Chapter 37
Pilot Virtual Experiments on ArUco and ArTag Systems Comparison for Fiducial Marker Rotation Resistance

Aufar Zakiev, Ksenia Shabalina, Tatyana Tsoy and Evgeni Magid

Abstract A growing number of researches and industrial projects use fiducial markers for scientific and commercial purposes. A large number of different fiducial marker types and difficulty of their comparison make impossible to reasonably and properly select a fiducial marker system for a particular task. This paper presents an efficient approach to compare different marker systems in virtual ROS/Gazebo environment and results of our pilot experiments that were conducted with ArUco and ArTag markers. The presented results show the difference of marker systems with regard to their resistance to rotations. Experiments were designed in a special way that maximally eliminates external environment influence, including light conditions, camera resolution, sensor noise, distance between a camera and a marker. In total, over 500,000 experimental outcomes were analyzed and interpreted to collect statistically significant amount of data.

Keywords Fiducial markers · ROS · Virtual experiments

37.1 Introduction

Fiducial marker systems (FMS) are the systems that consist of specially designed planar graphical signs and corresponding computer vision algorithms, which are developed to detect and recognize these signs. FMSs are used for scientific and technical purposes in physics, medicine, robotics, augmented reality, metrology, etc. Specifically, in robotics, navigation [1, 2], localization [3–6], mapping [7], and camera calibration [8] tasks could be effectively solved using various FMS. Moreover, calibration could be performed fully autonomously, and this corresponds to our long-

A. Zakiev (✉) · K. Shabalina · T. Tsoy · E. Magid
Laboratory of Intelligent Robotic Systems, Higher Institute for Information Technology and Intelligent Systems (ITIS), Kazan Federal University, 35 Kremlyovskaya Street, Kazan 420008, Russian Federation
e-mail: zaufar@it.kfu.ru

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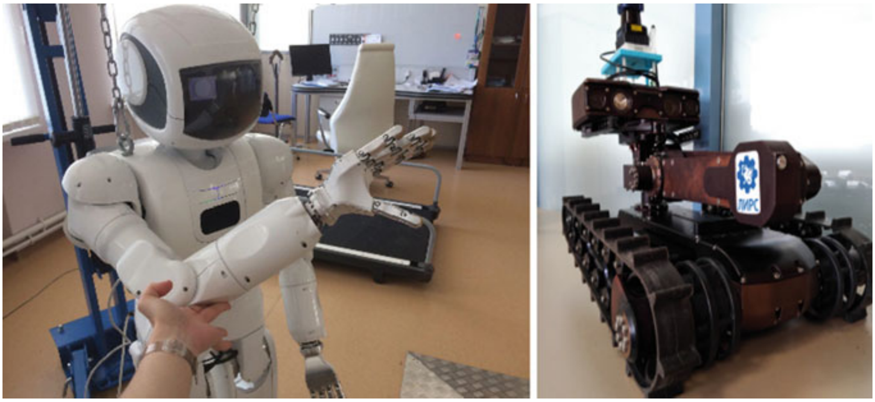

Fig. 37.1 AR-601 M humanoid robot (left); crawler-type Servosila Engineer robot (right)

term goal of calibrating several Russian robots, including humanoid AR-601 M robot and Servosila Engineer mobile robot (Fig. 37.1).

Modern FMSs have different designs and are developed for various purposes: each of them has its own advantages and drawbacks. Therefore, proper FMS comparison is essential in order to choose a suitable FMS for the task of interest. This comparison must be performed in a fair way while attempting to eliminate most of the external environment influences. Moreover, these experiments should compare FMSs for particular distinct criteria, which is the most important for a successful task completion. Our task is to calibrate robot cameras in an automatic manner using markers that are placed on AR-601 M humanoid robot's manipulator (e.g., on the palm) and on the main body of Servosila Engineer robot. The humanoid observes this marker, estimates, and programmatically eliminates camera distortions. Therefore, a proper FMS for this task should be detectable from different viewpoints and under a partial overlap of the marker by robot's parts; i.e., FMS must be resistive to manipulator rotations and partial occlusions.

