Inertial Attitude Verification for ADCS Test Beds by Single Camera Image Processing

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***Abstract*—Test beds for attitude determination and control systems (ADCS) are an essential tool during the development and qualification phase of satellites which are often tested under simulated mission conditions. One major challenge is to verify a complete ADCS with its sensors without introducing noise to these sensors with testing equipment. Active sensors might interfere with magnetic field sensors, sun sensors or the optical instruments of the satellite.**

This paper introduces a cost-effective approach which determines a satellite's inertial attitude inside a testbed by only using images from a single or multiple commercial cameras. The software utilizes so-called ArUco markers which need to be physically affixed to the satellite and testbed itself. The attitude estimation can then be done with help of a software package developed by the authors. This software utilizes the open-source ArUco software library for detecting the markers, their position and orientation in the camera coordinate frame. Since it only uses images to do so, there is no interference with sensors or instruments of the satellite.

Keywords—ADCS, testbeds, satellite qualification, ROS, image processing, attitude determination, open-source, space robotics

I. Introduction

ArUco markers are synthetic two-dimensional markers that consist of a black border and a black and white pattern which is unique for every marker so they can be distinguished. The ArUco library [1][2][3] provides functions to generate markers to the user's specifications including border length, marker dictionary and marker ID. The dictionary defines the size of the pattern, i.e. the number of black and white squares, and the total numbers of IDs.

In addition to markers, there are also so called ArUco boards which are a set of prearranged markers which act as a single marker. The markers can be arranged in any 2D or 3D layout. Since the relative position between the markers are already known, it is possible to use all markers to estimate the pose of the board. This increases the accuracy of the estimation. Additionally, not all markers need to be visible to provide a pose estimation. If at least one marker is not obscured, an estimation can still be performed.

II. Package Features

The purpose of the developed package, *aruco_analyzer,* is to simplify the usage of the ArUco library and to add new features. For example, it allows to average successive estimations to mitigate estimation errors. The package can be configured using a configuration file in YAML format. In this configuration file, amongst other things, it is possible to specify which markers and boards the package is supposed to detect. Furthermore, the software allows to differentiate between space-fixed (stationary) and body-fixed (dynamic) markers.

Additionally, a wrapper for the Robotic Operating System (ROS) was developed. It subscribes to camera streams which can also be configured in the configuration file. The processed detections are published as images with the detected markers drawn into it and the pose estimations as ROS transformations[1].

III. Performance Evaluation

To evaluate the performance of the pose estimation, several tests were performed which can be divided into attitude estimation tests and position estimation tests. The goal of these tests was to find the impact of different factors on the estimation quality. These factors are mainly:

1. Kind of markers and boards being used,
2. Angle and distance of the camera to the markers.

All tests were performed with an off-the-shelf Logitech C920 USB[2] webcam at a resolution of 1080p and 30 frames per second. For the attitude estimation tests a script was implemented that performed the tests automatically using a rotary table for adjusting the codes' attitude.

During the initial research, the paper "Accuracy analysis of marker-based 3D visual localization" [4] was found which also dealt with pose estimations. They found out that at optimal conditions at 5m, the angular error was about 0.01° and the radial error about 8cm. At a certain distance, the errors increased exponentially, caused by the markers not being

1 docs.ros.org/kinetic/api/geometry_msgs/html/msg/TransformStamped.html
2 logitech.com/en-gb/product/hd-pro-webcam-c920

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detected correctly. However, judging by the paper, all tests were conducted in a simulated environment.

A. Attitude Estimation Evaluation

The accuracy of the attitude estimation is especially important for the application as a verification tool for attitude determination and control systems (ADCS) of satellites.

In the tests, a marker was placed on a rotary table with the camera placed at different distances above the table. The marker was rotated using the table at angles between 0° and 360°.

