Application of Collaborative Autonomous Control and the Open Prototype for Educational NanoSats Framework to Enable Orbital Capabilities for Developing Nations

Jeremy Straub
Josh Berk
Anders Nervold
Christoffer Korvald
Donovan Torgerson

Available at: https://works.bepress.com/jeremy_straub/135/
Prosperous nations enjoy the benefits of orbital remote sensing data products. The spacecraft that provide this imagery are, predominately, large and expensive, placing them out of reach of most small or developing nations. Small spacecraft, however, represent a new paradigm for remote sensing applications. A cluster of small spacecraft can be used to capture imagery which can be super-resolved to rival the performance of larger and significantly more expensive spacecraft (compared to the whole spacecraft constellation). Alternately, the group can be spaced to provide higher temporal coverage. This paper presents work on three synergistic topics. First, it covers work on orbital super-resolution and mosaicking. Second, it presents work on a set of protocols that can be utilized to share tasks between multiple spacecraft. Finally, the synergy of these two aforementioned topics is considered and a collaborative mission design to enable a constellation of heterogeneous spacecraft, prospectively with different owners, to collaborate to collect and process data for direct use by users in a developing country is presented.

I. INTRODUCTION

Prosperous nations, such as those in North America, Europe and elsewhere, enjoy the benefits of numerous orbital remote sensing data products. These data products have applications in map making, urban and rural planning, civil disaster response, agriculture and a plethora of other areas. The spacecraft that provide this imagery are, predominately, large and expensive. They cost tens to hundreds of millions of dollars to build and tens to hundreds of millions of dollars to launch.

Small spacecraft, however, represent a new paradigm for remote sensing applications. They can be used, in conjunction, to capture imagery which can be super-resolved to rival the performance of spacecraft that are larger and significantly more expensive than the whole small spacecraft constellation. Alternately, they can be spaced to provide higher temporal coverage. Various intermediate configurations are also possible, making the collaborative small spacecraft approach extremely versatile.

This paper presents work on three synergistic topics. First, it covers work on orbital super-resolution and mosaicking. This work demonstrates the viability of the on-orbit operations required to combine and/or enhance images for direct user consumption on Earth. Second, it presents work on a set of protocols that can be utilized to share tasks between multiple spacecraft. This includes the imaging tasks required to capture the pictures required for mosaicking and enhancement. It also includes the processing tasks required for performing the mosaicking and enhancement.

Finally, the synergy of these two aforementioned topics is presented: a collaborative mission design to enable a constellation of heterogeneous spacecraft, prospectively with different owners, to collaborate to collect and process data for direct use by users in a developing country. A mission concept is presented and analyzed. The quality and resulting utility of the prospective data is considered. From this, its suitability for various applications is assessed. The paper concludes by discussing the prospective impediments to implementation of this plan. Various approaches to completion are considered.

II. BACKGROUND

Significant prior work in several areas forms the foundation upon which the proposed concept is built. This section provides an overview of this work. First, a brief overview of small spacecraft is provided. Next, autonomous control of spacecraft is discussed. Finally, a brief discussion of remote sensing data products is presented.

II.1 Small Spacecraft

Small spacecraft have existed for the entire history of human exploration in space. The first spacecraft, Sputnik, which was launched in 1957, had a mass of...
only 83 kg [1]. The following year, the United States launched Explorer I which had a mass of only 14.5 kg.

Modern spacecraft have considerably improved over the technical capabilities provided by these initial limited spacecraft. Craft with a mass of less than 2 kg are routinely being deployed for a variety of applications. Swartwout [2-5] has catalogued these spacecraft. Many come from educational institutions or involve an higher education partner. There are now nearly one-hundred institutions that have participated in a small spacecraft program (some have joined together to produce a collaborative spacecraft, other institutions have produced more than one) [4]. Outside of academia, small spacecraft are being developed by industry (e.g., [6]) and governmental (e.g., [7-9]) entities. This has demonstrated their ability for pushing technical boundaries [5, 10] as well as performing bona fide work [11, 12].

