To what extent can a decentralized system of small-scale Launch Vehicles equipped for imaging and data collection replace our current satellite imaging infrastructure

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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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The space launch vehicle (LV) industry is entering a period of growth that hasn't been seen since the Apollo program. According to the Space Foundation, in 2022 the space industry was valued at $469 billion, with the majority coming in from the commercial sector (Space Foundation, 2023). SpaceX is poised to launch every 2.5 days in 2024, and smaller companies like Rocketlab and Relativity Space are on their heels in terms of technological innovation and projected growth (Satellite Today, 2023b). According to a report by Deloitte, the aerospace industry is poised to grow by 15.7% each year after 2021 (Deloitte, 2021). The telecommunications and defense industries' increasing reliance on satellite technology is one of the main contributors to the growth in the industry. Furthermore, the use of satellite imaging has had an impact on environmental research, meteorology, aviation, urban development and the intelligence sector.

However, this expansion has held a light to the massive amounts of waste in the industry, with aerospace component manufacturing wasting 30-50% of materials used due to inefficient manufacturing methods (Shan, Guo, & Gil, 2016). Another problem being encountered is space debris, where satellites and components that orbit around earth stay in stasis past their system's shutdown. As of 2013, there is over 300 million kilograms of debris, (Shan, Guo, & Gil, 2016) with NASA recommending that 5-10 large space debris objects be removed every year to counteract the growth. Space Debris is incredibly dangerous, not just because of potential collisions with crewed and uncrewed craft, but a concept known as the Kessler syndrome. The Kessler syndrome occurs when the density of space debris in orbit is so high, that debris ends up colliding with itself, creating smaller fragments that then begin to orbit with a faster angular velocity around the earth, and colliding with more space debris (Olson, 1998). These fast-moving objects create an incredibly dangerous environment that would make parts of lower earth orbit (LEO) inhospitable for any craft, crewed or non-crewed. (Riley, 2016)

Furthermore, the amount of strain placed on local infrastructure due to the increase in launches has been documented by the DoD (Satellite Today 2023a). In conjunction with the Space Force, has determined that over the next two years, launches at both DoD spaceports will grow by 100%-200%, with ‘commercial activity [already] accounting for 90% of the launches’ (Satellite Today 2023a). The expected growth is determined to be fueled by commercial endeavors, With smaller launch companies like Stoke Space beginning to move past the development stage for their multi-use rockets, more companies besides market leaders require a more expansive infrastructure to be in place to continuously meet launch goals. This increase in demand creates significantly more overhead for the DoD, both in terms of increased costs, as well as general resources like power, fuel and personnel, that interferes with the locality in which the spaceports operate. Given the small number of launch sites in the US, and the current projected strain to be placed on them in the next few years, there is a growing necessity to move to a more decentralized system.

Given these parameters, while satellite imagery is becoming a prevalent resource for several purposes, finding an alternative that doesn’t result in as much waste during the device’s production and post-mission would have significant benefits both financially and environmentally. With these drawbacks in mind, deploying smaller LV’s equipped with unmanned aerial vehicle (UAV) payloads is a sustainable alternative. Additionally, space debris is eliminated, all parts of the system can be reused indefinitely, less resources are required to deploy, and specialized launch sites aren’t required. Given these technical benefits, the proposed solution is to use smaller UAV’s) for spatial image gathering instead.

Another benefit of UAV's is they require less computational resources to operate, with targeted data acquisition from these smaller missions means that there is less extraneous data being collected. Furthermore, by using the right imaging methods (infrared, optical, etc.) during collection, less post-processing or data filtering is required, leading to less time and energy being used during operation. (Manley, 2018) This research paper intends to look at the benefits of implementing UAV technology in lieu of relying on large satellite imaging infrastructure with the use of Geels' multilayered perspective (MLP) theory, as well as looking at cases where decentralized infrastructure can serve communities just as well (Geels, 2002).

MLP is a concept that has roots in Actor-Network-Theory (ANT), (Latour, 1992) but applies it to larger technological systems instead of individual artifacts by creating a series of layers in which the system can be analyzed (Geels, 2002) (Geels 2019). Geels first talks about the sociotechnical landscape, which can be explained as the cultural, political and environmental factors that shape and constrain technological systems for long periods of time. Within this landscape, a 'patchwork' of technical regimes can exist. Rip and Kemp's 1998 paper best describes technological regimes, "A technological regime is the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures" (Kemp et al, 2001, p 269). The final layer is arguably the most relevant to this research paper, the niche layer, in which technology transfer can be initialized. Smaller technological innovations on a technical regime level might not be adopted across an entire infrastructure immediately but can grow on the niche layer over time before being adopted into smaller regimes. From there, should the innovation be able to fit in the technical regime and embed itself in the sociotechnical landscape, then technological transition has occurred.

