A High-Accuracy 2D Visual Marker for Dexterous Manipulation Robot in Space

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Abstract

This paper describes developmental results of a new high-accuracy 2D visual marker for space application. It shows the results of experiments to evaluate the space environmental tolerance of the previous visual marker. It also shows the new redesigned marker based on the experimental results in conjunction with evaluation results of pose and position estimation by image processing. This new marker has the equivalent performance of pose and position estimation to the previous visual marker. This accurate, planar and space environmental tolerant visual marker will contribute to various space missions which require highly accurate position and pose estimation such as dexterous manipulation in space.

1 Introduction

A space robot requires precise position and orientation between the robot hand and the target to execute dexterous manipulation. Visual marker is known as an effective way for estimating position and orientation, and they are used in actual space proximity operations such as spacecraft rendezvous and docking and on-orbit servicing robot [1]. Many of the visual marker in space have three-dimensional (3D) structures such as a grapple fixture visual target with a protruded rod at the center of black plate which has been used for a robot arm operation in the International Space Station. The 3D structure of such markers, however, has a limitation of the installation location due to its protrusion shape in terms of safety and space limitation. On the other hand, two-dimensional (2D) marker such as AR marker which is widely used in terrestrial application, for example a field of robotics and Augmented Reality, has less limitation of the installation location than 3D marker, but its planar form limits ability to estimate the orientation accurately, and therefore restrict its use in space operation [1][2]. Thus, there is a need for a new approach to design visual markers for dexterous manipulation robots in space (See Figure 1). Such marker should have a planar form without protrusion unlike conventional 3D markers in space operation, and enable more accurate pose estimation than conventional 2D markers and also have high-tolerance property to harsh conditions in space environment.

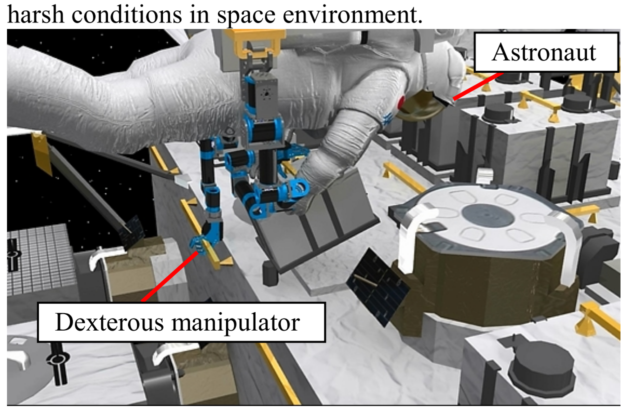

Figure 1. Our proposing space dexterous manipulation robot which is attaching to a spacesuit and needs a measure of estimating accurate pose and position of targets for dexterous manipulation

The National Institute of Advanced Industrial Science and Technology in Japan developed a novel visual marker “ArrayMark” (microlens Array-based 2-D moiré pattern Marker) which utilizes moiré pattern created by superimposing microlens array and crisscross patterns. The marker allows more precise pose estimation than conventional 2D marker [2]. The marker also has less limitation of the installation location for safety and space limitation because of the planar structure unlike conventional 3D marker. ArrayMark is expected to resolve problems of conventional 2D and 3D markers. We implemented space-environment protection measures to ArrayMark and developed the new 2D visual marker (See Figure 2) for space application.

This paper shows the developmental results of the new space environmental tolerant high-accuracy 2D visual marker. In the following sections, the previous visual marker, the evaluation results of space environmental tolerance of the previous marker, the new marker design which implements space-environment protection measures, and the pose and position estimation performance results of the new visual marker are described.

