FIDUCIAL MARKER SYSTEMS OVERVIEW AND EMPIRICAL ANALYSIS OF ARUCO, APRILTAG AND CCTAG

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The present paper advances an overview and comparison of existing fiducial marker systems. A fiducial marker is a 2D symbol that can be printed on a sheet of paper and glued to any flat surface to add distinctive characteristics to an environment. A system of fiducial markers consists of a set of unique fiducial markers that contain information and an algorithm that can recognize and process the respective information using images and videos. This paper describes an evaluation of the ArUco, AprilTag, and CCTag marker systems. With the help of a minimalist hardware system, we obtained a data set consisting of 13200 images. Based on the data set, we evaluated the three marker systems according to the following criteria: the distance between the camera and the marker, the intensity of light, the movement speed of the camera, the resistance to occlusion, and the performance of the algorithms. The results obtained show that ArUco is the fastest, detecting the marker in 2 ms. *Furthermore, the results illustrate that the CCTag is resistant to occlusion and performs very well in scenarios that simulate real-time detection, that is, scenarios with blurred pictures.*

Keywords: fiducial markers, ArUco, AprilTag, CCTag, experimental comparison, occlusion test

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1. Introduction

A fiducial marker is a 2D symbol (or a tag) that can be printed on a sheet of paper and stuck on any flat surface to add distinctive characteristics to an environment. A system of fiducial markers consists of a set of unique markers

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and an algorithm that can recognize them in images and videos. These marker systems are used in various fields: localization, tracking, robotics, camera calibration, position estimation [1], orientation, landing and automatic control for drones [2], and augmented reality [3].

Most of the existing marker systems are based on monochrome fiducial markers, composed of a black square inside which there is relevant information coded as 0 and 1 in terms of black and white. The most common example is a marker system using a QR code. However, there are alternatives such as marker systems using circular markers [4] or chromatic markers [5].

The present paper seeks to compare the performance of three fiducial marker systems: ArUco, AprilTag, and CCTag. The motivation for this experiment emerged following the state-of-the-art analysis concerning fiducial marker systems. Section 2 of the current work provides an overview of the fiducial marker systems analyzed, as well as the results of various experiments identified in the literature that sought to compare the performance of these systems. Section 3 expands on the motivation, materials, and methods of the current work. Section 4 presents the results of the comparison between ArUco, AprilTag, and CCTag. Section 5 describes the conclusions of the current work.

2. State of the art

2.1. Overview of marker systems

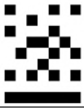
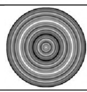
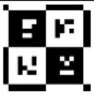
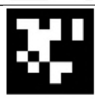
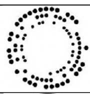
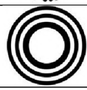
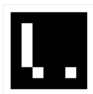
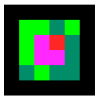
Multiple fiducial marker systems have been proposed in the literature. Table 1 provides an overview of the analyzed marker systems by presenting their name, the year of their first publication, an example of the fiducial markers, and the area of application. The marker systems in the table are ordered in ascending order by the year of appearance.

ARToolKit is the first and one of the most widespread marker systems used in augmented reality. It was first described and used by Hirokazu Kato and Mark Bilinghurst in 1999 [6]. The marker is represented by a white square with a black border in the middle of which various symbols or images can be added. The property of customizing the marker with various symbols has advantages and disadvantages. One advantage is that the marker is more easily distinguishable from classic black-and-white markers. A disadvantage is that the customized images inserted in the marker make detection difficult and increase the rate of false-positive detections [15].

ARTag, created by Fiala [8], is also among the first marker systems used in augmented reality. Unlike ARToolKit, ARTag uses an array of black and white squares. The black and white squares are interpreted as 0 and 1 by the detection algorithm. With this modification, it manages to improve the detection rate of the marker, so that ARTag achieves a better performance than ARToolKit and ARToolkit Plus [16].

