

# Robust Targeting for the Smartphone Video Guidance Sensor

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The Smartphone Video Guidance Sensor (SVGS) is a miniature, self-contained autonomous rendezvous and docking sensor developed using a commercial off the shelf Android-based smartphone. It aims to provide a miniaturized solution for rendezvous and docking, enabling small satellites to conduct proximity operations and formation flying while minimizing interference with a primary payload. Previously, the sensor was limited by a slow (2 Hz) refresh rate and its use of retro-reflectors, both of which contributed to a limited operating environment. To advance the technology readiness level, a modified approach was developed, combining a multi-colored LED target with a focused target-detection algorithm. Alone, the use of an LED system was determined to be much more reliable, though slower, than the retro-reflector system. The focused target-detection system was developed in response to this problem to mitigate the speed reduction of using color. However it also improved the reliability. In combination these two methods have been demonstrated to dramatically increase sensor speed and allow the sensor to select the target even with significant noise interfering with the sensor, providing millimeter level precision at a range of two meters with a 1U target.

## Nomenclature

SVGS	=	Smartphone Video Guidance Sensor
AVGS	=	Advanced Video Guidance Sensor
MSFC	=	Marshall Space Flight Center
DOF	=	Degree of Freedom
CMOS	=	Complementary Metal-Oxide-Semiconductor
GN&C	=	Guidance Navigation and Control

## I. Introduction

The Smartphone Video Guidance Sensor (SVGS) is a miniature, self-contained, autonomous rendezvous and docking sensor developed using a commercial off the shelf Android-based smartphone. It aims to provide a miniaturized solution for rendezvous and docking, enabling small satellites to conduct proximity operations and formation flying while minimizing interference with a primary payload. It is based on Marshall Space Flight Center's (MSFC) Advanced Video Guidance Sensor (AVGS), developed and flown on the Demonstration for Autonomous Rendezvous Technology and Orbital Express demonstration missions in 2005 and 2007 respectively. The AVGS concept is to use a known target pattern, illuminate the pattern, take a picture of the target, and then extract the 6-DOF state from the 2-dimensional image. Whereas AVGS used a laser and retro-reflector to illuminate the target and used a high quality CMOS sensor to take the image, SVGS has used the flash and camera on the smartphone to illuminate the retro-reflector target and take the picture. This concept of operations and a 3U target setup can be seen in Figure 1. Note that the smartphone acts as a self-contained sensor, performing all image processing and only providing the state output for the chaser spacecraft's GN&C system. The underlying image processing equations were codified by Becker.<sup>1</sup>

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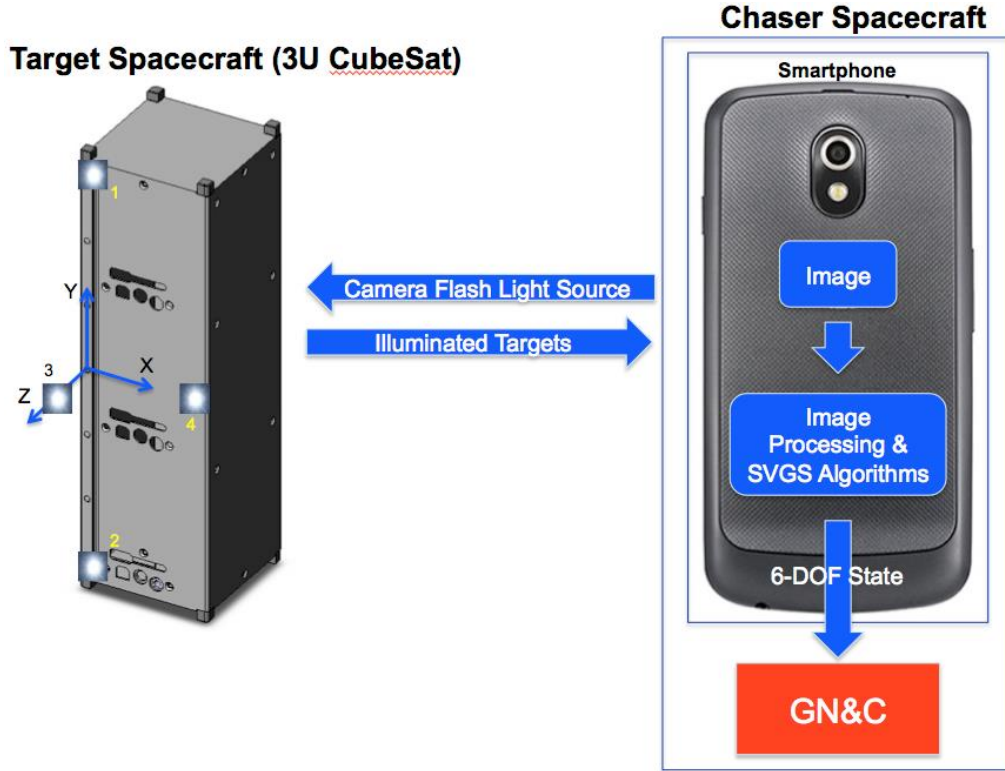


