# Validation of Fiducial Marker Systems Performance with Rescue Robot Servosila Engineer Onboard Camera in Laboratory Environment

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***Abstract*****—***Typical tasks of service robotics and special robotics fields, including Urban Search and Rescue, set a number of challenges for mobile robotics with automatic performance of various functions of mobile robots being a key task. To pursue automatic camera calibration processes using on-body markers in this paper we demonstrated results of validation experiments on mobile robot Servosila Engineer using fiducial markers, which we selected based on the results of virtual experiments with fiducial marker systems.*

***Keywords*****—** *camera calibration, fiducial marker systems, laboratory environment, Servosila Engineer robot, mobile robot.*

## I. Introduction

Along with natural disasters humanity faces other man-made catastrophes that might arise from terrorism, civil wars and other accidents being caused by human activities that create challenges for robotic Urban Search and Rescue (USAR) [1]. Robotic USAR implies human replacement by a rescue robot for safety reasons. Thus, the robot autonomy becomes vital for a robot to operate effectively. Urban environments after a catastrophe are challenging for autonomous robots due to unpredictability of a real mission scenario [2]. Therefore, for the past decade a large number of rescue robots was used in fields in teleoperation mode. A rescue team makes decisions that are based on remotely gathered sensory data and a robot on-board camera becomes essential for environment exploration around a robot. For this reason, in order to allow gathering accurate visual data camera calibration is required after each sensor installation or lens replacement. This became a challenging task for researchers taking into account that usually real USAR environments consist of debris being filled with dust, smoke and other obstacles that significantly interfere camera vision. Such facilities require launching calibration procedure periodically during the fieldwork. At the same time, we should emphasize that precise industrial equipment for calibration usage is costly and hardly achievable in field conditions. However, in most cases computer vision methods could be applied for camera calibration using only special software, robot onboard computer and additional onboard equipment.

Rescue robot camera calibration requires some level of autonomy that could allow excluding human assistance in order to avoid additional human victims in USAR operations. Additionally, in field conditions typically small robot size limits a use of large-sized boards for classic camera calibration (i.e., checkerboard type patterns), which are broadly used in laboratory facilities under ideal light conditions and with human assistance.

In this work, we present a detailed experimental setup for fiducial marker systems (FMSs) comparison with regard to a number of external criteria and validate two different FMSs behavior in laboratory conditions. The experimental setup is designed to cover comparison of FMSs resistance for systematic occlusion and marker size changes. Experimental validation is performed using an onboard camera of Russian mobile crawler robot Servosila Engineer (Fig.2).

The paper is structured as follows. Section II briefly presents related work including our previous research of the topic. Section III describes the experimental design. Section IV deals with the experimental validation. In Section V we discuss the results of the experiments. Finally, conclusions and future work are highlighted in Section VI.

## II. Related Work

Tsai [3] and Znang [4] presented successful and accurate methods for camera calibration, which became popular due to flexible design and easily printed equipment - a planar checkerboard pattern. However, modern methods consider new features being included into a basic method with checkerboard fiducial markers design. These features were classified in [5] and include light condition resistance, resistance to false positive effect or false negative effect, marker size, resistance to occlusion, and maximum distance to a marker.

Using a chessboard pattern is a reliable camera calibration method only for a well-controlled idealized laboratory environment: it cannot be detected in cases of occlusion, overexposure or small pattern size. However, the pattern geometry remains the best for calibration, and yet other

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research teams created their improved calibration boards that are based on chessboard geometry [6-9].

Fiducial marker families (FMFs) became popular in various robotic tasks, including localization and navigation [10] [11], hand-eye problem [12] [13], underwater marker recognition [14] [15]. FMFs were investigated in various environment conditions and applications, and usually they were used without human assistance (due to their recognition and detection algorithms). The later factor enables automated extrinsic calibration [16] and could be potentially used for a more complex calibration process of intrinsic calibration. Yet, it requires relevant research of FMSs in order to identify the best FMF for a particular purpose. Therefore, it is necessary to conduct a wide set of experiments in order to objectively evaluate the ways to solve this problem.

As our long-term project goal, we target to automate camera calibration processes using on-body markers. On the first stage of our research we had conducted series of pilot manual experiments [17] that used different resolution cameras, including standalone cameras as well as onboard cameras of Russian humanoid robot AR-601M. Since each FMS has different strengths and drawbacks, at the beginning we focused on experiments that consider marker occlusion and marker rotation. At this first stage, we had selected three potential marker systems: ARTag, AprilTag, and CALTag. The selection was based on markers popularity among computer vision and robotics fields researchers as well as open-source code availability and usability.

