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Sensor and Computing Resource Management for a Small Satellite

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Abstract—A small satellite in a low-Earth orbit (e.g., approximately a 300 to 400 km altitude) has an orbital velocity in the range of 8.5 km/s and completes an orbit approximately every 90 minutes. For a satellite with minimal attitude control, this presents a significant challenge in obtaining multiple images of a target region. Presuming an inclination in the range of 50 to 65 degrees, a limited number of opportunities to image a given target or communicate with a given ground station are available, over the course of a 24-hour period. For imaging needs (where solar illumination is required), the number of opportunities is further reduced. Given these short windows of opportunity for imaging, data transfer, and sending commands, scheduling must be optimized. In addition to the high-level scheduling performed for spacecraft operations, payload-level scheduling is also required. The mission requires that images be post-processed to maximize spatial resolution and minimize data transfer (through removing overlapping regions). The payload unit includes GPS and inertial measurement unit (IMU) hardware to aid in image alignment for the aforementioned. The payload scheduler must, thus, split its energy and computing-cycle budgets between determining an imaging sequence (required to capture the highly-overlapping data required for super-resolution and adjacent areas required for mosaicking), processing the imagery (to perform the super-resolution and mosaicking) and preparing the data for transmission (compressing it, etc.). This paper presents an approach for satellite control, scheduling and operations that allows the cameras, GPS and IMU to be used in conjunction to acquire higher-resolution imagery of a target region.

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1. INTRODUCTION
Description of Payload

The payload software onboard a small satellite is in charge of requesting image captures from the operating software. The operating software then returns a series of images to the payload system. Once received the images will either be mosaicked or analyzed for super-resolution depending on the job request. This process of mosaicking [1] the images together to create a larger stitched image will require analyzing each image individually using feature recognition algorithms [2] and the satellite IMU to align the images and combine them to form one large image that spans the requested area. If the job request was to create a super-resolution image the images will still need to be processed for their similar features but then the overlapping regions will have to be combined to form a higher resolution image [3] of the same region. In this way the satellite can increase the quality of very specific regions for better analysis at the ground station.

Since the communication window with the ground station is very limited (in the range of 1200 baud) the images will require some type of compression before being sent to the ground station. Depending on the time allotted to the payload software for power consumption a simple compression algorithm may be used to save storage space and especially transfer time from the satellite to the ground station. With efficient compression the satellite can be much more efficient when transferring data.

Components of Payload

REFERENCES..........................................................7
As demonstrated in Figure 1, there are four main components to the payload software: image registration, image mosaicking [1], super-resolution processing, and image compression. Each of these components plays a crucial role in the processing of images collected by the operating software and in the completion of the requested satellite job.

![Payload Software](image)

Figure 1. The four main components of the payload software are image mosaicking, super resolution processing, image compression, and image registration.

An important component to the payload software [4] will be the image registration. Image registration is the process of mapping out similar features in a set of images and then doing affine transformations on those images to place them in the same orientation and allowing the images to be easily processed relative to each other. Since both image mosaicking [1] and super-resolution processing require images to be accurately placed relative to one another the image registration plays an important role in the overall functionality of the payload software.

Second is the image compression component. Image compression is the process of reducing the overall number of bits used to store the images. Once the images have been processed and are ready to be sent to the ground station the compression component will run a standard lossless image compression algorithm (such as JPEG or fractal compression) to make the image files smaller and more manageable when being sent over a slow network to the ground station.

Next is the mosaicking component. Image mosaicking is the process of stitching multiple images together to create a larger image and reduce the overlapping components of a series of images. This process will be used to reduce the overall size and number of images that need to be sent from the satellite to the ground station.

