The Shift in Space Caused by Cube Satellite Development

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Since humanity first sent an artificial satellite to space in 1957, the idea of the space unknown has captivated society in different ways, igniting a pursuit to answer fundamental questions about what is possible in space. Questions like how far can we go, what can we see, where can we venture, how do we reach there, and what knowledge can we gain have propelled our interest in the cosmos. Society's obsession with space exploration has driven the development of new technologies, which in turn influence the ways in which we apply them. Among these innovations Cube satellites, small and versatile satellites known as CubeSats, have emerged as pivotal players in reshaping space exploration and scientific research over the past few decades. With their compact size, affordability, and adaptability, CubeSats have opened doors to new frontiers, democratizing access to space and creating a new era of space exploration and scientific discovery.

What was once only imagined has become a reality due to the accessibility of small satellites. Atmospheric data collected by CubeSats has been used to educate the public on the extent of our environmental impact. Communication systems among satellite constellations have been leveraged by governments to ensure national security. Smaller nations have been able to develop space programs due to the affordability of smaller spacecraft. A new wave of younger individuals, including university students, now have access to the space industry earlier in their lives than anyone that came before them, sparking increased interest in the space unknown. CubeSats have caused a shift within the space industry resulting in humanity's reach in outer space to be more conceivable for a new set of actors.

As the demand for cost-effective and versatile spacecraft continues to rise, Cube Satellites have emerged as a cornerstone of the modern space industry across scientific, commercial, and military domains. This research explores how the development of CubeSats has catalyzed a shift in the space industry and how that shift affects the diverse range of actors involved.

Background & Context

CubeSats originated as a collaborative project between Robert J. Twiggs at Stanford University's Space Systems Development Laboratory (SSDL) and California Polytechnic State University's Professor Jordi Puig-Suari (Martellato et al., 2022). Their idea was to teach their students about spacecraft design using a miniaturized satellite that students could build in a single academic year rather than attempting to build a larger satellite which would rarely reach completion. Defined as a 10 x 10 x 10 centimeter cube with a mass of less than 1 kilogram, CubeSats are designed to be inexpensive, making them more accessible to a wide range of users. Since the first CubeSat launch in 2003, over 2,000 CubeSats have reached outer space (Reim, 2023). In that time, advancements such as reducing the size and increasing the power of computational components have allowed CubeSats to become more applicable in a wider range of disciplines. The advantages given by lower costs, fast development, and the possibility of launching multiple CubeSats by means of a single rocket, have brought forth the potential for radically new mission architectures. Consequently, CubeSats have changed how missions are conceptualized and executed. Innovative mission strategies including distributed sensing networks, constellation formations, and collaborative ventures can be executed with efficiency and flexibility due to the modular design of CubeSats. These possibilities challenge the traditional notions of space exploration and alter the interactions between the scientific, commercial, and governmental sectors.

As the space industry rises to the forefront of technological priorities in today's world, continued development of CubeSats remains a focal point driven by societal factors. These include climate change concerns and a growing desire to minimize human impacts on the environment, as CubeSats offer unique opportunities for ecological monitoring and environmental research (Martellato et al., 2022). Moreover, the need for national security capabilities particularly in areas such as secure communications and surveillance, has propelled the development of military applications for CubeSats (Doicariu, 2022). Additionally, increased spending on defensive space operations, specifically related to deterring aggressive space actions and enhancing space domain awareness, reflect current geopolitical dynamics (Nayak, 2017). Lastly, the pursuit of space exploration and colonization underscores the public's desire to expand humanity's influence in space, positioning CubeSats as a vital tool for accomplishing this as they offer a cost-effective solution for technological testing and scientific research.