We created a single experiment design with different quality cameras, FaceCam 1000X and Basler acA640-90gc. The design considered such properties of an FM as its resistance to a systematic occlusion (Fig. 1, left), arbitrary occlusion (Fig. 1, center) and marker rotation (Fig. 1, right) [18]. The experiments were performed in laboratory environment with constant light conditions and ideal background of each FM. After series of these experiments, we concluded that ARTag and AprilTag have a strong sensitivity to edge overlapping, while CALTag showed the best success rate - CALTag was successfully detected even with 50% of its area being overlapped by another object. As for arbitrary occlusion and marker rotation experiments, all the three FMSs were rather equally successful.

Next, we designed experiments for marker validation in a *pseudo field environment* using AR-601M robot [18]. Here by a pseudo field environment we meant that while the experiments took place still within the same laboratory rooms, no special attention was paid for light conditions and the background of each FM during experiments was intentionally confused by various objects and images. In addition, while we kept the same procedure of marker occlusion experiments, we added a marker size factor in order to analyze the influence of both factors on the FM recognition. Results analysis demonstrated that a marker size (or a distance to a camera) plays a critical role for a successful identification of a marker. AprilTag FMS showed better results, while ARTag and CALTag FMSs success rates were significantly lower. Pseudo field experiments toward autonomous self-calibration of cameras by a robot demonstrated a direct dependence of success rate on a marker size, which should always be maximized within available limits of its placement location size on a robot body surface. Thus, we conclude that we need to focus not only on occlusion experiments but also on a marker size criterion.

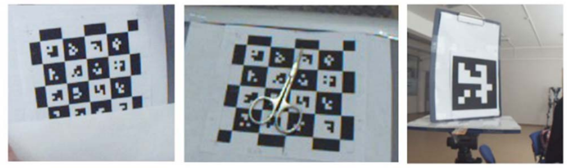

Figure 1. Systematic occlusion experiments with CALTag 4x4 (left), arbitrary occlusion experiments with CALTag 4x4 (center), marker rotation experiments with ARTag ID 2 (right) [15].

Manual experiments have significant and unavoidable disadvantages that clearly decrease experiment value. Such experiments are hardly scalable in order to perform a large amount of experiments in the exactly same manner with multiple fiducial markers, because a marker position and orientation, light/shadow conditions, and many other factors should be precisely controlled and reproduced multiple times. Moreover, real hardware choice is often limited and produces noisy sensory data that prevents exact reproduction of manual experiments in practice.

To cope with these disadvantages, our team designed virtual experimental environment in ROS (Robot Operating System)/Gazebo framework [19]. Virtual environment eliminates inaccuracy in camera and marker positioning and allows controlling virtual external conditions during the experiments. These virtual experiments were automated to obtain data about each marker in every FMS type. The analysis of virtual experiments' results showed that ArUco 16h3 and ChiliTag markers are most insensitive to marker angular size decrease – therefore, these FMSs types' markers were selected for further validation in the laboratory experiments with a mobile robot onboard camera, which are presented in this paper.

## III. Experimental Design

All experiments were designed using One-factor-at-a-time (OFAT) approach. In OFAT approach during an experiment an investigated factor of interest is varied while all other factors, which may influence experimental results, are kept constant [20]. This way we exclude the influence of other factors and estimate the effect of the single factor on the results. The design of the experiments is constructed according to the following pattern: validation procedure, permanent factors, a variable factor, experimental procedure, expected results.

We proposed 4 particular IDs of FMFs that had previously demonstrated superior performance relatively to other FMFs in various experiments. Next, we performed a validation procedure for the selected markers in order to identify which marker ID and FMF demonstrates the best performance. The experimental setup and design for each type of experiments are described in the next three subsections.

### *A. Hardware and software setup*

Our team performed experiments using mobile robot Servosila Engineer (Fig. 2), which has a 4 degrees of freedom (DoF) manipulator [21]. Four onboard cameras are located in the robot's head that is mounted above the manipulator end-effector. Image capturing of a marker was performed by onboard TWIGACam camera with 1280x720 resolution at 50fps. Based on virtual experimental results in Gazebo simulation, which were described in Section II, four fiducial markers were selected for further real world experiments:

ArUco 16h3 - ID 53 and 198, and Chilitag - ID 815 and 1015. For marker detection and recognition, we used informal ROS packages for ArUco[1] and ChiliTag[2] FMSs.