Edwin Olson [11] re-imagined the ARTag marker system to be used for a wider range of applications so that, in addition to augmented reality, it

TABLE 1. Fiducial marker systems

Marker	Year	Marker example	Used in
ARToolkit [6]	1999		Augmented reality
Cybercode [7]	2000		Augmented reality
ARTag [8]	2005		Augmented reality
FourierTag [9]	2007		Robotics, Virtual reality
CALTag [10]	2010		Camera calibration
AprilTag [11]	2011		Augmented reality, Camera calibration, Robotics
Rune-Tag [12]	2011		Localisation, position estimation
CCTag [13]	2012		Camera calibration
ArUco [14]	2014		Augmented reality Camera calibration, Robotics
ChromaTag [5]	2017		Robotics

could also be used in camera calibration and robotic research. This led to the development of a new detection algorithm named **AprilTag** that is faster than ARTag.

The **ArUco** marker system is similar to AprilTag. It also uses a marker represented by a square shape, with information coded in black and white. It was developed by S. Garrido-Jurado, R. Muñoz-Salinas, F. J. Madrid-Cuevas et al. in 2014 [14] and further developed in 2016 [17]. The detection algorithm of ArUco is open-source, a fact that led to the use of this marker system on a large scale. Additionally, it allows the generation of markers of smaller or larger sizes, based on needs. As small markers have less information, this leads to improved performance of the detection algorithm.

Finding a loss of time in false positive detections for monochromatic tags, Joseph DeGol et al. [5] introduced the **ChromaTag**. This marker system is based on a chromatic marker. It is specifically implemented to reduce the number of false positive detections. The marker is characterized by a red interior, followed by a green border, another black border, and another white border. The last two borders are used to precisely locate the corners of the tag. Other notable systems that use square-shaped fiducial markers are **Cybercode** [7] and **CALTag** [10].

However, systems based on square-shaped markers are limited by their ability to deal with image distortion and marker coverage by other objects in images. As a response, marker systems based on circular fiducial markers were advanced [18]. For example, the marker of the **Rune-Tag** [12] system consists of small circles arranged in a circular shape. It was first developed in 2011. The most common applications of this system are in location and position estimation. The main advantage of this system is resistance to occlusion.

The **CCTag** [13] is another marker system based on a circular-shaped marker. The marker consists of three concentric circles of different radii. Unique markers are obtained by changing the thickness of the circles. The most common application for this system is camera calibration. Yet another similar circular marker system is the **FourierTag** [9] marker system. In contrast to other fiducial marker systems, FourierTag allows for a gradual degradation of the number of data bits that can be extracted, thus allowing for better detection at distance.

2.2. Comparison of marker systems performance

In 2005, Mark Fiala [8] proposed a new type of marker system named ARTag. To convince of the utility and performance of ARTag, Mark Fiala compared ARTag with other existing systems: Data Matrix, Maxicode, QR Code, ARSTudio, and ArToolkit. There were several metrics taken into account for the comparison: the false positive rate, the inter-marker confusion rate, the false negative rate, the minimal marker size, the immunity to lighting conditions. During the experiments, it was concluded that Data Matrix, Maxicode, and QR Code are not good alternatives for augmented reality because they have poor performance in detecting at long distances, they are prone to distortions, and they do not allow 3d pose estimation. Therefore, the ARTag was compared only with ARToolkit, this being another system created specifically for augmented reality. The results of the experiments revealed that ARTag had a lower rate of false positives, false negatives, and inter-marker confusion when compared to ARToolkit. In a subsequent article, Fiala compared ARTag with ARToolkit Plus (an improved version of ARToolkit) [16]. The conclusions of this second analysis further endorsed the performance of the ARTag when compared to the improved version ARToolkit Plus.

Filippo Bergamasco et al. [12] compared their marker system, named Rune-Tag, with ARToolkit and ARToolkit Plus. Based on their analysis, it appears that Rune-Tag offers a higher accuracy for position estimation tasks.

Moreover, the circular design of the marker in the Rune-Tag system places Rune-Tag at an advantage over ARToolkit regarding resistance to occlusion. In this sense, Filippo's system can detect the marker with 2/3 occlusion of the image.

Another system based on an occlusion-resistant circular marker is the CCTag. It was compared with RuneTag and ARToolKit Plus [19]. The results of the comparison illustrated that the CCTag had the highest detection rate of all in terms of distance, occlusion, and motion blur.