The mutual shaping of CubeSats can be seen in two main ways. Firstly, data collected from CubeSats with detailed information about ozone levels in the atmosphere and the progress of glacial decay reveal the true extent of carbon dioxide emissions and global warming rates (Wu et al., 2017). This information causes stress amongst much of society as the looming threat of our environmental impacts reaches a point of no return. In efforts to save our planet, individuals and organizations put social pressure on the continued development of satellite technology creating a continuous cycle of innovation. The second way appears in the political arena. Military branches along with defense agencies use CubeSats in a number of ways to bolster national security. For example, many CubeSat programs focus on hypersonic system research. Hypersonics is a term used to describe speeds that are five or more times the speed of sound in air (Woellert et al., 2011). This research is used to develop hypersonic weapons which can evade most air defenses.

While the thought may be frightening, the United States is about a decade behind Russia and China in their hypersonic programs. Here we can see millions of dollars being spent on hypersonic research just to catch up to other countries that the US has not always had peaceful relationships with. The excess funding put towards weapons research using CubeSats reflects the political agendas within our government driven by the fear that the US is falling behind some of its current foreign adversaries. Therefore, social and political pressures determine CubeSat applications which in turn enhances their technical capabilities in those respective areas.

Actor Network Theory, or ANT, studies the activity of network builders who construct heterogeneous networks to solve a problem or accomplish a goal. By looking through the lens of ANT, we can identify both human and non-human actors that influence the activity of a techno-social system (Crawford, 2020). Within the framework of CubeSat development, this idea acknowledges that success is intricately linked to social, political, economic, and regulatory factors rather than being only a result of engineering and scientific proficiency. This framework will assist in the analysis of the different actors involved in the shifting space industry.

Methods

The evidence collected for this research is derived from a multitude of sources. Data from previous CubeSat missions, proposals outlining future applications for CubeSats, relevant news articles, and scholarly literature pertaining to the intricate connections between CubeSat technology and societal driving factors will all be used to support the shift in the space industry caused by CubeSats.

To address my research question of how CubeSats have facilitated a shift in the space industry, I completed literature reviews on the history of both successful and unsuccessful

CubeSat launches. Utilizing ANT, I analyzed how the diverse range of actors including private companies, governmental agencies, and academic institutions contributed to either the missions' success or failure in a few cases. Additionally, I reviewed the trends seen in the space industry related to CubeSat applications and opportunities that have arisen as a result of this new technology. Furthermore, I researched the effects CubeSats have had on democratizing access to the space industry for a broader set of actors including educational institutions, small startups, and developing nations. By performing a comprehensive analysis of previous missions, possible satellite applications, and greater accessibility caused by CubeSats, I will show how the advent of this disruptive innovation has transformed the aerospace sector.

Disruptive innovation is a concept that describes the process by which a new technology enters the market, eventually disrupts the existing platform, and displaces established technologies. Unlike sustaining innovations that improve upon existing technologies within an industry's established framework, disruptive innovations often have poorer performance than current solutions. They are also significantly cheaper than is the status quo and target underserved applications or users (National Academic Press, 2016). Typically, they are introduced by a non-mainstream player and their performance improves rapidly and at low cost. By examining the shift in the space industry caused by the introduction of CubeSats, we can identify this technology as a disruptive innovation in the satellite sector.

Results & Discussion

The first case I will be looking at is the failure of the recent Artemis 1 CubeSat mission. The Artemis 1 CubeSat mission, initially intended to deploy 10 CubeSats into orbit for various research purposes, ultimately faced significant challenges which led to its failure. Five of the launched CubeSats experienced a range of challenges. NASA's LunaH-Map spacecraft's propulsion system failed causing it to miss its scheduled burn-up. NASA's Near Earth Asteroid Scout mission failed to deploy its solar sail, hindering its visibility to ground based telescopes. Lockheed Martin's LunIR CubeSat suffered from radio signal issues causing ground stations to be unable to communicate with the satellite. BioSentinel, a low Earth orbit biosensor instrument, began to tumble after deployment. Lastly, a Japanese CubeSat, Omotenashi, failed to generate enough power through its solar arrays causing communications to be lost. Some analysts attribute the project's failure to a stuck valve in one CubeSat's propulsion system, a hydrogen leak during fueling, and partial battery drainage after the CubeSats had been secured to the rocket (Aubert, 2023). While acknowledging the importance of these actors, this view overlooks the role played by government agencies, private company funding, and environmental conditions that led to the project's failure. If we attribute the project's failure solely to the hardware failures, we have an incomplete narrative. It does not account for the range of factors that were integral to the project's downfall. Government agencies like the European Space Agency (ESA) and NASA are essential to the development of CubeSats. They offer launch possibilities, finance, and regulatory monitoring. Moreover, they frequently determine the strategic course for space exploration, which may have an impact on the goals of CubeSat missions. The involvement of private companies in CubeSat initiatives has grown. These businesses might provide funding, technological know-how, and launch assistance. They might upend established space exploration paradigms and bring fresh ideas to the field.