Early experiments design, which had been developed by our team [9], compared FMS in a systematic order manually in laboratory conditions. Those experiments estimated different FMSs' resistance to rotations and partial occlusions (both systematic and arbitrary). However, the approach of manual experiments has several crucial disadvantages:

- Overwhelming time consumption. Statistically significant amount of data collection requires performing hundreds of thousands experiments;
- Complexity of experiments' fairness control. External environment conditions, e.g., inclination angle, marker position with regard to a camera, lighting conditions, etc., are hard to monitor and control;
- Limited hardware selection. Hardware has unavoidable noises and often does not possess desired properties, e.g., a desired camera resolution, lens distortion level, optical sensor sensitivity, etc.

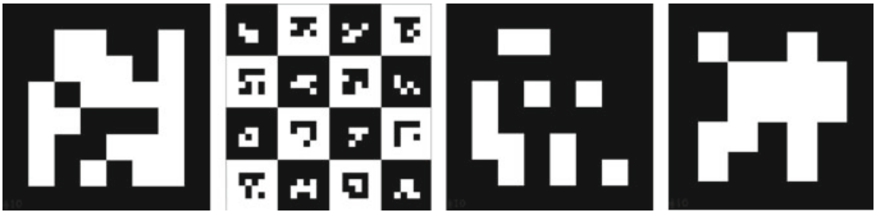

Fig. 37.2 FMS examples (from left to right): AprilTag, CALTag, ArUco, and ArTag

Moreover, these limitations violate the principle of experiment reproducibility, which is essential in every experimental research that is performed with the scientific method approach.

This paper presents virtual experiments design and ArUco [10] and ArTag [11] systems comparison for rotation resistance results. Section 37.2 describes previous research methods and results. Section 37.3 introduces ROS/Gazebo framework that was used as a virtual environment for experiments. Section 37.4 is dedicated to experiment setup, while Sect. 37.5 shows the experimental results. Finally, conclusions are presented in Sect. 37.6.

37.2 Related Work

Our previous pilot research [9, 12] was dedicated to manual experiments with several fiducial marker systems: AprilTag, ARTag, and CALTag [13] (Fig. 37.2).

Three of these markers (AprilTag, ArUco, and ArTag) are designed to encode binary sequences. They have strictly black border with encoding pixels of white and black color in it. CALTag is designed especially for camera calibration purposes and has a more sophisticated design that had been developed to make markers more resistive to different distortions and increase chances of marker detection in cases of data incompleteness.

We designed our experiments to validate markers' resistance to rotations, systematic occlusions, and arbitrary overlaps. First, low-cost equipment (Fenius FaceCam 1000X) was used to get initial data about FMSs applicability. Four types of experiments were conducted: marker rotation, systematic occlusion, marker rotation combined with systematic occlusion and arbitrary marker overlaps. These experiments were continued with AR-601 humanoid robot, using its integrated Basler acA640-90gc cameras. The experiments were conducted manually; therefore, a number of tested markers and experimental trials were significantly limited. Only four distinct markers of each type were used and only a few rotation and occlusion cases were chosen for testing (Fig. 37.3).

These experiments revealed a high resistance of all chosen FMSs to rotations; however, only CALTag marker demonstrated reasonable detection rate for different

