2017 International Conference on Mechanical, System and Control Engineering

Comparing Fiducial Marker Systems in the Presence of Occlusion

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***Abstract*—A fiducial marker system is a system of unique 2D (planar) marker, which is placed in an environment and automatically will be detected with a camera with a help of a corresponding detection algorithm. Application areas of these markers include industrial systems, augmented reality, robots navigation, human-robot interaction and others. Marker system designed for such different applications must be robust to such factors as view angles, occlusions, changing distances, etc. This paper compares three existing systems of markers: ARTag, AprilTag, and CALTag. As a benchmark, we use their reliability and detection rate in presence of occlusions of various types and intensity. The paper presents experimental comparison of these markers. The marker detection was performed with a simple inexpensive Web camera.**

Keywords-fiducial marker, ARTag, AprilTag, CALTag, occlusion, experimental comparison

I. INTRODUCTION

Fiducial markers are essential elements of camera tracking systems, which are used in robotics and augmented reality (AR) applications to stabilize a field of view. To ease the processes of tracking, alignment, and identification fiducial markers are applied to objects. For example, train cars bar codes allow to automatically identify and route them through stations. Circuit boards printed fiducials allow mask aligning from one layer to another and precise measuring of the board position in an assembling jig so that instruments could properly insert desired components. In robotics, fiducials allow calibration of cameras and mechanical parts of robotic systems, which are required for industrial applications [1], human-robot interaction and humanoids [2], SLAM [3], rescue robotics [4] and other fields.

In AR systems, fiducial markers are generally used for tracking various object in the scene. They are placed in fixed physical locations so that a moving camera location could be identified or they might be placed on moving objects so that a location relatively to the camera could be computed. AR systems depend on tracking algorithms in order to evaluate object position and orientation for supporting rendering graphics that is associated with the object. Such fiducial markers exist in many different forms: simple, such as pattern of small dots or complex, such as barcode elliptical or rectangular images. ARToolKit markers are one of the first popular fiducial marker systems, using square fiducial markers with a black exterior that enclose a unique image interior [5]. During operation, outer black square edges enable localization of a potential fiducial marker and then the potential marker interior allows identification of the marker from a set of expected markers. While using square markers, four corners of a located fiducial marker enable unambiguous evaluation of fiducial position and orientation relatively to a camera that is being calibrated.

This paper we briefly overview various fiducial marker systems and focus on comparing ARTag, AprilTag, and CALTag marker systems in presence of occlusion. As a benchmark, we use their reliability and detection rate in presence of occlusions of various types and intensity. The experiments were performed with a simple inexpensive Web camera. The rest of the paper if organized as follows. Section II describes ARTag, AprilTag, and CALTag marker systems in details, and briefly overviews a number of other marker systems. Sections III and IV present experiment design and experimental results respectively. Finally, we conclude in Section V.

II. FIDUCIAL MARKER SYSTEMS

Most markers, which are also often referred as tags, have a common design feature - an outlining square shape frame with a pattern image inside, which encodes information. The square shape is popular due to at least four special points (that correspond to the square corners) detection that allow camera calibration and marker position calculation with a help of a single tag. Majority of tags are made monochrome in order to reduce sensitivity to lighting conditions [6]. This way the need to identify shades of gray is avoided, and a *per pixel decision* is reduced to a threshold decision only. Many markers (e.g., ARTag), use some of their bits to encode redundant information that allows them to identify and correct errors while detecting and decoding.

In this section, we introduce ARTag, AprilTag, and CALTag marker systems. These markers have two stages of detection: unique features discovery and an identification (or recognition) stage [7]. For discovery stage, the marker square shape serves as a special feature. Identification stage checks the tag interior image to determine if the discovered image is a marker. The markers have different design, detection and recognition algorithms, which influence their advantages and drawbacks in different situations. Markers evaluation is performed applying such criteria as occlusion resistance (tag partial or complete overlap by other objects), inter-marker confusion (probability of confusion between the markers), resistance to lighting conditions changes, size of the marker (i.e., distance to marker) etc. [8]. Figure 1 demonstrates examples of ARTag, AprilTag, and CALTag.

