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Emerging technologies in military space operations: current applications and future research for educational and training purposes

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ABSTRACT

The rapidly evolving domain of military space operations has become increasingly integral to national security and defense strategies. Emerging technologies, including artificial intelligence (AI), simulators and extended reality (XR) tools such as virtual reality (VR) and augmented reality (AR), are revolutionizing how military forces train and operate. These innovations not only enhance the effectiveness of military missions but also necessitate a revaluation of the education and training required for space personnel. This paper explores the current applications of these technologies in military space operations, identifies potential challenges associated with their integration and proposes future research to guide the development of educational and training programs. By examining the historical evolution of military space activities, the roles and activities of space personnel and the integration of advanced technologies, this paper aims to provide an understanding of how emerging technologies are shaping military space operations and the current and future implications for education and training.

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1. Introduction

The domain of military space operations has evolved intensely since its beginning, having an increasingly fundamental role in national security and defense strategies. From the early days of satellite reconnaissance during the Cold War to the sophisticated space-based technologies used today, the militarization of space has continually adapted to emerging threats and opportunities (Hays, 1994; Lambeth, 2004). Simultaneously, technologies began to be developed, integrated and utilized in operations, introducing new capabilities and working methods. Artificial intelligence (AI), simulators, extended reality (XR) tools such as virtual reality (VR) and augmented reality (AR) are just a few examples of innovations that are transforming how military forces operate in the last years (Caso et al., 2024; Erwin, 2024a, 2024c; Fahnestock, 2020; Kasım et al., 2021; Stouch et al., 2023). Automatically, several questions arise regarding how these technologies are currently used, how they will be integrated and used in the future, how personnel should be educated and trained to use them and which technologies are most suitable for specific

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operations. Therefore, the primary aim of this paper is to explore the current technologies used in military space operations and the current applications for educational and training purposes. Further, the paper identifies the emerging tools, the potential challenges associated with their integration and propose future research that can guide the application of these tools for educational and training purposes.

To accomplish the objectives of this paper, its structure is outlined as follows. First, it begins with a brief historical overview of military space activities, tracing their development from the early days to the modern era. Following this, it delves into the various roles carried out by military space personnel, providing insight into who is using these technologies and who could potentially use them. Next, it examines the current knowledge requirements for personnel and the current educational and training programs, helping to understand the activities that military space personnel undergo to grasp technological applications. The exploration of emerging technologies is then detailed, highlighting innovations while thoroughly analyzing their applications. Finally, key considerations for the use of technology in education and training were discussed prior the exploration of the potential applications of these technologies for educational and training purposes, as well as potential future research.

2. A brief history of military space operations

Since the beginning of the space age with the launch of Sputnik 1 by the Soviet Union in 1957, space emerged as a critical domain for military operations. The strategic significance of space became increasingly apparent during the Cold War, as the United States and the Soviet Union raced to develop and deploy military satellites, reconnaissance systems and ballistic missile defense capabilities. Thus, the military's involvement in space activities began with the recognition of space as a new frontier for subjects such as strategic advantage, surveillance and communications (Coletta & Pilch, 2009; Hays, 1994; Lambeth, 2004; Mowthorpe, 2001).

The launch of the first reconnaissance satellites (e.g. the CORONA program in the early 1960s), marked the beginning of military space operations aimed at gathering intelligence, monitoring adversary activities and enhancing national security. During the Cold War, both the United States and the Soviet Union developed space-based surveillance and reconnaissance capabilities to monitor each other's military activities (Hays, 1994; Lambeth, 2004). Military satellites equipped with imaging sensors, electronic intelligence (ELINT) payloads and signals intelligence (SIGINT) systems provided intelligence to support national defense and decision-making. Advancements in space technology, including satellite communication systems, global navigation satellite systems (GNSS) and missile warning satellites, further expanded the military's capabilities in space operations (Czaplewski & Goward, 2016). The development of secure and resilient satellite communication networks enabled secure command and control of military forces, rapid dissemination of critical information and coordination of joint military operations across the globe. Further, space-based missile warning systems provided early warning and threat assessment of ballistic missile launches, enabling strategic deterrence and ballistic missile defense capabilities. These systems played a vital role in ensuring national security and deterring potential adversaries by providing warning of missile threats and facilitating rapid response and decision-making (Lambakis, 2024).