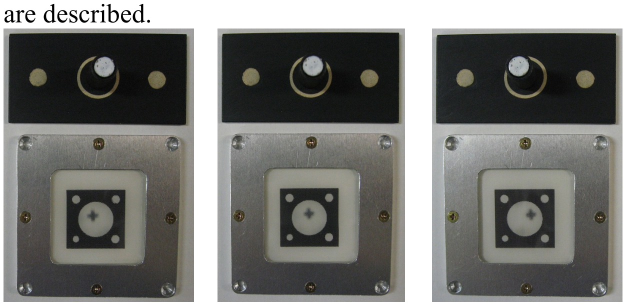

Figure 2. A high-accuracy 2D visual marker for space use and a 3D marker used in ETS-7 (Engineering Test Satellite) for comparison

2 2D Visual Marker "ArrayMark"

2.1 Design and Principle of ArrayMark

The design of ArrayMark is shown in Figure 3. It has four reference points which are used for pose estimation and image transformation. One reference point is smaller than the other points in order to distinguish the marker direction. The two-dimensional (2D) moiré pattern is displayed in the center circle. Figure 4 shows the structure of the center circle. Many small crisscrosses are printed on the back of a mirolens array. Figure 5 is a schematic diagram explaining the principle of the movement of the pattern. Each lens magnifies a different part of a small crisscross. The visible crisscross appearing in the center circle is an integrated image of many magnified parts of the crisscrosses. It is generated by 2D moiré effect. We use the mechanism to know a two-dimensional visual-line angle [2].

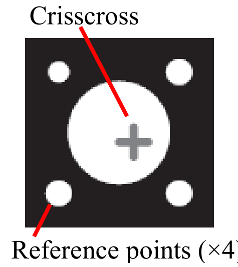

Figure 3. Design of ArrayMark

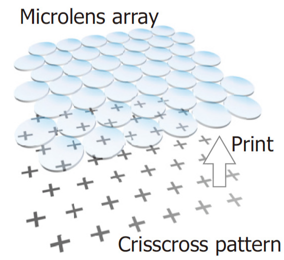

Figure 4. Structure of lens-area of ArrayMark [2]

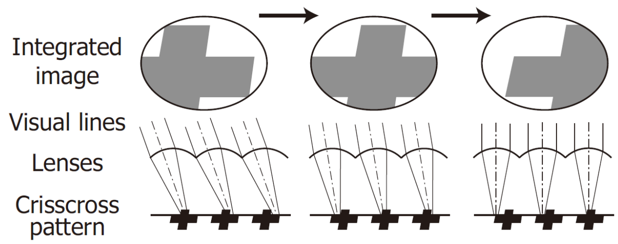

Figure 5. Principle of movement of integrated image according to visual-line angle [2]

2.2 Pose Estimation Algorithm

We estimate the pose of ArrayMark according to the following procedure [2].

A) Calculate 6 DOF pose using four reference points
B) Detect crisscross position
C) Calculate visual-line angle
D) Modify 3 DoF attitude using visual-line angle

Step A) corresponds to the conventional AR marker detection. We execute step B) to D) when we observe an ArrayMark from frontal direction, for more accurate pose estimation. Detailed algorithm of estimating accurate pose and position of ArrayMark is describe in the previous study [2].

3 Space Environmental Tolerance

3.1 Space environmental influences

The visual marker is required to have space environmental tolerance because it has to maintain the functions in directly exposed environment of space. The marker is supposed to be used in the manned space mission (International Space Station: ISS) in low Earth orbit (LEO), and the environment of LEO is vacuum, thermal cycle with wide temperature range, lightning environment which changes rapidly and dynamically. It is known that dynamically varying lighting condition makes it difficult to detect or track feature of marker by computer vision [4]. The LEO environment has also reactive atomic oxygen (AO), high-energy ultraviolet ray

(UV) and space radiation which causes the erosion and deterioration on polymeric material or metal oxidation [3]. Table 1 shows the main influences of LEO exposed environment on visual markers and vision system.

In the following, we show the environmental test results of especially-susceptible AO irradiation test and lighting environment test.

Table 1. Space environment influence of vision system

#	Environment	Influence
1	Atomic oxygen (AO)	Chemically active AO causes erosion on polymeric material of markers.
2	Ultra violet rays (UV)	UV causes discoloration of polymeric material of markers.
3	Lighting condition	Dynamically varying lighting condition causes difficulty to detect/track markers by camera.

