment with limited resources and medical expertise of the crew, as well as no immediate access to additional medical help should an emergency occur. Onboard the ISS, medical equipment is compact and portable, and astronauts receive limited pre-flight training in basic medical procedures, relying significantly on Earth-based communication and guidance for in-flight health assessments and mitigation of health contingencies. As such, preventative care is fundamental in the preservation of astronaut health and performance, while telemedicine is extensively leveraged to support in-flight health examinations. However, these healthcare practices will be rendered impractical and unfeasible as missions extend beyond LEO necessitating greater autonomy and resilience of medical systems aboard the spacecraft and self-sufficiency of the crew.

Astronauts come from various scientific disciplines such as engineering, mathematics, and biological sciences and a majority are not medical professionals [7], [8]. To ensure their health and safety during missions, the ISS program implemented a crew medical officer (CMO) designation to one astronaut in the crew. The CMO astronaut receives approximately 40-70 hours of medical training within 18 months before their mission [9]. Their training

enables them to act as an extension of the ground based medical team through real-time communication [10], [11]. They are responsible for overseeing the crew's health and well-being during routine medical operations. However, in emergencies, decision support is provided by an interdisciplinary team on Earth. Therefore, much of the CMO's training focuses on familiarizing them with spaceflight medical tasks with the reassurance of knowing ground support is available. For missions exceeding 210 days, the NASA-STD-3001 mandates that the CMO must be a physician astronaut [7]. It's important to note that, although the CMO is a physician astronaut in this case, they can rely on the MCC for real-time support, sharing the cognitive load and being provided expert assistance whenever needed [7], [12], [13].

3. Autonomous Medical Operations and AI-Enabled Training

As space agencies prepare for deep space missions, numerous gaps and challenges remain in the training and provision of healthcare for long-duration missions. For lunar missions, emergency evacuations will not be possible. However, despite the 1-2 second delay in communication, crew members can still receive ground support for routine and some emergency medical conditions. As we travel deeper into space, the CMO will be required to oversee all medical operations, managing both routine and emergency care with limited support from the ground. While flight surgeons will provide oversight, their input will be available in a delayed manner. Astronauts will not only need to monitor their health but also take an active role in medical decision-making and emergency response [14]. Furthermore, it is crucial that the crew is fully prepared to provide care in the event the CMO becomes incapacitated. Comprehensive training tools such as Just-In-Time (JIT) training and procedural support, are essential to mitigate skills degradation and ensure the team's readiness and safety when performing new or infrequently performed procedures [2], [3]. Traditional training methods that rely on pre-flight preparation and MCC support will be insufficient. Instead, AI-driven skills mastery will be essential to bridge knowledge gaps, provide real time procedural guidance, and enable adaptive learning [3], [15], [16]. These systems will help reduce cognitive load, allowing astronauts to focus on executing necessary procedures with confidence, even in high-stress scenarios [3]. To ensure reliability, AI-enabled technologies must operate within a human-in-the-loop framework – enabling seamless collaboration between astronauts, flight surgeons, and decision support technologies during routine care and emergency events. This systems-of-systems approach enables comprehensive, timely, and context-aware decision support by integrating data across hardware, software, while facilitating data sharing among users [17]. As humanity continues to push the boundaries of human space exploration, integrating AI-driven health and emergency management technologies will be fundamental to ensuring astronaut safety, optimizing performance, and sustaining life in the extreme conditions of deep space.

3.1 Autonomous Skills Training

Current spaceflight medical protocols rely on intensive pre-flight training where crew members receive hands on instruction for basic medical procedures, trauma response, and the use of onboard medical kits [7]. AI-enabled systems can function as adaptive medical trainers and decision support tools, ensuring astronauts can not only recognise health issues early on but also have the capability to respond under high stakes conditions. A major concern in this context is skill degradation especially for procedures that are rarely performed [18]. This is critical for emergency procedures where crew members will not be afforded the time to review and practise these procedures during a high stakes' situation. Some of the key functionalities for skills training that will be required include real-time procedural guidance, augmented reality (AR) and virtual reality (VR) training, automated decision support, and cognitive load management [19]. The designs of these systems for future missions must account for cognitive task distribution, information clarity, and intuitive interfaces to mitigate decision fatigue.