In this case, the niche is identified as UAV technology being used for imaging/information gathering in several use cases that intersect with satellite-imaging. Empirical studies have shown that the technology used in UAV systems is approaching the high technical level shown in satellite imaging systems ((Kubitza et al., 2020b)), while requiring less resources, both in terms of cost and the technology and infrastructure required. Furthermore, information collection can be customized based on individual use cases, allowing for less pre/post processing of data when obtaining information from larger satellite systems. It can be concluded that UAV imaging does fit the role of the niche layer in MLP (Tessmann & Elbert, 2022), (Loorbach et al., 2017).

Looking at the current 'regime', satellite imaging makes up a significant share of spatial information collection technology, being the primary technology used in defense systems, meteorological and environmental monitoring, as well as in urban development. MLP defines a regime as being stable and having inertia, being embedded within economic, political and cultural contexts, and being multidimensional. Given that in 2021, the global satellite imaging market was valued at $3.3 billion, with projections to grow to $9.2 billion by 2031 (Allied Market Research, 2022), it is reasonable to assume that the system has inertia and stability. While this does show that it is in the sociotechnical regime, it does mean that it will be more difficult to allow technical developments in the niche to penetrate the regime.

This brings us to looking at the current sociocultural landscape involving spatial information technology. Currently the landscape does facilitate the use of satellite imaging, with programs like the United Nations SPIDER, which is trying to provide satellite imaging for disaster relief for all countries to access. Additionally even China's Belt and Road initiative (BRI) stipulates the use of a space information corridor to enhance satellite communication, Earth observation, and will provide infrastructure for satellite imaging and data sharing across Asia, Africa and Europe (Gran, 2024).

Using the MLP framework, it does seem that the current regime and sociotechnical landscape are synergized with each other, which would make it difficult for a technical niche to make its way into the regime. However, this synergy does stifle any immediate urgency to introduce technical innovations to the regime, which can create adverse effects in the long term. In the case of the technical problem, current launch vehicle and satellite infrastructure wasn't designed with the need to keep LEO 'clear' of traffic, and current launch complexes were designed for a much lower output than is being projected for the next few years. Because of this, innovations in the niche should not just comprise of making the current launch infrastructure more efficient, but be replacing it entirely in certain use cases, as it was never designed to handle such a logistical load.

One way that a niche can develop and prove that it is an acceptable solution is by testing it in smaller use cases, such as the development of peer-to-peer networks for computers. By creating a smaller socio-technical landscape in which the regime is more malleable, these niches can integrate into the landscape quickly, by developing on a more decentralized infrastructure. Decentralized infrastructures not only can allow for the rapid development of niches, but they also may serve communities better, just like in the proposed technical solution.

One argument in favor of the proposed technical solution is that smaller decentralized UAV imaging systems may provide greater information equity than using satellite imaging services to underserved communities. Decentralization can be described as the principal force delegating decision making to local agents to make use of their superior knowledge (Aghion and Tirole

1997, Dessein 2002, Mookherjee 2006, Acemoglu, Aghion, Lelarge, Van Reenen, and Zilibotti 2007, Bloom, Sadun, and Van Reenen 2012), however Bó's study also found that this creates a fundamental drawback in decentralization, as the agents' objectives may not always lay in parallel with those of the principal force (Bó et al, 2021).

In Lievruow and Farb's paper, 'Information and equity', information is classified as a good (Lievrouw & Farb, 2003). Historically, the dichotomy was between those who were 'information poor' and 'information rich'. Kagan (1999 p1) defined the information poor as:

> (1) The economically disadvantaged populations of the developing countries (The South); (2) Rural people who are often geographically isolated by lack of communication and transportation systems; (3) Those disadvantaged by cultural and social poverty, especially the illiterate, the elderly, women, and children; (4) Minorities who are discriminated against by race, creed and religion; and (5) The physically disabled.

These groups are already marginalized in other forms, and based on their access to information, it was easy to conceptualize information as a form of wealth similar to capital given this dichotomy. This is characterized as the vertical perspective of information by Lievruow and Farb (Lievrouw & Farb, 2003). While this does create a 'chicken and egg' scenario, this high correlation between being a marginalized demographic and being 'information poor' is clear. It was further supported by the high correlation between the socioeconomic gap between classes, called the 'Knowledge gap hypothesis' by Tichenor, Donohue and Olien (1970), which states information flows into a community can produce "an increase of the gap in information acquisition between members of lower and upper socioeconomic status (SES), thereby exacerbating the existing inequities" (Viswanath, Kosicki, Fredin, & Park, 2000, p. 28). This is further supported by a study by Lipinski (1999, p13) which found that ‘lower order litigants’ (those who need legal assistance but lack the means) are less successful in finding and citing unpublished precedents to support their cases as opposed to ‘upper order litigants’. This shows the nuance in the information gap, as it shows that information access isn’t the only factor in a socioeconomic groups’ use of information, but demographics such as social status, education and wealth also play a role. Given these reasons, allowing underserved communities to have access to their own spatial imaging systems creates the initial framework in allowing for the independent growth of information within the community, further closing the information gap, and in turn perhaps allowing the socioeconomic gap to close in turn, providing greater overall equity. Furthermore, not only is information as a good delivered to the end user, but the knowledge to support, develop and integrate this technical system into their community creates a foundation for further ownership of decentralized technological systems directly under a community’s control.

