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Space Vision Marker System (SVMS)

Michel Bondy[1], Rubakumar Krishnasamy[2], Derry Crymble[3], Piotr Jasiobedzki[4]
MDA Space Missions
9445 Airport Rd., Brampton, ON, L6S 4J3, Canada

Visual targets are used in space proximity operations to help in alignment of mechanical interfaces during, for example, spacecraft rendezvous and docking, and in robotic servicing of space structures. Distinctive and precisely placed target features facilitate unambiguous and reliable detection, and accurate estimation of relative position and orientation (pose) by the human operators or automatic vision systems. Existing targets used by vision systems typically do not allow for identification or for multiple targets to be visible in the field of view. The targets are detected in the first image and are tracked in successive frames, which introduce a potential failure condition. This paper describes a novel concept of a Space Vision Marker System (SVMS). Inspired by past designs of space targets and terrestrial marker systems, SVMS combines positive features of both and extends them to space applications. SVMS includes: the design of a family of markers, preferred imaging arrangement (camera, light, marker material), and software algorithms to detect the markers. The markers are reliably detected under a wide range of viewing distances and angles, and illumination (including direct sun light and shadows); encoded redundant features allow identification even with a partial data loss. Three dimensional structures of the markers allow accurate pose estimation. The detection algorithms operate on each image separately and in real time, which does not require tracking between frames and allows instant recovery from failures due to, e.g., marker occlusions. Results of laboratory tests performed under conditions representative to proximity operations in lower earth orbit are also presented.

I. Introduction

Visual targets are used in space proximity operations to help in alignment of mechanical interfaces during spacecraft rendezvous and docking, satellite capture and berthing, and in robotic servicing of space structures including replacement of Orbital Replaceable Units (ORU) and servicing. Distinctive and precisely placed target features facilitate unambiguous and reliable detection, and accurate estimation of relative position and orientation (pose). The targets are designed for use by astronauts (direct observations or using camera images) or for automatic detection by vision systems.

Space targets designed for humans include multiple features in a three dimensional arrangement and redundant markings that help in precise alignment. Targets designed for vision systems are of a minimalist nature that simplifies processing but can potentially cause misdetection or failures if some of their features are not visible or cannot be detected. Automatic vision systems often operate by tracking to achieve high frame rates. However, this introduces a failure mode if the target is lost momentarily as the target must be re-acquired or the mission aborted. Space targets are non-unique, i.e., they provide information about the exact location but not the target identity.

Marker systems have been developed for identification of labeled objects for terrestrial applications. Such markers can be detected reliably only if a camera is placed close to the nominal position and are therefore not well suited for estimating relative position and orientation. Augmented Reality marker systems contain features for encoding identification and allow detection at a wider range of distances and orientations than standard marker systems. However, these targets are planar, which limits ability to estimate their orientation accurately and therefore restricts their use in space operations.

[1] Member of the Technical Staff, michel.bondy@mdacorporation.com
[2] Software Engineer, rubakumar.krishnasamy@mdacorporation.com,
[3] Systems Engineer, derry.crymble@mdacorporation.com
[4] Staff Scientist, piotr.jasiobedzki@mdacorporation.com

II. Visual Targets and Marker Systems

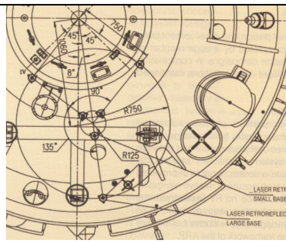
Visual targets are used to simplify detection and increase accuracy and robustness of their detection (and therefore of objects equipped with these targets). Different designs of targets exist but in one class of applications the targets are typically the same and are not distinguishable. Visual markers are used to identify tagged objects; typically cameras must be placed at predefined locations to read the markers correctly and the marker designs do not allow estimating pose accurately. This section provides an overview of existing visual targets and markers.

A. Visual Targets Used in Space Operations

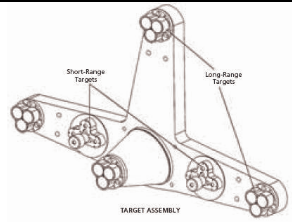
Both the human and autonomous operations in space have relied on detection of visual targets in form of retro-reflectors or special patterns. Such targets help in alignment of docking or capture interfaces by providing unambiguous cues and increasing accuracy through their design (e.g., 3D shapes and high contrast). Examples of such targets are listed in Table 1 and their images are shown in Figure 1.