3.1.1 Just-in-Time (JIT) Training

AI-assisted step-by-step instructions tailored to the astronaut's proficiency level and medical expertise can help the astronaut feel confident in their decisions and actions when immediate medical expertise/support may not be available [9]. Presently, CMOs on the ISS have access to paper-based procedures and computer-based tutorials at point-of-care to quickly familiarize themselves with the knowledge and procedural skills necessary to execute medical

tasks [20]. Additionally, they have access to ground support for assistance in decision-making. However, in the context of deep space exploration missions, JIT training will be essential, particularly for medical procedures that are performed infrequently and may not be retained through preflight training alone. Another important consideration is the need for adaptive JIT training programs where the training meets the user at their medical proficiency level. JIT training is widely used in terrestrial healthcare and has demonstrated significant promise in enhancing procedural readiness and reducing error, particularly in high-stakes or time-sensitive scenarios. A pertinent example is NASA's study on Autonomous Diagnostic Imaging performed by untrained operators using AR as a form of JIT training [21]. This study demonstrated that AR-guided tutorials can enable individuals without prior experience to perform diagnostic imaging procedures such as abdominal ultrasounds effectively [21]. In addition, by incorporating systems with contextual awareness, training tools can dynamically adjust the information based on the current situation, avoiding information overload and ensuring the most relevant guidance is provided [22]. This can help foster a sense of control and ensure the astronaut remains focused on execution rather than recall [18], [19]. Confidence in medical decision-making is not only essential to performance but also to psychological resilience during prolonged mission stressors.

3.1.2 Training Simulations and skills degradation

Through AR and VR, astronauts can reinforce their procedural knowledge of probable medical scenarios, enabling skills acquisition in a hands-on, risk-free environment [11], [20], [23]. VR/AR research has grown exponentially since its inception and has been applied in multiple disciplines. VR immerses users in a fully digital environment whereas AR enhances real-world interactions by superimposing instructional visuals onto the user's field of view. Mixed Reality (MX) combines both VR and AR by allowing digital and real-world objects to interact in real time [24], [25]. These technologies have been used previously on the ISS and other commercial flights to enhance training, operations, and for research [26]. Notably, for healthcare delivery, Alexa's Holographic Teleportation Behavioural experiment aboard the Axiom-1 private astronaut mission to the ISS tested two-way communication between crew members aboard Axiom-1 to the ISS and ground using MX [27]. This experiment demonstrated the feasibility and effectiveness of this technology in space and its potential applications for private medical conferences [27]. In deep space missions, where astronauts face prolonged isolation and limited medical support, maintaining medical proficiency is critical [19]. Simulation-based training provides a risk-free, immersive environment that supports long-term skills retention and minimizes potential harm to patients by allowing for repeated, hands-on practice without clinical consequences. The CMO and other crew members can practise medical techniques and procedures to increase their competency and as a result their confidence. Confidence, in turn, has been shown to correlate with reduced hesitation and improved outcomes during emergency scenarios [20]. Skills degradation over time can compromise the crew's ability to respond to emergencies [20]. VR, AR, and MX technologies demonstrate immense promise in mitigating skill decay especially with integrated training programs that are capable of assessing clinical skills over time and providing feedback for continuous improvement to improve.

3.1.3 Intuitive Procedural Support

Presently, Portable Document Format (PDF) documents are used aboard the ISS for medical reference and procedural guidance. Astronauts have real-time communication with ground-based medical experts, allowing PDFs to serve as a supplementary reference rather than standalone tools. However, in more autonomous missions – where delays or loss of communication is expected – PDFs are likely to be insufficient. These static documents are challenging to navigate and interpret in high-pressure medical scenarios. Without dynamic updates, contextual guidance, or adaptability to the crew's skill level and the situation at hand, such documents cannot effectively support real-time decision-making.

Effective procedural support in space requires technologies that are not only accurate but highly intuitive to minimize cognitive load in high-stress or time-sensitive situations. Since astronauts may be operating outside their primary areas of expertise, they need tools that enable quick access to relevant medical information—without the complexity of navigating dense PDFs or complex interfaces. A notable example of AI-driven procedural support in real-time is the EZResus application, the winner of CSA's Deep Space Healthcare Challenge [28]. EZResus, a Canadian-developed application by Paratus Medical, is an AI-powered resuscitation support application that provides structured, real-time medical guidance to emergency personnel in critical care situations. It is designed for healthcare professionals such as nurses, physicians, and paramedics but it can adapt to the user's level of experience and expertise,

making it accessible even to non-experts. The application is designed to reduce cognitive load, minimize errors, and improve patient outcomes by guiding the user through complex resuscitation protocols step-by-step [28], [29]. The application tailors resuscitation protocols based on real-time patient vitals, medical history, biometrics, and emergency severity. It then provides just-in-time, adaptive instructions for procedures like advanced airway management, in-depth drug dosing recommendations and calculations, guidance in equipment preparation, and cardiopulmonary resuscitation protocols [29]. By integrating clinical decision algorithms, the application ensures responders are not overwhelmed by complex medical information and only receive the critical, actionable steps required to respond to an emergency scenario. This not only supports rapid and confident execution of high-risk procedures but also reduces reliance on memory recall in high-stress environments – a notable key contributor to medical error [30].