3.2 Space environmental simulation tests

3.2.1 AO irradiation test

We conducted AO irradiation test to evaluate the material and functional influences of ArrayMark against AO in the ISS environment. The test conditions were determined from the standard to evaluate material tolerance of AO in ISS orbit (See Table 2). The irradiation amount 3.1×10^{20} atoms/cm^2 in A-a-03 is equivalent to the irradiation amount received in exposed environment of the ISS for 30 days. Figure 6 shows specimens placement on the jig plate of the test before the irradiation.

As results, Table 3 shows the variation in mass and thickness of two specimens (A-a-02, A-a-03) after AO irradiation. The difference of two specimens is the irradiated amount of AO. The loss of mass and thickness are increased approximately linearly with the irradiated amount. Figure 7 and 8 show the appearance of the specimens before and after the irradiation (1.5×10^{20} atoms/cm^2 in A-a-02 and 3.1×10^{20} atoms/cm^2 in A-a-03). The crisscross feature of the marker in Figure 7 can be barely recognized by human eye, but the feature in Figure 8 utterly disappeared. It could not be detected by computer vision in both makers after the irradiation.

Table 2. Conditions of AO irradiation test

#	Item	Condition
1	Specimen ID	#1: ArrayMark A-a-02 #2: ArrayMark A-a-03
2	Specimen Size	50mm×50mm×1mm
3	Beam velocity	8 km·s^{-1}
4	Beam flux	3.0×10^{15} cm^{-2}·s^{-1}
5	Total irradiation flux	A-a-02: 1.5×10^{20} atoms/cm^2 A-a-03: 3.1×10^{20} atoms/cm^2
6	Vacuum	1.0×10^{-7} Pa (Pre-irradiation) 1.0×10^{-2} Pa (Under irradiation)

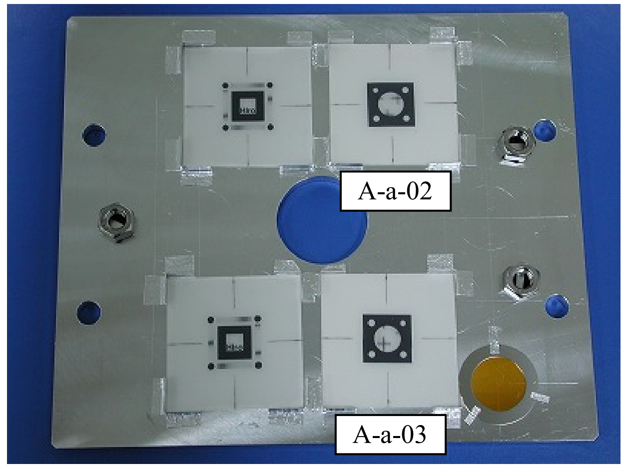

Figure 6. Specimens placement on the jig plate of AO irradiation equipment (pre-irradiation)

Table 3. Results of AO irradiation test (it shows variation in mass and thickness of each specimen)

#	ID	Mass [mg]		Thickness [µm]	
1	A-a-02	$M_{\_pre}$	ΔM	$T_{\_pre}$	ΔT
		2983.56	-26.06	1013.57	-8.89
2	A-a-03	$M_{\_pre}$	ΔM	$T_{\_pre}$	ΔT
		3028.61	-50.54	962.66	-20.17

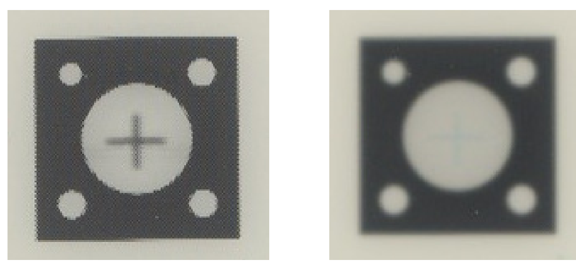

Figure 7. ArrayMark (A-a-02) in pre-irradiation (left) and post-irradiation of 1.5×10^{20} atoms/cm^2 (right)