Table 1 Visual Targets Designed for Use in Space

	Mission or Target name	Main use	Appearance	Human or Machine Use	Typical range [m]	Comments
A	ISS target for ATV docking	Spacecraft docking	Two sets of 3 retro-reflectors	RVS (Lidar)	< 100s	Planned mission
B	Video Guidance System	Spacecraft rendezvous & docking	2 sets of 4 retro-reflectors	Vision system with a camera and laser illuminators	< 100	Shuttle and DART
C	ETS-VII rendezvous	Spacecraft rendezvous	One retro-reflector	RVD Lidar	2 < & < 100	Used in a demo mission in 1997
D	Apollo docking	Spacecraft docking	3D dial	Direct viewing	< 10s	Used in Apollo missions in 60s
E	ISS target for Shuttle docking	Spacecraft docking	3D dial	Human viewing camera images	< 10s	Used on ISS
F	ISS target for Progress docking	Spacecraft docking	3D dial	Human viewing camera images	< 10s	Used on ISS
G	SVS/OSVS circular targets	ISS assembly	4-5 high contrast circles	Vision system with a camera	3 < & < 10	Used in early ISS assembly
H	Berthing Cues System Target	ISS assembly	Line pattern	Human viewing camera images	< 1	Used in ISS assembly
I	Grapple Fixture target	Shuttle payload / free-flyer capture	T-shape with a post	Human viewing camera images	< 2	Used by Canadarm 1 & 2
J	OE capture target	Free-flyer capture, ORU replacement	2 arrays of 4 circular targets	Vision system using a camera + light	< 2	Orbital Express Demonstration Mission in 2007
K	Micro-grapple fixture target	ORU replacement	3D cross with 4 circles	Human viewing camera images	< 1	Used on ISS
L	MTC target used by SPDM	ORU replacement	Truncated cone with markings	Human viewing camera images	< 1	Used on ISS
N	ETS-VII docking	Spacecraft docking, free-flyer capture	3 high contrast circles	Vision system with a camera + light	< 2	Used in a demo mission in 1997
O	ETS-VII Targets	ORU replacement	high contrast circles & posts	Vision system with a camera	< 1	Used in a demo mission in 1997

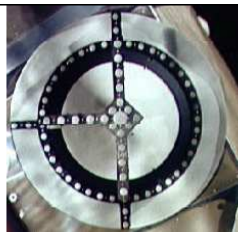


A. ATV retro-reflectors on ISS



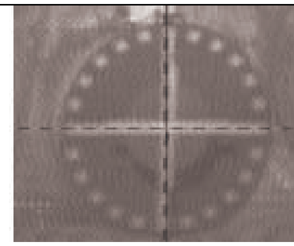
B. VGS retro-reflectors

C. ETS-VII rendezvous target

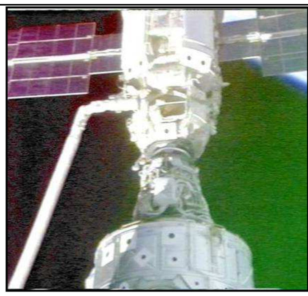


D. Apollo docking target

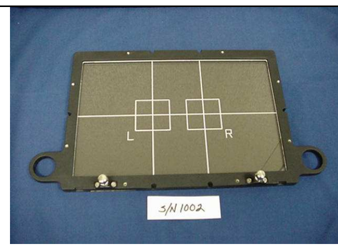
E. Shuttle docking target



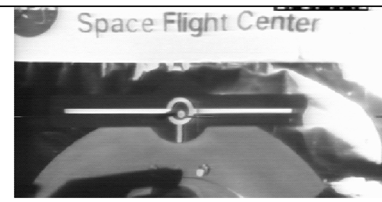
F. Progress docking target



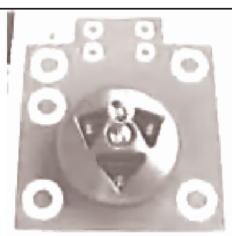
G. SVS targets



H. Berthing Cues System Target



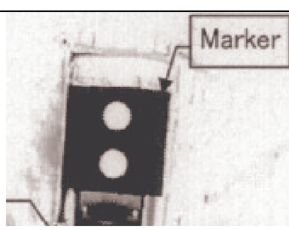
I. Grapple Fixture Target



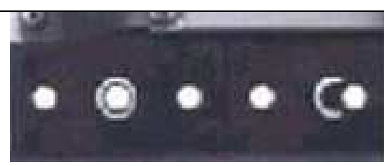
J. Orbital Express Grapple Fixture & Target

