# VISION-BASED LOCALIZATION OF MODULAR SATELLITE INTERFACES FOR ROBOTIC ON-ORBIT MANIPULATION

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## ABSTRACT

On-orbit servicing can be a powerful enhancement to modular satellites, if combined with vision-based localization. Deriving accurate 6D poses from the manipulation objects of interest, however, is hard in space, due to challenging illumination conditions. In this paper, we present two different approaches that use common and well established localization methods and deploy them for a satellite servicer. Both approaches show promising results during robotic manipulation experiments in a lab environment.

## 1 INTRODUCTION

In recent years, the concept of building modular satellites has gained much momentum. Modular in this scenario refers to operational modular, i.e. single modules will be exchanged and satellites will even be assembled on-orbit out of those modules. In comparison to conventional, monolithic satellites this advantage can lead to an extension of system lifetime and to a reduction of overall mission costs.

Manipulating those modules poses a challenge to current systems and will play a central role when robotic on-orbit servicers operate with a high degree of autonomy. 2D localization of the objects of interest, as is often sufficient in visual servoing approaches, has limitations in combination with manipulation tasks, which require non-straight trajectories and collision-free path planning.

Therefore, the need arises for full 6D object localization with high precision, as in the range of a few millimeters in transitional and few degrees of rotational displacement. While object localization is well investigated on earth, it is not directly portable for space applications. There are few solutions for objects to be manipulated from various distances, angles of views and under varying visibility in space.

Within the research project iBOSS (intelligent Building Blocks for On-Orbit Servicing and Assembly), granted by the German aerospace agency (DLR), we develop a system for robotic on-orbit manipulation of modular satellites. In this paper, we tackle the problems of 6D object localization in space with two approaches: One approach, that uses conventional and well

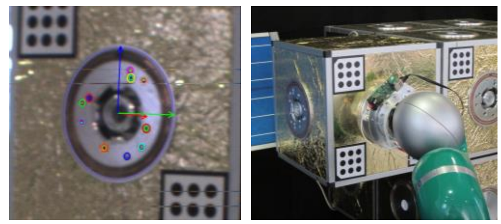

*Fig. 1: Vision-based localization of modular satellite interfaces. Left: 6D pose estimation of the iBOSS interface. Right: Successful grasping process in a lab environment.*

established methods, based on simple marker detection and a more advanced approach exploiting characteristic features and involving a chain of image processing algorithms. We discuss advantages and disadvantages of both approaches and evaluate their feasibility in a lab environment.

## 2 RELATED WORK

Although visual object recognition on earth [1] is not a new field, it is difficult to apply to space applications. Future concepts of modular satellites and robots [10] will, however, depend on precise localization capabilities in space. Currently, few solutions exist in this field. This can be attributed to a combination of limitations in sensors and computing performance, especially in former applications, and to the extreme conditions in space, such as direct exposure to sunlight and strong reflections. For space, markers for object detection and pose estimation can be used, e.g. on flat surfaces [3], or, instead of requiring markers, features on the objects can be exploited for localization [5]. Other approaches leverage sensors for range images and perform 3D model matching [4]. For those, geometric information is important and can lead to good results, however, often those approaches lose precision in close proximity to the objects of interest due to noise in the sensor data.

In terms of visual servoing [6], approaching objects is often solved iteratively by locking and tracking the object in the image [2], and exploiting the fact that final docking or berthing is mechanically supported through sufficient clearance between the mating parts, e.g. with nozzles [5], rather than relying on estimated 6D poses for precise manipulation. This approach, however, is rendered infeasible if the manipulators move in constrained workspaces and require collision-free path planning. Our approaches, presented in this paper, include both possibilities. They can be used for visual servoing and also succeed in one-shot scenarios, i.e. when localizing objects from a single image, and therefore bridge the gap to planning approaches and on-orbit manipulation.

# 3 METHODS

On-orbit manipulation in the iBOSS context uses special designed interfaces for grasping. The satellite modules are cubes, which are equipped with up to six 4-in-1 standardized interfaces for mechanical coupling, electrical power, data and thermal interconnection [7].

For the localization a high resolution monocular camera is used, which is mounted on a mobile platform for lab experiments. The platform is equipped with omnidirectional steering and supports two 7DOF robotic manipulators. In the remainder of this paper two developed approaches for the localization problem are presented:

*The marker based approach:*

Various markers are attached to the cubes, adhering to a pattern to allow both redundancy and fusion of computed 6D poses.