Procedural guidance tools can function as real-time cognitive aids by externalizing decision pathways and action plans. These tools help mitigate errors caused by information overload, fatigue, stressful environments, and inexperience. This is particularly important in environments where expert oversight is unavailable, and time-critical decisions must be made under pressure. Currently, EZResus is used globally and is capable of working offline – an essential feature for remote and austere locations[29]. The challenges faced by emergency responders on Earth such as high cognitive load, complex procedures, and limited time for decision-making mirror the challenges astronauts will face in deep space missions. The application offers a compelling framework for AI-driven astronaut medical support.

4. Discussion

4.1 Steps Towards Enhanced Autonomy

As space agencies take the first steps towards enhanced medical autonomy, terrestrial innovations offer valuable proof points for how intelligent procedural support systems can be adapted to the unique demands of spaceflight. Building on these insights, the ISS4Mars Earth-Independent Medical Operations (EIMO) initiative—established by the ISS partners through the Multilateral Human Research Panel for Exploration—aims to use the ISS as a Mars analog to assess the needs, gaps, and challenges of delivering medical care during deep space missions [2]. Led by CSA's Health Beyond Initiative in collaboration with other space agencies, the EIMO use case focuses on evaluating autonomous approaches to routine medical examinations. In this context, tools that provide real-time procedural guidance could empower astronauts to manage medical events when expert support is limited or delayed. Unlike static PDF documents, intelligent platforms could deliver dynamic, step-by-step instructions enriched with visual aids and interactive checklists. By tailoring guidance to the crew's medical skill level and situational demands, such systems have the potential to increase safety, autonomy, and confidence during health-related challenges in space.

4.2 Connected Care Medical Module Framework

Building on the vision of enhanced autonomy explored through initiatives like ISS4Mars EIMO, the CSA Connected Care Medical Module (C2M2) represents a key component in operationalizing medical autonomy within a larger framework. Developed under the CSA's Health Beyond Initiative, C2M2 is a system-of-systems design framework where intelligent procedural support and just-in-time (JIT) training are key components to support crewmembers in the management of their health. At the heart of the C2M2 architecture is an AI-enabled computational platform that supports a modular health informatics environment. This platform allows for the integration and coordination of Commercial Off-the-Shelf (COTS) medical devices through standardized interfaces.

Launched in 2023 under the Health Beyond Initiative, five Canadian companies developed a medical system capable of integrating various medical devices in a sea container, including point-of-care diagnostics, ultrasound imaging, and vital signs monitoring, alongside interactive skills training modules, digital procedural guidance for common space-relevant medical scenarios, and early-stage clinical decision support tools for triage and treatment prioritization. A second round of C2M2 development was completed in 2025, advancing the system's capability and readiness for spaceflight applications, while also demonstrating potential for use in terrestrial remote healthcare. In this phase, particular emphasis was placed on enhancing procedural support for users with different medical backgrounds including interactive step-by-step guidance, embedded JIT training modules, and explainable outputs

generated by AI-driven decision support engines. It's important to note that these systems do not intend to replace ground-based flight surgeon support. Rather, they are designed to enhance autonomous decision-making while maintaining periodic support from the ground, ensuring a human-in-the-loop framework. In emergency situations where real-time ground support is not available, these systems can autonomously analyze incoming data, prioritize potential diagnoses, and suggest evidence-based interventions. By combining autonomous capability, JIT training modules, and interactive procedural guidance, the system supports both medical readiness and crew confidence – ensuring that astronauts have the tools they need to react to emergencies effectively.