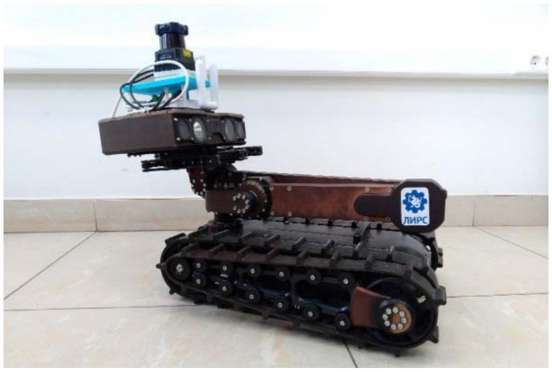

Figure 2. Mobile robot Servosila Engineer.

*B. General experimental settings*

For both types of experiments, a number of external environment conditions were kept constant. Permanent factors included light conditions, distance to a marker, marker pose and orientation, camera parameters and pose.

***Light conditions***: uniform room artificial lighting, with no overexposure or lack of lighting.

***Distance to a marker***: constant distance of 0.7 meter from a camera to a marker.

***Pose and orientation of a marker***: all markers were attached to a flat smooth surface of the robot body without tilting. All markers were located in front of the robot camera. A marker was attached to the mobile base of Servosila Engineer robot (Fig.5).

***Camera parameters***: the following intrinsic camera parameters were fixed during experiments: camera resolution, distortion model, zoom. We used TWIGACam camera with 1280 x 720 camera resolution, barrel distortion model, no zoom, 50 fps. Focus length was also kept constant correspondently to zoom selection.

***Camera pose***: for all experiments the camera was positioned strictly opposite to the marker. A process of reaching a desired position and orientation of the cameras was individual considering kinematic model of the manipulator.

Other factors and procedures that varied for the experiments are described in the two next subsections (Section III C and Section III D).

***Expected results***. In each experiment we expected to obtain a particular percentage of successful recognitions of each selected marker at each step. The results are to be summarize into a single table, which will allow concluding about the most successful marker family that could resist systematic occlusion (Section III C) or a marker family that succeeds with the smallest physical size of a marker (Section III D).

*C. Experiment I - Systematic occlusion experiments*

This section describes systematic occlusion experiment design. In addition to the permanent factors that were detailed in Section III B, we kept a constant marker size while varying the percentage of marker's occluded (covered) area. We used a certain size of a marker that cannot influence the results of the occlusion experiment. An optimal size of each marker was selected experimentally and its upper limit depends on available space on the mobile robot base surface where the marker could be potentially placed. We used marker sizes varying from 12 cm x 12 cm to 1 cm x 1 cm.

***Variable factor*** was the percentage of marker's covered area. The percentage of an overlap increased with a constant step of 15 percent and took a value within [0%, 15%, 30%, 45%, 60%, 75%] set. Based on our previous virtual experiments as well as pilot manual experiments, we assumed that overlapping of over 10 to 15% of marker area was critical and prevented its recognition.

***Experimental procedure***. Each marker instance was covered with a white non-transparent rectangular paper template. The template size expanded gradually from marker's bottom to the top in order to hide 0%, 15%, 30%, 45%, 60% and 75% of the marker area respectively, including the marker edges. During the experiment, at each step ten images were captured by the robot camera. After six steps of increasing occlusion area size the experiment was restarted with a new marker ID. Figure 3 demonstrates an example of systematic occlusion experiments.

***Expected results.*** We expect to obtain a particular percentage of successful recognitions of each of the selected markers at each step. We summarize the results into a single table and select the most successful marker family, which resists systematic occlusion better than its selected counterpart markers.

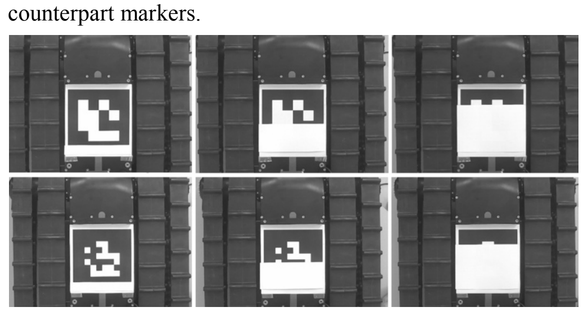

Figure 3. ArUco 16h3 ID 198 (upper row) and ChiliTag ID 815 (lower row) occlusion for 15, 45, 75% (from left to right).