Finally the super-resolution processing component will be used to enhance specific regions of the satellite imagery when necessary or requested. Super-resolution processing is the processing of artificially increasing the resolution of a picture. Multiple solutions exist for doing this, but the proposed satellite will focus on using four images to increase the resolution. It will do this by taking numerous images and using the GPS/IMU to determine the ordering of the pictures. The ordering will be the first image taken from the top will be one, the second on the top will be two, the first on the bottom will be three, and the second on the bottom four. From these images, image registration will find features to accurately determine the overlap on any two or more pictures. The satellite will then break down these images pixel by pixel and take a pixel from one and put it half a pixel to the right of the first pixel.

The third pixel will be the same pixel as the first and second

![Super Resolution](image)

Figure 2–Multi-Image Super-resolution uses four images taken of the same region/area. The pixels are matched up and then inserted next to each other in an image with four times the number of pixels of the original photos. This type of super-resolution can increase the original image quality by 1.0x to 2.0x.

The main functionality of the payload software is to send a request for execution of a “take picture” command to the operating software. The operating software will then record the picture at the desired time, and pass the image frames to the payload software. The image frames will then be processed by the image registration component, then either processed through mosaicking or super-resolution, before being compressed by the compression component. The processed image frames are then sent back to the operating software for storage and potential transmission to the ground station.

Image mosaicking solves two main issues of image processing: correcting geometric deformations, and stitching images together to reduce overlapping areas of multiple images. This process will be done by aligning images with their GPS and IMU data and then using image registration to find feature of the images that can be used to map the similar areas in the images to one another. Then the process can stitch the images together by removing the overlapping areas and creating a wide view image.

Super-resolution is the process of artificially increasing the resolution of a picture. Multiple solutions exist for doing this, but the proposed satellite will focus on using four images to increase the resolution. It will do this by taking numerous images and using the GPS/IMU to determine the ordering of the pictures. The ordering will be the first image taken from the top will be one, the second on the top will be two, the first on the bottom will be three, and the second on the bottom four. From these images, image registration will find features to accurately determine the overlap on any two or more pictures. The satellite will then break down these images pixel by pixel and take a pixel from one and put it half a pixel to the right of the first pixel.

The third pixel will be the same pixel as the first and second
and place it half a pixel under the first pixel in the new image, and the last pixel will be taken from the fourth image and placed half a pixel to the right and half a pixel down effectively creating a rectangle of pixels. This new super-resolution image will be twice the size as the original overlapped section effectively doubling the resolution. Figure 1 shows the process of four 2x2 pixel images being made into one higher resolution image through super-resolution. The resulting super-resolution image may not always provide more detail, as the new picture is based off of the four original pictures, those pictures must differ in some perspective in order for the super-resolution image to show much change. The new image will also only be up to a maximum of twice the resolution of the original pictures.

The purpose of image compression is to reduce the size of the image data in order to more efficiently store and transmit the image. The satellite image compression software will be using JPEG compression to reduce the size of the image while attempting to preserve the overall quality. To further compress the images, Huffman encoding (a lossless compression) will be applied to the JPEG files. Finally, Model Based Data Transmission will be utilized to effectively compress the transmission data being passed to the ground station, achieving significant improvements over standard transmission protocols [9]. The compression component of the payload software is the most used component but also one of the easier components to implement.

2. BACKGROUND

Prior work on Mosaicking

There has been a lot of research done on image mosaicking and the processes involved in creating seamless transitions between the stitched images. Much of this research is covered and re-analyzed in Bowne and Lowe’s paper [5]. This includes Automatic Panorama Straightening, Multi-Band Blending, Gain Compensation, and Bundle Adjustment. Automatic Panorama Straightening is a process in which the final image mosaic is straightened out to correct for the changes in camera angle that can cause a curved mosaic in the end.

