Matthew Martin, Author

Alexander Shirley, Subsystem Lead

Keith LeGrand, Chief Engineer

Henry Pernicka, Principal Investigator
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1 Introduction

1.1 Scope

This document is the Conceptual Design Document (CDD) report for the Stereoscopic Imaging subsystem. The intent of this report is to highlight and document the current stereoscopic imaging subsystem design being integrated on the Missouri-Rolla Satellite (MR SAT).

The current design for stereoscopic imaging has two cameras that take simultaneous images of the Resident Space Object (RSO). These cameras work similar to our eyes, combining two images of a given object to determine its relative distance. An onboard computer combines the images using an algorithm written in C++ and calculates the distance between the cameras and the object. This algorithm will be used to track the RSO with respect to MR SAT.

The stereoscopic imaging subsystem was chosen based on its low-power usage. This system is also a passive sensor, such that the RSO cannot detect MR SAT sensing it, compared to radar and LIDAR sensors that are active sensors. The system can be implemented using commercial off-the-shelf hardware, which makes the system inexpensive.

2 Description of System

The stereoscopic imaging subsystem consists of two parts. The first part is the hardware components such as processing unit and cameras. The second part is the software that determines the relative position vector to the RSO which enables the GNC system to perform proximity operations.

2.1 Hardware

There are two primary hardware systems that compose the stereoscopic imaging subsystem. The first is the camera assembly, which includes the two cameras, lenses, and sun shades. The second system is the onboard computer. Both of these systems are composed of commercial off-the-shelf (COTS), or custom in-house manufactured products to reduce the cost.

The camera assembly consists of two cameras along with a lens assembly and sun shade for each. The cameras used are Point Grey Firefly MV cameras. The cameras can capture $752 \times 480$ greyscale images at up to 60 frames per second (FPS). The two cameras are mounted in simple stereo with a 38 cm baseline (distance between cameras). In simple stereo, the cameras lie on the same axis and point in the same direction parallel to each other. The baseline can be increased/decreased to fit on larger or smaller spacecraft. Larger baselines allow the system to determine the position of RSOs that are farther away; however, the minimum distance that the position of the RSOs can be determined is also increased. Each camera is fitted with a COTS lens assembly with a focal length of 12 mm and a field of view (FOV) of $22.1^\circ$. A custom sun shade was designed and manufactured to mount to the lenses. The sun shade reduces the amount of stray light that enters the camera, thereby increasing the image quality. A summary of the camera assembly’s specifications are shown in Table 1.

The onboard computer is a Overo EarthSTORM COM [3]. The CPU of the EarthSTORM has a TI Sitara AM3703 processor that runs at 1 GHz. The EarthSTORM has 512 MB of RAM and 512 MB

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>38 cm</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>6 $\mu$m</td>
</tr>
<tr>
<td>Field of View</td>
<td>22.1$^\circ$</td>
</tr>
<tr>
<td>Focal Length</td>
<td>12 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>$752 \times 480$</td>
</tr>
</tbody>
</table>
of onboard flash memory with a MicoSD slot for upgradeable flash memory. An 8 GB MicroSD card is used to ensure that there is sufficient memory to store images for the entire mission. A summary of the onboard computer’s specifications are shown in Table 2.

### 2.2 Software

The algorithm employs techniques to accurately identify the RSO and calculate relative angles to the RSO to enable GNC to perform accurate position determination. A flowchart of the algorithm developed in Fig. (1)

#### 2.2.1 Collecting Images

The main loop of the algorithm begins with taking simultaneous images of the RSO with both cameras. Examples of the left and right images are shown in Figs. (2). These images are used to demonstrate how the algorithm performs.

#### 2.2.2 Feature Detection

The next step of the algorithm is to detect features from the two images. The goal of this step is to detect features that appear in both images. The Features from Accelerated Segment Test (FAST) [5] and [6] algorithm is chosen to detect features in each of the images due to its fast performance. Examples of the detected features of the left and right images can be seen in Figs. (3). The images are scaled to better display the features.
The FAST algorithm performs quickly by performing a high-speed test to exclude non-corner pixels in the image. Corners are used for features because they are easy to identify and match. For each pixel $p$ in an image the algorithm uses two tests to determine if $p$ is a corner. Let $I_p$ be the intensity of $p$. Pixel $p$ is considered a corner if there exists a set of 9 contiguous pixels in a circle of 16 pixels surrounding $p$ which are all brighter than $I_p + t$ or all darker than $I_p - t$ for a given threshold value $t$. The first test is a high-speed test to quickly determine if a given pixel is a candidate corner. This high-speed test examines pixels 1, 5, 9, and 13 shown in Fig. (4). If at least two consecutive of the four pixel’s intensities are greater than $I_p + t$ or less than $I_p - t$ pixel $p$ is considered a candidate corner pixel. For each of the candidate corner pixels the full test criterion explained above is applied. If the pixel $p$ passes that criterion it is considered a feature.
2.2 Software

2.2.3 Feature Extraction
Once features have been detected from both images, the next step is to extract feature descriptors from each of the features. Feature descriptions are extracted for use in the next step of the algorithm to match the features in the separate images. The feature description consists of information that is used to match features between images. The Speeded-Up Robust Features (SURF) [1] algorithm is used to extract descriptions from these images. To create the feature description a $16 \times 16$ neighborhood around the feature is taken and divided into 16 blocks of size $4 \times 4$. An 8 bin orientation histogram is created from each block for a total of a feature vector of length 128 that describes the feature. In addition, several metrics are taken to add robustness against changes in illumination.