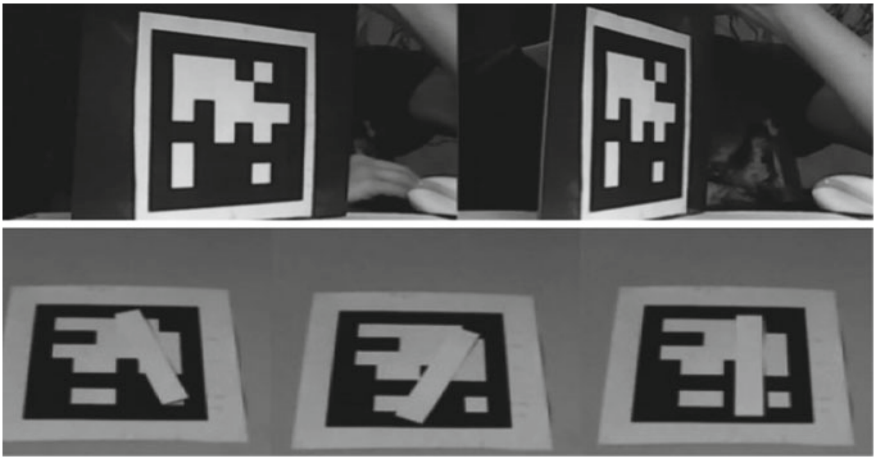

Fig. 37.3 Examples of manual experiments with AprilTags: rotations (top) and arbitrary overlaps (bottom) [12]

occlusions. AprilTag and ArTag appeared to be sensitive to marker edge overlaps, and this could be caused by detection process flows: Edge detection is a decisive bottleneck of the procedure, and if it fails, the entire detection process stops.

However, as we previously mentioned, these results are hardly reproducible: Multiple external environment properties are sophisticated to control and repeat across several trials; collecting significant amount of data requires a lot of time; it is impossible to distinguish a detection fail that was caused by a hardware imperfection (lens distortion, noises, etc.) from a fail that was caused by the particular marker detection algorithm.

These disadvantages could be overcome if experiments are conducted in a virtual environment of a simulator. This includes all external conditions control and reproducibility, allows to conduct thousands of experiments with all FMSs and gives a chance to repeat and peer review multiple times every single result that was retrieved across experimental trials. A simulator has a crucial property of predictability: In case of a proper software implementation, the same initial conditions lead to the same result steadily.

37.3 ROS/Gazebo Environment

Robot Operating System (ROS) is a fast-growing framework for robotics development. Its architecture consists of nodes and topics between them for communication. Such a distributed structure allows creating various data and command flow schemas, making sensor data analysis and robot motion control easy. ROS is distributed in a form of minimally functional units called packages.

The following FMS have their detection algorithms, which are encapsulated in ROS packages: AprilTag, ArUco, Alvar [14], and ChiliTag [15]. Actually, ArUco is a universal detection library that could be used to detect ArUco markers and, in addition, AprilTag, ARTag [9], ARToolKitPlus [16], and ARToolKitPlusBCH (binary-coded hexadecimal). These ROS packages serve as wrappers around original detection algorithms that were presented by their authors.

A virtual environment is simulated using Gazebo simulator, which could be easily integrated into ROS. Gazebo simulates different situations where FMS detection could be applied [17]. The simulator imitates real-world properties and psychical forces that are applied to virtual objects: gravity, light conditions, material reflections, collisions, sensor noise, etc.

37.4 Experiment Setup

The virtual experiment follows ROS guidelines and consists of nodes set and topics between them. Nodes retrieve messages from topics, process obtained data, and send processing results to the specified topic. General experiment scheme is presented in Fig. 37.4.

Two robots were added into the virtual environment to conduct the experiments: a robot-performer that holds the marker and R2D2-like robot with a camera (Fig. 37.5). The marker is rotated by the robot-performer, which rotates the marker for a predefined angle within a user-defined angles range (the scheme is shown in Fig. 37.6). Camera robot has a fixed camera and simulates a static camera stand (Fig. 37.7). Numerous parameters of experiments were kept constant through all the experiments (see Table 37.1) in order to eliminate their influence on comparison results and compare FMSs in a fair way.

The virtual experiment parameters could be controlled using a graphical user interface, which is integrated into a package. These parameters include distance between a camera and a marker, a camera noise level, rotation ranges, and a number of simulation threads. Parameter values are kept constant throughout all the tested markers, including light and reflection conditions; thus, the experiment fairness is guaranteed and to be secured.