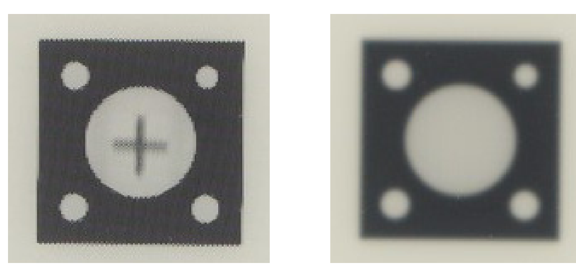

Figure 8. ArrayMark (A-a-03) in pre-irradiation (left) and post-irradiation of 3.1×10^{20} atoms/cm^2 (right)

3.2.2 Lighting environmental test

We conducted lighting environmental test to evaluate the functional influence of ArrayMark against lighting environment in the ISS. Table 4 shows the conditions of the test and Figure 9 shows a setup of the lighting environment test. All the test equipment was set up in the blackout curtain and artificial solar lighting XC-100 was used as light source to simulate the space lighting environment. We took camera images of scenes where ArrayMark was put on various background settings assumed in space such as satellite surface (Figure 10), solar panel (Figure 11), MLI (Multi-layer insulation), handrail for EVA and so on. Then, we evaluated how precisely position and posture of the visual marker in several scene could be detected and estimated in the simulated lighting environment.

As results, marker on all the background settings in simulated lighting environment in space were detected and estimated position and posture, although the diaphragm of the lens had to be adjusted in response to the illuminant intensity of the environment.

Table 4. Conditions of lighting test

#	Item	Condition
1	Atmosphere	Blackout curtain (lighting intensity without light is 0.0 lx)
2	Image sensor	ARTCAM-036MI-BW (USB2.0 CMOS camera), 752×480 pixel, COSMICAR TELEVISION LENS 6mm 1:1.2 (ARTRAY Co., Ltd.)
3	Lighting devices	1. Artificial solar lighting: XC-100 (SELIC Ltd.) 2. LED light: NSPW515DS (Nichia Corporation)
4	Background setting	1. Solar panel 2. Satellite mockup (ETS-7) 3. Satellite PAF mockup 4. MLI 5. Handrail for EVA

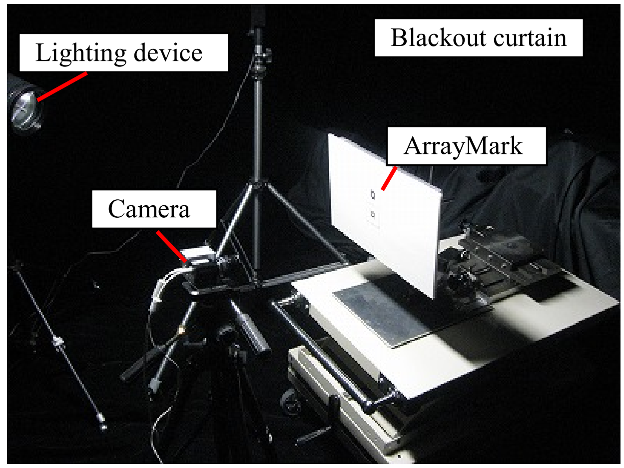

Figure 9. Setup of lighting environment test

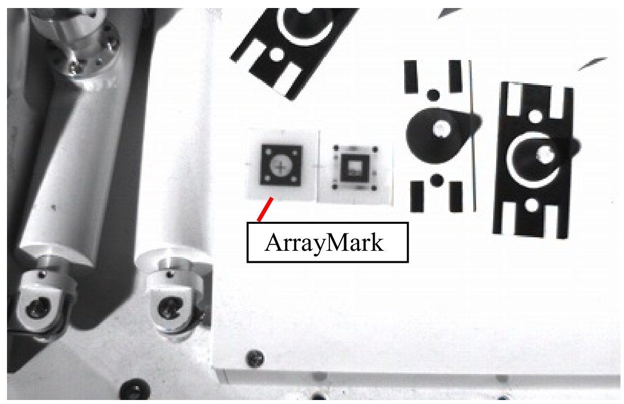

Figure 10. ArrayMark on surface of satellite mockup on which visual markers used in the ETS-7 mission are on