Figure 1: SVGS Concept of Operations

This sensor was attempted to be used as the primary sensor in a control loop for RINGS at Florida Institute of Technology. However, in attempting to integrate the SVGS in a control loop, multiple problems were found in the sensor. The primary problems were false positives and a slow sensor refresh rate. The false positives were primarily caused by lights in the background, though the flash itself also caused reflections off of background objects, as in Figure 2. As a result, the sensor could not correctly identify the set of target points, giving distorted and widely varying results, making a control loop nearly impossible to close. This difficulty was only compounded by a refresh rate of less than 2 Hz. Thus, a new targeting method was needed to increase the sensor’s robustness and solution refresh rate.

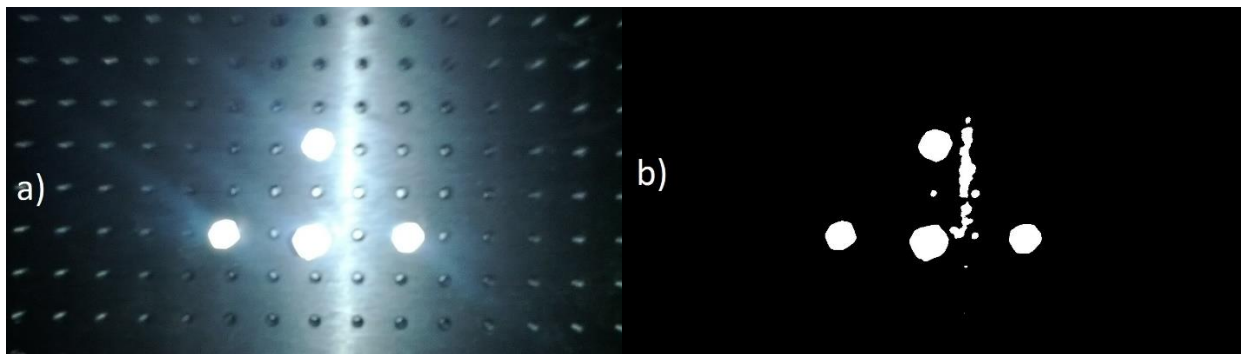


Figure 2: a) SVGS Retro-reflector Original and b) Thresholded Image with Background Reflections: *The thresholded image can be seen to have an essentially identical target set at 90 degrees relative to the intended target*

## II. Modifications to the SVGS Targeting

In response to the two main flaws of the SVGS, a failure to easily distinguish targets and a slow refresh rate, the targets of the SVGS were changed from retro-reflectors to LEDs, and the targeting algorithm was modified from a broad search of the image to a focused search, using the stored location of the target to begin the search. Changing

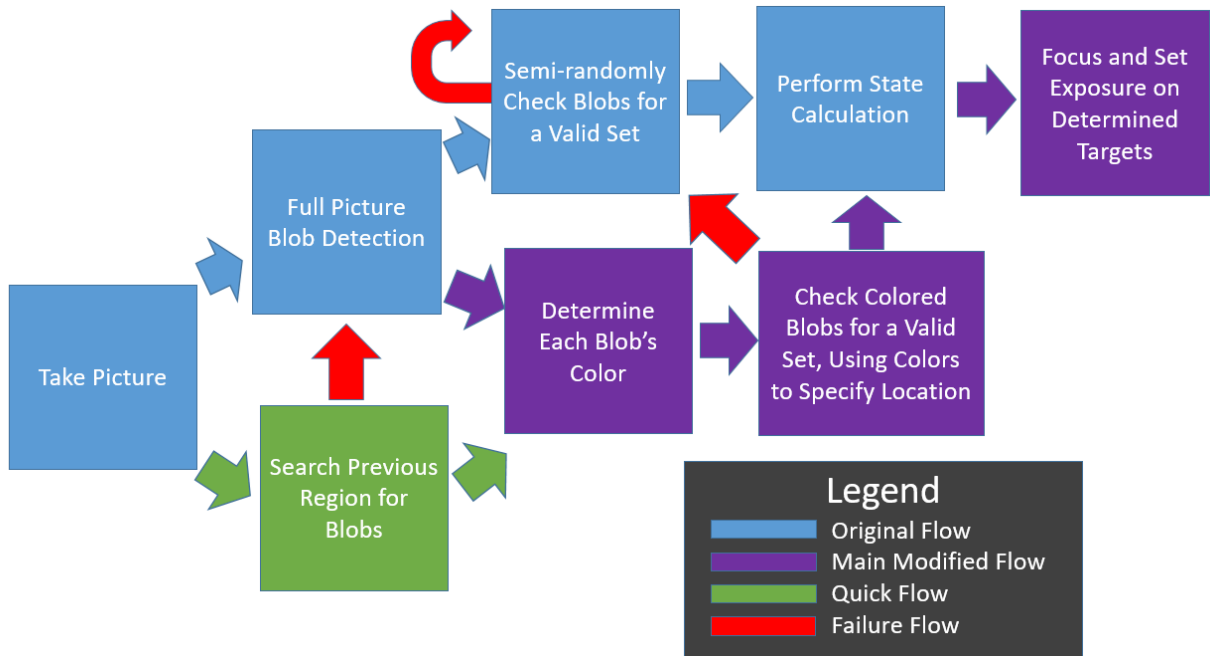
the target to LEDs also required modification to the original image processing flow. These changes can be seen in Figure 3.