In the post-Cold War era, the militarization and commercialization of space have introduced new challenges and opportunities for military space operations. Emerging threats such as anti-satellite (ASAT) weapons, space debris and cyber warfare have heightened concerns about the vulnerability of space assets and the need to enhance space situational awareness (SSA) and space traffic management (STM), resilience and deterrence capabilities (Baird, 2013; Lambeth, 2004; Mowthorpe, 2001). In response, there have been significant governmental and organizational developments in recent years. For example, in 2019, the U.S. Space Force (USSF) was established (Godshall & Thomas, 2021) and the North Atlantic Treaty Organization (NATO) recognized space as a distinct operational domain, on par with air, land, maritime and cyberspace, as stated in the NATO Overarching Space Policy (NATO, 2024). Finally, before delving into education, training and related technologies, it is important to understand the roles within the military space. This helps identify the end users of these tools and the individuals who require education and training.

3. Military space operations and roles

Space military operations involve a broad range of activities conducted by military forces to protect national security interests, enhance defense capabilities and ensure strategic advantage in the space domain (Hays, 1994). These operations involve various roles such as the space operators, space mission planners, spacecraft controllers, space intelligence analysts and space policy experts (Hays, 1994; National Research Council et al., 2005). Space operators are responsible for managing and controlling military satellites, space-based surveillance systems and other space assets. They oversee satellite operations, monitor SSA and conduct space-based reconnaissance to gather intelligence and support military missions. Space mission planners develop mission plans, schedules and operational procedures for military space missions. They coordinate spacecraft activities, orbital maneuvers and payload operations to achieve mission objectives while optimizing resource utilization and mission success. Spacecraft controllers operate and maintain military satellites and spacecraft systems, ensuring their proper functioning and performance in orbit. They monitor spacecraft health, control propulsion systems and execute commands to support mission requirements and operational needs. Space intelligence analysts analyze satellite imagery and other space-related intelligence to assess potential threats, monitor adversary activities and provide situational awareness to military commanders. They identify patterns, trends and anomalies in space activities to support decision-making and operational planning. Space policy experts develop and implement policies, regulations and strategies related to military space operations. They advise policymakers on space governance, international agreements, arms control initiatives and space law compliance to ensure responsible and sustainable use of space resources (Figliola et al., 2006; Hays, 1994; National Research Council et al., 2005). Yet, it is important to note that the number of military satellites and the scope of operations vary significantly between countries, impacting the size of personnel, their roles and their activities. For example, the Dutch defense currently manages three satellites, whereas the United States oversees more than 239 military satellites. This discrepancy naturally influences the scale and complexity of personnel assignments, the variety of roles and the range of activities conducted within each country's military space programs (En Klimaat, 2024; Mishra, 2022).

In conclusion, the roles within the military space have been outlined. The next section will examine the overarching education and training needs, as well as the current programs in place.