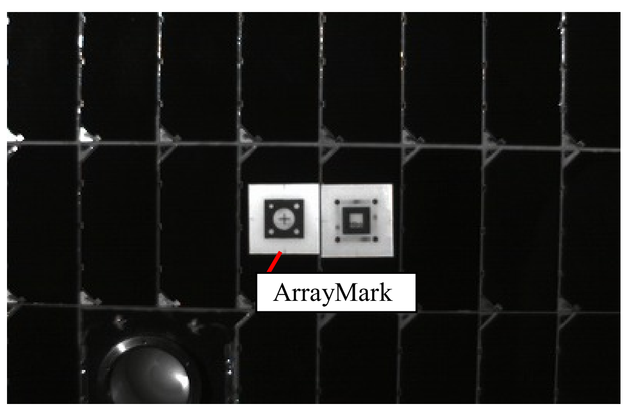

Figure 11. ArrayMark on surface of solar panel

3.2.3 Problems of ArrayMark for space use

As results of environmental tests, AO has a significant influence on the marker in LEO regarding the material degradation, but we got a prospect that it is possible to cope with the lighting conditions by adjusting the settings on the camera. There are two possible improvement methods against the material degradation that are to change material of the lens in the outermost layer of marker itself into AO-resistance material or to cover or coat the marker with AO-resistance material. We show the measure taken against the material problem to improve ArrayMark for space use in the next section.

4 2D Visual Marker for Space Use

4.1 AO/UV-resistance coating material

There are several AO-resistance materials such as silicon dioxide (SO_2), silsesquioxane and induium tin oxide (ITO). However, it is difficult to use these materials as the marker lens itself because of the property and workability of the materials. Therefore, it is a suitable measure to cover the marker with AO-resistance material against material deterioration by AO in LEO. We chose silsesquioxane-based coating material which was already proved to have AO resistive feature in LEO from the experiments in the ISS by JAXA [3], and it is practically used in the ISS mission. The liquid coating material is easy to obtain, use and coat. In regard to a measure against UV in space, UV absorber Ceriguard made by Daito Kasei Kogyo Co., Ltd. was used as UV-resistant coating material.

Figure 12 (left) shows ArrayMark directly coated with silsesquioxane-based coating material. It shows that the contrast intensity of the crisscross pattern was decreased. The reason is considered that the coating liquid soaks into tiny hollows between microlenses (See Figure 12 (right)) and forms a thin film that changes the optical property of the marker lenses.

Therefore, we decided to encase ArrayMark in the protective flat polycarbonate cover which is coated with silsesquioxane-based coating material and UV absorber Ceriguard for space use.

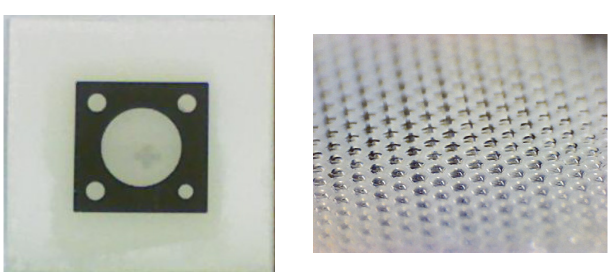

Figure 12. ArrayMark coated with silsesquioxane-base coating material (left) and the microscopic image of surface lens-area (right)

4.2 ArrayMark with AO/UV coated cover case

Figure 13 shows structure of a newly developed 2D visual marker which encases ArrayMark in a protective polycarbonate (PC) cover. The left figure of Figure 14 shows the coating operation using a wire bar coater (#7) and the right figure shows a PC cover coated with AO-resistance coating material on ArrayMark. It shows the crisscross pattern of ArrayMark is able to be recognized clearly.