**A. Target Design**

The target itself has four points, set at specified positions. The positioning of the LEDs remains the same as the retro-reflectors. The largest difference is that the LEDs are emitting light rather than reflecting it. This drastically increases the number of options. The primary considerations examined were the intensity and wavelength of the light emitted by the LEDs. The optimal design for the target would be a source of light which is not present in the background, whether in space, the space station, or on Earth. Thus, an ideal target would likely compose of near-infrared LEDs in four different wavelengths, each individually sensed by the camera. However, since a smartphone camera is being used, infrared cannot be used. Thus, visible light LEDs were used, spread as far across the spectrum as feasible, with blue, yellow, red, and green LEDs all of approximately the same brightness. These were chosen to allow the LEDs to be selected from the background and from each other, while preventing each of the LEDs from appearing a different size from the others.

**B. Original Image Processing Algorithm**

The original image processing flow is in blue, with red representing failure conditions. First the image is captured by the smartphone, searched for regions where the pixels exceed a brightness threshold, and then these regions or “blobs” are added to a set of possible target positions. From this set, all the combinations of different blobs are compared to the expected shape of the target and the first set of four blobs that matches the general shape of the target is considered to be the target. After this target is determined, the collinearity equations developed by Rakoczy<sup>2</sup> are used to calculate the 6 DOF state, giving the target’s position in the phone’s frame. One of the major problems with the initial target determination algorithm was that once the blobs were found, including all extraneous reflections, the first set of four blobs that vaguely matched the shape of the target was considered to be the correct state without doing any further checks on the validity of the solution.



**Figure 3: SVGS Modified Image Processing Flow**

**C. Modified Image Processing Algorithm**

The Modified Image Processing Algorithm is very similar to the original one, though there are significant differences. The modified algorithm uses an initialization and a quick mode. The first mode, initialization, searches the whole image for blobs, and then after it thresholds based on brightness, it looks at the region around the blob and converts those pixels into HSV, selecting only highly saturated pixels for use in determining the hue of the blob.

After the hue is determined, each blob is sorted by color, automatically rejecting anything that does not match the target colors. Once the colors of the blobs are known, the algorithm places the blobs in the target set at the location corresponding to that color and compares the relative positioning of the objects to each other to determine if those blobs indeed make a valid target set. If it cannot find a solution, it will revert to checking all the blobs, in any order. After the target set is determined, the state calculation is performed in the exact same way as before, using the same photogrammetry equations. In the initialization mode, the camera will change the focus and the exposure to be set on the target locations. After the SVGS has been initialized and has an initial solution, it will begin its quick mode. In the quick mode, the SVGS will search the image for bright regions in only the locations where the previous blobs were detected, cutting significantly the number of pixels searched and entirely eliminating any temporary noise. Furthermore, if this search fails to find a solution, the entire image will then be searched. This prevents the SVGS from losing a lock and from detecting and honing in on any transient false positives.

### III. Test Setup for the Modified SVGS Targeting System

To verify the success of the modified SVGS Targeting System, both the retro-reflector and LED targets were placed approximately 2 meters away from the camera, and, to simulate background lights and potential reflections, an additional set of bright white LEDs was added to the target setup, with the same shape as the targets as in Fig. 4. This was done to ensure that there would be false positives in the image so that the modified method's robustness could be tested. The additional target set was oriented 90 degrees relative to both of the targets so that target misidentification could be easily detected. To characterize the steady-state response of both systems, the target and camera were kept in this orientation for about 40 seconds and operated at its maximum speed as the sensor measured the 6 DOF state. It should be noted that in this test, there were only three colors used for the target. This was because there was not a color of LED available which was easily distinguishable and the same brightness as the other three LEDs. The target determination was only slightly affected.