That being said, the key players in the case of Artemis 1 failed to work together effectively. The sharing of knowledge, assets, and vital information was hampered by this lack of coordination, which led to mission failures. Government agencies placed financial restrictions and inadequate funding affected component selection, system redundancy, and quality control on the Artemis 1 CubeSat program. The setbacks experienced by the Artemis 1 CubeSat program highlight the crucial role that social factors play in CubeSat development. The success of the program was determined by a combination of technical factors, budgetary constraints, collaboration, and regulation. As a result of rapid CubeSat development, the urgency to get missions into space caused multiple parties to overlook crucial mistakes, rush the launch process, and ultimately waste the time and money spent on the Artemis 1 mission.

Looking through the lens of disruptive innovation theory, innovative technology that is cheaper than current systems require deliberate management and personnel that are cognizant of the issues that arise from such a catalytic technology. It is important to recognize the potential importance and scope of CubeSats as they evolve. While private investment and commercial support may be substantial, CubeSat development can benefit from government intervention in areas such as standards development and deorbiting strategies (National Academic Press, 2016). By standardizing CubeSat launch requirements and leveraging public-private partnerships, CubeSats can become more useful to society while simultaneously creating value for stakeholders. In the case of Artemis 1, the CubeSats' potential was diminished because the patterns of disruptive innovation were not properly recognized or addressed.

While this failure makes the prospect of CubeSats seem less promising, there have been many successful CubeSat missions. For example, the STU-2 CubeSat mission is a small CubeSat constellation that was launched in 2015 for the purpose of Antarctic glacier and sea ice observation (Wu et al., 2017). The STU-2 consists of 3 CubeSats equipped with Earth observation cameras designed for polar conditions of low solar elevation angle and high surface reflectance. This specialization resulted in higher quality images of the Antarctic coast than the publicly available images as it eliminated the oversaturation problem that other imaging systems struggled with. Comprehensive observation of glaciers and sea ice is extremely important to global climate change research. There have been many other satellites designed for polar observation, most of which lacked specially designed polar cameras and cost millions of dollars to implement and launch. Disruptive innovation theory highlights the innovations typically being advanced by an enabling technology. Advances in non-space-related areas, in this case camera technology and processing power, have helped CubeSats become a solution to both of the aforementioned problems by allowing for a dedicated design for Antarctic observation with low material costs. This is a perfect example of how CubeSats have altered recent practices in the industry. They have opened the door to low-cost, high-accuracy technology that provides valuable data related to society's most pressing issue.

Concern over climate change and increasing global temperatures highlights the importance of CubeSat applications. There are several applications for CubeSats, but I'm going to focus on environmental research applications and military defense applications. Earth observation CubeSats equipped with advanced sensors can monitor environmental conditions such as atmospheric ozone and carbon dioxide levels, deforestation rates, and sea level rise. These provide crucial data for researchers and policymakers to educate the public and make informed decisions related to conservation efforts. This data aids in our understanding of the extent of our impact on the planet, which in turn shapes societal views and increases the pressure placed on individuals and organizations to engage in sustainable practices. Additionally, CubeSats contribute to disaster management by providing real-time information during natural disasters such as wildfires, hurricanes, and floods. For example, the Disaster Management Constellation (DMC-1G) constellation was made up by five satellites, which were launched within a time window from 2002 to 2005, into a sun-synchronous orbit (SSO), and resulted in being particularly effective during the large-scale Indian Ocean Tsunami (2004) and Hurricane Katrina (2005) disasters (Martellato et al., 2022). The satellites provided remote sensing imagery to the UN Space-based Information for Disaster Management and Emergency Response (SPIDER) (Woellert et al., 2011). This information allowed those in danger to be warned sooner and for first responders to take action earlier, possibly saving lives in the process.