4.3 Consideration when using AI

Integrating AI into medicine and space exploration offers transformative potential by enhancing diagnostic accuracy, personalizing treatment plans, and enhancing medical training. However, it also presents significant challenges such as the well-known black box nature of AI models, where decision-making processes are not transparent and easily interpretable [12], [31]. This opacity can hinder trust and acceptance in the healthcare system on Earth and for astronauts who will rely on these systems to make critical decisions [22], [32]. In a high-stakes environment, understanding the rationale behind AI-generated decision support is crucial for crew safety, especially in cases where a non-physician astronaut is delivering care. Trusting the diagnosis or treatment options presented without real-time connectivity with Earth is imperative. Therefore, enhancing explainability of AI models is essential to build trust and facilitate effective collaboration between humans and AI systems [12]. Beyond explainability, these systems must also be designed without bias and align with users' mental models, reduce cognitive burden, and enable rapid comprehension under stress. Trust in AI is not only about transparency but about usability and consistency of performance.

In clinical settings, the lack of interoperability among AI-driven systems introduces significant ethical, legal, and operational challenges, particularly related to patient safety and regulatory compliance[33]. AI tools that fail to integrate seamlessly with electronic health records (EHRs), CDSSs, or mission-specific data architectures contribute to data silos, latency in decision-making, and increased cognitive load. This concern is amplified in space medicine, where crew members may operate autonomously for extended periods and depend on context-aware decision support tools to manage both routine and emergency medical scenarios [3], [34]. Furthermore, if an AI system recommends a specific treatment without providing a clear rationale as to how it arrived at that decision, clinicians may hesitate or question the recommendation as the ultimate responsibility for patient outcomes rests with them [12], [31]. This lack of transparency can also complicate the consideration of alternative solutions if the initial treatment proves unsuccessful.

Another critical challenge is the potential for inherent bias within AI algorithms [22]. These biases can arise from unrepresentative training data, flawed designs or existing data sets where bias is already present, leading to disparities in medical diagnosis and treatment. For instance, when an AI system is predominantly trained on data from a specific population, it is unlikely to perform accurately for individuals from underrepresented groups [32], [34]. This can lead to inaccurate diagnosis and unequal access to medical treatment [[34]. In the context of space medicine, the lack of diverse astronaut health data presents significant challenges. Astronauts represent a highly specific demographic, and without diverse data, AI systems may fail to account for variations in health and treatment needs across different populations, potentially putting astronauts' health at risk during long duration missions [31]. This underscores the importance of comprehensive data collection, particularly from environments that are analogous to where the AI system will ultimately be used [31]. Given the physiological changes experienced in space such as musculoskeletal atrophy, neurovestibular disturbances, and fluid shifts, there is a pressing need for data from space and deep-space missions to ensure accurate and reliable AI outputs [4]. In space medicine, this means ensuring the inclusion of data from a broader range of astronauts, including different sexes, ethnicities, and health profiles to better reflect population diversity. By addressing these gaps, we can ensure that AI systems are trained on data that represents the diversity of the individuals they are intended to serve, thereby improving accuracy, fairness, and ultimately, the quality of care.

The black box nature of AI, lack of interoperability, potential for bias, and the need for large comprehensive datasets represent only a subset of challenges at hand [15], [22]. Addressing these multifaceted challenges along with other challenges when using AI in healthcare that are not mentioned in this paper, requires a concerted effort and

should be considered at the initial design phase. Demystifying AI treatment recommendations allows the user to build trust and feel confident in their decision-making. This transparency is crucial for widespread adoption of AI technologies in both medicine and space exploration, ensuring they augment human capabilities without compromising safety or ethical standards whether it is used on Earth or in space.

5. Conclusion

As human space exploration extends beyond low Earth orbit toward the Moon, Mars, and beyond, the need for autonomous, resilient healthcare systems becomes increasingly critical. The constraints of limited medical personnel, communication delays with Earth, and the risk of unforeseen medical events necessitate the development of robust, intelligent medical systems. AI-enabled technologies offer a promising solution by providing JIT training support, enabling adaptive training systems that mitigate skill degradation, and providing clinical decision-making support. For successful future exploration-class missions, these systems must be designed with a deep understanding of both clinical workflows and operational engineering constraints. Designing tools that optimize usability, cognitive workload, and situational awareness will instil confidence in the crew to perform medical tasks without immediate ground support. The successful deployment of AI-driven medical support tools in space will depend on their ability to function intuitively and effectively in dynamic, high-pressure environments. New approaches to procedure guidance with intuitive applications have the potential to empower crewmembers. These innovations will not only advance the safety and sustainability of exploration-class missions but also catalyze the development of autonomous healthcare solutions for remote and medically underserved populations here on Earth, to provide accessible healthcare wherever the need is.

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