A. ARTag

ARToolKit is a classical open-source visual tracking library that was released in 2004 (last public release date) and allows calculating orientation and position of a camera relatively to markers in real time being popular for projecting virtual objects, games, and animations onto a real world environment. ARTag is an alternative to ARToolKit fiducial marker system that was inspired by ARToolKit [8] and uses more complex data processing in order to increase reliability and light influence resistance. ARTag is supposed to replace ARToolKit due to improved 2D-based markers as it succeeds avoiding a known issue of its predecessor in detecting non-existing markers - i.e., false positive reporting on a marker detection at the locations where the markers do not present. New ARTag label uses a concept of squares with an internal image in it (a barcode), but the internal ARTag template processing is replaced by a digital approach of reading the internal pattern binary code.

ARTag system contains 2002 individual tags of square shape, which are featured by a black or white frame (1001 and 1001 respectively) with an image inside. It detects tags with edge points based approach: edge point detector finds edge pixels that form segments, which are then grouped into quadrilaterals. A tag internal image forms a 6x6 cell grid, which is composed of black and white cells, each representing 36 bit-values of "1" and "0" [9]. The sequence encodes first 10 bits (referred as the marker ID), while the remaining 26 bits (which are redundant) are used to detect and correct errors and to insure the uniqueness of the four possible marker orientations. For each of four possible marker orientations, a 10-bit sequence is extracted from the 36-bit set, but only one orientation could be further used for decoding as (other) wrong orientations would cause errors. The marker ID value is processed during the identification phase.

Figure 1. ARTag, AprilTag, and CALTag examples

B. AprilTag

AprilTag system by Edwin Olson [5] is applicable for a wide range of tasks, including camera calibration, robotics and augmented reality. AprilTag detection system calculates exact position, orientation and identity of a marker relatively to a camera. Representing a two-dimensional barcode, these tags look similar to QR code. However, AprilTag is designed to encode less data (4 to 36 bits), which allow quick and accurate detection of the tag.

The discovery process consists of several stages: searching for linear segments, detecting squares, calculating the position and orientation of the tag, decoding the barcode. Directed linear segments search uses similar to the ARTag approach, and then sequences of segments are processed to form a square. A square detection applies a recursive 4-level depth search and at each level, the tree adds one side of the square. At the identification stage the validity of the barcode inside the discovered tag is verified. To encode an internal picture, AprilTag uses a lexicode system characterized by two parameters: number of codeword (internal pattern) bits and minimal Hamming distance between any two codes. Lexicode generates codes for tags, which allows detecting and fixing bits' errors. AprilTag has several tag families that differ in two parameters: the number of bits to encode and the minimal Hamming distance. For example, "Tag36h11" means a 36-bit tag (6x6 array) with a minimal Hamming distance of 11 bits between any two codes; "Tag16h5" refers to a 16-bit tag (4x4 array) with a minimal Hamming value of 5 bits between any two codes.

AprilTag system is characterized by increased number of different codes (barcodes), increased number of bit errors that could be detected and corrected, reduced false positives and confusion between the tags, reduced total number of bits in the tag, and decreased tag size.

C. CALTag

After analysis of classical chessboard-based camera calibration and fiducial markers approach, CALTag marker was proposed as a specially designed for camera calibration solution [10]. This system consists of two components: marker design and detection algorithm. A calibration marker is used in a proposed calibration grid, which is externally identical to a chessboard. The tags layout within this grid has two variations on tags density.

A grid with a highest markers density provides a larger number of calibration points and is thus more reliable and efficient for recognition.

Each marker consists of MxN matrix of black and white squares, which are encapsulated with a border that contains strictly black or white pixels (Fig.1, right). After initial detection of potential markers, they are filtered and verified by accessing their binary codes. Any missed calibration points of the template are restored as the chessboard layout is known by CALTag system. The binary tag code is validated by calculating the first P bits checksum and comparing it with a checksum that is obtained from four possible marker positions.

D. Other Fiducial Marker Systems

There exist a large number of marker systems, and this section provides brief overview of other solutions. Some types of the described below markers are presented in Fig. 2.