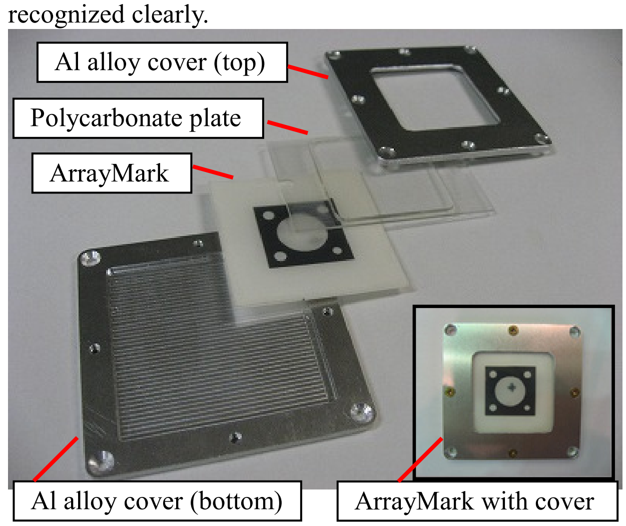

Figure 13. Structure of a newly developed 2D visual marker which encases ArrayMark

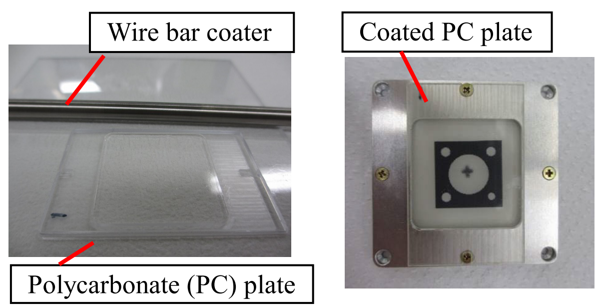

Figure 14. Coating process (left) and PC cover coated with AO/UV-resistance coating material (right)

4.3 Performance verification tests

We verified the performance of estimating position and posture of the new 2D visual marker (with coated cover), comparing with the previous visual marker (without coated cover).

Figure 15 shows a setup of the performance verification test. The marker is mounted on a rotation table. The vision sensor is same as the vision sensor in Table 4. The marker coordinate is shown in Figure 16. We estimated 6 DoF pose and position of the marker while the marker is rotated every 15 degree around the rotation axis. Figure 16 shows images taken by vision sensors in 15 degree rotation (left) and in 45 degree rotation (right). The accuracy was evaluated by the absolute angle difference between the estimated vector and the real vector of each coordinate axis (See Figure 17) [2]. The results are shown in Figure 18 and 19.

Figure 18 shows the measurement error $\Delta\theta_z$ of three types of markers which are ArrayMark (previous one), ArrayMark with non-coated cover and ArrayMark with coated cover (new marker). Figure 19 shows the measurement error of 6 DoF pose and position ($\Delta\theta_x$, $\Delta\theta_y$, $\Delta\theta_z$, Δx, Δy, Δz) of the new marker, ArrayMark with coated cover. These results indicate that there are no influence of the protective cover and coating. We can say that the new 2D visual marker has equivalent performance of estimating pose and position to the previous ArrayMark in addition to AO/UV-resistance function.

Table 5. Test cases of performance verification tests

#	Case	Test piece
1	Case 1	ArrayMark without cover
2	Case 2	ArrayMark with non-coated cover
3	Case 3	ArrayMark with coated cover

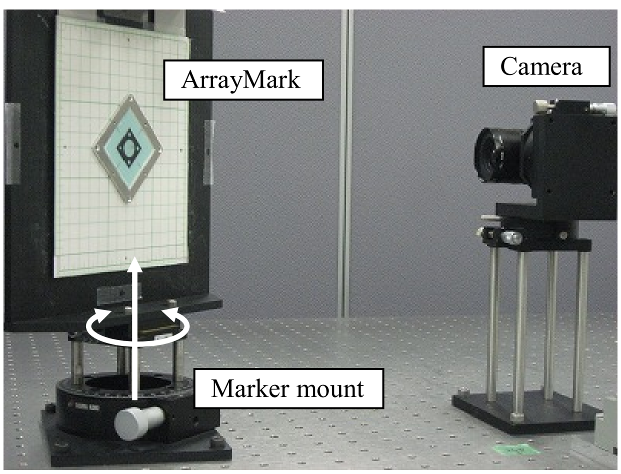

Figure 15. Setup of performance evaluation test

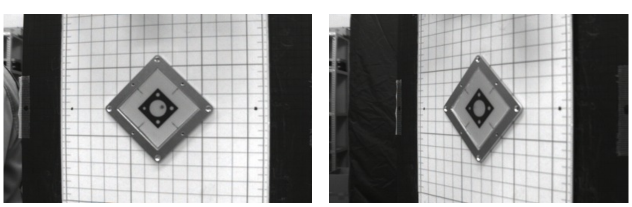

Figure 16. Example images by vision sensor in the angle of rotation table at 15 degree (left), and 45 degree (right).