Multi-band blending is a technique to help reduce the edges between mosaicked images by correcting for vignetting and parallax effects due to camera motion and lens effects. Gain compensation is a method to create a constant gain across all of the images. This is easy for multiple images, even if the images are taken at the exact same location, and there are differences in gain and brightness. Gain compensation evaluates the overall gain of the images and evens it out as much as possible to reduce inconsistencies. Bowne and Lowe [5] have set up a simple list to combine all of the above techniques and create crisp consistent mosaics:

Input: n unordered images

1. Extract SIFT features from all n images

2. Find k nearest-neighbors for each feature using a k-d tree

3. For each image:
   a. Select m candidate matching images that have the most feature matches to this image
   b. Find geometrically consistent feature matches using RANSAC to solve for the homography between pairs of images
   c. Verify image matches using a probabilistic model

4. Find connected components of image matches

5. For each connected component:
   a. Perform bundle adjustment to solve for the rotation \( \theta_1, \theta_2, \theta_3 \) and focal length \( f \) of all cameras
   b. Render panorama using multi-band blending

Output: Panoramic image(s)

Prior work on Super-resolution

When a camera captures an image, the light is funneled through the lens, and accumulated by the CCD sensor, the charge is shifted and recorded by an analog to digital converter where color values are extracted based off of interpolation of Beyer mask filter data. When light first passes through the camera, the image gets distorted, aliased, blurred, and noise is introduced [10]. This is what led to the introduction of super-resolution. Super-resolution takes multiple images and artificially increases the resolution of a picture.

The goal when doing super-resolution is to get an image that provides more detail than the original individual images contained. There are several methods available to do super-resolution: neighbor interpolation, bilinear interpolation, and bicubic interpolation to name but a few. Nearest neighbor interpolation takes the nearest pixel to the interpolated point and makes it the same color, effectively enlarging the size of each pixel. Bilinear interpolation doubles the resolution of the image by assigning all the new pixels average color of the four closest pixels (see Figure 1). Bicubic interpolation is similar to bilinear interpolation, except it uses the nearest 16 pixels and averages them out, while giving the nearest pixels more weight to change the color. Bicubic interpolation produces the sharpest image out of the three methods discussed [11].

The discussed forms of interpolation can help with multi-frame super-resolution. Multi-frame super-resolution takes images, identifies a common landmark, and combines the four images to make a new image with up to twice the resolution of the original. Interpolation can aid in this by smoothing out pixels that are irregular, or pixels that do not
match the other surrounding pixels. This adds a more constant color for groups of pixels within the super-resolution image.

Prior work on Inertial Measurement Units

Traditional image registration has been done strictly with feature matching between the images, but there has also been research into using Global Positioning System (GPS) and Inertial Measurement Unit (IMU) from UAVs to more easily match up images to one another. This can be achieved by having the changes in location and orientation of the camera recorded when the camera captures the images. Most such projects have focused on using very high quality IMU and GPS systems that return very accurate results. In a paper by Mitch Bryson et al. the topic of using small UAVs with lower quality GPS and IMU systems is discussed along with the benefits these systems can provide for the image processing. [12].

They used the IMU and GPS to gather the position and altitude of the UAV and its trajectory. From the image data, point features are found and matched across the group of images. The position altitude map is then used with the feature-mapped images to form a more accurate mosaic in which the orientation of the UAV has been taken into account. This process of using GPS and an IMU to ease the processing of images onboard the CubeSat will help to reduce the time it takes to create the mosaics.

The Purpose of Payloads on Satellites

The payload of a satellite is the equipment in the satellite dedicated to execute the satellite's primary mission. These systems may include a variety of sensors, such as radio, infrared, visible, ultraviolet, x-ray, gamma ray, particle or field sensors [13]. These sensors collect the data for direct transmittal to the ground station or for further processing by the payload software before transmittal.

Typically, the higher the quality data that is required for the purpose of the satellite, the larger the sensor will be. In the case of CubeSats on the other hand, payload space is extremely limited. Creative techniques such as significant post-processing of the data are thus utilized to maximize the quality of the data being delivered by the limited-in-size payload. As discussed in the introduction of this paper, the Open Orbiter payload system will utilize techniques such as image mosaicking and super-resolution to increase the overall quality of the data acquired, and reduce the amount of data needed to be transmitted to the ground station. These creative techniques can also be utilized in larger satellites to increase quality of the data without requiring hardware and/or size upgrades.