**Figure 4. Target Setup for the Comparison Test:** *Various reflective surfaces were added to the background to test robustness in the face of known false positives.*

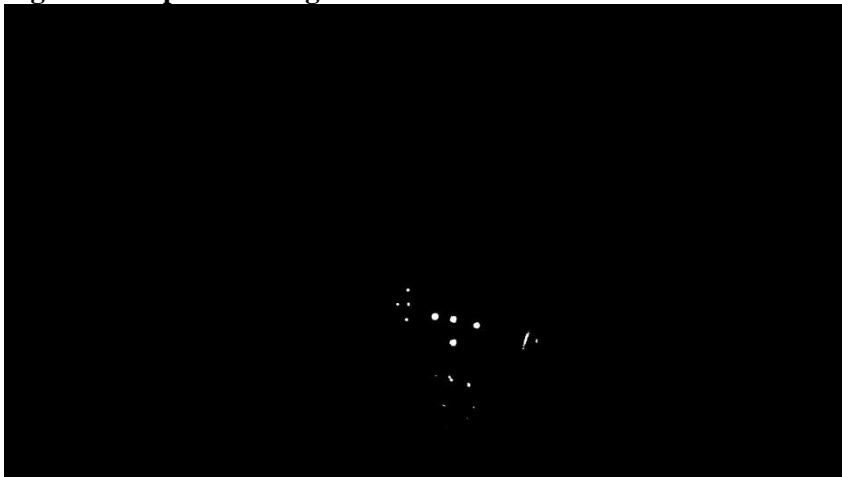
## IV. Results and Analysis

### A. Test Results

The test showed that the LED setup is able to filter out the reflections and provide a quick, precise solution under conditions which cause the retro-reflector setup to give meaningless results. The images in Figures 5 and 6 show significant problems for the retro-reflector setup. In the first image, there are many bright reflective surfaces besides the false target, and these bright spots are seen in the image after the image has been filtered using a brightness threshold. At a minimum, the retro-reflector algorithm was searching through 12 different blobs to determine the correct set of target coordinates, with no way of knowing the correct target.