4. Education and training

A strong educational foundation is vital for military space personnel (Godshall & Thomas, 2021). There are several topics that military space personnel should be familiar with. One example is the understanding of the fundamental principles of astronomy and astrophysics. This is essential as it provides insights into the behavior of celestial bodies and space phenomena. This includes a grasp of orbital mechanics, space weather and the physical properties of the space environment (Stouch et al., 2021). Additionally, space systems engineering forms a core component of foundational knowledge. This discipline encompasses the design, development and utilization of space systems such as satellites, sensors and launch vehicles. Proficiency in propulsion systems, spacecraft design and satellite communications is fundamental for effective space operations. Therefore, technical proficiency is a cornerstone of military space operations. Personnel must be adept at satellite operations, including launch procedures, orbit management and anomaly resolution. This extends to satellite payload operations and data analysis, ensuring that space assets function optimally and provide critical information (Chang et al., 2007). Given the vulnerability of space systems to cyber threats, cybersecurity knowledge is vital. Personnel must be skilled in protecting space assets from cyber-attacks, understanding secure communication protocols and implementing defense mechanisms. Furthermore, strategic understanding and tactical expertise are crucial for military space personnel. Knowledge of national and international space policies, treaties and agreements is essential, as it informs the strategic implications of space operations and the role of space in national security. Finally, another way to have an overview of the key topics is by referencing the NATO Space Guidelines, as examined by Caso et al. (2024), who identified the current education and training needs for military space operations. These topics were organized under several categories. The first was Space Domain Awareness (SDA), which includes SSA, STM, and Space Weather. The second category is Space-based Services, which covered areas such as Global Navigation Satellite System (GNSS) for Positioning, Navigation, and Timing (PNT), Early Warning (threats), Intelligence, Surveillance, and Reconnaissance (ISR), and Satellite Communications (SATCOM). Under the category of Security, the relevant topics included Secure Communications, Cybersecurity, and Counter-Space Operations. The next category, In-Space Operations, included Satellite Operations, Payload Operations, and Rendezvous Operations and finally, in the category of Access to Space, the category included Launch Operations.

In the military space domain, the emphasis on competency-based training is central to ensuring personnel are prepared for the challenges that they will face in real-world scenarios. Competency-based training focuses on developing the practical skills, behaviours, and abilities that are directly aligned with operational needs and performance requirements. This type of training often involves simulations, exercises, and real-time decision-making that mirrors the demands of space operations. A range of educational and training programs are already in place to train military space personnel. For example, training in space warfare tactics, including offensive and defensive operations, electronic warfare and SSA, prepares personnel for the complexities of space conflict. Hence, advanced training and specialization are provided to address the dynamic nature of space operations. Space mission simulations provide realistic scenarios that help personnel practice decision-making, mission planning and other (Kasım et al., 2021). Such trainings are typically performance-oriented, with clear assessments of personnel's ability to apply learned skills in dynamic and high-pressure environments. For example, military exercises and courses such as the Fundamentals of space operations course at the Netherlands Ministry of Defense, the advanced SSA course at Fraunhofer and Bundeswehr and at European Space Agency (ESA), the NATO Exercise Steadfast Jupiter and the USSF exercise Global Sentinel. Wargaming exercises simulate potential conflict scenarios, enhancing strategic thinking and readiness for real-world contingencies. Thus, interdisciplinary collaboration is fostered through joint operations training, which ensures interoperability with other military branches and allied forces. For instance, the AsterX joint exercise (NATO, 2023). Accordingly, partnerships with academic institutions and entities such as the NATO for advanced research and education in space sciences and technology further support innovation and expertise development. Accordingly, NATO offers courses such as the NATO School Oberammergau space course and NATO space support coordinator course (Caso et al., 2024; NATO, 2024). Moreover, military entities such as the USSF offers courses such as the Coalition space course and the Space operations qualification course, while the Royal Netherlands Air Force offers courses such as the Space weather course.

The educational courses and training programs from these organizations, as well as those directly within the space force, could benefit from the integration of advanced training technologies to enhance teaching and training. Furthermore, they may facilitate learning and development in all stages of the military space professional. The need for highly competent personnel keeping continuously current with new operational concepts, procedures, systems, and technologies is high and urgent. The next section outlines the current technological applications. After that, it is discussed on how to optimize the usage of these technologies and the need for future developments.

5. Current technological applications

Several key technologies are involved in military space activities. Interestingly, the Chief of U.S. Space Operations recently discussed technological innovations, noting that the current space domain is vastly different from the one he grew up with (Erwin, 2023) and emphasizing important strategies to leverage commercial tech innovations (Erwin, 2024b). Given the limited literature in technological applications for educational and training purposes, this section provides information on both the general technological applications and the few existing applications specifically for education and training.