Disruptive ideas thrive when individuals within organizations allow for experimentation while also focusing on promising applications (National Academic Press, 2016). By facilitating more comprehensive and accessible monitoring of the Earth's environment, CubeSats beneficially contribute to society. However, other areas of CubeSat research may prompt some debate amongst our society as to their ethical application. Particularly, the use of CubeSats for global surveillance and weapons research introduces a necessary discussion about the actions of the US government and their role in global politics.

Seeing as the most prominent space organization in the country, NASA, is a U.S. government agency, it is not surprising that CubeSats have found extensive applications in military operations. Their compact size and versatility makes them perfect candidates for surveillance and reconnaissance as they can be equipped with high-resolution cameras to provide real-time intelligence to military and government officials. CubeSats can monitor hostile activities, track movements of military assets, and assist in making tactical decisions for defensive forces. This raises an important question: Why is it necessary to monitor possible adversaries? Nayak argues that it is feasible that within the next decade, we will see North Korea fielding a surveillance capability via a crude optical sensor on a CubeSat, in competition with South Korea, which is today developing a CubeSat-based telescope system (Nayak, 2017).

Equally probable is Iran fielding a rudimentary missile warning system onboard a vehicle similar to the "Promise of Science and Industry" national satellite, recently built by Iranian university students and launched from a modified long-range missile.

The emergence of CubeSats has raised concerns regarding their potential exploitation for military purposes by foreign entities. As adversaries deploy CubeSats, the United States government faces pressure to fund, research, and develop space-based weapon systems in an attempt to maintain a strategic advantage. However, society's perception of the US's role in the current geopolitical climate is multifaceted. Some view the efforts to bolster national security as necessary, while others are apprehensive about the militarization of space, the potential for conflict escalation, and the immoderate allocation of government resources put towards the US military. This debate reflects broader discussions on international relations and the ethical implications of widespread weaponization of space technologies. This supports the idea that CubeSats are a disruptive innovation which has caused a shift in the space industry. New questions are being raised concerning the relationships between private, commercial, and government actors in the aerospace sector as well as the proper application of this new technology considering both their value to society and possible detrimental outcomes.

The final way that CubeSat development has facilitated this shift can be seen in the democratization of space accessibility for university students, smaller satellite organizations, and nations with underdeveloped space programs. From their conception at a university level, the standardized design and low cost of CubeSats have lowered several barriers to entry associated with space missions. Currently, the University of Virginia, among other undergraduate and graduate programs, offer spacecraft design classes which engage students in hands-on CubeSat projects, providing valuable experiences preparing students to enter the aerospace industry.

Similarly, small companies and startups can leverage this disruptive technology to enter the space market without requiring significant financial resources. Lastly, CubeSats allow smaller countries to develop their space programs in order to establish their presence in space, reaping the benefits of scientific research, national security, and aerospace advancements. It is in these ways that CubeSats have altered the ways in which society approaches the space unknown and how that will continue to shape the future of space exploration.

Conclusion

In conclusion, the emergence of CubeSat technology represents a crucial moment in the history of space exploration, with extensive implications for society. Their compact size, affordability, and versatility have allowed for the democratization of space accessibility, created new possibilities for satellite applications, and facilitated opportunities for a wide range of actors. CubeSats challenge the dynamics of the space industry and reshape the way society approaches complex political issues related to space militarization. It is clear that CubeSats fit the criteria set out by disruptive innovation theory, causing a shift towards a more inclusive era of satellite utilization. Moving forward, the role of CubeSats will remain at the forefront of humanity's journey into outer space, sculpting the future of our reach beyond the atmosphere.

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