Small spacecraft have been shown to provide educational benefit, by enabling experiential education [13-15]. They have operated and provided services on numerous communications frequencies [16, 17] and CubeSats have even been proposed for interplanetary use [18, 19]. Starting from an initial 1U (one-unit) size, a variety of multiple-unit configurations have been suggested including 2U, 3U, 6U and larger configurations [20]. The ability to incorporate significant processing power onboard has been demonstrated [21, 22]. The spacecraft have also been shown to be able to produce synergistic outcomes, when utilized in clusters [23-25]. A recently proposed design specification update will now allow propulsion onboard, further expanding the possible missions and their duration [26]. Some are even pursuing smaller spacecraft to further reduce development and launch costs [27].

II.II Autonomous Spacecraft Control

Significant progress has been made in the autonomous control of spacecraft. Early spacecraft were teleoperated; however, significant autonomous control has been demonstrated in more recent missions [28]. Autonomous docking was demonstrated by the Soviet IGLA and KURS spacecraft [29] and by the United States’ ASTRO and NextSat craft [30]. Autonomous planning has been shown by the Remote Agent Experiment [31] and CASPER [32]. Health assessment and correction was shown to work by the DS-1 MIR [33] and EO-1 Livingstone Version 2 [34] systems, while command software has been demonstrated on DS-1 [35], Hayabusa [36], Rosetta [37] and the Deep Impact Impactor [38, 39], among others.

Beacon methodologies have been demonstrated [35] as a way of conserving communications bandwidth, as have other technologies [40-42]. Autonomous control of complex entry, descent and landing maneuvers has been demonstrated [43, 44], amidst significant concern over entrusting these delicate maneuvers to automated control [45]. Prior work [46] has shown that autonomy in space still faces significant acceptance challenges.

II.III Remote Sensing Data Products

While a wide variety of data products can be generated via remote sensing (including thermal infrared imaging, multi-spectral imaging, microwave and LIDAR imaging and gravitational data [47]), the primary focus of this paper will be on visible light imagery (and near-visible light imagery that can be produced via changing the filtering applied to standard sensing equipment).

Visible light remote sensing data is defined by its coverage and spatial and temporal resolution as well as other qualitative aspects [47]. Coverage of desired areas is clearly important. Spatial resolution is a measure of the size represented by each pixel on the imagery. The utility of spatial resolution levels ranging from sub-meter to over a kilometer has been demonstrated [48]. Temporal resolution is a measure of how frequently data for a given area can be re-obtained (e.g., how current the data product is).

For agriculture, visible light sensing data can be useful for assessing where to deploy and the deployment of fungicides and pesticides, assessing crop damage due to weather and assessing drainage patterns and designing drainage solutions [49]. The utility of both aerial and satellite imagery has been demonstrated for this purpose [47, 49, 50]. The resolution required varies by application; however, the utility of 20-meter data has been demonstrated by the International Space Station Agricultural Camera [51]; the use of 10-meter [49] and much higher resolution [50] data has also been demonstrated. Temporal requirements vary, based on the desired phenomena under study; in addition, data may be needed on-demand for use in storm damage assessment and other cases.

Remote sensing of urban areas, such as might be used for municipal or county/state-level planning has been performed with data ranging from 100-meter to 10-meter or higher resolution [52]. This data can be used to determine material composition, land cover and land use for planning and other purposes. The level of temporal coverage required varies significantly, with one-a-year resolution being acceptable for some applications and more frequent imagery (including imagery at given times) being required for others. Miller and Small [53] proffer that remote sensed imagery is particularly important for developing regions as it can serve to replace the growth and environmental condition data collected in-situ (or by other means) in more developed nations. They also note the utility of
remotely sensed data being unobstructive and consistent.
Remote sensed data has also been shown to be useful for the response to hazards such as earthquakes, volcanos, floods, landslides and costal inundations. In this context, data can be used to prioritize response efforts, direct responders as well as to, in the longer term, perform risk assessments and establish policies to prevent future issues [54].
A multitude of other uses for remote-sensed data exist, many of which would be relevant to developing nations. These include its use in aquaculture (sea farming), such as was demonstrated in India [55] and water policy [56].

III. REQUIRED TECHNOLOGIES AND MISSION

Three key technologies are required to support a prototypical remote sensing mission for developing countries. These are super-resolution, mosaicking and task-sharing between craft. Super-resolution enhances imagery beyond the physical collection capabilities of the craft. Mosaicking combines images together to produce a more ready-to-use data product and it eliminates the re-transmission of overlapping areas. Task sharing between craft may be required to collect the level of data required to meet temporal and spatial coverage goals. Each of these technologies will now be discussed, followed by a discussion of the prototypical collaborative mission.