3. TECHNICAL APPROACH

The payload software onboard the small satellite will be used to complete the more computationally expensive tasks of the satellite:

- Create a list of times when the satellite should collect image data to complete a certain task.
- Create a mosaicked image from a set of images.
- Create a super-resolution image from a set of images.
- Use lossless compression to reduce the amount of data that needs to be transferred.

Each of these tasks is required for the small satellite to efficiently collect and transfer high-resolution imagery or mosaics to the ground station.

Implications of Using Onboard IMU and GPS Data

A satellite in low-Earth orbit is vulnerable to changes in perturbations that may have negative effects on the stability of the satellite. This in turn affects the input data to the satellite through external sources. In the case of CubeSats, the small size of these satellites renders them more prone to such changes/perturbations. The perturbations in satellite orbits can be created by a number of factors; some of which being the atmospheric drag, Attitude Determination and Control Subsystem (ADCS) generated movement, solar emission pressure and others. Solar emissions and ADCS-generated movement will fluctuate throughout the orbit – particularly when ADCS control is utilized (from the control reaction wheels). Atmospheric drag varies somewhat over time; however, it will change (additionally) during the lifetime of the satellite as its altitude decreases.

A satellite that takes input as images from a camera attached to it and intends to build a clear imagery of the scenario requires being robust to the rotational and angular variations occurring. To compensate for these variations after the fact, it is proposed to use an IMU and a GPS to keep track of the orientation and position of the small satellite. Chon et al. states, “the position and orientation of the camera can be derived from GPS and IMU data with sufficient accuracy to allow direct georeferencing without the need for Ground Control Points” [1].

Determining the Image Capture Time

The satellite will receive two GPS coordinates from the ground station as a task. The two coordinates represent the upper left and the lower right corners of a boxed region from which to collect image data. This task will be for a single image request, a mosaicked image request, a super-resolved image request, or both a mosaicked and super-resolved image request. Each request from the ground station will be analyzed by the satellite operating software and then passed to the payload software to be broken into small jobs for the operating software. Each job will consist of a specific time the satellite should capture an image. The image data can then be stored for later processing by the payload software.
The process of determining when the satellite needs to capture images to complete the specified task is a mission critical software process and can be computationally expensive. The satellite needs to determine if the current region has been photographed recently, and if not, what is the earliest time it can be photographing that region. The current location (GPS) and velocity (IMU/GPS) of the satellite can be used to calculate when the satellite will be over the region of interest and at what interval images need to be captured in order to create a sufficient overlap for mosaicking or super-resolution. Since energy consumption is an important factor for a small satellite the payload software must determine optimal times for image capture. When creating mosaics, image overlap is necessary to find enough features to properly match regions of each image but less overlap means fewer images are required to cover the entire area requested by the ground station. A proper distance between each image capture is necessary to save energy consumption of the satellite while still allowing enough overlap for accurate feature recognition.

**Mosaicking with IMU Data**

Imaging depends on the factors whether an image, or sequence of images, is being captured from earth’s lower orbits or further away. The problem of distortion caused by this can be solved through an approach of mosaicking and utilizing IMUs. A question that still needs to be answered is whether an IMU can aid the system in determining the appropriate orientation and angular displacement of the camera onboard. This in turn could aid in determining the displacement, direction, and the positions of the consecutive images taken, with respect to one another. This in turn would aid in the construction of correct mosaics of the sequence of images. For instance: Let translational displacement between two overlapping images be $S$, angular displacement as $\Phi$, and the rotational displacement be another angle $\Theta$. If the IMU aids in determining values of these parameters, then these values could be simultaneously decided for each consecutive image. The rotational displacement would determine the depth of the image, contributing to its 3-D measure.

After determining the value of each parameter for each image, they are brought together according to their displacements and stitched by using various available algorithms, into the mosaic.