Rotation experiments flow works as follows:

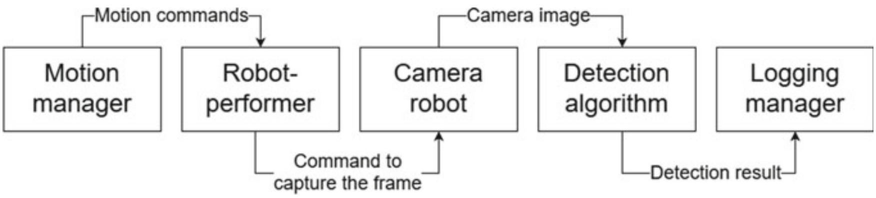

Fig. 37.4 Virtual experiment data and command flow scheme

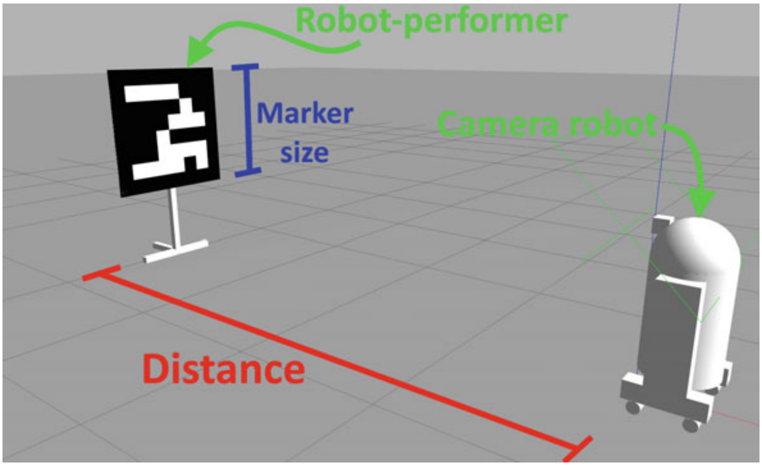

Fig. 37.5 Virtual experiment general view

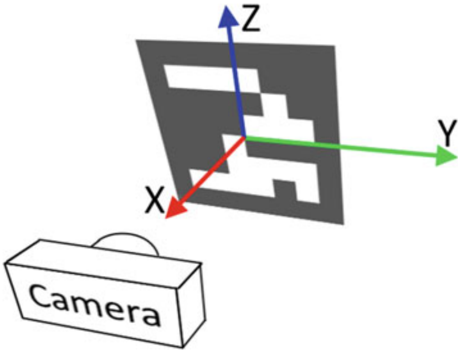

Fig. 37.6 Virtual experiment rotation scheme

Table 37.1 Virtual experiment constant parameters

Parameter	Value
Camera resolution	640 × 480 px
Camera distortion level	0 (ideal lens)
Camera noise level	0 (ideal device, shown on Fig. 37.8)
Distance	2 m
Rotation range (*X*-axis)	[−180°; +180°)
Rotation range (*Z*-axis)	[−90°; +90°]
Marker side size	0.4 m
Light angle of incidence	45°
Light spectrum	White light
Light conditions	Uniform at whole marker area

