Air Force Orbital Mechanics / Space Operations Training in Virtual Reality

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ABSTRACT

Airmen and Space Professionals' understanding of orbital mechanics and space operations is critical for U.S. military superiority and national defense. Concepts like Hohmann transfers and Rendezvous and Proximity Operations (RPO) for spacecraft orbital maneuvers can be time-consuming to teach and difficult to comprehend. Current teaching practices involve extensive textbook descriptions, whiteboard sketches, and two-dimensional (2D) animations. This research paper suggests Virtual Reality (VR) technology and gamification could positively impact learning by improving comprehension and retention of orbital mechanics and space operations concepts. A review of relevant training literature is cited as evidence. Basic orbital mechanics concepts are currently taught via traditional textbook methods during Space 100, 200, and 300, and Advanced Orbital Mechanics, and other relevant courses. However, research on how people experience and comprehend VR, information about VR technologies being developed, and new theories about learning – including gamification and connectivism – offer promising alternatives to current military training paradigms. Introducing VR technology into training while incorporating new learning theories could modernize training of orbital mechanics and space operations, possibly resulting in shorter learning times and greater retention of critical information and skills. The space domain is more congested and contested than ever, and VR is the right tool to prepare the next generation of space operators for this fast-paced and continually evolving environment.

ABOUT THE AUTHORS

Matthew Fahnestock is a satellite design analyst for the National Air & Space Intelligence Center. He has spent ten years researching and analyzing foreign spacecraft design. He received his master's in Military Operational Art and Science, Joint Warfare Concentration from the Air Command and Staff College (ACSC) in 2020. As part of his thesis he participated in a VR/AR and Emerging Technologies Research Elective, demonstrating the ability of ACSC to teach in a virtual environment. He went on to research the possibility of using VR as a tool to teach orbital mechanics.

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INTRODUCTION

Events of the 20th Century spurred U.S. involvement in space exploration as the U.S. raced to bring its space capabilities on par with and surpass those of Russia, thereby gaining tactical and strategic advantages offered through space domain superiority. Over the last sixty years, the U.S. Air Force (USAF) has operated Global Positioning System (GPS), positioning navigation and timing (PNT), communications, weather satellites, and intelligence, surveillance, and reconnaissance (ISR) satellites, giving the U.S. Department of Defense (DoD) unprecedented advantages in global conflicts.

Our adversaries covet these advantages and increasingly threaten U.S. space superiority. China and Russia view space as important to modern warfare, and counter space capabilities as a means to reduce U.S. military effectiveness. Both countries are developing jamming and cyberspace capabilities, directed energy weapons, on-orbit capabilities, and ground-based anti-satellite (ASAT) missiles that threaten U.S. space superiority. (Defense Intelligence Agency, 2019) In light of these threats, and because of the critical role space plays in the U.S. National Defense Strategy (NDS), the United States Space Force (USSF) was established as the sixth branch of the U.S. armed forces on 20 December 2019. Space is no longer an uncontested domain. New tactics, techniques, and procedures (TTP)s will need to be developed to counter our adversaries' capabilities, and new Airmen and space operators will need to be trained in orbital mechanics and space operations.

The USAF is currently using textbooks and computer visualizations to teach these complicated concepts. Attempting to describe this three-dimensional (3D) environment using words and two-dimensional (2D) pictures is difficult and often requires hours of study for a new student. Switching to a Virtual Environment (VE) and teaching students using Virtual Reality (VR) could substantially improve comprehension and retention of orbital mechanics and space operations.

CURRENT APPROACH TO TEACHING ORBITAL MECHANICS

Before USAF and USSF operators can fully understand threats from jamming and cyberspace capabilities, directed energy weapons, on-orbit capabilities, and ground-based ASAT missiles, they must be taught basic orbital mechanics. Orbital mechanics is the science behind flying a spacecraft. The concept of a satellite orbiting around the Earth sounds simple, but the space environment is unique and there are many common misconceptions about it. For instance, space is not a zero-gravity environment; rather, objects in orbit are actually in a constant state of free fall around the earth. Second, while space is a vacuum, satellites in low-earth orbit (LEO) still have to deal with atmospheric drag. Also, oxidation, or rust, is another problem faced by satellites in space due to atomic oxygen. Finally, heat transfer is challenging because there is no air to conduct heat to and from a spacecraft. (Sellers, 2005, p. 83) All of these concepts are important to teach students who are unfamiliar with the space environment because they help to illustrate the complexity of flying a satellite and conducting space operations.