As discussed above, it is critical for a satellite to be stabilized. In situations when its motion is not very stabilized, it must be efficient enough to render its geolocation information. By doing so, it would aid in identifying the correct location of the source of the images, of the satellite. The correct angles of the images, and even the depth of the objects can become difficult to determine. At this point, the role of an IMU can become invaluable in determining the attitude and direction of the satellite. An IMU is being used on the small satellite to increase the accuracy and efficiency of mosaicking and super-resolution algorithms.

The IMU aids in the process of aligning images by providing information about how the satellite has changed attitude and direction between image captures. This would allow a mosaicking algorithm to more quickly match features in images with large rotation differences. For example if an image was taken and for some reason the satellite was rotationally displaced 90° between the next image capture the onboard IMU would be able to relay this information and the mosaicking or super resolution algorithm would be able to compensate for this change prior to using a more computationally expensive method.

The addition of the IMU can potentially save a large amount of processing time for the limited onboard hardware resources. The small satellite will have very limited computation capabilities and battery life, this means if even a small amount of computational resources can be saved by collecting IMU data it could mean a monumental increase in overall satellite productivity.

**Image Sequencing and Feature Recognition**

Once the satellite collects the images, the payload software must determine the proper order of images to create the requested mosaick or super-resolved image. This is not a difficult process since GPS data, IMU data, and current time are collected along with the capture of each image. This data can quickly be used to determine the how the images align and overlap. The known overlapping regions of each image can be used to reduce the computations required for the feature recognition algorithm since it only needs to find features in overlapping regions. This process can help reduce the processing time and overall energy consumption of the satellite to boost satellite efficiency.

**Mosaicking Approach**

Mosaicking is the concept of stitching images sharing common regions, or, bringing together the overlapping regions of more than one image. The mosaicking done on the satellite is done to reduce the overall amount of data needing to be transferred by removing any overlapping regions in the images of the photographed area. In this way images can be mosaicked and a single image of the photographed area can be sent to the ground station.

The mosaicking process involves feature correlation to be done between the overlapping regions of two or more images. With the IMU allowing for faster feature correlation a large number of images can be mosaicked using a feature recognition tool such as SIFT (Scale-Invariant Feature Transform).

**Super-resolution Approach**

Super-resolution is the concept of combining the a group of low resolution images of the same object to create a higher resolution image in the hopes of adding to the overall image resolution.
quality. The purpose of the on the satellite is to allow for higher quality images from the small satellites onboard camera.

The satellites super resolution will be similar to the mosaicking process in that it required a set of images to be matched by correlating unique features across the images. Once this is done we can super-resolve the images to create a new, higher quality image. By doing this onboard the satellite it reduces amount of data that needs to be transmitted to the ground station and thus increases satellite performance.

Super-resolution and Mosaicking Approach

The implementation of mosaicking with super-resolution is done with a goal of producing a final image with higher resolution. The super-resolution approach is used to accomplish this. A question that has yet to be answered is whether super-resolution would enhance the data quality of the overlapping regions in the image mosaics. According to Zomet, Peleg [8] the super-resolution algorithms make use of the image displacements on the overlapping regions. This in turn provides for a dense sampling, which restores high frequencies and improves resolution.

Compression of Onboard Data

The payload software will also be responsible for image compression on the satellite. This compression will take place after any large processing task such as mosaicking or super-resolution. Since the image will be transmitted from the satellite to the ground station using very slow data transfer rates (approximately 1200 baud) and transfer will only be available for very short periods of time, it is very important to consider the amount of data being transferred.

It is important to preserve the image quality since the images collected at the ground station will most likely require careful analysis or will be further processed in some way. Because of this, the image compression used must be lossless. Methods such as fractal compression can be used to greatly compress the satellite images however the algorithm is highly anti-symmetric and can be very computationally expensive when compressing the images. This method would be very effective for transmitting the images however we must also consider the computational expense of fractal compression. Due to the limited satellite resources we must also consider the use of other lossless compression algorithms.