*D. Experiment II - Marker size*

This section describes a marker size experiment design. The permanent factors that were mentioned in Section II B were kept constant while varying a marker size. It is important to notice that a marker was always kept entirely visible and no occlusion of marker interior or boundaries occured.

***Variable factor*** was the size of a square marker. Its width and height equally decreases with a constant step of 2 cm (and by 1 cm at the last step), until it reaches 1 cm x 1 cm size. Thus, a marker edge sequentially took a value within the set [12, 10, 8, 6, 4, 2, 1] cm.

***Experimental procedure***. We started from a maximal marker size and at each step; the marker size was decreased by 2 cm simultaneously in width and height (1 cm at the last

[1] http://wiki.ros.org/ar_sys

[2] https://github.com/chili-epfl/ros_markers

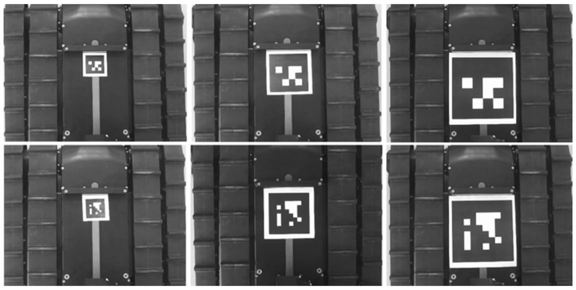

Figure 4. Examples of size scaling for ArUco 16h3 ID 198 (upper row) and Chilitag ID 1015 (lower row) FMs, which were placed on the main body of Servosila Engineer robot.

step from 2 cm to 1 cm edge size). During the experiment, at each step the robot camera captured ten images. When the minimal size of the marker was reached, the experiment was restarted with a new marker ID. Figure 4 demonstrates examples of experiments for ArUco 16h3 ID 198 (upper row of the figure) and Chilitag ID 1015 (lower row of the figure) FMs that were placed on the main body (mobile base) of Servosila Engineer robot.

## IV. Experimental Validation

In validation experiments of Experiment I type (Section III C) the mobile robot verified FMs behavior for occlusions with environment conditions and robot position being kept constant throughout the experiments. Figure 5 (left image) demonstrates Servosila Engineer robot during occlusion experiments. The images of each FM were taken by onboard TWIGACam camera of the robot, while a human manually replaced FMF IDs and arranged a corresponding overlapping for each marker.

In Experiment II type (Section III D) the robot validated FMs with different marker sizes under the same environment conditions and a fixed robot position as it was set for Experiment I (Fig. 5, right image).

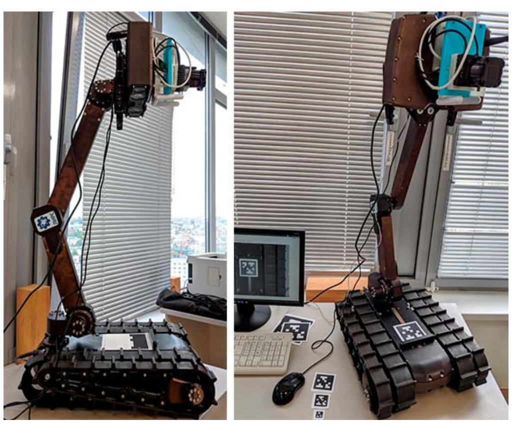

Figure 5. Experimental validation with Servosila Engineer robot in laboratory conditions using onboard FMs and TWIGACam onboard camera: marker occlusion experiments (left) and marker size experiments (right).

## V. Discussion

Table 1 presents results of Experiment I set. All FMFs showed equally high sensitivity to edge overlap; ChiliTag ID 1015 performed slightly better than other markers. These results demonstrate that not all of the selected FMFs are applicable for practical tasks if an occlusion of a marker exceeds 15%.