K. Micro-grapple fixture target

L. MTC target



N. ETS-VII capture target



O. ETS-VII ORU targets

Figure 1 Visual Targets Used in Space

Targets designed for humans rely on a concept of a dial with an alignment rod (Apollo, Shuttle, Progress, Shuttle Remote Manipulator System (SRMS) grapple fixture target). Targets used by vision systems include patterns that can be reliably and accurately detected, and draw inspiration from terrestrial photogrammetry. Examples include black and white circles placed on International Space Station (ISS) for use by Space Vision System (SVS), high contrast rings used in Orbital Express mission, and retro-reflective dots used on ETS-VII for close range docking and robotic operations. Some targets, such as the Special Purpose Dexterous Manipulator (SPDM) micro-grapple fixture target have been designed both with humans and machine vision systems in mind. In general, targets used by human operators are difficult to detect by vision systems automatically and the targets that are easy to detect by such systems offer high accuracy but are not suitable for human interpretation.

The targets designed for human interpretation contain highly redundant information, which combined with human perception and skill provide reliable and accurate detection. However, the targets designed for vision systems have been rather minimalistic and have contained either the minimum number of elements necessary for the task or a small number of redundant features for validation. These minimalist targets have been motivated primarily by the cost of target installation and combination of relatively low performance of space-qualified computers and the computational cost of detecting targets under space illumination. Typically, only one target design is used in a specific application, thus precluding the option of having multiple targets in one image (unless additional disambiguation techniques are used).

B. Visual marker systems for identification

Visual marker systems have been developed for identification of tagged objects; they include popular 1 dimensional barcode, which is gradually being superseded by two dimensional systems that allow encoding more information for the same surface area: 2D barcode, DataMatrix, QR and Maxicode. These markers are useful for identification but not for pose estimation as they can be read from only a limited range of viewing angles and distances and do not contain enough positional landmarks for accurate pose estimation.

Figure 2 Example marker systems used for identification

C. Visual Marker Systems for Augmented Reality Applications

Augmented Reality applications require an ability to detect and identify specific makers and estimate their locations in 3D space. Numerous systems have been developed and tested in laboratory environments. Such system use planar markers that encode unique identifiers and are augmented with visual features for detection from a wide range of distances and viewing angles. Geometrical features (lines, corners, circles, polygons) are detected in images and allow estimation of the marker pose. Reviews of various marker systems including experimental comparisons have been published in several technical papers [1], [2], [3], [4]. Figure 3 shows examples of such maker systems.