ARToolKit Marker System, that was mentioned above, is a library in C and C ++ languages, which was originally created for augmented reality applications in industrial and scientific research in 1999. One of these applications was camera position and orientation evaluation in space relatively to the set of static tags. ARToolKit tag is a black bordered square shape with a user-defined image inside. By default, internal image contains icon "Hiro", which is the name of its inventor Hirokazu Kato from Nara Institute of Science and

Technology. ARToolKit uses a simplified marker detection algorithm and any detected potential marker is then matched against existing tag templates. If the marker is successfully mapped, it is accepted as valid and the value inside the black frame is decoded [11].

Hoffman Marker System (HOM) was originally developed in 1994 for camera calibration by Siemens and Framatome ANP to handle only static images [12]. The marker has a square shape with a main pattern for recognition inside, while an additional column on the right side of the marker improves its recognition. This tag was applied for 3D reconstruction and augmented reality applications using high-resolution images.

IGD Marker is a square that consists of 6x6 binary cells of equal size and each cell is colored black or white. 4x4 internal cells determine the marker orientation and position. It was used for industrial applications of augmented reality within ARVIKA research project [12].

SCR Marker is designed by Siemens Corporate Research to track objects movement. Each marker provides 8 relevant points for determining the object position [12]. SCR system has a low speed detection and retrieval of marker features within one frame, but provides high reliability in terms of accuracy and marker decoding.

ARToolKit Plus Marker is a newer version of ARToolKit that was inspired by ARTag design and technology. The marker uses the same principle of detection as the original ARToolkit, but differs in its approach to tag identification [7]. Although the marker looks similar to ARTag, the process of coding an internal image is completely different.

ReacTVision Marker is a system that was designed to track markers position and orientation in real time. It applies topological fiducial recognition, building a contiguity graph a binary image by a segmentation process. The segmentation algorithm determines the marker position and orientation, while the adjacency graph ensures the stability of markers tracking when markers move [13].

Circular Data Matrix Marker is a concentric circular marker, which is generated applying three basic criteria: unambiguous identification of marker points with high accuracy and speed, an ability to generate thousands of different variations of internal codes, and a high degree of reliability of marker recognition [14]. The structure of the tag is as follows: the first external ring is always black, the internal ring (in the center) consists of a black circle and a white dot in the center (an "eye"), while data rings in between are used to determine the marker orientation and contain its identification.

Data Matrix is a 2D barcode, which is a square shaped object and contains black and white cells arranged in a square or rectangular shape. It is capable of encoding text or numeric information and is widely used for manufacturing in electronics, automotive and defense industries.

CyberCode Marker pattern is designed to be recognizable with low-cost and mobile cameras. While the marker is targeted to determine the position of a marked object wit, it has a number of additional functions, including built-in links and application of the tag as a pop-up menu.

Projective Invariant Marker (PI-Tag) consists of a set of 12 arranged black dots on a white square background. The dots are located on the square perimeter, four points on each side, including the obligatory corner points. Such pattern is targeting to provide high level of occlusion resistance and a reduction of false positive detections. The algorithm for detecting and identifying the marker is considered effective and easy to implement [15].

III. EXPERIMENTS DESIGN

We performed experimental work in order to compare ARTag, AprilTag, and CALTag marker resistance to occlusion, which identified advantages and drawbacks of each system. We define occlusion is as a partial overlapping of the marker with other objects.

A. *Type 1 - Systematic occlusion*

Image capturing during experiments was performed with Genius FaceCam 1000X camera. It should be noted that a low quality camera for the experiments was selected on purpose in order to verify the tag capabilities for inexpensive hardware. For each marker we provided the same conditions of room illumination and camera posture with respect to the tag. To analyze the effect of occlusion on tag recognition, we selected four different ARTag tags, four AprilTag tags and two CALTag tags of with 4x4 and 9x6 grid size. Two types of experiments were conducted: systematic occlusion and arbitrary overlap with an object. A part of each tag was covered with a white paper template starting from the bottom so that the template was occluding *K%* of the marker's area, where *K* gradually increases while taking a value from the 5-values array [0, 10, 20, 50, 70]. Figure 3 demonstrates examples of AprilTag and CALTag occlusions for 10, 20, 50, 70 percent.