Table I shows some of the results of the attitude estimation test with different marker types and camera distances. In this test, the camera was always directly above the markers. The single marker performed significantly worse than all boards with a higher average and maximum error. At each distance, there is an optimal board type. In general, a board with more markers performs better. However, if the individual markers on the board get too small, the board is not detected reliably anymore at which point the attitude estimation deteriorates significantly. In the best case, we achieved an accuracy of less than less than 0.1°.

TABLE I. ATTITUDE ESTIMATION WITH DIFFERENT MARKER TYPES

Board type	Distance in cm	Error averaged over all angles in °		
		Average	Standard Deviation	Maximum
Single	56	-0.510	1.398	4.327
2x2		0.069	0.454	1.571
7x7		0.019	0.078	0.338
7x7	35	-0.003	0.054	0.226
10x10		0.000	0.029	0.066
15x15		-0.026	0.062	0.228

Table II shows some of the results of the attitude estimation test at different camera angles and a constant camera distance of 30cm. A camera angle of 90° means that the camera is directly above the marker. An angle shallower than 20° was not tested, as the markers were not detected reliably anymore. In the test, a 4x4 board with an edge length of 10cm was used. At the extreme cases of almost 90° and 20°, the accuracy is up to 5 times worse than at cases in between. The best result was delivered at 54°.

TABLE II. ATTITUDE ESTIMATION AT DIFFERENT CAMERA ANGLES

Camera angle in °	Error averaged over all angles in °		
	Average	Standard Deviation	Maximum
20.130	0.002	0.064	0.218
32.259	0.000	0.038	0.135
54.851	0.001	0.027	0.079
75.633	0.006	0.029	0.105
89.686	0.059	0.106	0.588

B. Position Estimation Evaluation

The position estimation is not as important as the attitude estimation for ADCS verification. However, applications such as the identification of landmarks for robotic navigation, it is crucial.

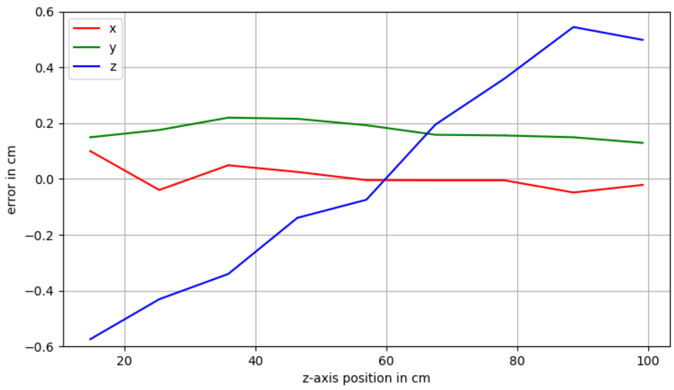

Fig. 1. Position estimation accuracy in all three axes. The camera was pointed directly at the marker. The z-axis can also be interpreted as the distance of the camera to the marker.

In this test, we investigated the accuracy of the position estimation by placing an ArUco board at different positions on a grid placed on the floor. This allowed to verify accuracy on the x- and z-axis, the x-axis being the horizontal position and the z-axis being the distance from the camera. The used ArUco board had an edge length of 10cm with 4x4 markers on it.

Fig. 1. shows the accuracy error of the position estimation dependent on the distance of the marker. The error in the x- and y-axis is relatively stable with a maximum error of around 0.1 and 0.2, respectively. The error along the z-axis increases with an increasing distance. This error follows a linear function which can be used to correct the position.

IV. CONCLUSION

We have shown that the ArUco library can be a useful tool for space-related projects. They can be utilized for the qualification of the attitude control system of a satellite to provide a simple and cost-effective method to verify the system's output. With its precision of less than 0.1°, it should deliver sufficiently accurate results.

For space rover projects or robotic projects in general, the ArUco markers can be used to mark important landmarks or objects which can be interacted with, like buttons or switches. Furthermore, it could be utilized to verify the output object recognition software based on another approach such as machine learning. The position estimation accuracy is around 0.2cm at distances from several centimeters to around 2m. However, to reach these levels of accuracy, the software must be properly calibrated beforehand.

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