ArUco and AprilTag were compared based on metrics such as light variation, floor pattern, image blur level, and detection distance [18]. ArUco and AprilTag had similar performances in tests of light variations and floor patterns, regardless of the size of the tag. However, the two systems registered slightly different performances in terms of speed and flexibility. AprilTag was faster than ArUco, while ArUco was more flexible in generating the desired tag.

The ChromaTag marker system was compared with AprilTag, Rune-Tag, and CCTag [5]. ChromaTag was faster in marker detection by up to 13 times, compared to the next ranked. CCTag had the slowest detection algorithm, up to 180 times slower than ChromaTag and 13 times slower than AprilTag. The comparison between these systems also revealed that ChromaTag should be used when the task involves detecting a marker from a short distance and positioned perpendicular to the camera, while AprilTag should be used when the task involves detection from a greater distance or a sharp angle.

Often used in Unmanned aerial vehicle (UAV) applications, the AprilTag, ARTag, and ArUco were also compared in terms of performance [1]. Regarding distance variations, AprilTag had the best detection rate, while ARTag had the lowest. For orientation variations, AprilTag and ArUco detected the marker in 90% of cases, while ARTag only in 45%. Regarding computational costs, AprilTag had the highest cost, while ARTag had the lowest cost.

Francisco J. Romero-Ramirez et al. [20] proposed a new approach for the ArUco marker, resulting in a new project called ArUco3. Their approach consists in detecting the marker not in the original image but in an image smaller than the original. The image being smaller, implicitly there is less information in it, so the algorithm can detect the marker faster. The results revealed that ArUco3 was 17 to 40 times faster than ArUco (the variant implemented in the OpenCV library). Additionally, ArUco3 was faster than AprilTag and ARToolkit, say the authors. Moreover, the same experiments revealed that ArUco was faster than AprilTag. and ARToolkit.

3. **Comparison methods**

We have identified three widely used, open-source, easy-to-use fiducial marker systems which have not been compared. In the previous section, we presented a comparison between AprilTag and ArUco in 2016 [18], where AprilTag had better results than ArUco. Then, in 2017, an article comparing AprilTag and CCTag revealed that CCTag had a poorer performance in terms of the algorithm running time, but a better performance in the detection rate [5]. If in 2016 the performance of AprilTag was better than ArUco, and in 2017 the performance of CCTag was better than AprilTag, it then follows, by transitivity, that the performance of CCTag is better than ArUco. But in the previous section, we also detailed another comparison from 2018 between ArUco and AprilTag, where the algorithm that performed better was ArUco [20]. Thus, not only that our assumption above falls, but we can also say that ArUco had received improvements regarding the algorithm embedded in the marker system. This gives us the opportunity to investigate and compare the performances of the ArUco, AprilTag, and CCTag.

Setup: Before making the setup, we took into account the fact that we needed to change the marker, the distance between the camera and the marker, the light, and the exposure time. Thus, three 10 cm x 10 cm size markers were printed on separate A4 sheets of paper. The paper sheets were glued to a piece of PFL (fiberboard), and the PFL was glued to a tripod, which made it easy to position and move. Furthermore, to adjust the distance between the camera and the markers, we also positioned the camera on a second tripod as in Figure 1. The advantage of this setup is that it can be moved anywhere, thus allowing the change of the background and the distance of the camera from the marker.

(A) Right view (B) Center view (C) Left view

FIGURE 1. Setup

Dataset: In order to obtain a suitable data set for our purpose, we first sought to understand how similar images were collected by others. Michail Kalaitzakis et. al [15] built a special stand where the marker could be rotated to the desired angle vertically or horizontally. They also used, among others, a Raspberry Pi 3B and a piCam camera to take pictures. Francisco J. Romero-Ramirez et al. [20] used the mobile phone to take short videos in which they approach and move away from the marker, totaling a data set of 10666 pictures.

Taking into account the previous work, we chose to collect the data using a camera and a servo motor connected to a Raspberry Pi 4B. The servomotor was used to obtain blurred images. We chose to print the markers each on a different sheet like Michail Kalaitzakis et. al [15] and Sagitov [21]. In creating the data set, we used markers whose id is 10, and the family to which they belong is as follows, in Table 2.

