THE FIRST EXPERIMENT OF
A HIGH-ACCURACY 2D COLOR MARKER IN SPACE

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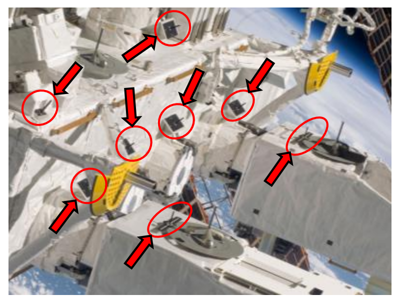
ABSTRACT

This paper discusses a new planar two-dimensional (2D) color marker for space applications. Specialized visual markers are commonly employed to measure position and attitude using image processing technology. In previous missions, a three-dimensional (3D) visual marker utilizing a rod was used for rendezvous and docking with the International Space Station (ISS) or for capturing a module with a robotic arm on the ISS. The 3D marker is equipped with a protruding rod on a flat plane. A central purpose of the protruding rod is high-precision measurement of relative attitude by triangulation. Due to the shape of the protruding rod, mounting positions for the 3D visual marker are limited to avoid collision with astronauts and space robots. In addition, depending on the camera angle, flat plane's feature points may be obscured by the protruding rod. In this case, accurate measurement of position and attitude is unobtainable. In this study, the objective is to develop a new 2D visual marker for space applications that solves the above mentioned technical issues. In addition, colorization of the 2D visual marker is envisioned to improve marker detectability in the space environment. An on-orbit experiment was conducted using a 2D color marker to verify its performance. The following is a discussion on the results of this experiment.

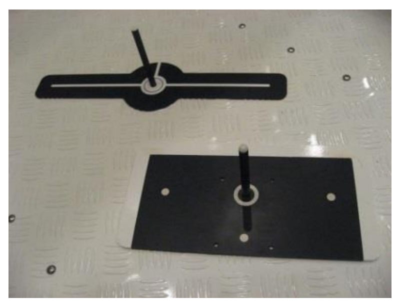
1 INTRODUCTION

The robotic arms on the ISS are used for on-orbit servicing. The space-craft rendezvous docking or experimental device placement are examples of on-orbit services done by the robotic arm. On-orbit servicing by the robotic arm requires accurate position and attitude between the robot end effector and its target. The position and attitude are measured via image processing with a camera mounted to the robotic arm [1][2].

Specialized visual markers are typically employed in measuring position and attitude using image processing technology [3]. In previous ISS missions, a 3D visual marker such as a grapple-fixture visual target with a protruding rod has been used to measure position and attitude [1][2][4], as shown in Figure 1.



a) Visual marker attached on the ISS. ©NASA



b) Example of 3D visual marker.

Figure 1: Visual marker for on-orbit servicing using robotic arm.

The 3D marker is equipped with a protruding rod on a flat plane. A feature shape or point is painted on the flat plane of the 3D marker as an image processing target. A feature point of protruding rod is used to measure attitude with high-precision using triangulation. Therefore, the accuracy of attitude measurement will decrease by any damage to the rod. Due to the shape of protruding rod, mounting positions of the 3D visual marker are limited to avoid collision with astronauts and space robots.

In addition, depending on the camera angle, a flat plane's feature points may be obscured by the protruding rod. Consequently, accurate measurement of position and attitude is unobtainable. For example, the contrast of a feature point on a flat plane decreases in the shadow of the rod, making the image unsuitable for image processing, as shown in Figure 2.

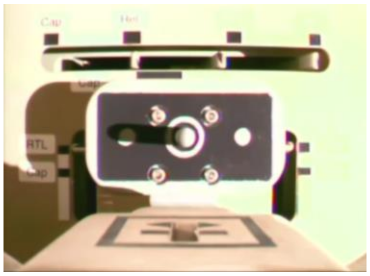


Figure 2: Shadow of the rod and contrast of the feature point on the flat plane. ©JAXA/NASA

For the above reasons, a 2D visual marker is indispensable for robust and accurate measurement. However, the primary disadvantage of a 2D visual marker is that attitude measurement is inaccurate when the marker is observed from the frontal direction. Thus, a new high-accuracy 2D visual marker called ArrayMark (microlens-array-based 2D moiré pattern marker), was developed by the National Institute of Advanced Industrial Science and Technology, Japan. ArrayMark has attained accurate attitude measurements from a wide range of perspectives without a rod attachment. [5].

In this study, the objective has been the development of a new 2D visual marker for space applications based on ArrayMark. In addition, details and discussions of the on-orbit experiment for the new 2D visual marker are presented. Furthermore, several suggestions are provided to improve the performance of the visual marker for future missions.