III.I Super-Resolution and Mosaicking

Super-resolution is used to enhance imagery; it produces a higher level of output resolution than the imagery fed to the engine. While a variety of single-source super-resolution algorithms exist (based on patterns in the image [57], heuristics [58, 59] and other techniques), these may place too much reliance on unsupported inference to be suitable for many applications. Multi-source super-resolution algorithms (e.g., [60-62]) make use of subtle differences between images to make a more educated inference as to what the pixel configuration would be at a higher resolution. Super-resolution techniques may introduce false positives (non-existent feature inclusion) and false negatives (feature exclusion) into the imagery [63]. It has been shown useful for processing raw imagery as well as other types of geospatial data [64, 65].

Mosaicking is used to combine multiple images into one composite one. The mosaicking software must not only identify the correct relative position of the two images (by lining up shared points, for example), it may also need to correct the shape of the images to match each other. Two common mosaicking techniques exist: Scale-Invariant Feature Transform (SIFT) and Speeded Up Robust Features (SURF) [66-68]. The use of mosaicking prepares the images to be directly-useful to users, allowing possible transmission directly to the point of use (e.g., broadcasting to multiple handheld computers for use in the field, etc.), presuming that a sufficiently robust communication channel exists.

Previous work has considered the inclusion of super-resolution and mosaicking into small spacecraft [69, 70]. Finding more optimized algorithms (which may potentially make use of certain data not available in the general case scenario) will significantly enhance software and, as this is a critical-path operations task, mission performance.

III.II Task Sharing Between Craft

An orbital services model [71, 72] has been proposed under which craft can collaborate to perform tasks. Under this model, supplier craft advertise the services that they can provide and prospective consumers evaluate the service-suppliers available to them, making a selection based on a combination of factors (e.g., quality, timeliness).

A mission from a developing country could utilize the entire (presuming future deployment) network of providers; however, this same methodology can also be applied to a small cluster of craft which communicate and provide/consume services within the group.

Both the image collection and processing could be distributed. This would facilitate greater temporal coverage (and the collection of the imagery required for multiple-source super-resolution) as well as lower cost, by concentrating processing capabilities onto a subset of spacecraft.

Figure 1. OpenOrbiter (OPEN framework-based) Spacecraft Superimposed on Earth [73].

III.III Collaborative Mission for Developing Countries

The proposed collaborative mission could incorporate multiple spacecraft from a single country, spacecraft from multiple countries or a combination of the foregoing. While an economic model could be devised entailing payments from one to another for services rendered, an alternate (perhaps easier to manage) approach would be to require a contribution proportionate to the level of benefit that is expected (or the attributable level of expense). This could range
from some countries participating as partners in a spacecraft, to others (who would enjoy more benefit providing multiple craft).

There is no requirement that the countries be neighbors; in fact, dispersed countries may be ideal as this may reduce contention for craft use when over the general vicinity. It would, of course, be necessary for all of the target regions to be served from the selected orbits. However, the use of other resources (e.g., processing capabilities) would require only communications opportunities between orbital craft.

IV. THE VALUE OF THE OPEN PROTOTYPE FOR EDUCATIONAL NANOSATS

The Open Prototype for Educational NanoSats (OPEN) is poised to offer a low-cost solution for the development of CubeSat spacecraft. A single-unit (1U) CubeSat (10 cm x 10 cm x 10 cm, 1.33 kg) built based on this may be possible for a parts cost (excluding payload) of under USD$5,000 [74]. Current work has considered scaling this design up to a 3U configuration with a proportionate increase in cost.

Work on the OPEN design was initially undertaken to facilitate educational activities (see [15, 75]); however, the design documents, instructions and other materials will also be available to developers with different aims. Its use in supporting planetary science missions, for example, has already been considered [76]. The OpenOrbiter spacecraft [77] is being developed to validate the OPEN designs and begin the process of their space qualification, decreasing risk for subsequent developers using the OPEN framework.

A CAD rendering of the OPEN design (superimposed on the Earth) is presented in Figure 1. Figure 2 depicts a top-down view of the OPEN design.

V. QUALITATIVE ANALYSIS

A brief review of the utility of the proposed approach is now undertaken. This will consider the quality and utility of the data, the suitability for applications potentially of interest to developing countries and impediments to the proposed plan, qualitatively.