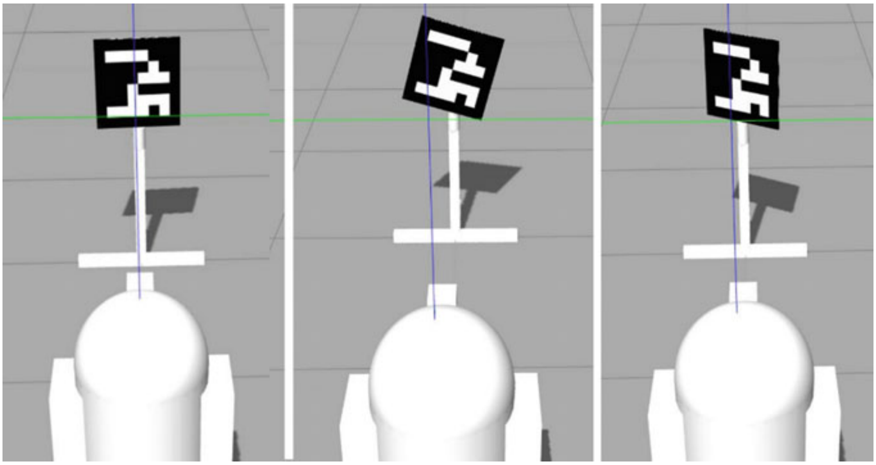

Fig. 37.7 Virtual experiment design: initial marker position (left); rotated for −15° around *X*-axis (center); rotated for −20° around *Z*-axis (right)

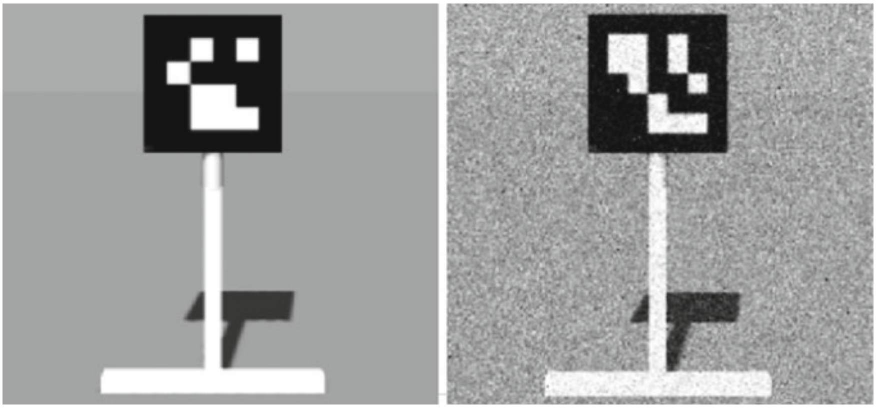

Fig. 37.8 Virtual camera frames: zero noise level (left), Gaussian noise with 10% standard deviation value (right)

1. The robots spawn at a constant distance from each other. Initially, a marker inclination angle around a (particular) user-defined rotation axis is zero.
2. A logger thread waits for a half of second for the marker detection.
3. The logger logs an inclination angle and a result of the detection procedure, which could be successful or unsuccessful.
4. The robot-performer rotates the marker for 1 degree around the user-defined axis (*X*-axis or *Z*-axis).

37.5 Experimental Results

Markers are selected to collect statistically significant amount of data: 100 ArUco (type is 25h7) markers and 1022 ArTag (there is no type separation for this marker family) markers. Markers of type 25h7 have 25 encoding pixels, and Hamming distance between any of them is equal or more than 7. Hamming distance value is equal to the number of positions at which the corresponding symbols are different. This metric is typically used for FMS that encodes binary sequence and measures the difference between distinct markers. For example, marker A encodes "10001111" sequence and marker B encodes "10111011" sequence. Sequences are different in third, fourth and sixth digits; therefore, Hamming distance between markers A and B is equal to 3. Higher value of Hamming distance allows to perform error correction in cases when data are noisy or corrupted. In the example above, if the sequence retrieved after decoding is equal to "10011011", then it is more likely that detected marker is marker B, because Hamming distance to marker A equals 2 and Hamming distance to marker B equals 1. Higher minimum Hamming distance value leads to better error correction; however, it limits a maximum number of sequences that can be encoded in FMS.

Each distinct marker was tested twice to collect reliable data about each rotation step angle. Experimental results are presented in Table 37.2.

The experimental results allow concluding both marker families are practically insensitive to *X*-axis rotations; however, ArUco family markers have slightly better resistance to *Z*-axis rotations. In addition, failed detection distribution for *Z*-axis for each marker family is presented in Fig. 37.9. *Z*-axis rotation results are explained by a straight dependence of a successful detection on the rotation angle of a marker: Increasing rotation angle leads to worse detection rate. As FMS rotates, visible to the camera marker area decreases, tending to zero as the angle approaches 90°.