Advanced radar systems, optical telescopes and space-based sensors are few technological examples used to monitor STM (e.g. space surveillance and tracking). These tools are used to monitor objects in Earth orbit, detect potential threats and maintain SSA (Weeden et al., 2010). In relation to STM and SSA, XR tools enable the visualization of space domain entities (e.g. satellites orbits) and concepts (e.g. sensor coverage and maneuvers) in 3D, offering to the trainees and operators a dynamic, engaging and intuitive tool to improve their understanding of space-relevant topics such as astrodynamics, fuel usage, tactics and space operations (Stouch et al., 2021). Accordingly, the USSF has recently made significant investments to develop an XR training environment (Erwin, 2024a). XR environments include VR, AR and mixed reality (MR) tools provide a rich and immersive user experience and enable trainees to participate in lifelike scenarios and receive real-time guidance while performing the tasks (Stouch et al., 2021, 2023). VR immerses users in a computer-generated environment that transcends physical world limitations. In this artificial digital setting, users interact with their surroundings using devices like headsets, gloves and motion controllers (Alnagrat et al., 2014; Chan et al., 2022). Conversely, AR combines real-world information with computer-generated content for an interactive experience (Azuma et al., 2001; Billinghurst & Kato, 2003; Vincenzi et al., 2003). Combining machine vision and computer graphics, it integrates real and virtual objects into unified, real-time scenes (Macchiarella et al., 2005). Finally, MR goes further by integrating the experience of the user with both real and virtual elements. It holds a distinctive position in the extensive virtual field, combining aspects of VR and AR (Milgram & Kishino, 1994; Speicher et al., 2019). This hybrid nature of MR enables users to engage with virtual elements within the real-world environment. This synergy of real and virtual elements fosters high levels of interaction and immersion (Maas & Hughes, 2020; Milgram & Kishino, 1994; Speicher et al., 2019). In the military space context then, XR tools create immersive simulations that enable personnel to train in realistic environments without the risks associated with live training exercises (e.g. virtual space operations centre [SpOC]) (Stouch et al., 2023). Further, these technologies help improving the decision-making skills and operational readiness by providing interactive and engaging training scenarios that closely mimic real-world conditions (Erwin, 2022). For instance, Jenkins et al. (2018) and Stouch et al. (2023) developed an AR tool for space operators, enabling enhanced spatiotemporal understanding for proximity-based hazards assessments, maneuver planning and scenario evaluations. Another example is Fahnestock's (2020) exploration of VR as an effective tool for training complex concepts within the USSF.

Technologies such as ground-based radars, space-based telescopes and tracking algorithms enable accurate tracking of satellites, debris and other space objects. Accordingly, the USSF is collaborating with companies to deploy AI and machine learning models (Erwin, 2024c). AI and machine learning are used for SDA, which involves monitoring and analyzing space environments to predict and respond to potential threats (Felton et al., 2021). AI algorithms can process vast amounts of data to detect anomalies, satellite failures and predict the behavior of satellites and other space objects (Erwin, 2022). Another example is ARGUS, a SSA tool from the Netherlands Aerospace Centre (NLR) which it uses available data sources (e.g. Spacetrack) and can monitor orbital events and other advanced functionality such as Space Object Characterisation, Rendezvous- and Proximity Operation, an automated warning system and a 3D output capability (NLR, 2024b). These type of systems analyze real-time telemetry data to detect early signs of potential malfunctions, allowing for proactive maintenance and reducing the risk of unexpected satellite downtimes. Further, this capability allows to take timely defensive measures (Erwin, 2024c). Additionally, AI and machine learning are used in missile detection systems to differentiate between real missile threats and false alarms, thereby improving the accuracy and speed of threat responses (Demarest, 2024; Hitchens, 2024).