2 THE 2D COLOR MARKER IN THE SPACE ENVIRONMENT

This section presents a detailed description of ArrayMark and describes the effectiveness of the colorization marker in the space environment.

2.1 2D Visual Marker "ArrayMark"

ArrayMark comprises four reference points and a center circle. One reference point is smaller than the other three points in order to distinguish the marker in-plane direction. The position and attitude of ArrayMark are measured by four reference points on a camera view. In addition, attitude is corrected using a moiré phenomenon in the center circle. This center circle utilizes the moiré phenomenon with micro lenses and dot patterns and displays a dot of moiré, as shown in Figure 3. The dot in the center circle behaves in much the same way as a 3D marker without the degradation caused by the shadow of the rod. The dot position in the center circle deviates according to seeing-angle of the observation camera, as shown in Figure 4. The attitude estimated by ArrayMark is measured with high accuracy by the dot position in the center circle. The planar marker satisfies safety requirements and performs accurate position and attitude measurements similar to images processed by the 3D marker [5].

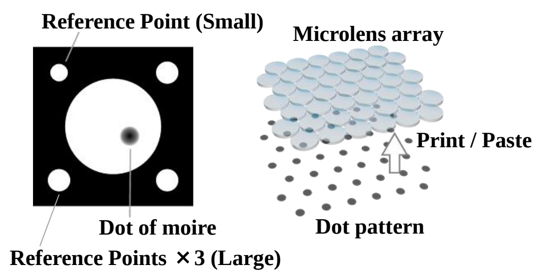


Figure 3: Design and structure of ArrayMark.

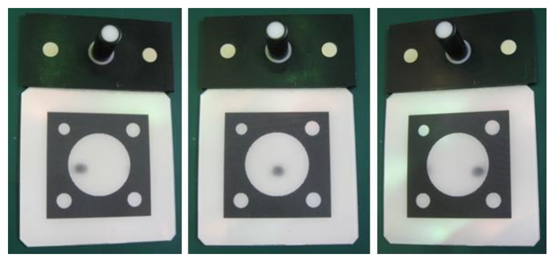


Figure 4: ArrayMark and 3D visual marker with rod. (three photos taken from different seeing-angles.)

2.2 Color Marker for Space Application

The on-orbit lighting environment is altered considerably according to the orbital motion of spacecraft. However, visual markers must be robust against an on-orbit lighting environment in order to detect a marker for image processing.

In previous research, a colorized 3D marker was proposed to improve marker detectability in the space environment [6]. However, in this study, a colorized ArrayMark was envisioned as a new 2D color marker for space applications, as shown in Figure 5. To further improve discrimination, the 2D color marker has two additional functions a) a reference for adjusting image parameters and b) an ID function for recognizing multi-markers.

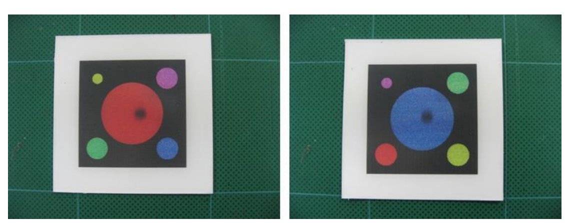


Figure 5: Examples of the proposed 2D color marker.

Pixels in a typical image are represented by the luminosity of red, green, and blue colors. For the 2D color marker's image processing, pixels are represented by the HSV color space. This is due to the ability of the HSV color space to distinguish luminosity from color hue. In the HSV color space, pixels are represented by three values, i.e., H, S, and V, where H represents hue and indicates position on the color spectrum from 0° to 360° (red, orange, yellow, green, blue to purple), S indicates saturation, and V represents the value of luminosity (Figure 6).

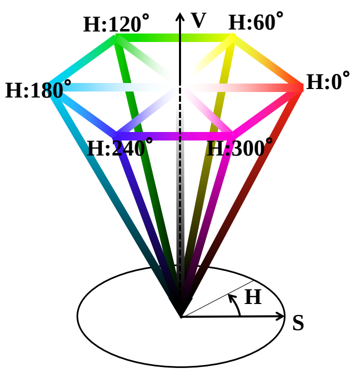


Figure 6: Visualization of HSV color space model.

Image parameters are adjusted by S (saturation) and V (value) of the color marker's center circle, as shown in Figure 7. The color of the marker is differentiated by H (hue) for the ID function.