Understanding Space (Sellers, 2005) is a common textbook used to teach introductory-level courses in astronautics and orbital mechanics. The textbook starts by laying out the basics of the space environment and the corresponding terminology, progressing into more advanced concepts of maneuvering in space like Hohmann Transfers, combined plane changes, and co-orbital rendezvous. (Sellers, 2005, p. 205) All of this coursework must be completed in order to be sure students understand how satellites fly and operate in space. Only then can they begin to learn the specifics of U.S. space operations and what they will be expected to accomplish day-to-day. For many students, reading a textbook and doing homework problems is not the most effective learning strategy. There is room for improvement in the current training approach, particularly when teaching 3D concepts. For instance, it takes six pieces of information to describe a satellite orbit. These are commonly called a classical orbital element, and when visualized in VR are more inherently understood than a 2D visualization (see figure 1).

LEARNING THEORIES FOR THE DIGITAL AGE

While informative, the current approach, involving extensive textbook descriptions, whiteboard sketches, and two-dimensional (2D) animations, could be improved by supplementing it with more immersive and stimulating methods. Two learning theories support this position—Constructivism and Connectivism.

People actively construct or create their own subjective representation of objective reality when presented with a new idea or concept. (L, Constructivism, 2015) This means they use their prior knowledge to create a mental representation of new information. This concept forms the basis of constructivist learning theory. Because it is based on an individual's prior knowledge, the objective reality they create will be different for everyone. One of the key drivers of constructivism is experience. Students must experience new things and take the time to reflect on them. Each new experience must be reconciled with past experiences to determine if a student's beliefs must change, or if the new information is irrelevant and can be discarded. (Bada, 2015)

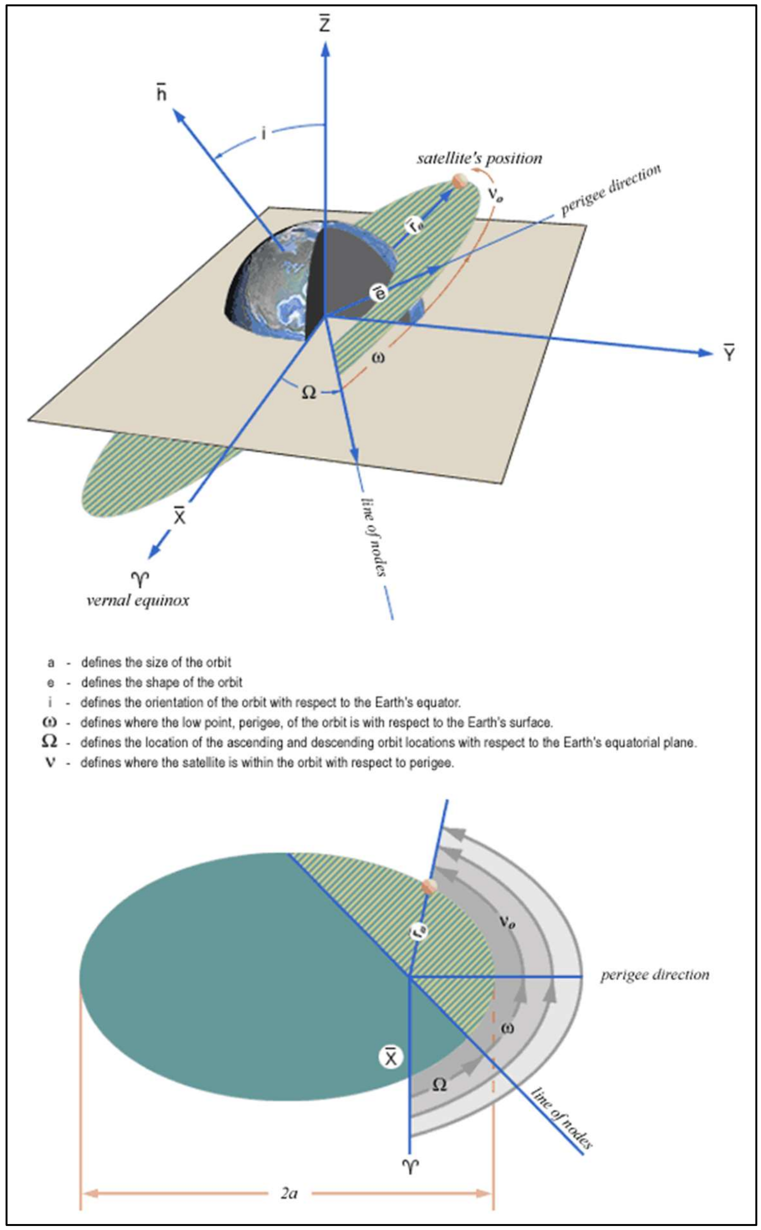

Figure 1: Classic Orbital Elements

Connectivism is described as self-paced learning that is primarily done autonomously while still providing opportunities for peer-to-peer networking. (Mallon, 2019) This learning theory works well with social media and emerging technologies because of its ability to meld peer collaboration and individualized learning. The diversity of opinions is what makes the social aspect of learning so important. In the digital world, new information is constantly being generated and decisions have to be made quickly. The ability to recognize important information and apply it to a decision-making process is critical. (Siemens, 2005)

There are many ways to incorporate Constructivism and Connectivism into teaching methods. Mounting evidence suggests that incorporating game elements into education results in a more effective teaching method. This process is called gamification.