In practice, numerous companies are leveraging AI and machine learning technologies for military space operations. For instance, NurjanaTech provides precision long-range object identification, tracking and video recording using advanced AI and machine learning technologies. Their autonomous systems are used worldwide for various surveillance, protection and safety-enhancement missions. By integrating AI with real-time data fusion, they developed solutions that quickly detect, identify, track and disseminate information to operators in real-time, thereby supporting informed decision-making processes. Therefore, their system enables operators to autonomously command and control the detection and tracking of diverse targets, leveraging cutting-edge AI and innovative machine learning techniques ('Optical Tracking Systems' 2024). Another example is the Maris-Tech's which its strength lies in leveraging intelligent video analytics and AI solutions to enhance real-time monitoring capabilities in space operations ('Low Latency, Wireless, AI Edge Video Solutions' 2024). Their Jupiter AI product is a surveillance solution that integrates high-quality video and audio capture, encoding, decoding and low-latency streaming. It supports advanced AI features such as detection, classification and tracking, crucial for preempting potential threats like collisions with space debris or adverse space weather conditions. Complementing Jupiter AI is Pearl, an ultra-HD edge computing platform designed for powerful AI applications in space. It offers detailed environmental views and precise tracking of objects across different orbits, setting the standard for SSA technology ('Space Situational Awareness' 2024). These practical examples are interesting, although neither company specifies whether they utilize these tools for educational and training purposes. Nevertheless, their advancements could serve as inspiration for the integration and developing educational and training programs, especially in equipping military personnel with the skills to utilize these tools.

Finally, satellite communication systems provide communication links for military forces operating in space and terrestrial environments. Technologies such as encrypted data transmission, anti-jamming capabilities and satellite-based network architectures ensure secure and reliable communication (Tedeschi et al., 2022). For example, Boeing has demonstrated its anti-jam satellite communications technology through the successful integration of its Protected Tactical Enterprise Service (PTES) with a user terminal. This system enables Boeing-built Wideband Global SATCOM (WGS) satellites to utilize the US military's Protected Tactical Waveform (PTW), allowing data transmission in hostile environments by mitigating interference and jamming attempts (Dobberstein, 2024). Moreover, military satellites equipped with high-resolution imaging sensors, synthetic aperture radar (SAR) and electronic intelligence (ELINT) payloads enable space-based reconnaissance and intelligence gathering (Tedeschi et al., 2022). These satellites collect imagery, signals intelligence and geospatial data to support military operations, intelligence analysis and threat assessment. ASAT weapons systems are designed to disrupt, disable or destroy adversary satellites in orbit. Technologies such as kinetic kill vehicles, directed energy weapons and cyber warfare capabilities enable offensive and defensive counter-space operations to protect military assets and deter potential adversaries in space. Space-based infrared sensors detect and track ballistic missile launches, providing early warning and threat assessment for missile defense systems. Technologies such as infrared surveillance satellites and ballistic missile defense interceptors enhance strategic deterrence and missile defense capabilities. In addition, autonomous spacecraft and robotic systems enable unmanned space missions for reconnaissance, surveillance and inspection tasks. Technologies such as autonomous navigation, rendezvous and docking and robotic arm manipulation enable autonomous space operations for military applications, including satellite servicing, repair and refueling (Lueschow & Pelaez, 2020; Tedeschi et al., 2022).

Thus, few studies have explored the use of technological tools in the military space for education and training purposes (Caso et al., 2024; Fahnestock, 2020; Jenkins et al., 2018; Kasım et al., 2021; Stouch et al., 2023). Before examining the potential expanded uses of these tools, the next section outlines key considerations for their effective utilization.