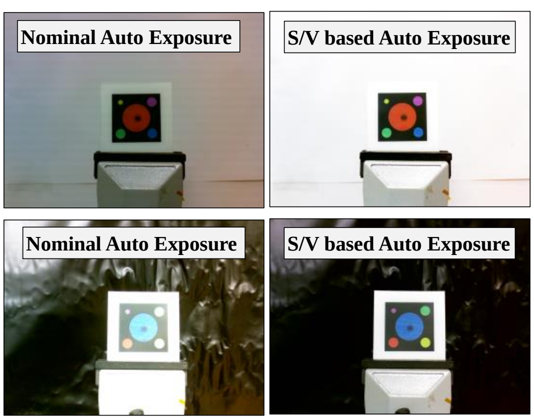


Figure 7: S/V-based adjustment of exposure as an image parameter. Unsuitable brightness of image is due to the nominal autoexposure function of the camera.

Ground experiment results have confirmed the effectiveness of image parameter (exposure) adjustment and color differentiation [7].

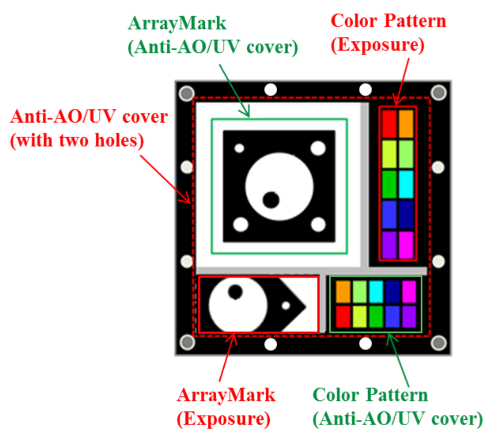
3 OVERVIEW OF ON-ORBIT EXPERIMENT

To verify the performance of the proposed 2D visual marker, an on-orbit experiment was conducted based on the hypothesis that a resin in the space environment deteriorates from exposure to atomic oxygen (AO) and ultraviolet (UV) light. In this experiment, the 2D visual marker was exposed to the space environment to verify tolerance.

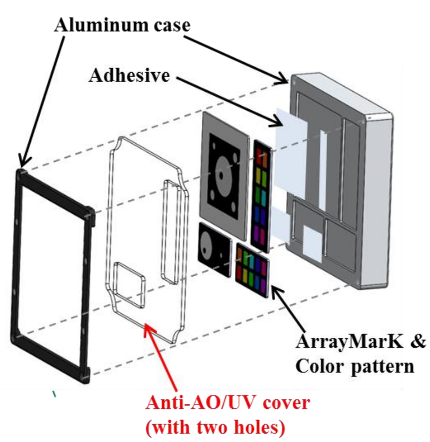
The experimental sample kit used in the space environment and an overview of the on-orbit experiment are presented below.

3.1 Experimental Sample Kit

The specialized sample kit designed for the on-orbit experiment comprises two ArrayMarks and two color patterns. No specialized material was utilized in ArrayMark and color pattern of the sample kit in their exposure to the space environment, but these markers were covered by a polycarbonate plate coated with anti-AO/UV material (anti-AO/UV cover). However, one ArrayMark and one color pattern was directly exposed to the space environment through holes in the anti-AO/UV cover, as shown in Figure 8.



a) Front view of sample kit



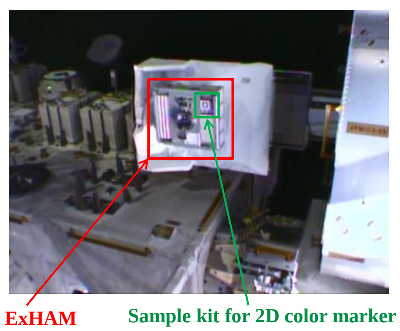
b) Exploded view of sample kit
Figure 8. Markers of sample kit covered by polycarbonate plate coated with anti-AO/UV material.

Tolerance levels to the space environment of two markers were analysed; one applied with the anti-AO/UV cover, and the other without the anti-AO/UV cover.

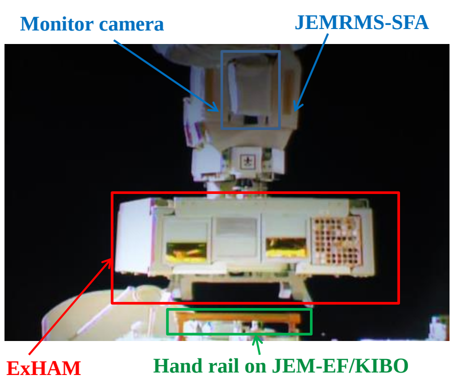
3.2 On-orbit Experiment

The on-orbit experiment utilized an Exposed experiment Handrail Attachment Mechanism (ExHAM), which is used in space exposure experiments at the Exposed Facility of the Japanese Experiment Module (JEM-EF/KIBO) on the ISS [8].