2.2.4 Feature Matching
The next step of this algorithm is to match the features from the separate images. To match the features, the feature descriptors collected from the previous step are used. The matching algorithms used are in the Fast Approximate Nearest Neighbor Search Library (FLANN) [4]. This is found to be the fastest method to complete this step. An example of the feature matching is shown in Fig. (5). The regular nearest neighbor algorithm matches each feature of one image with the feature closest to it when calculating the Euclidean distance of the feature vectors computed in the previous state. FLANN approximates this algorithm, meaning that it doesn’t guarantee that it returns the closest feature to a given feature but it does so much quicker than the regular nearest neighbor algorithm.

2.2.5 Feature Pair Selection
The next step is to select feature pairs that are accurate and are actual features of the RSO. Some feature matches found may be in the background of the image such in the case where the Earth or stars appear in the background. This, along with false matches caused by using the FLANN algorithm instead of a slower more accurate algorithm, poses a problem on the accuracy of the algorithm. An example of such spurious matches is shown in Fig. (5). To that end, the Random Sample Consensus (RANSAC) [2] algorithm is employed. This algorithm helps remove outliers and false matches from the set of feature pairs which yields a more accurate distance calculation. The resulting matches selected using RANSAC can be seen in Fig. (6).

2.2.6 RSO Tracking
Once outliers have been removed from the matched features the geometric center of the RSO must be determined for each image. The geometric center is approximated by taking the average of the maximum and minimum values in the $x$ and $y$ dimensions. Once the geometric center is approximated $\alpha$ and $\beta$ angles are calculated which are the angles on the $XX$ and $YZ$ planes, respectively, that pass through the geometric center of the RSO. These four angles are passed to the GNC subsystem to determine relative
The values for $\alpha$ and $\beta$ are calculated using

$$\alpha = \frac{\gamma_x \hat{x}}{2P_x}$$

(1)

$$\beta = \frac{\gamma_y \hat{y}}{2P_y}$$

(2)

In Eqs. (1) and (2), $\gamma_x$ is the FOV along the $x$ dimension, $\gamma_y$ is the FOV along the $y$ dimension, $P_x$ is the number of pixels along the $x$ dimension, $P_y$ is the number of pixels along the $y$ dimension, and $(\hat{x}, \hat{y})$ is the position of the geometric center.

2.2.7 Saving Images

To accomplish the secondary mission, images from the imaging system must be saved. Instead of saving all images from both cameras, only images from a single camera will be saved. This is due to the fact that a vast majority of the information stored in a single image is the same as the other. Thus, saving both images would be an unnecessary use of the spacecraft’s data budget. All of these images are saved onto onboard memory. These images will be downlinked to the ground station during ground passes. The strategy for downlinking these images is described later.

To save space on onboard memory the images will be cropped to only include the RSO. This is done by finding the maximum and minimum positioned feature along the $x$ and $y$ dimensions. These values, given a small buffer value, will define the edges of the final image. This ensures that all, or a majority, of the RSO will be present in each image while minimizing the size of the image.

The images will be saved as JPEG files. The JPEG image format compresses the image, which is ideal for the data and link budget. Using high quality JPEG compression allows for up to a $10\times$ compression rate while having very low image degradation. The JPEG format is very effective at preserving edges and corners inside images which is also ideal for this application. The JPEG format also allows the storing of meta-data inside the images. A timestamp, cropping positions, number of features and other useful information will be stored inside the images for use later.

2.2.8 Brightness Adjustments

During orbit, the satellite may experience significant changes in lighting conditions. Because of this an algorithm is implemented that can adjust camera settings to aid in capturing ideal images with as many viable features as possible. This algorithm works by adjusting the exposure time of the camera relative to the pixel intensity histogram. Ideally the pixel intensity histogram of each channel is a normal distribution centered on the middle pixel value (127). As the lighting conditions get brighter, the distribution will shift higher. As the lighting conditions get dimmer, the distribution will shift lower. When a lighting change

![Figure 6: Example of RANSAC used on the matched features in the sampled image pair](image-url)
is detected, the exposure length will be shortened to reduce the average pixel intensity, or lengthened to increase the average pixel intensity. The exposure length for the next image capture is calculated using
\[ E_{x+1} = E_x + \delta(127 - \bar{I}) \]  

In Eq. (3) \( E_x \) is the exposure length from the last image capture, \( \delta \) is a scaling factor, and \( \bar{I} \) is the average pixel intensity of the cropped image.

2.2.9 Downlink Strategy
Once images have been captured and saved, they can be downlinked to a ground station for further analysis. Ideally, all of the images captured will be downlinked. However due to uncertainties, it is prudent to downlink higher quality images first in case all images cannot be downlinked. Each image will be given a priority and registered with inventory of the images. When making a ground pass, images will be downlinked from the inventory based on the priority assigned to them by the stereoscopic imaging subsystem.

Priority is determined by two primary criteria. Each of the criteria is based on the criteria of capturing good images for the secondary mission. The first priority is obtaining a high number of features found in the image. The second priority is the images being consecutive. Thus, the priority is based on the number of features in a given image as well as the number of features in preceding images. This is due to the requirement that images for the secondary mission share features. This occurs most readily in consecutive images.

3 Conclusions
This document describes both the hardware and software aspects of the stereoscopic imaging subsystem. The algorithm described employs algorithms to track the RSO and provide position information to the GNC subsystem which enables them to determine the relative position of the RSO with respect to MR SAT

References