TABLE 2. Tags and their categories

Marker	ID	Symbol	Category	Dimension of the marker
ArUco	10		DICT_6X6_50	10 cm x 10 cm
AprilTag	10		tag36h11	10 cm x 10 cm
CCTag	10		N/A	10 cm x 10 cm

The data set was divided into two scenarios: with a fixed camera at a distance of 50, 100, 150, 200, and 250 cm from the marker, and with a moving camera that moved with a certain speed on the Z axis of the servo motor. Also, for each parameter that changed, we took 20 pictures. The size of the three markers was the same, namely 10 cm x 10 cm. In the end, by varying the distance, the light, the exposure time, and the speed of the camera, we managed to create a vast data set, collecting a total of 13200 pictures.

First Scenario - Fixed camera Considering the fixed camera, positioned perpendicular to the center of each marker, the following parameters were modified: the distance of the camera from the marker, the light, and the marker. For these scenarios, we kept the exposure time constant at 3000 microseconds. The distances from the marker were 50, 100, 150, 200, and 250 cm. The pictures were taken in 2 different light conditions, approximately 100 and 500 lx. Figure 2 illustrates the images for the AprilTag marker at all the 5 mentioned distances with an exposure of 3000 µs, taken in a room where the light intensity, measured with the mobile phone, was around 500 lx.

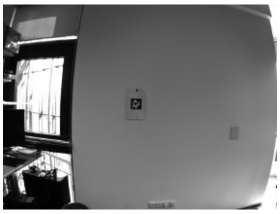
The impact of the two light intensities on the photos taken can be seen in Figure 3, where the AprilTag marker is illustrated in "light" conditions (500 lx) and in "dark" conditions (100 lx), and the distance of the camera from the marker is 50 cm.

Second Scenario - Moving camera The moving camera scenario involved the use of a servomotor with a certain angular speed to move the camera. This scenario was created to test how the detection algorithms behave on blurry, distorted pictures.

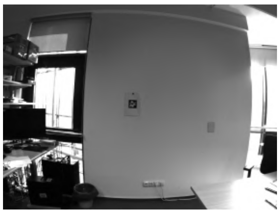
For this type of scenario, we added the parameters, namely the exposure time between 1000 µs and 18 000 µs, and the angular speed of the camera,