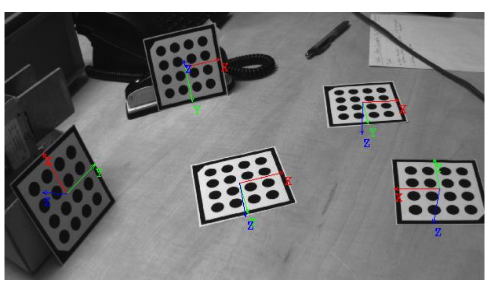

*Fig. 4: Various markers with their respective coordinate systems. Every marker has a unique 6D pose associated with it. The coordinate systems are shown as computed by the localization algorithm*

*The feature based approach:*

Methods from machine learning are leveraged for identifying the main interface on the cubes' faces. Based on edge detection in this area a 2D surface consisting of prominent features of the interface's geometry is matched.

## 3.1 The Marker-Based Approach

For this application, a combination of rectangles and circles is used to compose markers, as depicted in Fig. 4. The known dimensions of the markers allow in combination with calibrated cameras for a good estimation of the markers' positions. Their

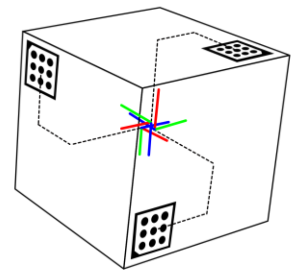

*Fig. 2: Fusion of three cube coordinate systems as indicated by their respective markers.*

orientation is resolved using elliptical distortion of circles within the markers. For deriving the 6D poses, the industrial computer vision software HALCON [9] was used. Leveraging an established

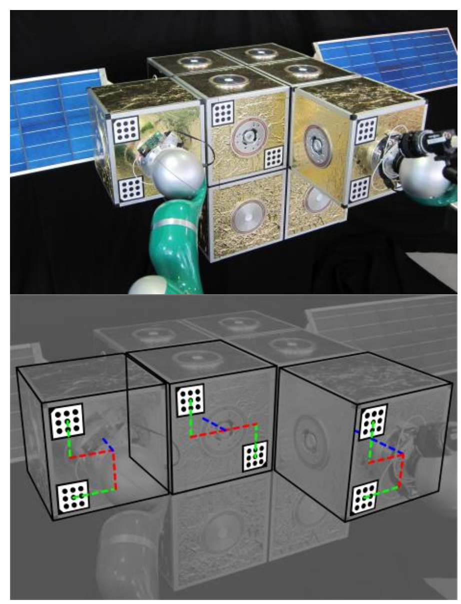

*Fig. 3: Above: Experiment with iBOSS cubes and markers for module localization. The redundancy of the markers assures a safe localization in case of occlusions.*
*Below: Schematic highlighting of individual markers and their offsets. The colored offsets show the constant transformation for each marker to its respective cube center.*

localization algorithm from industry for marker detection was chosen in congruence with the goal to raise the technical readiness level of the iBOSS project. All markers used within this work are identical and don't require any decoded information to make them unique. Although a specific marker type is chosen, the approach described here is applicable to all sorts of markers, as long as they individually hold enough information to compute their 6D poses respectively.

To deal with ambiguity, i.e. to compute the pose of an iBOSS cube from redundant marker information a methodology to perform marker fusion was developed. Fig. 2 shows the various coordinate systems representing the origin of a cube. The convention used in this work demands every marker to direct its coordinate system to the center of the cube the marker is associated with. Those coordinate transformations don't change and are the same for every marker. With this methodology up to four markers could be attached to each cube side, enhancing localization quality in the case of occlusions.

The fusion of the individual pose information is done in two steps: First, all markers are grouped with respect to their according iBOSS cube, and then the pose information of all markers, belonging to the same cube, is merged.

The grouping of markers is achieved with a nearest neighbor search in a kdtree. It exploits the fact that cube centres, as derived from their markers, can never appear closer to each other than the length of one cube side. Not satisfying this constraint would mean a collision and penetration of cubes. A compound of iBOSS cubes therefore always has the cube centres positioned in a 3D grid with aequidistant grid size of approximately one iBOSS cube. A threshold is then chosen to allow for small deviations in the cube centres as imposed by the individual markers for a single cube. Fig. 3 illustrates the static transformation that transforms the coordinate system of each marker to the center point of its according cube.