This leads to Lievruow and Farb’s second perspective, the horizontal perspective, which states that information equity relies on willing participants to utilize information, not just developing infrastructure and giving ready access to information (Lievrouw & Farb, 2003). Cole says that “Information [is] a subjective phenomenon, constructed at least to some extent by the user, and not an objective phenomenon” (Cole 1994, p465). Essentially, information is only as good as how the end user utilizes it.

This can be seen in Paraguay’s implementation of over 200 agricultural extension agents, (AEA’s) (Bó et al, 2021). Each AEA belongs to approximately 2 or 3 rural municipalities and would serve as a subject matter expert for rural farmers across six specific subjects: ‘soil improvement, food security, product diversification, marketing, improving quality of life, and institutional strengthening' (Bó et al, 2021). A study done by Bó et al (2021) found that introducing a cell phone system to help agents both connect with organizational leaders to log how they assisted farmers, as well as communicate with farmers through images and video for remote assistance yielded much higher productivity, and a higher turnaround in rural farmers helped. Tying this back to the vertical perspective, while the information being transferred between parties was niche, and the technology used was incredibly simple (GPS cellphones), what was utilized was incredibly relevant to the community, helping bridge the information gap through a decentralized system. It is important to note that this success was also due to theAEA's themselves, as the technology itself did not generate the information needed, but rather allowed the agents to efficiently get the relevant information to the end user.

Another benefit of using UAV's imaging systems is their general accessibility to the public. A case study in Slovakia looked at the feasibility of using UAV imaging systems to gain spatial data from a surface mine, as opposed to relying on traditional surveying methods (Kršák et al., 2016). This was done to create a digital elevation model (DEM) which would be compared to previous years to determine the mine's output and ensure that it is operating in accordance to local legislation. The benchmark to determine whether using the UAV was successful was based on legislature which required there to be an average error of or less than 12 centimeters.

The control DEM relied on the spatial polar method (SPM), which relies on a large camera to be placed at several intervals to obtain data, after which the data is interpolated digitally to create a 3D topographical map. The problem is, this method has been described as 'laborious and tedious' by surveyors. The alternative UAV assisted technology, photogrammetry, requires a UAV that is equipped with a GPS, and inertial measurement unit (IMU), and a digital camera to fly around a specific site. It creates the 3D map by combining the UAVs telemetry data (orientation, speed, altitude, GPS) along with the images it gathers from the cameras along with some computational assistance.

One of the main benefits found when using the UAV system was the ease of procuring a drone with all the specialized equipment required. Currently over 850 types of commercial UAV's are produced globally, and due to the size of the market, many come with their own control software, and have post-processing packages available to interpolate data for the user, requiring less time spent training users, and less resources required by the users to post-process the data. Comparing this to the SPM method, which had a range of approximately 400 meters, and had to survey over 400 points, marking their polar coordinates relative to the SPM system. These coordinates had to be verified from different positions that the SPM system was put into, as the error grew exponentially from interpolating the coordinates into the cartesian plane. The UAV system on the other hand, only required a singular flight path that had to make its way over 10 checkpoints to gather the 135 images necessary for creating its 3D map.

Once the two DEMs were created, with the SPM's DEM being the control, it was found that the mean standard error (root mean squared error) of the UAV's map was approximately 8.36 cm, well below the legislative limit of 12 cm, with only 3 out 237 points exceeding the limit due to technical limitations in identifying the depth of surface cracks that exceeded 50 cm. Given the technical success of the UAV, this does present it as a viable technical solution. What is more relevant to the paper however, is the comparative ease of using the UAV compared to the SPM. It was cheaper, more time effective, and required less resources and time for post-processing, furthermore, it has the ability to conform to local and regional standards based on the end user, making it incredibly accessible for communities.

In conclusion, the rapid growth of the launch vehicle industry, while exciting, will have adverse impacts on the current infrastructure designed around it. From the increasing danger of space debris in LEO, to the strain placed on current launch complexes on earth, there are clear warning signs that the current sociotechnical system in place is not ready to meet future demand, nor does it seem to take sustainability into account. Given the proposed technical solution of replacing satellite imaging with UAV systems in certain use-cases, this should cut some of the demand to launch imaging satellites, reducing the load on launch complexes, and by extension, putting less machinery in space that would crowd LEO. Furthermore, UAV's have a smaller scope, meaning that they can exist in smaller contexts without relying on larger corporate supply chains, leaving the information and technology in the hands of the end users, furthering equity in underserved communities by bridging the technological divide. Additionally, this smaller scope means that it is easier for the technology to enter the mainstream, making it a viable solution in the context of MLP. Given the socio-technical benefits of these system, it is plausible for UAV's to replace larger satellite imaging systems for certain use cases, while maintaining sustainability and equity in the long-term.

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