**Figure 5: Captured Image from the retro-reflector test**

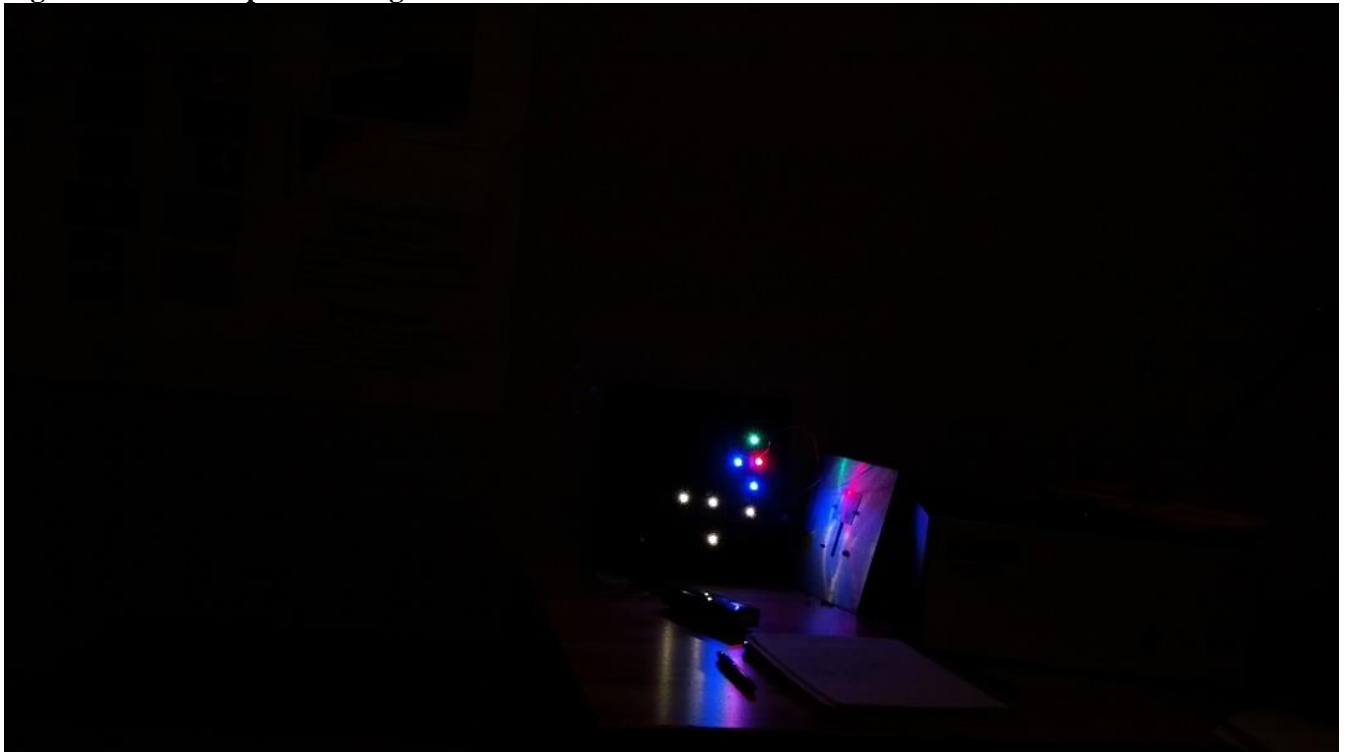


**Figure 6: Potential Targets for the retro-reflector**

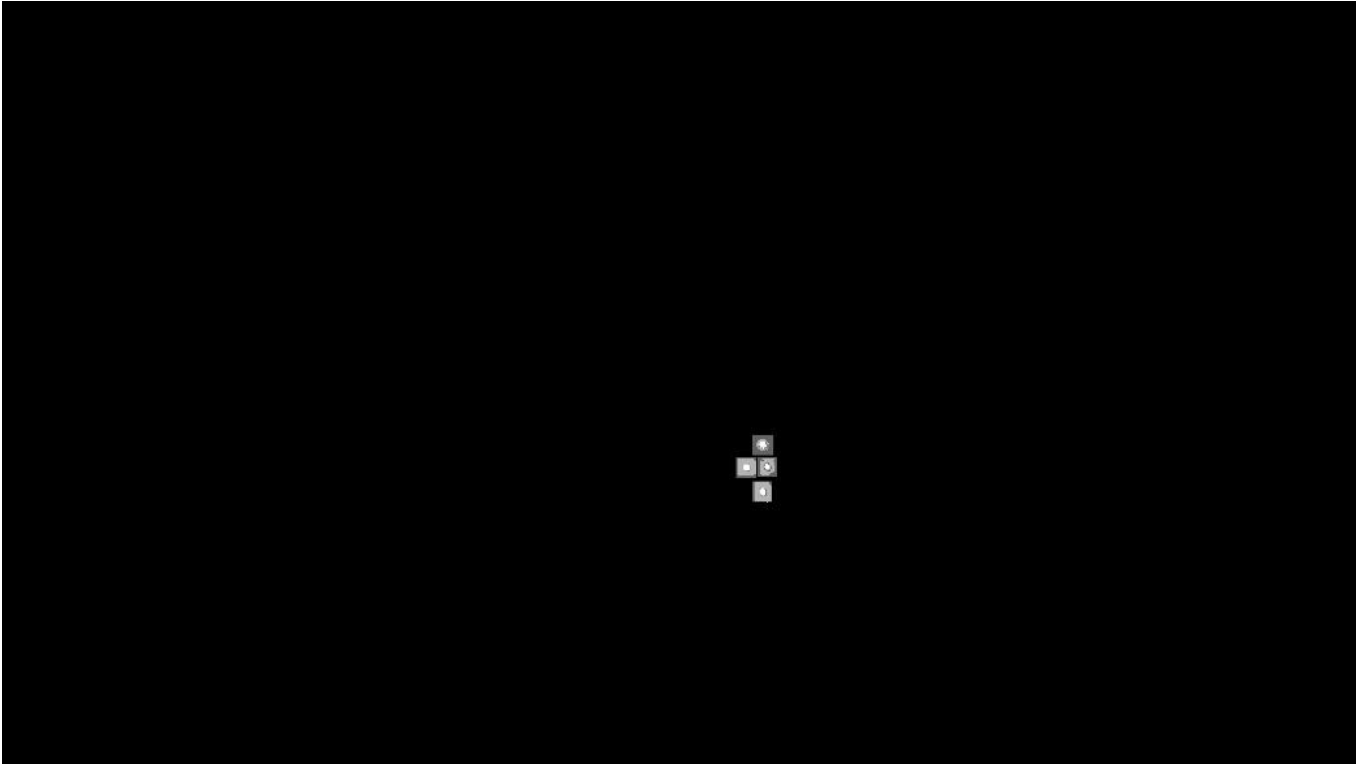
In contrast, the LED target determination method can be seen to select the correct set of targets through the process seen in Figures 7 through 9. From Figure 7 to 8, the results of the initialization can be seen to eliminate much of the background noise and provide a much more distinct target set, preventing the bleeding of colors which confuses the color determination algorithm. In Figure 9, the SVGS can be seen to have only searched in the region of the previously detected targets. The darker gray box shows the region of the last known target which has been searched in this image. The lighter region shows the pixels which helped determine the color of the neighboring blob, and the white regions show the blobs themselves. The combination of these regions shows that the SVGS has correctly identified the target, even with the identical target next to it. However, it can also be seen that the green point on the target was barely identified as green because the green LED does not emit as much light to the side. This could potentially cause a failure to determine target detection at longer ranges.