4. Evaluation of Technical Approach

This paper has presented an approach for satellite control, scheduling and operations that allows the cameras, GPS and IMU to be used in conjunction to acquire higher-resolution imagery of a target region. It reviewed the techniques that are best suited for this task in light of power budget, transfer time, image quality and computing time considerations. Strategies for balancing onboard preprocessing and transfer time have been reviewed and a selection methodology has been discussed. The value of the IMU and the GPS sensors in decreasing processing requirements was also discussed.

Beyond the work presented, several key areas of consideration remain. This includes consideration of the tradeoffs between image quality, quantity and timeliness. A framework that can be used to determine a highly optimized approach for determining when to capture imagery, when and what to transmit, and techniques for conserving power and computing cycles is also required. Significant ground-based processing must be incorporated to prepare the imagery and associated data for transmission to data users. Repackaging and region-slicing considerations and techniques to optimize the data for public and secondary research purposes must be incorporated.

5. Future Work and Conclusions

Further work will look into the algorithm that will be utilized for aligning the panorama into various panoramic images and then applying super-resolution on each of the panoramic aligned strip. There are various other super-resolution techniques that could be utilized. Starting with the color image super-resolution, with the help of coloring pixels in the overlapping regions, similar features could be distinguished. The use of fast-Fourier transforms (which are computationally economical) could determine the behavior of various frames of the scene or in a mosaic, based on the frequency matching criteria. As discussed before, the use of scale invariant feature extraction (SIFT) would be one of the prominent approaches to look at. Figure 3 illustrates a mosaic image comprised of 6 separate frames.

![Figure 3–SIFT Feature Matching](image)

The above has presented a framework that can be used to determine a highly optimized approach for determining when to capture imagery, when and what to transmit and techniques for conserving power and computing cycles. Also discussed is the ground-based processing that is required to prepare the imagery and associated data for transmission to data users. Repackaging and region-slicing considerations are discussed as are techniques to optimize the data for public and secondary research purposes.

The lesson of the OpenOrbiter spacecraft mission resource management is of main importance for the operational robustness of entire mission, both for students and researchers. The approach laid forth in this paper can acquiesce functional and edifying outcomes in two ways.
From an edification position, the project participants gain “real-world” understanding of responding to the needs of future employers. From a programmatic position, the lack of payload utilization introduces lack of mission relevance.

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Biographies

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Atif Farid Mohammad is an MIT certified Systems Architect and currently a PhD student in the Computer Science department at the University of North Dakota working on Cloud Computing Security. Atif has more than sixteen years of experience in software engineering, professional business systems analysis, design, application development and staff management for diversified business and educational organizations. He is a member of IEEE, ACM and AST.

Christoffer Korvald is a MS student in the Department of Computer Science at the University of North Dakota. Christoffer is the President of the local chapter of the Upsilon Pi Epsilon Honor Society. He is currently the president of the Association of Norwegian Students Abroad - USA, which has over 1500 members. Christoffer holds a BA in Computer Science with a Software Engineering specialization from the University of North Dakota. He is also the Associate Director of Software for the Open Orbiter Satellite Initiative.

Anders Kase Nervold is an undergraduate student at the University of North Dakota pursuing a BA in Entrepreneurship with a minor in Space Studies. Anders is currently serving as the Associate Director for Communications, Outreach and Policy for the Open Orbiter Satellite Initiative. While at UND, Anders worked as a console operator for the International Space Station Agricultural Camera (ISSAC). In 2012, Anders and his business partner claimed the 1st prize in the GIANTS international business plan competition for their planned service venture in the aerospace industry. Anders is currently serving as the treasurer for the nationwide student organization, the Association of Norwegian Students Abroad – USA, which has over 1300 members. He has also served as the local president for the Association of Norwegian Students Abroad and as the treasurer for the Interfraternity Council. He was awarded the competitive Mueller Scholarship in 2012 and the Lillian Elsinga Outstanding Student Leader Award in 2011. Anders is also a member of the Dakota Space Society and mentors other international students at UND.