(A) 50 cm

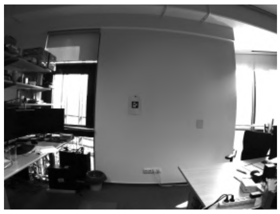
(B) 100 cm



(C) 150 cm



(D) 200 cm



(E) 250 cm

FIGURE 2. Apriltag, distance variation, *light intensity* = 500 lx

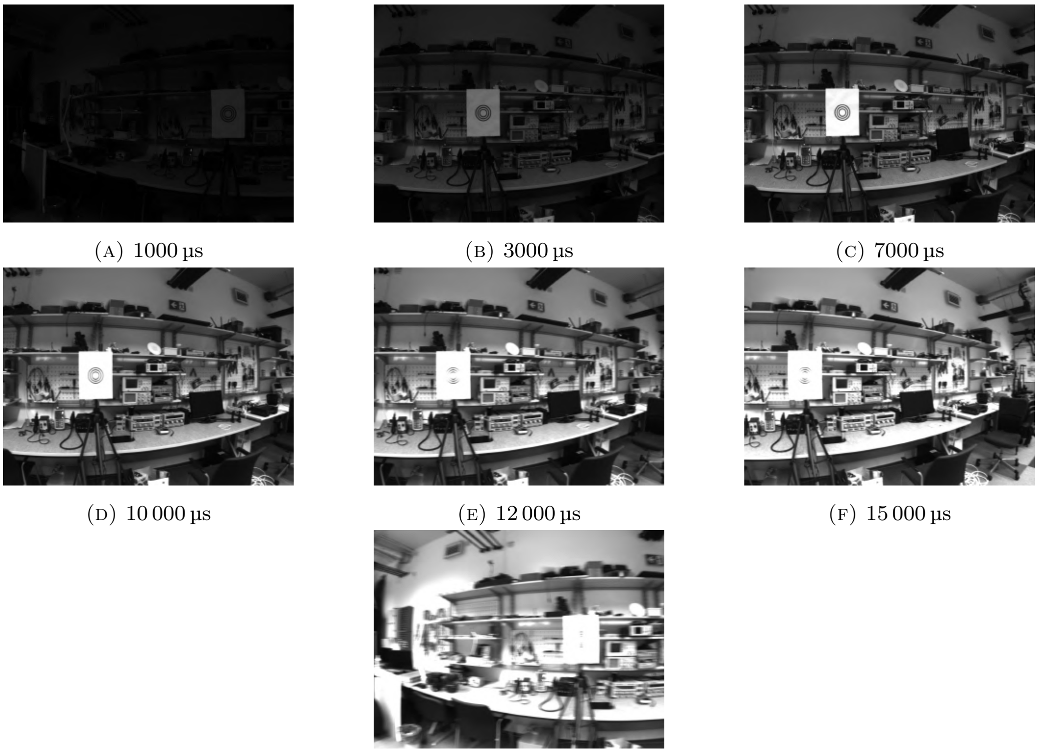
(A) Light (500 lx, 50 cm)

(B) Dark (100 lx, 50 cm)

FIGURE 3. Apriltag, light variation

varying from 45 °/s to 180 °/s. The distance only took values of 50, 100, and 150 cm. To exemplify, Figure 4 illustrates an image of the CCTag tag at 100 cm, the light intensity of 325 lx, and the speed of 45 °/s. As the speed at which the servo motor moves increased, we expected to see more blurred pictures. To see what happens at variable speed with the ArUco tag, we chose an exposure time of 10 000 µs, distance 50 cm, and dark light 170 lx. The results can be found in Figure 5.

The two most common criteria for comparing fiducial marker systems are performance, i.e. how long the algorithm can detect a marker, and detection rate, i.e. in what percentage of images it succeeds in finding the marker. These 2 criteria were also proposed by DeGol et. al [5] in the work on ChromaTag, and in Delfa et al. [18]. A separation of the analysis according to light and speed of movement was also conducted. Thus, based on the data set that we obtained with the help of the setup presented above, and taking into account the evaluation criteria from other articles, we decided to evaluate the three marker systems using the following criteria: the immunity of the algorithms to variations in the distance of the camera from the marker, light, camera movement speed, occlusion resistance, and algorithm performance.

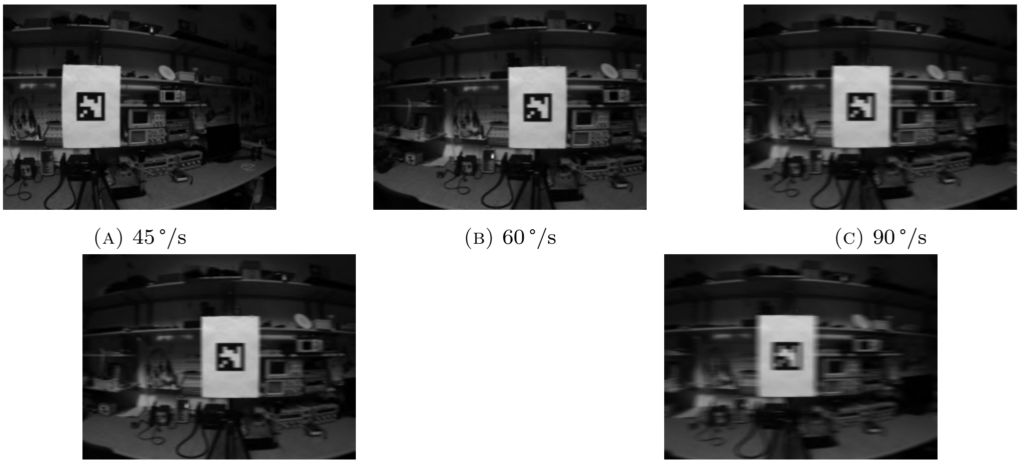


(A) 1000 µs (B) 3000 µs (C) 7000 µs

(D) 10 000 µs (E) 12 000 µs (F) 15 000 µs

(G) 18 000 µs

FIGURE 4. CCTag: exposure time variation; *light intensity* = 325 lx, *distance* = 100 cm, *speed* = 45 °/s