High success rates were obtained during Experiment II (Table 2). We concluded that all FMFs had equal resistance to marker size in marker edge size range [12 cm; 2 cm] at a fixed distance 0.7 m to a camera assuming relatively high resolution and quality of a camera. Consequently, FMF should be selected randomly for tasks with similar environment conditions. However, if we consider recognition of the smallest size of a marker (1x1 cm) the better results were demonstrated by ChiliTag family and AprilTag 36h11.

According to the obtained results for Chilitag FMF for a fixed marker size and occlusion presence (Table 1), marker success recognition rate drops down to 0% starting from the 15 and 30 percent overlapped area for Chilitag ID815 and ID1015 respectively. Chilitag ID1015 demonstrated better results compared to Chilitag ID815 as it was recognized at 15% occlusion. Marker identification process features cause this difference and Hamming distance (HaD) for different markers, where HaD value equals to the number of positions at which the corresponding symbols in two sequences are different. Every marker ID encodes a particular binary sequence and if a marker is partially overlapped, part of encoded data is lost. However, even partially decoded sequence could be used to recover lost data using HaD evaluation. HaD metric is used to determine how different are the sequences (and corresponding markers). For instance, decoded sequence is "11011" and FMS has markers A (encoding "11001") and B (encoding "01100"). HaD equals 1 in the first case and equals 4 in the second case; therefore, it is more likely that the detected marker is marker A. Therefore it is naturally recommended to select a small set of markers that would maximize HaD values, which will guarantee their dissimilarity. Such identification process causes differences in detection even in comparison with same type markers. It is interesting to notice that the results of the experiments were purely binary: the markers were recognized ideally or not recognized at all. This facts hints on the necessity to consider repeating experiments within a range [0%, 15%] for ArUco and Chilitag ID 815, and within a range [15%, 30%] for Chilitag ID 1015.

As for the results of varying marker size experiment (Table 2), recognition success rate shows the same results for both Chilitag representatives, which is 100% for each marker size employed.

Table 1. Success recognition rate (%) at systematic occlusion experiment with ArUco 16h3 (IDs 53 and 198) and Chilitag (IDs 815 and 1015) FMSs.

| | Occlusion percentage (%) | | | | | |
|---|---|---|---|---|---|---|
| FM ID | 0 | 15 | 30 | 45 | 60 | 75 |
| ArUco 16h3, ID53 | 100 | 0 | 0 | 0 | 0 | 0 |
| ArUco 16h3, ID198 | 100 | 0 | 0 | 0 | 0 | 0 |
| Chilitag, ID815 | 100 | 0 | 0 | 0 | 0 | 0 |
| Chilitag, ID1015 | 100 | 100 | 0 | 0 | 0 | 0 |

Table 2. Success recognition rate (%) at marker size experiment (A = ArUco 16h3 FMF; B = Chilitag FMF).

| | Square marker side size (cm) | | | | | | |
|---|---|---|---|---|---|---|---|
| FM ID | 12 | 10 | 8 | 6 | 4 | 2 | 1 |
| ArUco 16h3, ID53 | 100 | 100 | 100 | 100 | 100 | 100 | 90 |
| ArUco 16h3, ID198 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Chilitag, ID815 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Chilitag, ID1015 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

## VI. Conclusion and Future Work

The paper presented intermediate results of our autonomous camera calibration with fiducial markers project. Instead of using classical checkerboards for camera calibration, we selected two IDs of ChiliTag family and two IDs of AprilTag 36h11 based on analysis of virtual experiments results. Our team constructed validation experiments design and ran validation experiments with real mobile robot Servosila Engineer in laboratory environment. The goal of the experiments was to establish the best fiducial marker (FM) with regard to marker's area occlusion and marker size criteria among the preselected shortlist of four FM candidates.

In the experiments all FMs performed equally poor with regard to marker's area occlusion as for 15% area occlusion the markers were not recognized; Chilitag ID1015 showed slightly better results than other selected markers and was still recognizable at 15% occlusion, but failed at 30%. Experiments with marker size selection showed perfect recognition on FM sizes that ranged from 12 x 12 cm to 2 x 2 cm. The recognition of 1 x 1 cm marker size was perfect for all candidate markers except ArUco 16h3 ID53.

In future work we plan to establish a more precise occlusion percentage resistance rate of the markers within 0 to 30 percent range at systematic occlusion experiments while running them with small-sized markers. Additionally we plan to switch from paper FMs to the ones that are produced from weather resistant materials in order to further use them in real world environments, including USAR scenarios.

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