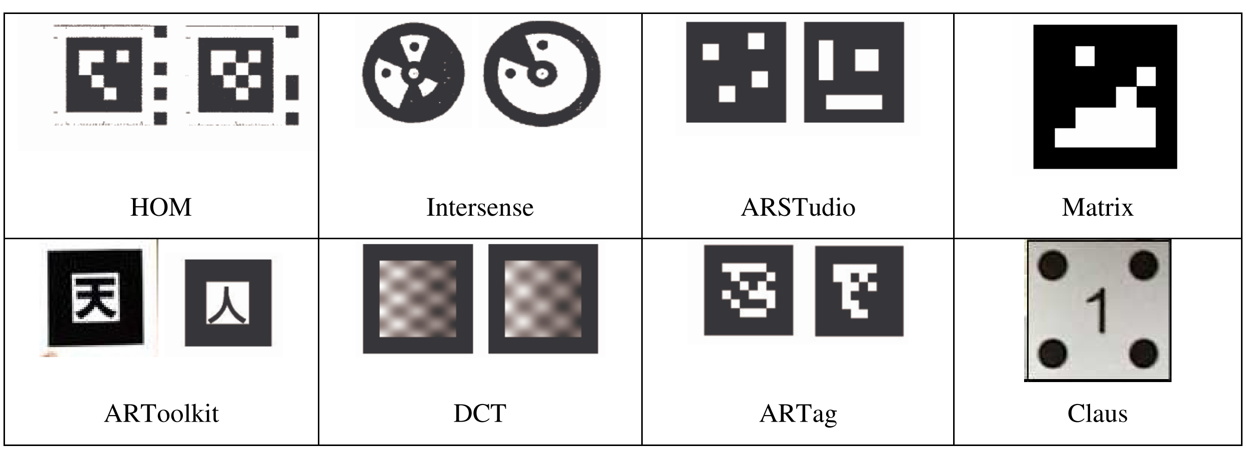


Figure 3 Various Augmented Reality marker systems

The Intersense markers[5] are used for motion tracking and because of their circular pattern these markers can only provide location of a single point without orientation information. Multiple Intersense targets (at least 3) must be visible within the scene for full 6DOF pose estimation.

HOM[4], Matrix[6], ARStudio[7], ARToolkit [8], and ARTag[1,2] are used for both identification and pose estimation. Because of their square shape the homography created by the four corners of the projected quadrilateral can be used for pose estimation from a single target.

Matrix relies on the quadrilateral outline of the marker for detection, and encodes both digital information and checksums. ARStudio uses the homography created by the four corners of the black outline of the marker to unwrap the internal image within the marker. This image is then compared with a library of images (through image subtraction techniques) to determine which marker has been located. ARToolkit works by correlating the pattern located at the centre of the marker with a library of known markers (the library contains each marker stored in all four possible orientations).The marker with the highest correlation is the most probable marker in the image. However, this process is vulnerable to variations in lighting conditions and is computationally expensive – especially if the library of known markers is large. Because of the correlation based identification method used by ARToolkit, this system must make a trade-off between false negative and false positive marker recognition. Owen[3] used DCT transform to design a set of markers that minimizes the similarity (defined as correlation) between different markers to increase the reliability of correct detection.

The ARTag system encodes the identity, and orientation or the marker as a binary code represented by black and white regions within the marker. Once the four corners of the marker are identified in the image, the projection of the internal grid of ones and zeros can be determined and the binary code can be read. This method does not require any stored templates for correlation as the binary code read from the marker is enough to mathematically determine the identity of the marker. This approach is less computationally expensive than the correlation based ARToolkit. The ARTag system is also very robust as it uses forward error correction as well as checksums to avoid false positive and false negative matches.

Claus [9] uses a marker that includes four circles for easy detection. Marker identification is performed using a code (number) placed at the centre. The system is trained on example images and uses a cascade of classifiers to detect most likely location of the marker in the image, and to reject early incorrect matches.

D. Summary

3D structure of a visual target allows estimating the target pose more accurately than using planar targets, hence the space targets for precise operations include either posts or recessed features. Many space targets designs exist but they are not supported by different vision systems and only one design is used for a specific application. This does not allow for multiple targets in the camera field of view or for using the targets for identification. Targets specifically designed for human use are often difficult to process by vision systems. Existing targets designed for automatic detection contain a minimum number of features, which makes them prone to potential failures. Visual targets for space are often detected in the first image and tracked in the subsequent images, which introduces a failure mode. Marker systems designed for product identification or augmented reality typically have redundant feature and allow encoding. However, they do not have visual features suitable for detection under wide range of viewing conditions and/or do not allow for estimating their pose with high accuracy required for space operations.

There is a need for a new approach to designing visual targets and markers for space operations. This approach will incorporate both redundant designs and suitable computer vision algorithms that will allow reliable detection even with significant data loss in the image. Encoding marker identity will allow using the same structure for both object identification and pose determination. 3D target structure is preferred as it will enable more accurate pose estimation. The markers should be detected in every image without any reliance on processing previous images (no tracking). The following sections describe design of such a marker system, several prototypes, and results of laboratory testing under representative conditions.