GAMIFICATION

Gamification is the application of game design principles in a non-game context. (Robson, Plangger, & Kietzmann, 2015) In the case of education, this primarily focuses on user experience and user engagement. Gamification in education seeks to harness the engagement a person experiences while playing a game and use it to facilitate student learning. Education based gamification requires incorporating motivational game elements such as narratives, player control, progression indicators, fun, and social connection. (L, Gamification in Education, 2016) All of these elements combine to keep a player interested in continuing the game and learning.

In the case or orbital mechanics and space operations a game could involve building satellite orbits and then testing them in a simulated space environment. This activity is important for learners because it requires them to learn and comprehend the different types of orbits, the various things that affect satellite orbits, and the laws of orbital mechanics needed to keep a satellite in orbit. Current teaching methods involve textbook readings, memorization, and testing in a classroom setting; none of which encourage students to attempt developing an understanding beyond the bare minimum.

Another learning concept would be to have students respond to increasingly difficult situations such as. Scenarios could include onboard satellite anomalies like power failure that students have to overcome, or threat scenarios involving other satellites. These would encourage learning progressing, problem solving, and expose operators to stress of abnormal operations. Such an approach could likely be tailored to the individual learner. A scoring system could be developed that would evaluate the student players, track and denote progress, provide valuable data for comparison in the immediate and with other cohorts, and also drive and encourage students to engage in the learning by placing them in competition with classmates.

VIRTUAL REALITY

Virtual reality is an artificial environment that is immersive enough to convince the user they are actually inside it. (Rubin, 2018, p. 28) This artificial environment can be just about anything from a photograph, to a video game, to a computer-generated world. The important concept is that this environment is not where you physically are. Immersive enough means that the environment does not have to be perfect for VR to feel like an experience. When these essential elements are combined, a VR user can experience psychological presence powerful enough to forget they are in a virtual world. Psychological presence, or presence, is the “being there” feeling the user gets from a good VR experience. Presence is the fundamental characteristic of VR. (Bailenson, 2018, p. 19)

Perhaps the biggest benefit of VR is that the brain treats it as an experience. When VR establishes a sense of presence for the user, the effect is similar to that of running drills in real life. This is helpful for teaching high-risk procedures or difficult concepts like orbital mechanics. In VR, students could not only see objects in orbit, but also take a virtual ride along on a satellite. They could experience what happens as thrusters are fired and orbital maneuvers are executed.

LEARNING IN VR

A recent study conducted by the University of Malaysia analyzed different learning styles and compared the performance of people with these different learning styles in different learning environments. The three environments they tested were VR with guided exploration, where additional navigation aids are provided to the user; VR with unguided exploration, where no navigational aid is provided, and Non-VR or traditional teaching methods comprised of lectures and reading material. (Chen, 2015) The results showed that learners benefited most from guided VR experiences irrespective of their learning styles. Additionally, guided exploration VR was shown to have a significant positive effect over non-guided VR. This highlights the importance of proper instruction when designing a VE with specific learning outcomes in mind. (Chen, 2015) In the case of space operations training, it would be important to allow students to try different orbital scenarios but limit the parameters to keep the exercise relevant. Given complete freedom in the virtual environment, students might spend too much time exploring the game and less time on learning objectives.

A study conducted by the Air Force Research Laboratory (AFRL) addressed the knowledge retention aspect of skills-based training, specifically a simulated assembly of mechanical components. The two methods tested were VR based training and traditional 2D computer-based training (CBT). The CBT group and VR group were given the same instructional content. The results trended towards favoring the subjects who used the VR. (Stiles, 1998) This is likely because of the perceived experience VR training provides over 2D CBT. Experiences are better for skill development than CBT's.

In the surgical world, VR simulator training has demonstrated improved surgical performance. (Maagaard, 2010) Doctors have been able to use VR surgical trainers to practice surgeries to improve their chances of success. There is also evidence to suggest that VR surgical trainers can improve retention of those skills. A study performed on laparoscopic surgeons to determine if skills learned in VR can be retained for an extended period. The results suggest novice surgeons who practiced with the VR trainer retained skills for a minimum of six months before they started to deteriorate. (Maagaard, 2010)

THE GAMIFIED VR ALTERNATIVE TO ORBITAL MECHANICS/SPACE OPERATIONS

The implementation of VR into space operations is already being investigated, and this work may inform learning objectives for teaching space operations. Space domain awareness (SDA) is a key piece of the puzzle to enable commanders and space operators to maintain an advantage in the space domain. A VE combined with a VR or augmented reality (AR) display can allow users to perceive, reason about, explore, and act on timely intelligence to support SDA. Charles River Analytics has done research on an AR application that will allow intelligence information to integrate with a VE and form an operating picture to allow space operators and leadership to develop better courses of action (COA). (Jenkins, 2018)