6. Key considerations for technology utilization

Firstly, before considering training technology, a 'training needs analysis' (TNA), to identify training objectives and requirements (Gould et al., 2004; Training Needs Analysis – NLR, 2024), as well as designing a training program (Van Merriënboer et al., 1992) needs to be performed. Often training design is done with having specific training media in mind. However, a more effective approach is to design an 'ideal' outline of the training first with disregard of the constraints of training media. With this outline, training media can be assigned. There may be several factors that constrain the decision of training media, such as available resources (e.g. facility and budget), health and safety risks (Doolani et al., 2020), validity (Tarnanas et al., 2013) and fidelity (Rompapas et al., 2021; Stoffregen et al., 2003). Once the needs, objectives and constraints are clear, the following phase to consider is the 'training media analysis' (TMA). In this phase, the selection of technological tools that best align with the educational and training objectives is considered. For instance, which XR tools are more suitable to educate SSA activities in that specific context (Training Media Analysis – NLR, 2024).

During the TMA phase, careful consideration is given to fidelity and validity in relation to the demands of the training objectives. Fidelity and validity refer to specific qualities of the simulation that contribute to successfully train (Gray, 2019). In particular, validity relates to accurate measurement or reproduction of real task performance (Stoffregen et al., 2003). Whereas, fidelity refers to how well a simulation reconstructs operational systems and the real-world environment, both in terms of appearance but also the emotional states, cognitions and behaviors it elicits from its users. Further, fidelity can be related to different levels: physical fidelity (i.e. how a simulation looks, feels and sounds), psychological fidelity (i.e. the extent to which the environment replicates the perceptual-cognitive demands of the real task), construct fidelity (i.e. the extent to which the simulation provide the accurate representation of the real task performance), emotional/affective fidelity (i.e. the extent to which the simulation elicit emotional responses) and ergonomic and biomechanical fidelity (i.e. the extent to which the simulation demand or allow realistic motor movements) (Harris et al., 2021; Ijsselsteijn et al., 2004).

To develop effective simulations, attention should be paid to test a range of fidelity and valid metrics, as well as scenario realism (Harris et al., 2021). For example, modern VR devices provide a range of integrated and non-integrated tools that can be utilized for scientific experiments to assess the validity and fidelity (or representativeness) levels. In terms of fidelity, certain tools can be used to examine human responses, including physiological and psychological aspects. One such application could involve investigating differences in heart rate (HR) patterns, eye tracking (Zhang & Hansen, 2019), inertial measurement units (IMU) (Caserman et al., 2016), electrocardiogram (ECG), electrodermal responses (EDR) (Betella et al., 2014) electrodermal activity (EDA) (Arquissandas et al., 2023), electroencephalogram (EEG) (Bauer et al., 2019), electromyography (EMG) (Dwivedi et al., 2020), HR monitors (Blackmore et al., 2024), photoplethysmogram (PPG) (Chauhan et al., 2018) and others. While few of these tools may not directly apply to military space personnel, eye-tracking technology may stand out as a valuable asset for training purposes. For instance, in SpOCs, eye-tracking could be used to analyze how personnel acquire and process information, enhancing situational awareness and decision-making skills. An example from the aviation domain is the INSPECT project, where the Dutch defense utilizes eye-tracking technology to enhance military air traffic controller training. This tool monitors real-time gaze and pupil dilation to assess situational awareness, workload management and problem-solving (NLR, 2024c). Whereas, to test the validity level, there are several methods that may be used. For example, the use of surveys and interviews (e.g. assessing the experience of the users during a specific training) and behavioral observations (i.e. assessing via notational analysis certain behaviors and performance metrics of the 'X' technology users) (Howie & Gilardi, 2021; Kamińska et al., 2019). For example, in the VR ICARUS project, Satellite Assembly, Integration, and Testing (AIT) engineers completed a survey after using VR to simulate the CubeSat manufacturing process to measure the fidelity and validity of the VR tool. Their performance was further assessed with a behavioral evaluation sheet, providing a view of both subjective and objective measures of task competency (NLR, 2024a).