III. Space Vision Marker System

The Space Vision Marker System (SVMS) described in this paper addresses the above described need for a marker system for reliable detection, accurate pose determination and identification. SVMS consists of a set of scalable markers and a vision system for detecting and recognizing them. Unique features of this system that make it particularly suitable for use in space proximity operations include

- Design of the markers enabling their reliable detection from a wide range of distances and viewing angles
- Encoding information in the markers allowing unique identification of objects and their position and orientation

- Redundant design and encoding allowing correct operation even when partial data is lost due to shadows and occlusion
- Three dimensional structure of the markers that allows computing pose accurately
- Markers are detected in every frame without inter-frame tracking, which enables instant recovery from occlusion or image loss
- Optional selection of target material and imaging arrangement that enables detection and under a very wide range of illuminations
- Ability to use multiple markers in the same workspace for different objects or to increase the pose estimation accuracy

A. Summary

The basic SVMS marker consists of a planar base with a central black square surrounded by a white stripe. Attached to this stripe are data bits, which encode the marker identity. A black post with a white top is mounted in the centre of the black square – location of the post tip in images allows accurate estimation of the marker orientation. Figure 4 shows three markers of different sizes (note different encoding); the image on the left shows markers on a flat surface and the image on the right shows markers detected in the scene. Overlays of different colours indicate identified markers.

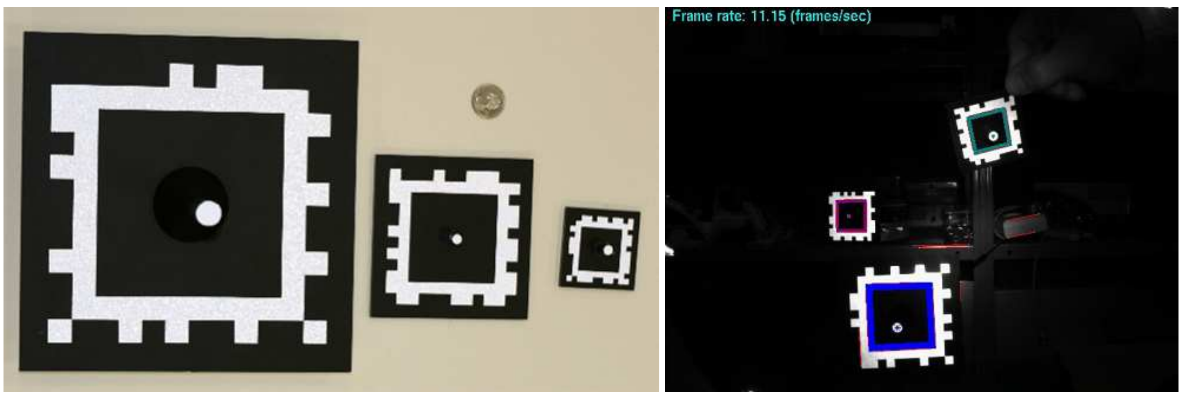


Figure 4 SVMS markers on a planar surface (left) and detected in a scene (right)

The SVMS marker is detected by performing a sequence of operations. First, edge points are detected and connected edges are linked into chains, which are then segmented into straight line segments. The straight lines are fitted into the segments and grouped into quadrilaterals using proximity of their end points and segment lengths. The algorithm calculates intersection points of these four lines and these points are used to determine the homography matrix of the projected planar target. Once the homography matrix is determined, the algorithm samples the intensity values and obtains the intensity values of the data bits. The data bits are decoded to identify the target (or to reject the quadrilateral if it is not a marker). Initial pose is computed using four corners of the square and it is refined using location of the tip post. The pose estimation uses information on the camera calibration and size of the marker.

The current design of the SVMS markers includes 44 data bits, which are used for both encoding of the marker identity and for redundancy. The actual split depends on the required redundancy level and number of unique encodings. The BCH (Bose, Ray-Chaudhuri, Hocquenghem) encoding[10] is used for error correction with 17 bits used for storing information. This allows encoding of 2^15=32768 unique markers (after removing symmetrically ambiguous cases) while being able to recover from 5 data bit flips potentially caused by occlusion, noise or unfavorable illumination. If necessary, it is possible to increase the number of data bits (by for example surrounding the current marker with additional data bits.

B. Multiple Markers

SVMS recognizes individual markers, which allows detecting and recognizing multiple markers simultaneously, see Figure 4 (right). The color overlays (red, green and blue) indicate correctly identified target: the squares indicate locations of the black squares and stars locations of the tips of the posts.

The markers may be attached to different objects, which pose is then computed independently. If the markers are attached to the same object and their relative locations are known, the overall object pose can be computed by combining measurements obtained for individual markers to increase accuracy.

Markers of different sizes may also be combined into one marker (a marker within a marker) that can be detected reliably and accurately over a longer range of distances. A dual SVMS marker is shown in Figure 5.