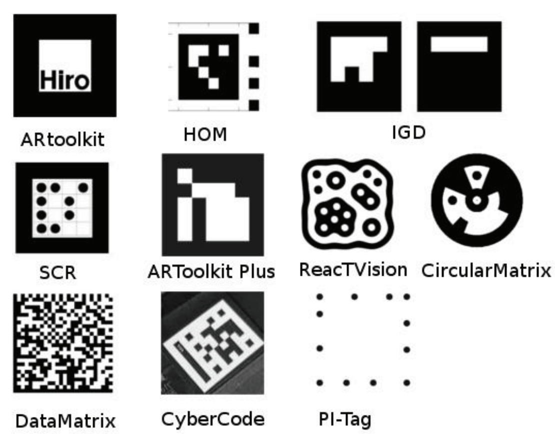

Figure 2. Variety of existing markers

B. *Type 2 - Arbitrary Overlap with an Object*

Each tag was randomly overlapped with one of two different objects so that an object was entirely located within tag's area and thus the overlap percentage was always kept constant. The first object was a white thick paper strip of 13 cm width and 2.5 cm length with 32.5 cm^2 area. The second object was a metal scissors with 7.99 cm^2 area. This way, for each experiment the constant overlap percentage was always known in advance. Figure 4 presents image set with arbitrary overlap of the ARTag ID2 with the strip object (top set of images) and the scissors (bottom set of images).

We emphasize a special case for the 4x4 size CALTag: if the strip is placed strictly along the marker side, the occupied area percentage decreases as strip's width exceeds marker size. In this case, the overlap percentage varies between 25.5% and 33.84%.

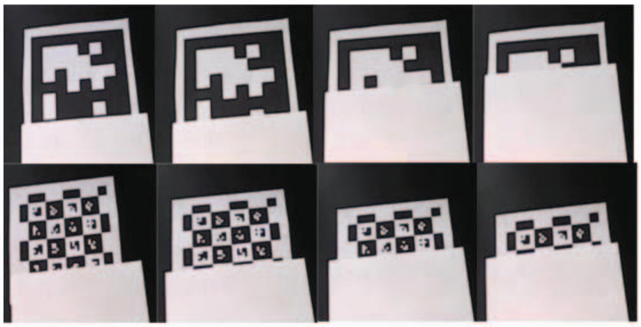

Figure 3. AprilTag (top set of images) and CALTag(bottom set of images) occlusion for 10, 20, 50, 70% (from left to right)

IV. Experimental Results

For the experiments, we applied the official software packages of AprilTag and CALTag, which are available for public use. For ARTag we used ArUco library, which allows detecting and recognizing various kinds of tag families [16].

The tags were printed on white paper with the following sizes:

- ARTag: 15.2 x 15.2 cm, total area 231.04 cm^2
- AprilTag: 13.5 x 13.5 cm, total area 182.25 cm^2
- CALTag 4x4: 9.8 x 9.8 cm, total area 96.04 cm^2
- CALTag 9x6: 21.7 x 14.7 cm, total area 318.99 cm^2

For experiments the ARTag (Fig. 5, top set of images) and AprilTag the particular marker IDs were selected randomly. Each tag has its own unique ID, which is encoded in the internal pattern of the tag. ARTag ID is encoded in 10 bits of 36 bits and it determines a unique bit sequence that passes through several stages to produce a 36-bit binary sequence, which is encoded in the marker as white and black cells [9].

For experimental work, all AprilTags were selected from "36h11" tags family, i.e., each of tag ID is encoded in a 36 bit codeword with a minimum Hamming distance of 11 bits; we have arbitrarily selected tags with IDs 4, 6, 8, and 9 (Fig. 5, bottom set of images).

It is important to emphasize that the two types of occlusion had slightly different experimental implementation. For Type 1 occlusion, which is reflecting a very typical real world occlusion situation, the object occluded the tag interior and the edges. As tag edges form a unique feature of the tag for its discovery, this type of occlusion influenced both tag discovery and tag recognition stages. Type 2 occlusion had the overlapping object completely within internal pattern of the tag, which effected only on the recognition stage of tag pattern detection.