After completing the various TNA and TMA phases, attention shifts to the training design phase, focusing on the methodology and structure of the training programs (e.g. the type of exercise, the duration and the difficulty levels) (Training Media Analysis – NLR, 2024). Hence, training design theories then shape how individuals acquire skills and enhance learning. Additionally, as technology evolves at an increasingly rapid pace, it is important to integrate lifelong learning strategies into the TNA and TMA phases. Lifelong learning allows for the continuous updating of knowledge, ensuring that military personnel remain proficient in the latest technological advancements. The next section outlines how technologies could potentially be integrated within these training designs and education.

7. Future applications and research

Education and training play a vital role in preparing military space personnel for the complexities of space operations (Stouch et al., 2023). The rapid evolution of technologies is poised to significantly transform military space activities and by leveraging them and addressing research gaps in education and training, military space personnel could enhance readiness, proficiency and effectiveness.

In recent years, one technology that has developed rapidly is XR technologies (Jenkins et al., 2018; Stouch et al., 2023). Trainees can engage with realistic simulations of space missions, gaining hands-on experience (Atta et al., 2022). For example, XR tools enable the visualization and analysis of strategic scenarios, offering a more understanding of spatial relationships and dynamics. This would improve the planning and execution of space missions, allowing users to anticipate and mitigate potential issues. Further, these tools could create immersive mission simulations that allow operators to rehearse maneuvers, docking and emergency procedures in a risk-free environment. These simulations provide realistic scenarios for trainees to practice critical tasks, such as satellite control, orbital maneuvers and emergency procedures. XR could be used also for immersive environments for SDA visualization and understanding orbit mechanics. By visualizing satellite orbits and space debris in a 3D environment, operators could gain an understanding of spatial relationships and dynamics. Further, XR technologies offer immersive training environments for simulating space missions, spacecraft operations, SSA and STM (Stouch et al., 2023). Future researches may take inspiration also from studies conducted with air traffic controllers. For instance, Lee et al. (2020) showed improved detection of potential collisions in air traffic control scenarios using VR headsets compared to 2-dimensional displays. In addition, continuous professional development is essential to maintain and enhance the capabilities of military space personnel. Therefore, through the use of XR technologies, personnel could have the possibility to educate themselves and train anytime and for how much they needed.

AR provides real-time information overlays during operations, enhancing situational awareness and decision-making. Its applications enable on-the-job training by overlaying instructional information, guidance and visual aids onto physical spacecraft components and control interfaces (Jenkins et al., 2018). These tools assist space operators in performing maintenance tasks, troubleshooting issues and executing operational procedures. Utilizing AR, educational and training programs could simulate realistic space environments, satellite conjunction scenarios and orbital debris mitigation strategies to improve operators' ability to monitor, analyze and respond to space threats effectively. Simultaneously, AI and machine learning contribute to SSA and STM by improving the accuracy and speed of data analysis. AI algorithms can process vast amounts of data from various sensors and satellites to identify potential threats, predict satellite collisions and optimize orbital paths (Kyriakopoulos et al., 2021). This enable more proactive and efficient management of space assets, reducing the risk of collisions and enhancing overall mission success. Therefore, the integration of XR tools, AI and synthetic data generation represents a significant advancement in the education and training of space operators, mission planners and controllers. Additionally, machine learning models trained on historical data enable accurate prediction of space object trajectories (Little & Frueh, 2020). Educators and trainers could leverage AI-powered simulations to teach trainees how to use predictive analytics for decision-making, such as manoeuvre planning and orbital optimization. Accordingly, the integration of AI and machine learning into decision-making processes allow for more sophisticated predictive analytics and scenario planning (Duan et al., 2019). These technologies can simulate various scenarios and predict the outcomes of different strategies, helping military planners develop more effective plans. AI can also optimize resource allocation, ensuring that critical assets are available when and where they are needed most.