**Figure 7: Initial Captured Image for the LED Test**

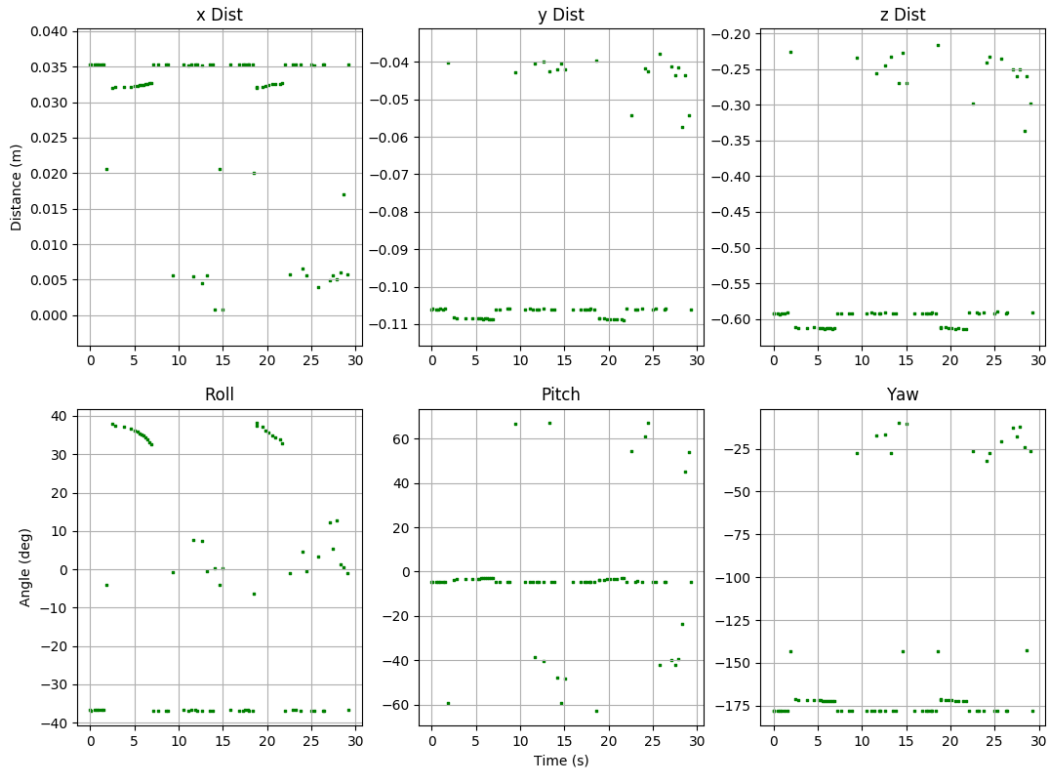


**Figure 8: Exposed Image for the LED Test**



**Figure 9: Target Identification and Detection for the LED Test**

By examining the pictures taken by the SVGS, it cannot be determined what the calculated state is, however, so the validity of the modified SVGS targeting system can only be proven by examining the 6 DOF state output taken over the testing period. Fig. 10 shows this output for the retro-reflector targeting system. The sensor does not settle on any state. Instead, it rapidly oscillates between different states. Furthermore, it can be seen that none of these states are accurate, for the target was set 2 meters away, yet the magnitude of the z distance doesn't go above 0.6 meters. Thus, it is likely mixing the blobs from the different targets in its evaluated sets, giving vastly incorrect results.



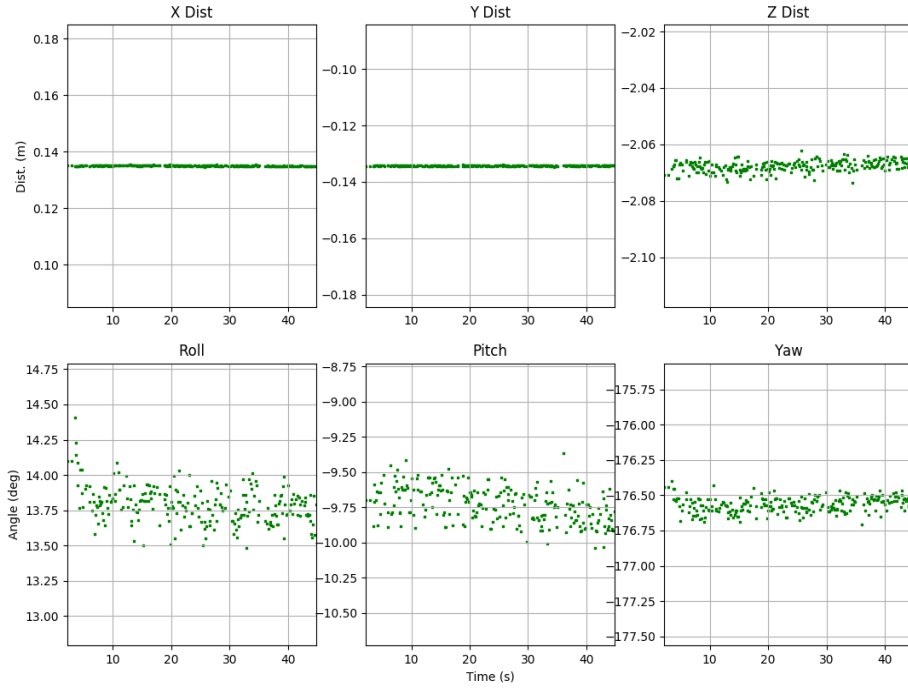
**Figure 10: Output 6 DOF state for SVGS using retro-reflector targets, in the camera reference frame**