Next the fusion is done for the translational part and the orientational part individually. The translational part was chosen to be the weighted sum of all individual offsets giving each marker an equal weight for the localization accuracy. In order to compute the mean orientation the coordinate systems are transformed into one reference frame. To preserve the fine offsets of each orientation only transformations with 90° steps about each axis are tolerated, making the comparison of different orientations feasable. A high level reasoner keeps track of the computed 6D cube poses, derives the exact pose of the interfaces to grasp, and continuesly integrates them into an internal representation, which is also used for hierarchical task planning.

### 3.2 The Feature-Based Approach

The feature-based approach does not rely on individual markers, but uses the unchanged satellite modules and their faces in which the iBOSS interface is embedded. It leverages a shape-based model matching in a reduced region of the original image. In order to make the matching fast, various reductions and optimizations are applied.

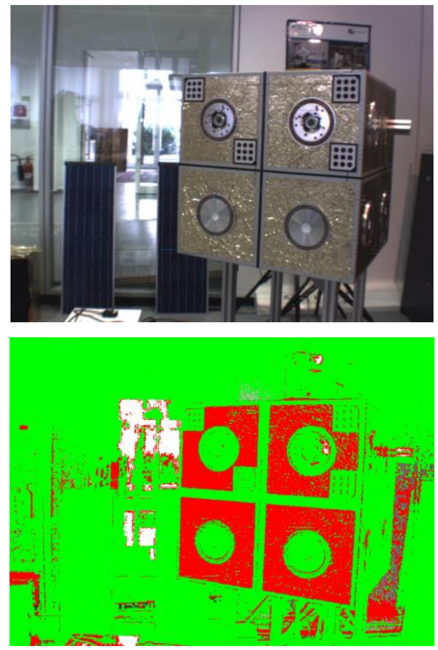

*Fig. 5: Above: Example picture with satellite cubes. Below: Pixel wise classification of the satellite cubes into module face (red) and surrounding (light green).*

First, the search region is reduced as follows: The pixels in the images are classified to belong to two classes, the class 'module side' and the class 'surrounding'. This classification uses the foil that is attached to the outer module sides to reflect radiation, as shown in Fig. 5. Under varying illumination conditions the foil possesses good characteristics to be distinguishable from its surroundings and also from the inner mechanical interface.

For the classification of the module interface a neuronal network is used [8]. It was trained with samples taken by hand. The labeling process included the selection of dozens of regions which provided the pixel-based working neuronal network in total with millions of samples.

The resulting classification identifies the module sides and allows for reducing the image into those areas, as depicted in Fig. 5. The classification is not perfect and considers various artifacts from the surrounding to belong to the module side. However, the quadratic shaped regions, which enclose the iBOSS interfaces, are sufficiently recognized. The interfaces themselves appear as elliptic regions within these squares. Those regions represent the regions in which the 2D model is searched. To further simplify the final model matching, a rough orientation around two axis and the approximate size of the interface is estimated. This is done as follows:

The roll angle of the interface, i.e. the rotation around an axis, thought of as the normal to the image, is estimated with first approximating the individual module sides with square shaped regions. Then, their sides are aligned with the vertical sides

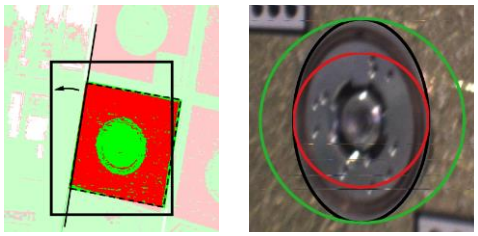

*Fig. 6: Left: Estimation of the angle between vertical module sides and camera frame. Right: Estimation of a hull ellipsis for the interface.*

of the camera frame, allowing to compute the angle between the two. Furthermore, the elliptical shaped regions of the mechanical interfaces are approximated with ellipses, giving a first estimate of size and distortion of the underlying circular model of the interface. Both operations are illustrated in Fig. 6.

The model to match is simplified to a minimal representation of characteristic edges. This step is