37.6 Conclusions and Future Work

This paper presented a set of pilot experiments with ArTag and ArUco marker systems in a virtual environment and a comparison of their resistance for rotations. The designed virtual environments could be used for comparative researches of new FMSs as their detector packages become available in ROS. The virtual environment includes GUI that allows distance to a marker, a sensor noise level and threading

Table 37.2 Average detection rate through all the markers in rotation experiments by FMS type and rotation axis

	Rotation axis	
Marker family and type (if available)	*X* (%)	*Z* (%)
ArUco—25h7	99.968	86.066
ArTag	99.9995	84.383

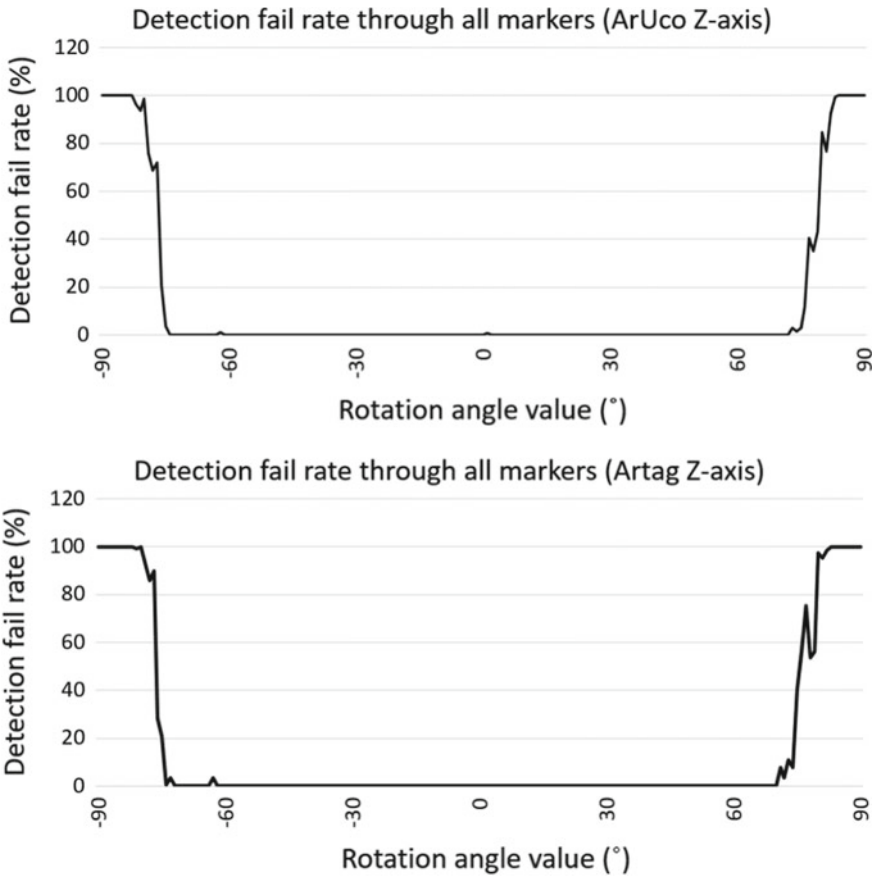

Fig. 37.9 Virtual experiment results for *X*-axis rotation: detection rates through all markers depending on a rotation angle for ArUco (top) and ArTag (bottom)

control. This makes virtual experiments easily reproducible, which guarantees an opportunity to peer-review the environment code and results without limitations. Our future work is dedicated to different FMS comparison for their resistance to occlusions (both systematic and arbitrary) and exploring dependence of maximum detection distance on camera resolution.

The results of these pilot experiments will be used to choose suitable markers for multiple camera calibration of AR-601 M humanoid robot and mobile crawler robot Servosila Engineer. In addition, the developed software will be improved to eliminate hardware and software influences and provide precise FMS comparison results.

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