The experimental results are summarized in Tables I-IV. Table I presents the results of Type 1 occlusion experiments. "1" marks successfully detection of the tag, while "0" means that the application failed to detect the tag. ARTag and AprilTag demonstrated particular sensitivity to tag edges overlapping. Edge overlapping disables tag unique feature (edge) detection, which in turn resulted into a failure of tag discovery stage.

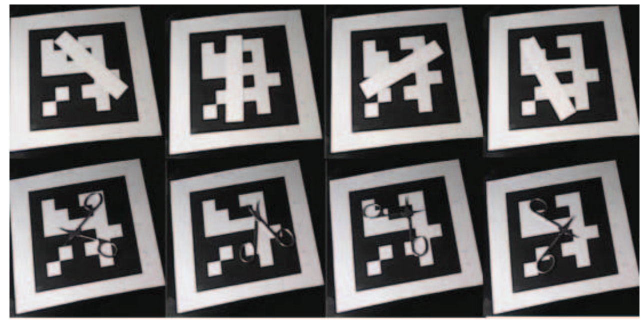

Figure 4. Arbitrary overlap of the ARTag ID2 with the strip object (top set of images) and the scissors (bottom set of images)

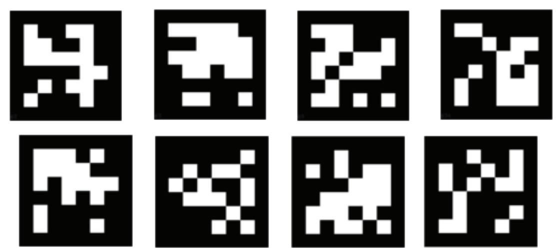

Figure 5. ARTag with IDs 2, 3, 6, 34 (top set of images, from left to right), AprilTag with IDs 4, 6, 8, 9 (bottom set of images, from left to right)

Additional experiments confirmed that these markers could be discovered only in a case of minimal occlusions of their edges. CALTag was the only marker that was resistant to edge occlusions, which could be explained by its detection algorithm approach. When a part of the CALTag grid is occluded, not all calibration grid marks are required to be detected [10]. CALTag 9x6 was successfully detected with 50% of its area being occluded, while CALTag 4x4 was successfully detected with a 70% occlusion. Thus, CALTag system showed to be more adapted for real situations with partial visibility of the tag.

Table II demonstrates the results of Type 2 occlusion experiments for a strip object. As the tags have different sizes while the strip size is constant, the percentage of occluded tag area differs between the tags. During an experiment, the strip was arbitrarily placed within an internal part of the tag. For each tag, four experiments were performed so that the position of the strip on the tag was different in each experiment. The white color of the strip makes it difficult to read binary code of the tag, because all of tags consist of monochrome colors and the we used an inexpensive camera for the experiments. A special case was CALTag 4x4 tag, because due to its small size the overlapped by the strip area varied from 25.5% to 33.84%. Particular values of the overlap (percentage) for each of the four experiments are listed in Table III. In all four experiments, CALTag 4x4 was successfully detected. While ARTag and AprilTag were not resistant to this type of occlusion, both CALTag markers were recognized at any position of the strip due to markers' design and recognition algorithm.

TABLE I. RESULTS OF TYPE 1 OCCLUSION EXPERIMENTS

Tags	**Occlusion percent**				
	0%	***10%***	***20%***	***50%***	***70%***
ARTag (ID 2)	1	0	0	0	0
ARTag (ID 3)	1	0	0	0	0
ARTag (ID 6)	1	0	0	0	0
ARTag (ID 34)	1	0	0	0	0
AprilTag (ID 4)	1	0	0	0	0
AprilTag (ID 6)	1	0	0	0	0
AprilTag (ID 8)	1	0	0	0	0
AprilTag (ID 9)	1	0	0	0	0
CALTag 4x4	1	1	1	1	0
CALTag 9x6	1	1	1	0	0

TABLE II. RESULTS OF TYPE 2 OCCLUSION EXPERIMENTS WITH A STRIP OBJECT

Tag	**Occlusion percent**	
	Occlusion percent (%)	***Success rate***
ARTag (ID 2)	*14.06*	*0*
ARTag (ID 3)	*14.06*	*0*
ARTag (ID 6)	*14.06*	*0*
ARTag (ID 34)	*14.06*	*0*
AprilTag (ID 4)	*17.83*	*0*
AprilTag (ID 6)	*17.83*	*0*
AprilTag (ID 8)	*17.83*	*0*
AprilTag (ID 9)	*17.83*	*0*
CALTag 4x4*	*25.5 – 32.5*	*100*
CALTag 9x6	*10.18*	*100*

Table IV shows the results of Type 2 experiments for scissors object. For 16 experiments with ARTags only one failure occurred, while for AprilTags the number of failures within 16 experiments increased to 2. Yet, both CALTag markers were successfully recognized in all trials.