VR may be particularly effective for teaching orbital mechanics given the environment. Because the space environment is not something a person can typically experience, VR provides a unique opportunity for students to learn. They can experience what it is like to ride along on a satellite. Using gamification, a training course could be developed that would allow students to learn as they play. Students would start with basic orbital mechanics. Simple challenges that involve identifying various types of orbits will draw the students in. After they have proven they understand the different types of orbits, or "cleared the orbits checkpoint," they will move on to more complicated tasks. They would be expected to execute a Hohmann transfer to reach a satellite in GEO, or maintain a constellation of satellites flying in formation. Finally, they would move on to the advanced operations involving full mission scenarios with RPO's and anti-satellites (ASAT). Incorporating exaggerated failure scenarios into physics-based modeling of satellite trajectories will make a fun consequence that will encourage a student to try again. For instance, a satellite exploding after colliding with another satellite because the orbital trajectory chosen by the student resulted in insufficient fuel, or one satellite firing a rocket launcher at another for getting too close.

This program should be built as a guided VR experience. Students would have the freedom to try different scenarios based on their progression in the course, but still be bounded to modules to reduce distractions from the learning objectives. The ability to run through a variety of scenarios multiple times gives the user more experiences. Because the brain treats VR as an experience, students will not only grasp the concepts more quickly, but will also develop and retain skills. A virtual classroom would allow students to progress at their own pace while interacting with their classmates. Creating a scoring system would allow for grading, as well as creating competition between students in a social environment. This classroom could have a scoreboard to foster competition and encourage students to keep playing. (Cline, 2011, pp. 27-70) For example, a teacher could offer a reward to the student who creates a scenario that accomplishes the objectives with minimal fuel usage. These types of ideas would also allow students to share scenarios they created and learn from each other. The diversity of thought would likely lead to a variety of scenarios and encourage students to come up with new ideas. This could be applicable to competencies including problem solving and adaptation.

CHALLENGES OF IMPLEMENTING VR

Building a VE to be used as an educational tool in VR requires a balance of gamification and traditional teaching methods. While VR has become commercialized, it is still a new enough technology that many people will have never used. This means that any VR based educational tool will require a tutorial for new users. It will likely also require time built in to the lesson plan to allow new users to adjust to VR. In addition to a tutorial, creating a VR training program to teach orbital mechanics and space operations will likely require developing a lesson plan and problem sets that are both educational and fun. The development of a training program in conjunction with the initial cost of VR hardware will require an investment by the USAF and/or the USSF.

One of the physical responses to VR is simulator sickness, or motion sickness (MS). MS most commonly results from a lag between what the user sees and what their body is telling them they should be feeling. For instance, the user sees the environment moving around them because they are moving in it, but they do not feel their body moving in the real world. There is evidence to suggest that people who use VR regularly develop resistance to MS, but many new operators will have little if any experience with VR. Specifically, the star fields in the background of the VE may trigger MS in new and experienced users. The relative speeds of satellites in orbit during an RPO, as well as the relative motion of the satellite with respect to the Earth, may also cause a problem. These things may need to be modified or eliminated to prevent nausea in users. The FOV might need to be narrowed or customizable for individual users to help prevent MS. The sizes of satellites will likely also need to be changed, at the expense of realism in the scenarios, so that they are large enough to be seen.

Another concern is using commercial VR devices in a Sensitive Compartmented Information Facility (SCIF). While the science behind orbital mechanics is public knowledge, the manner in which the USAF & USSF conduct space operations is often classified. Teaching space operations using relevant scenarios and intelligence will likely require a SCIF. Unfortunately, most commercial VR systems require multiple cameras, a microphone, and either Bluetooth or Wi-Fi. Creative solutions will need to be developed if VR is to be incorporated into space operations training.

CONCLUSION

Global communications, PNT, weather, and ISR capabilities depend on space. Threats to U.S. space superiority abound. The USSF will organize, train, and equip U.S. space forces to conduct space operations and respond to these growing threats. This requires the development of new training. VR has demonstrated effective in training complex concepts that are highly visual in nature. When VR is able to establish presence, the user perceives it as an experience and is more likely to learn from it. VR is also shown to be a more effective teaching tool than traditional methods, particularly when the learning objectives are accomplished through gamification. By taking a complex subject like orbital mechanics and turning it into a game, students become more engaged and more willing to put in the time and effort required to learn. Using VR to teach orbital mechanics and space operations could improve comprehension and retention of USAF and USSF students, better preparing them for contested space control environments.

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