(A) 45 °/s (B) 60 °/s (C) 90 °/s

(D) 135 °/s (E) 180 °/s

FIGURE 5. ArUco: speed variation; *light intensity* = 170 lx, *distance* = 50 cm, *exposure time* = 10 000 µs

4. **Results**

The algorithms for each marker system were run on a Linux 18.04 system installed on an HP ProBook 440 G4 Notebook PC with the following specifications:

- Intel Core i7-7500U Intel HD Graphics 620,
- 2.7 GHz, up to 3.5 GHz with Intel Turbo Boost technology,
- 4 MB L3 cache.

4.1. Distance variation

The data set contains pictures where the distance between the marker and the camera is from 50 to 250 cm, and the size of the markers is 10 cm x 10 cm. To see how the algorithms of each marker system compare at various distances, we ran and presented the results obtained in Table 3.

TABLE 3. Results by distance

Marker	Type of image	Distance (cm)	No. of frames	No. of detection	Detection rate
ArUco	Fixed	50 - 250	200	200	100%
	Moving	50	1391	901	64,35%
		100	1400	699	49,92%
		150	1400	598	**42,71%**
AprilTag	Fixed	50 - 250	200	200	100%
	Moving	50	1400	821	59,02%
		100	1400	640	45,71%
		150	1400	518	37%
CCTag	Fixed	50 - 200	200	200	100%
		250	200	75	37,5%
	Moving	50	1400	1045	**74,64%**
		100	1400	786	**56,14%**
		150	1400	581	41,5%

For moving pictures, we observed that CCTag had the highest detection rate for 50 and 100 cm, with a percentage of 74.64% and 56.14%, respectively. In addition, we noticed that on the distance of 250 cm, we did not manage to obtain a 100% performance as with ArUco and AprilTag. We can therefore conclude that the maximum detection distance of the CCTag markers is 200 cm between the camera and the marker, at the size of the marker of 10 cm x 10 cm.

4.2. Intensity of light variation

In order to determine the performance of the three systems considering variations in light intensity, we analyzed two situations, the first with artificial light from the laboratory turned on, called light (325 lx), and the second without artificial light, called dark (175 lx). Considering the results based on distance, we decided that there was no need to run and display the results for the fixed images anymore.

In Table 4 we see there was a small difference between dark and light conditions on all 3 systems, with a surprise that CCTag had a higher detection rate in dark conditions; and a lower detection rate in light conditions. This is due to the fact that we started from a small exposure of 1000 microseconds and went up to 18 000 µs. That is, long exposures of 15 000 − 18 000 µs disadvantage light pictures and advantage dark ones in the CCTag system.

TABLE 4. Results according to light intensity on moving pictures

Marker	Light intensity	No. of frame	No. of detection	Detection rate
ArUco	Dark	2100	1069	50,90%
	Light	2100	1129	53,76%
AprilTag	Dark	2100	922	43,90%
	Light	2100	1057	50,54%
CCTag	Dark	2100	1331	63,38%
	Light	2100	1081	51,47%

4.3. Angular velocity variation

In this subsection, we focus only on the pictures taken while the camera was moving using the servo motor at five different speeds: 45, 60, 90, 135, 180 °/s; with 840 pictures per each speed.