In contrast, the output state of the LED targeting system shows a very steady output result in Fig. 11. There is no hint of other targets or extraneous reflections. Instead, the scatter-plots show very high precision results across all the different states. The accuracy of these results, however, could not be fully determined, for the measurements taken of the test setup were very rough and were only used to confirm that the target selected was the correct one. As can be seen in Table 1, the standard deviations of the different measurements at these ranges are extremely small, with all the distances having at least millimeter level precision. The angles likewise, were very high precision, with a precision of a tenth of a degree. Figure 12 further illustrates the sensor characteristics. The average refresh rate of this method was 5.8 Hz, compared to the retro-reflector’s 2.6 Hz, which is a clear improvement. Using color takes more time than using just brightness, so this increase in speed is due to using the focused target detection method.

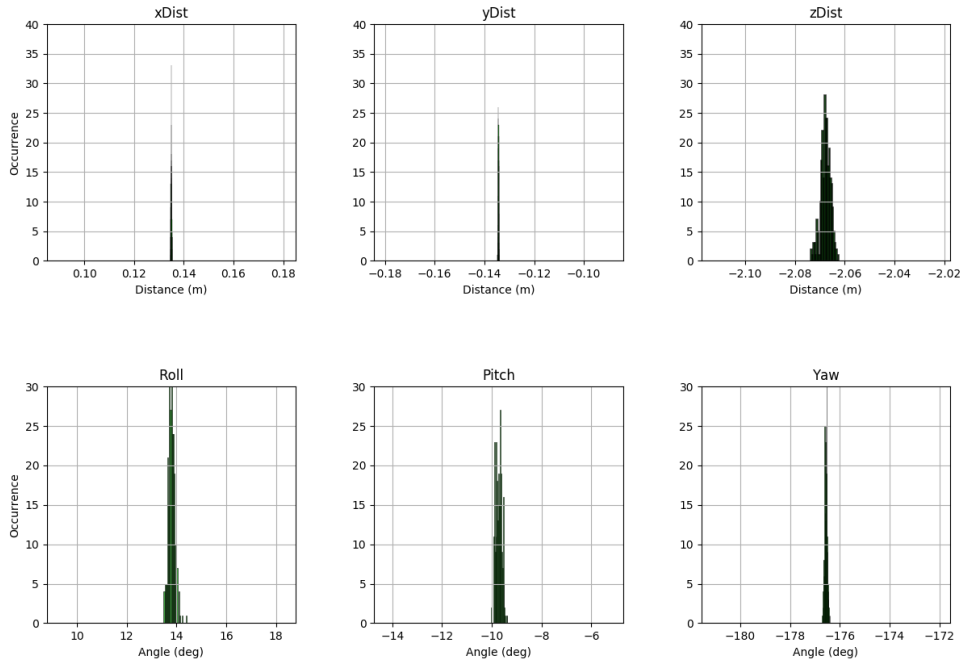
**Table 1: LED 6 DOF State Output Measured and Calculated Statistics**

	LED Mean	LED Std.	Measured
X-distance(m)	0.13	1.3E-4	0.1
Y-distance(m)	-0.13	1.2E-4	-0.1
Z-distance(m)	-2.07	1.9E-3	-2
Roll (deg.)	13.8	0.13	~ 15
Pitch (deg.)	-9.73	0.13	~ -5
Yaw (deg.)	-176.6	0.05	~ -180