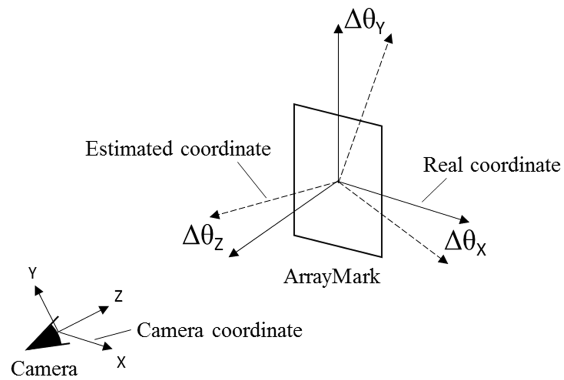

Figure 17. Coordinate system of ArrayMark and camera and the definition of error angles

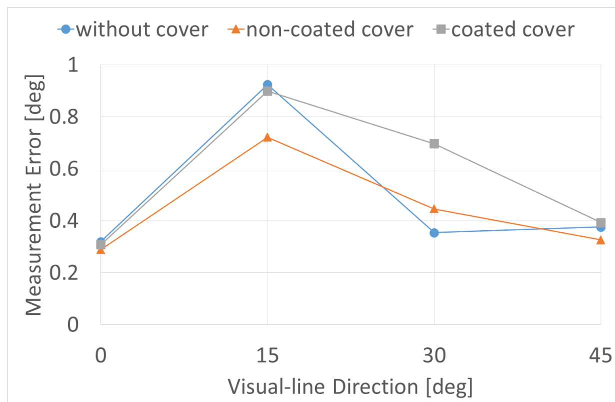

Figure 18. Comparison of pose estimation accuracy around z axis between the new marker and previous one

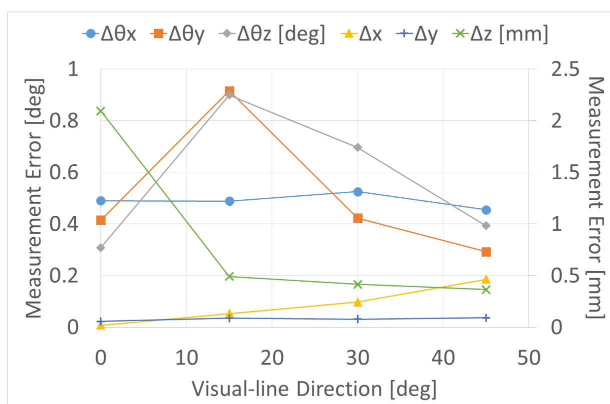

Figure 19. Results of estimation accuracy of 6 DoF pose and position of the new marker

5 Conclusion

This paper described developmental results of a new high-accuracy 2D visual marker for space application. It showed the evaluation results of the space environmental tolerance of the previous terrestrial-application visual marker “ArrayMark”. We conducted the experiments of AO irradiation and the space lighting environment which the visual marker is especially affected by such environments in the exposed area of ISS. The experiment showed the material degradation significantly by AO irradiation and a prospect of coping with the space lighting conditions by adjusting the settings on the camera. We redesigned the marker based on the test results to encase ArrayMark in the transparent cover coated with AO/UV-resistance material. The pose-estimation test verified that the new designed visual marker has the equivalent performance of pose and position estimation to the previous visual marker.

In the future works, we will conduct the integrated space environmental tests to the new marker even though the coating material is used in the ISS mission and validated in space. We will also conduct system integration test to verify the validity as a vision system for robot dexterous application.

Acknowledgment

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