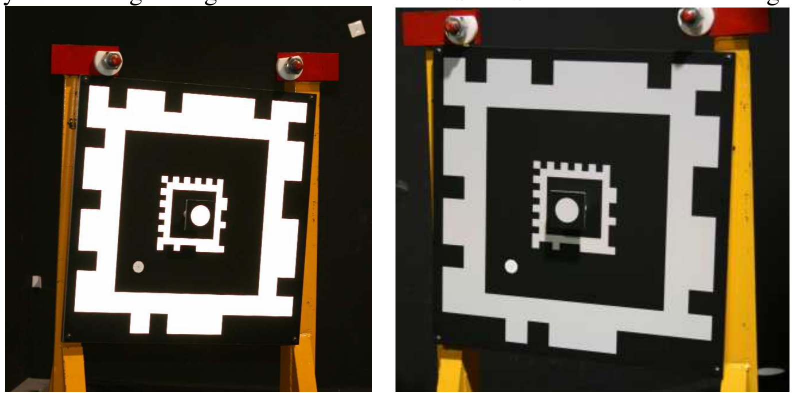


Figure 5 Dual SVMS marker

A concave version of the marker can be used in situations where protruding posts are not desirable, Figure 6.

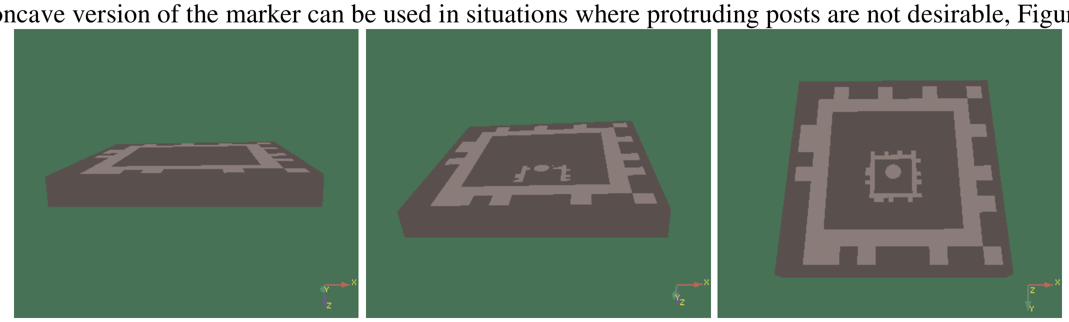


Figure 6 A concave version of the SVMS marker

C. Marker Materials and Imaging System

The SVMS markers can be manufactured using surface finishes that provide high contrast and diffuse reflective properties. Such markers can be used under any illumination that produces images adequate for processing.

Alternatively, the white parts of the marker can be manufactured using retro-reflective materials that reflect light towards the light source for a wide range of surface orientations. In this case the imaging system consists of a monochromatic light source (for example an LED light) located close to the camera, and the camera lens is equipped with a band pass filter that transmits the source light and attenuates any other illumination, see as illustrated in Figure 7.

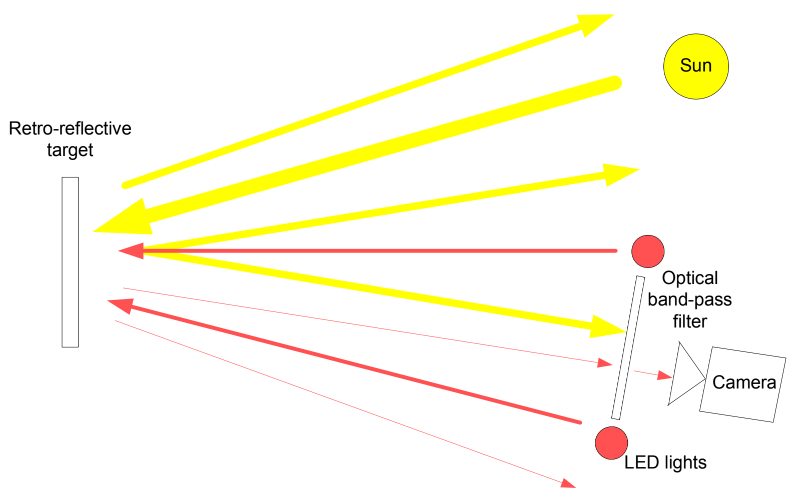


Figure 7 Imaging arrangement with a retro-reflective material and monochromatic light source

IV. Marker Detection and Pose Determination

Reliable detection and identification of markers requires that the markers are fully visible in the camera field of view, occupy at least 30x30 pixels in images and are within the specified range of orientations. The actual maximum distance is a function of the marker size, camera field of view and image resolution. The minimum distance corresponds to the case when the marker fills up the camera field of view. The allowed range of marker orientations depends on the height of the post.