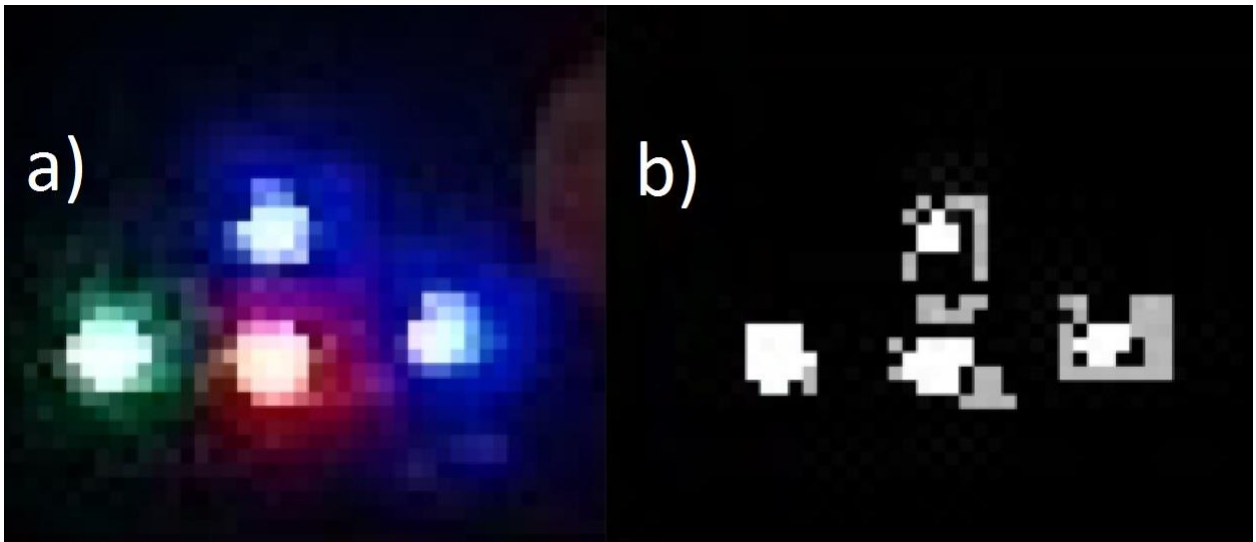
**Figure 11: Output 6 DOF state for the SVGS using LED targeting in the Camera Reference Frame**



**Figure 12: Histogram of the LED 6 DOF output state**

## B. Additional Results and Observations

In addition to the test examining the selectivity of the target detection system, other tests were run to further characterize the modified SVGS targeting system. Most of the problems found occurred at ranges greater than 6 meters. In Figure 13, taken at 12 meters, one of the problems noticed was that the different colors started to bleed together as the separation between the camera and the target increased. This resulted in unexpected hues and low saturation of pixels, making successful color determination more difficult. Another problem found was that in dark rooms or at long distances, the target LEDs started to bleed into each other, creating a single large blob where there should be four. This can be seen in Figure 14, which was taken in a dark room at 6 meters. The LEDs are clearly washed out and the individual LEDs cannot be distinguished. The combination of these two serves as the primary restrictions on the range of the LEDs. The maximum distance at which a consistent solution could be found was examined and determined to be dependent on the lighting conditions, with a max. range of 12 meters under ideal conditions and a max range of 2 meters under worst case conditions. Surprisingly the worst case condition of the modified SVGS targeting system is in a dark room. In that situation, the camera automatically overexposes the LEDs, for the image around the LED is extremely low brightness and the Android automatically tries to push the average brightness count of the image towards a fixed value. If the targets are spread in the 3U configuration rather than the 1U configuration, the range is significantly increased and the camera does not over-expose the image of the LEDs. However, under bright lighting conditions, the range is still significantly decreased from what is expected.



**Figure 13: a) 12 meter Image Capture and b) Resulting Blobs and Color Selection:** *This image shows the image captured at 12 m and on the right, shows the pixels used to determine the blobs in white, and those used for the color in grey*



**Figure 14: LED image at 6m in a Dark Room**

## V. Conclusion

The modifications made to the SVGS allow it to perform over a wider range of applications than the retro-reflector because in many situations the SVGS can be seen to provide a faster, more robust solution when using LED targets and its image searching algorithm. However, using LEDs adds complexity to the system, and at the current stage in its development, there are clear situations when using the LED system will fail to provide a solution where using the retro-reflector will succeed, specifically when there is very low background light and the target is far away from the camera, a condition which will likely be present in a spaceflight mission. The easiest way to fix this would be to use dimmer LEDs or have both short range and long range targets, as AVGS did. Another way could be to change the architecture of the SVGS, either upgrading the smartphone to a newer model, or moving away from a smartphone camera and instead using a more programmable camera along with a different computing platform. This would also likely provide an upgrade to the system, which, used in conjunction with new optimized computer vision libraries, could enable the SVGS to operate much more quickly and in a configuration which is conducive to being used aboard a cube-satellite, where out-gassing and other factors need to be controlled, a very difficult task to achieve using a smartphone. The bulk of further efforts, however, should be focused on improving SVGS's capabilities under different lighting conditions.

## Acknowledgments

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## References

- <sup>1</sup>Becker, C., "Smartphone Video Guidance Sensor for Small Satellites," AIAA Small Sat Conference SSC13-1-7, Logan, UT, 2013
- <sup>2</sup>Rakoczy, J., "Application of the Photogrammetric Collinearity Equations to the Orbital Express Advanced Video Guidance Sensor Six Degree-of-Freedom Solution," Memo, Marshall Space Flight Center, AL, March-April 2003.