V.I Quality and Utility of Data

The quality and utility of the data will be a function of several different factors. First, will be the quality of the collection equipment. Even if the data is of a
suitably high resolution, if it is blurry or otherwise degraded, it may be of little use. Image processing techniques may be able to resolve (or mitigate the impact of) some imperfections.

Second, the number of images that can be collected of the given region in a given period of time will directly affect the level of enhancement that will be possible. These images can be provided to the super-resolution algorithm to produce a combined higher-resolution image.

Third, the quality and capabilities of the super-resolution software will impact the quality of the produced data. Poor-quality super-resolution software may consume more computational resources, reducing the level of enhancement possible and/or create artifacts and other image defects. The mosaicking software could create similar issues, with poor-quality software limiting the amount of image processing that can be performed onboard (necessitating, in the case of the mosaicking software, the transmission of redundant areas to the ground) and/or introducing image quality defects.

V II. Application Suitability

The spatial resolution of the enhanced data will be a function of the collection hardware, selected orbit and the level of software enhancement possible. Section II. III provided an overview of the uses of remotely sensed visible light data products and provided some ballpark resolutions that have been used to serve these applications. The references cited in this section provide greater detail as to many of these past systems and the use and utility of the data they collected.

Several considerations must be kept in mind as one is assessing the suitability of the data prospectively collected for a given application. First, of course, are the particulars of the application. Data that was suitable for one purpose within a general category (e.g., land cover assessment and planning) may not serve another (e.g., roadway planning). Thus, specific needs must be identified and the compliance of the solution with those needs assessed. Wertz, et al. [78] discuss this process, both in general and in the context of an imaging spacecraft. Jensen [47] provides numerous examples of previous remote sensing missions and their capabilities.

The second consideration is the degradation of capabilities over the life of the mission or if one partner fails to deliver their equipment. In a cluster configuration, degradation can be gradual (as opposed to the all-or-nothing statuses provided by a single craft approach) with proper planning. For risk mitigation purposes, critical elements should be spread between partners and orbital locations. Through this, the impact of a partner failing to deliver, pulling out during operations or equipment failure or damage can be mitigated. Special consideration may be required if a dominant partner is paired with numerous smaller ones in a given plan. The utility of the resulting cluster should be assessed under various possible degradation scenarios.

Third, the utility of a given resolution (or quality) of data should be considered relative to projected costs. Care should be taken to adjust costs (which, for example, for labor) may be commonly discussed in terms of the labor rates in more affluent regions. This should also be considered in the context of the build/buy decision.

V III. Plan Impediments

The proposed plan has several possible impediments. First, it requires co-operation between countries. This may be difficult to attain and maintain.

Second, export control regimes and other political considerations may impede the design and development of the system. As the product of fundamental research, the current OPEN design may enjoy favorable treatment under U.S. export regulations. Modified versions (created by commercial entities) may be subject to regulation and the fundamental research classification may not exist or be as favorable under other nations’ laws.

Finally, technical problems, a lack of skilled staff, training issues and other hurdles may impede deployment. This may intensify political and other impediments (particularly if blame is cast onto a particular partner-nation).

VI. CONCLUSIONS AND FUTURE WORK

This paper has presented an overview of how a low-cost spacecraft platform can be utilized to deliver high-quality remote sensing data products to aid nations without the financial resources required to support a fleet of larger spacecraft. It has highlighted a combination of technologies that, when combined, allow the production of data that can aid urban and crop planning, disaster response and many other endeavors. A qualitative analysis of this approach has been presented and its benefits and drawback, as well as possible implementation impediments, have been discussed.

Work on the development of the Open Prototype for Educational NanoSats is ongoing. Future work will include the dissemination and evaluation of the OPEN plans as well as their on-orbit demonstration via the OpenOrbiter spacecraft.

VII. ACKNOWLEDGEMENTS

Small satellite development work at the University of North Dakota is or has been supported by the North Dakota Space Grant Consortium, North Dakota NASA EPSCoR, the University of North Dakota Faculty Research Seed Money Committee, North Dakota
The involvement of the numerous students from multiple disciplines in this project is gratefully acknowledged. Also, thanks are given to the numerous faculty mentors who have helped make this project possible.

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