AI and machine learning can personalize training programs by adapting to the learning pace and style of individual trainees (Chen, 2023; Upadhyay & Khandelwal, 2019). In particular, the VARK (Visual, Auditory, Reading/Writing, and Kinesthetic) model, which highlights different learning preferences, may be integrated into AI-driven simulations and personalized learning systems. By tailoring training experiences based on trainees' preferred learning styles, training programs might become more effective (Carey et al., 2024). Intelligent tutoring systems can provide real-time feedback and adjust training scenarios based on performance, enhancing the effectiveness of training programs. Additionally, AI-driven simulations can create complex, dynamic training environments that better prepare personnel for real-world challenges. Future research could explore personalized learning approaches tailored to the individual needs and learning styles of space professionals. For example, researchers may explore the optimal interactive tools, tailored for specific age groups within students (Taillade et al., 2013). Adaptive learning algorithms and learning analytics can be leveraged to customize educational and training experiences and optimize learning outcomes in space-related subjects Learning Analytics - NLR, (2024). Moreover, AI technologies can enhance training programs by providing intelligent tutoring systems, virtual trainers and personalized feedback mechanisms. AI-driven simulations and scenario-based training exercises can adapt to trainees' performance levels, preferences and areas of improvement, facilitating more effective skill development and knowledge acquisition. Lastly, machine learning models and AI-driven simulations require specialized training, not just for space operators, but also for those tasked with maintaining and improving these systems. The use of AI in training environments requires not only the expertise of developers and engineers but also the understanding of how the military space personnel can work effectively with these tools. This involves training military operators to interpret AI outputs, make decisions based on predictions, and integrate those insights into their decision-making processes. The lack of sufficient personnel with expertise in these technologies could hinder their effective use.

Finally, collaborations between academia, research institutes, organizations and companies could facilitate the integration of these technologies for education and training purposes. For example, the SDA lab is a collaborative tech accelerator for U.S. companies, academia, federally funded research and development centers, industry experts and the USSF which they team together to solve critical SDA challenges. The lab invite industry to solve problems such as using commercial or public imagery to detect the start of a space launch cycle automatically; using publicly available weather data to predict weather conditions that satisfy space launch; using orbital data to evaluate whether a detected launch in an ASAT (acro) and other problems such as those related to debris and radio frequency (SDA TAP LAB, 2024). These collaborations can help mitigate the costs associated with developing technologies, such as through consortiums of companies and organizations, as cost is a vital factor in the adoption of technology-supported training. In addition, these collaborations could also facilitate the adoption and integration of emerging technologies used in other fields, such as the Apple Vision Pro, a new mixed reality headset with a 4k display and spatial computing capabilities (Waisberg et al., 2024). Lastly, with the increasing cyber threats to spacecraft, cybersecurity training for spacecraft controllers is essential. Using simulation tools and joint training (Kasım et al., 2021), controllers can learn to identify vulnerabilities in spacecraft systems and implement mitigation strategies. Therefore, these collaborations could foster joint-trainings to create realistic cyber-attack simulations for helping controllers to practice response protocols and enhance their resilience against actual cyber threats.

8. Conclusions

In conclusion, the integration of emerging technologies is revolutionizing military space operations. These innovations not only enhance the effectiveness and efficiency of military missions but also necessitate a comprehensive re-evaluation of the education and training programs for space personnel. This paper has explored the current applications of these technologies in military space operations, identified potential challenges associated with their integration and proposed future research to guide the development of education and training programs. The historical evolution of military space activities underscores the growing importance of space as a critical domain for national security. The establishment of entities like the USSF and NATO's recognition of space as a distinct operational domain highlight the strategic significance of space in modern defense strategies. The diverse roles and activities of space personnel, from satellite operations to space policy development, require a strong educational foundation and specialized training to ensure proficiency in this dynamic field. Future research should focus on developing advanced and possibly personalized training methodologies utilizing XR, AI and machine learning technologies to improve the skills and readiness of space personnel, via TNA and TMA methods (Training Media Analysis – NLR, 2024; Training Needs Analysis – NLR, 2024). This includes exploring the potential of AI-powered predictive analytics, machine learning models for trajectory prediction and immersive XR environments for realistic training scenarios. Addressing these research gaps will ensure that military space personnel are well-prepared to navigate the complexities of space operations.

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