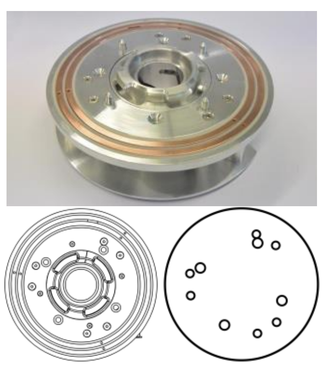

*Fig. 8: Top: Multifunctional interface for coupling of individual satellite cubes. Taken from [7]. Bottom left: 2D model with view from the top. Bottom right: Final 2D edge representation for shape-based matching.*

important to further reduce the computation time. Since the front of the mechanical interfaces is aligned in parallel to the surrounding module side, a 3D model matching would be too overweight in comparison to the little gain in precision. Fig. 7 shows the interface as currently used within the iBOSS project and its simplifications. The exact dimensions of the simplified model are known and obtained from the CAD data. The selection of prominent circles within the 2D model has shown good matching capabilities. However, any kind of 2D model could in general be used for the shape-based matching. In a last step, the matching is performed using the edge image from the search region and a distortion table containing possible distorted and scaled shapes of the given 2D model. For the best match the 6D pose is then computed using an affine transformation provided as a standard algorithm within the HALCON library. Although a distortion table with a big bandwidth could replace before mentioned optimizations like e.g. a rough estimation of size and partial orientation, a lean database to match the searched region against has a significant performance benefit and was thus chosen.

## 4 EXPERIMENTAL RESULTS

We tested both approaches in a lab environment. Fig. 8 shows results with the feature based approach. The solution was robust to interfaces appearing from greater distances of up to two meters. However, the localization failed in some cases when lighting conditions of the module sides where too inhomogeneous or did not provide good enough contrast to the surrounding. Choosing trained networks for different lighting conditions could partly remedy this effect and added robustness to the approach. In addition, Fig. 9 shows a successful module replacement using the marker based approach. For this execution, the localization was precise enough to grasp the iBOSS modules, which require a precision in positioning of less than five Millimeters measured from the rotational axis of the interface and less than 5 degrees of rotational

*Fig. 7: Satellite modules with localized interfaces.*

displacement around any axis. Currently, the markers are recognized and localized with industrial cameras. We expect the approach to work equally well with special space approved systems which were not considered yet. As for the markers, LED technology might add additional robustness. Good visibility for

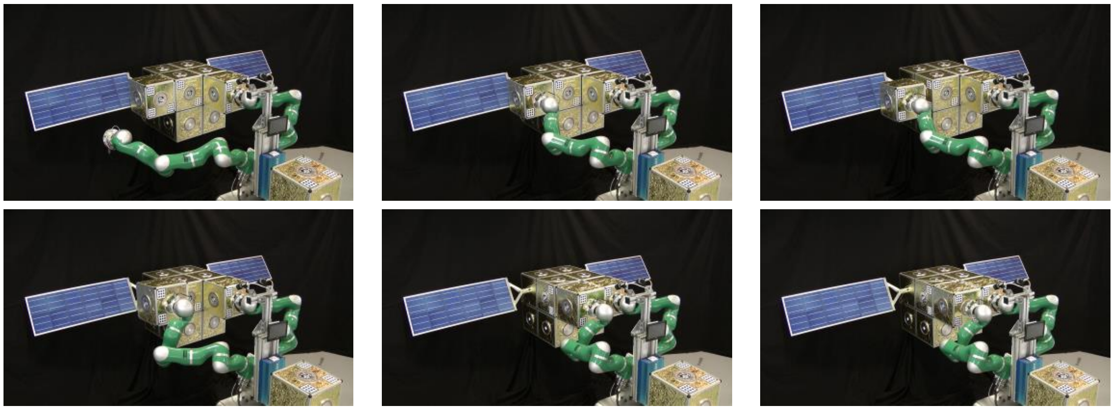

*Fig. 9: A satellite cube is repositioned using the marker-based localization.*

the human eye is no requirement in space and could be replaced by markers having their characteristics in different spectrums.

## 5 CONCLUSION

Localization of objects in space is currently applied especially in satellite berthing and initial docking in combination with visual servoing approaches. On-orbit manipulation, however, poses higher constraints to the accuracy of the localized objects and often requires 6D localization for collision-free path planning. In this work, we integrated conventional and well established methods from computer vision into a servicing system, and used the 6D poses of satellite modules to perform a robotic manipulation task.

Both described approaches show a robust localization under the conditions in a lab environment. While the marker based approach leads to higher precision in the poses, the feature based approach excels when images are out of focus, of less resolution or are taken from greater distances. The markers used in this work can be replaced by any arbitrary marker, as long as the individual markers contain sufficient information to compute a unique 6D pose.

Depending on the highly different illumination conditions in space, it might be necessary to train various networks and thus have a pool for the initial classification to choose from.

Future work will focus on strategies to compensate for occlusions with bringing SLAM methodology (simultaneous localization and mapping) to modular satellites, allowing localization and online updating of models.

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