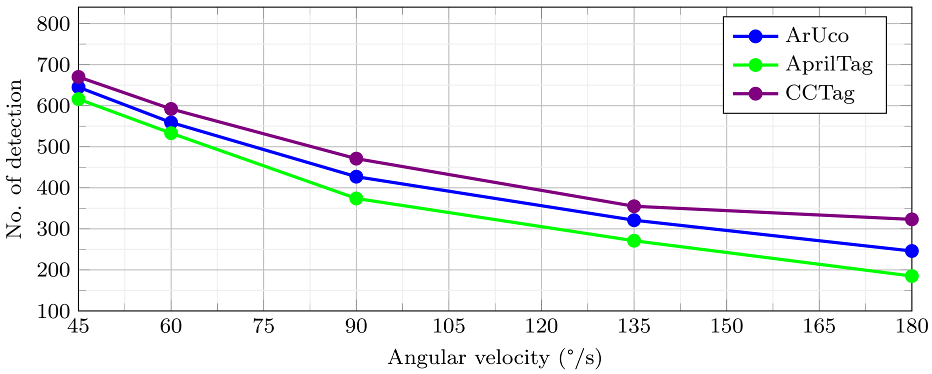


FIGURE 6. Results according to angular velocity variation

What we noticed from the results was that as the speed increases, the detection rate of all markers decreases, which is expected because the higher the speed, the more blurry the pictures become. The second thing we noticed is that throughout all the runs, the markers have kept their place in the hierarchy, thus AprilTag had the lowest detection rate of all three, followed by ArUco and CCTag. The first place with the best detection rate was CCTag. If at the speed of 45 °/s the scores concerning the number of detected markers were relatively close (CCTag = 670, ArUco = 645, AprilTag = 616), there were higher disparities at the speed of 180 °/s(CCTag = 323, ArUco = 246, AprilTag = 185). Regarding the latter scenario, it can be observed that CCTag detected almost twice as much as AprilTag.

4.4. Resistance to occlusion

To test the resistance to occlusion, we took a picture where the marker was alternately covered on its left, right, top, and bottom half with a blue square. The pictures, as well as the results of the detection algorithms for the three systems, are presented in Figures 7, 8, 9. The figures illustrate that

AprilTag and ArUco were not immune to occlusion: when an object appeared in front of the marker, the algorithm stopped detecting the marker. On the contrary, CCTag was able to successfully detect 3 out of 4 pictures. This made us conclude that CCTag is resistant to occlusion. Moreover, we also identified this as the reason why it had the highest detection rate in previous tests on moving pictures. When the pictures are moved, the entire marker is no longer visible, but only a part of it, as if it was hidden behind an object.

FIGURE 7. Apriltag in occlusion test

FIGURE 8. Aruco in occlusion test

FIGURE 9. CCTag in occlusion test

4.5. Performance of algorithms

To analyze the performance of the algorithms, we started a clock just before calling the detection function and stopped it immediately thereafter. We ran the algorithms of the three systems on the fixed data set separately from the moving set and averaged how long it took for the algorithms to detect whether or not there is a marker in a picture.

TABLE 5. Performance of the algorithms

Marker	Type of image	Run time(s)	Slower than ArUco	Fixed / Moving
ArUco	Fixed	0,002100	-	-
	Moving	0,002872	-	1,36
AprilTag	Fixed	0,009641	4,59	-
	Moving	0,011441	3,98	1,18
CCTag	Fixed	0,123745	58,92	-
	Moving	0,160017	55,71	1,05

The marker system with an outstanding 2 ms performance was ArUco, which we then used as a benchmark for the other 2 systems. Dividing the running time of AprilTag by the running time of ArUco, we concluded that AprilTag was about 5 times slower than ArUco on still images and about 4 times slower on moving ones. CCTag had a rather low performance, respectively 58 and 55 times slower than ArUco.

5. Conclusions and further work

After comparing the performance of the three fiducial marker systems using multiple criteria, we can conclude that CCTag can be used with confidence in real-time detections and detections involving occlusion. However, ArUco is a better alternative when only detection speed is considered. The latter obtained the best running time of only 2 ms. AprilTag also performed well on various metrics, but not as well as CCTag and ArUco. It should also be noted that neither AprilTag nor ArUco are occlusion resistant: if an object covers part of the fiducial marker, the algorithms no longer detect the marker.

CCTag is a fiducial marker system that has special properties, properties such as an outstanding detection rate on blurred pictures or resistance to occlusion. However, the performance of the algorithm in terms of run time is rather low. Therefore, further work will focus on a deeper understanding of the algorithm behind the CCTag fiducial marker system with the aim of improving its runtime performance.

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