The pose estimation accuracy depends on the marker size, post height, camera resolution and field of view, and the distance. Using the dual target allows using the larger marker for longer range of distances as at close ranges, when the large marker goes out of the field of view, the algorithm detects the smaller marker. Example images of the dual SVMS marker captured at different distances are shown in Figure 8.

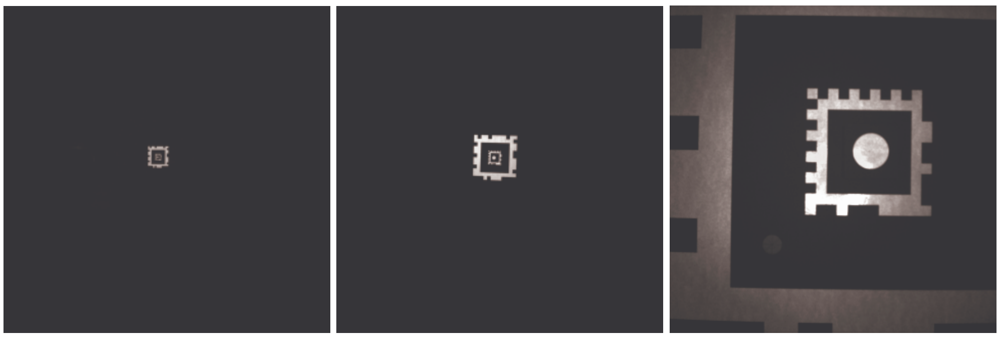


Figure 8 Images of the dual SVMS marker at distances of 16m, 7m and 0.8m

An example graph showing the range error distribution as a function of the distance,, for the dual SVMA marker, is shown in Figure 9. The range error is less than 1mm at close range of 0.8 m and 42 mm at the maximum range of 16 m. Errors in estimating the marker orientation are 0.16 deg and 1.7 deg respectively. These results have been obtained for a marker with the marker size of 0.432 x 0.432 m, and a camera with image resolution of 1024 x 1024 pixels and field of view of 25 degrees.

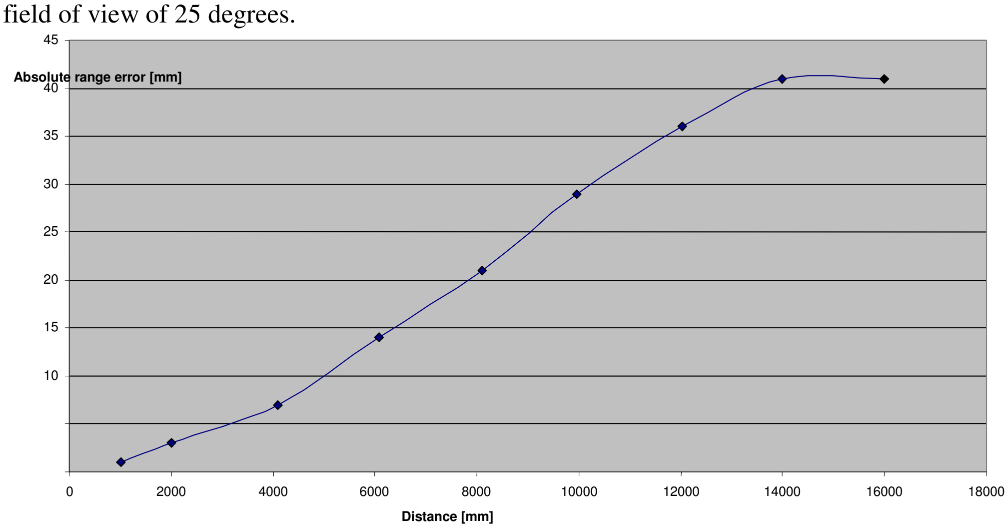


Figure 9 Range Measurement Error as a Function of the Distance for a Specific Marker and Camera

The SVMS detection algorithm operates on each image separately without relying on results of processing previous images – no inter frame tracking is performed. This requires additional computation but ensures that SVMS recovers instantly (for the next image) from data loss due to, for example, occlusion. SVMS does not require any initialization and uses the marker models (encoded identity and dimensions) and camera calibration data stored in a file system. The processing time depends on the image resolution, complexity of the scene and computing platform. For example, the pure software version operates at 15 frames (VGA resolution of 640 x 480 pixels) per second on a desktop computer, and a hardware accelerated version operates for 1024 x 1024 images at 10 frames per second.