TABLE III. RESULTS OF TYPE 1 OCCLUSION EXPERIMENTS WITH A STRIP OBJECT FOR CALTAG 4X4 MARKER

Occlusion percent in different experiments (%)			
Trial 1	Trial 2	Trial 3	Trial 4
30.25	*25.64*	*27.66*	*26.4*

TABLE IV. RESULTS OF TYPE 2 OCCLUSION EXPERIMENTS WITH A SCISSORS OBJECT

Tag	***Occlusion percent in Experiments (%)***				***Success Rate (%)***
	1	**2**	**3**	**4**	
ARTag (ID 2)	*3.45*	*3.45*	*3.45*	*3.45*	*100*
ARTag (ID 3)	*3.45*	*3.45*	*3.45*	*3.45*	*75*
ARTag (ID 6)	*3.45*	*3.45*	*3.45*	*3.45*	*100*
ARTag (ID 34)	*3.45*	*3.45*	*3.45*	*3.45*	*100*
AprilTag (ID 4)	*4.38*	*4.38*	*4.38*	*4.38*	*100*
AprilTag (ID 6)	*4.38*	*4.38*	*4.38*	*4.38*	*50*
AprilTag (ID 8)	*4.38*	*4.38*	*4.38*	*4.38*	*75*
AprilTag (ID 9)	*4.38*	*4.38*	*4.38*	*4.38*	*75*
CALTag 4x4	*8.32*	*8.32*	*8.32*	*8.32*	*100*
CALTag 9x6	*2.5*	*2.5*	*2.5*	*2.5*	*100*

V. CONCLUSIONS AND FUTURE WORK

In this paper, we presented a brief overview of existing solutions for camera calibration with different marker systems. We conducted experiments with three types of fiducial marker systems – namely, ARTag, AprilTag and CALTag – in order to evaluate their sensitivity to different types of occlusion. The purpose of the experiment was to analyze the weaknesses and strengths of each tag with regard to partial marker occlusion. ARTag and AprilTag markers demonstrated high sensitivity to edge occlusions, which limits their effective use only for the cases where it could be guaranteed that no edge occlusions occur. These markers performed at satisfactory level for the cases when the object occluded only the internal part of the tags, and their detection rate varied between 50 to 100% for different tag IDs.

CALTag showed a significantly better occlusion resistance for both cases of systematic and arbitrary occlusions, including edge occlusions. For systematic occlusions, CALTag successfully performed even with 50% of the tag being occluded. Among the two variations of CALTag markers, CALTag 4x4 demonstrated better occlusion resistance, and thus we conclude that this tag should be selected if we expect significant systematic occlusions of the tags, which reflects typical real world scenarios.

As a part of our future work, we plan to conduct occlusion resistance experiments using different quality cameras and to identify the strengths and weaknesses of the markers using an increased set of criteria, which includes inter-marker confusion, resistance to lighting conditions changes and influence of marker size (or distance to a marker). We consider to enlarge the set of evaluated markers and to significantly increase the number of experiments for better statistical analysis, to add rotations of the markers in different planes and to utilize various real-world scenario backgrounds instead of a uniform laboratory background. Special attention will be paid to the behavior of CALTag 4x4 marker, which have demonstrated the best performance in our current empirical research. As the long term goal of our research targets for a best tag selection, which will be further applied for humanoid robot vision-related applications, the later stages of experimental work will include verification of the tags with AR-600 robot hardware [2] in both laboratory and real-world environments.

Acknowledgment

This work was partially supported by the Russian Foundation for Basic Research (RFBR) and Ministry of Science Technology & Space State of Israel (joint project ID 15-57-06010). Part of the work was performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

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