V. SVMS Applications

SVMS targets and vision system have been installed at MDA's Space Vision Testbed as part of a hardware-in-the-loop docking simulator. This testbed includes two large industrial robots that manipulate mockups of space structures equipped with mechanical interfaces and sensors. The robots are driven by software simulations of spacecraft and/or robot motion; a solar simulator provides representative illumination. Figure 10 shows the SVMS markers installed on a ½ scale mockup of a space module with a passive docking interface, and the SVMS camera with a ring light mounted on an active docking interface.

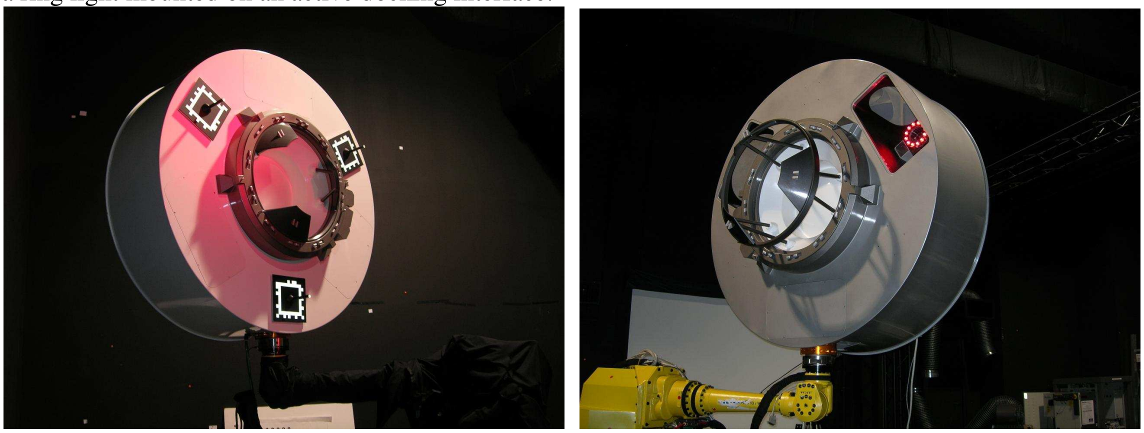


Figure 10 SVMS Markers Installed on a Mockup of Space Module (left) and SVMS Camera and Lights Installed on a Mockup of Spacecraft (right)

In this application SVMS provides relative pose of an approaching spacecraft during simulated docking by processing images of the marker. The hardware simulator operates in an automatic closed control loop with the vision system sending pose data to a Guidance, Navigation and Control system controlling a simulated spacecraft.

Other space applications of SVMS include identification and pose estimation for robotic tools, instruments, containers and replaceable units for orbital servicing and planetary exploration, and vision guided convoy driving, see Figure 11.

Figure 11 Example Space Application of SVMS: Robotic Tool Grapple Fixture and Marker (left), Visual Target for Robotic Convoy Driving (right)

VI. Conclusions

This paper describes a novel concept of a Space Vision Marker System (SVMS) that includes design of a family of markers, imaging arrangement to detect markers under wide range of illuminations (direct sun light and shadows), and software algorithms to detect the markers. The markers are reliably detected under a wide range of viewing distances and angles, and illumination; encoded redundant features allow identification even with a partial data loss. The three dimensional structure of the markers allows accurate pose estimation. The detection algorithms operate on each image separately and in real time, which does not require tracking between frames and allows instant recovery from failures due to, e.g., marker occlusions.

The optical properties of the marker material, camera, camera light and camera filter, and optimized algorithms constitute a complete vision system solution for space applications. Prototype SVMS has been successfully tested and characterized under lighting conditions representative to proximity operations in lower earth orbit using a solar simulator.

Acknowledgments

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