The sample kit was delivered to the ISS aboard the SpaceX CRS-6 in April 2015 and was subsequently mounted on ExHAM in the ISS. ExHAM was attached to a handrail on JEM-EF/KIBO in May 26, 2015, as shown in Figure 9. From then onward, the sample kit has been exposed to the space environment. As such, the on-orbit experiment has continued for approximately one year, and during this time, observations of the sample kit have been scheduled three times using a monitor camera mounted on a Small Fine Arm of the JEM Remote Manipulator System (JEMRMS-SFA). Images captured by this monitor camera were used to verify the performance of the sample kit in the space environment.



a) ExHAM with sample kit on JEM-EF/KIBO.



b) Attach ExHAM to JEM-EF/KIBO by JEMRMS-SFA.

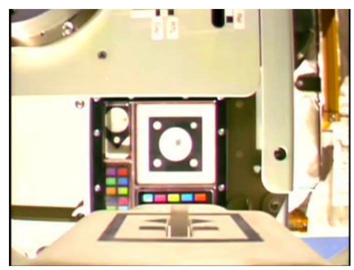
Figure 9: ExHAM and sample kit in space environment. ©JAXA/NASA

The first observation was performed in May 28 and 29, 2015, within a few days of exposure of the sample kit. The second observation was performed in November 12, 2015, approximately six months after the first observation. The third observation has been scheduled to be performed in May, 2016, approximately six months after the second observation. The sample kit will be repatriated to Earth after the third observation.

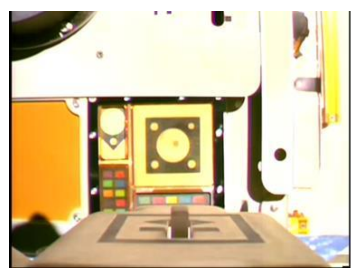
In the following, we describe the transmutation of the sample kit after a six-month exposure to the space environment.

4 RESULTS OF ON-ORBIT EXPERIMENT

This section describes the performance of the sample kit based on captured images from the first and second observations. The sample kit change to a yellow hue was confirmed by images of the second observation, as shown in Figure 10.



a) First observation



b) Second observation

Figure 10: Captured image of on-orbit experiment

The performance of sample kit in the on-orbit experiment is presented in detail in the following sections.

4.1 Position and Attitude Measurement Accuracy by ArrayMark in Space Environment

The accuracy of position and attitude measurements of a visual marker is its most important performance indicator. Thus far, verification of position and attitude measurement accuracy in this report, used the image captured by the first observation. The position and attitude of the sample kit was measured using the feature points of ArrayMark in the image. Moreover, the position and attitude of the monitor camera was calculated by the telemetry of the joint angle. By using the two experimental results, the relationship of the position and attitude of the sample kit was confirmed. Images were captured from multiple locations using JEMRMS-SFA. Then, we compared the position and attitude measurement results using ArrayMark with the degree of movement of the monitor camera by JEMRMS-SFA.

We verified the accuracy of position and attitude measurements using an image captured from the frontal direction that general 2D visual marker is bad at.

When verifying the performance of ArrayMark, images were captured at distances of 300 to 400 mm and with attitudes of −5° to +5° in the out-of-plane axis of the sample kit. We measured the position and attitude of ArrayMark using several images captured from the same location.

The position and attitude of ArrayMark is expressed by a camera coordinate system whose origin is the focal point of the monitor camera, as shown in Figure 11.

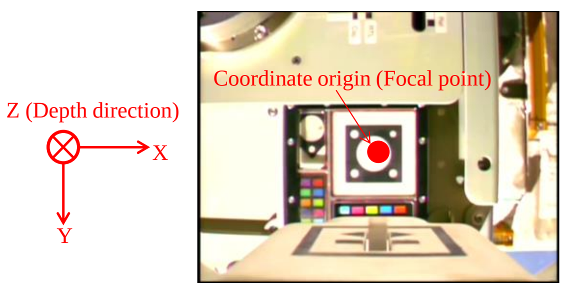


Figure 11: camera coordinate system

The difference between results obtained using ArrayMark and those obtained by the degree of movement of the monitor camera was less than the positioning accuracy of JEMRMS-SFA (±10 mm and ±1°) in most locations, as shown Table 1. In addition, the measurement accuracy by ArrayMark is less than positioning accuracy by a 3D visual marker with the JEMRMS monitor camera [9].

However, the error in attitude measurement was significant in location No. 3. The Z-axis attitude error of location No. 3 was greatest. The Z-axis attitude represents the in-plane rotation of ArrayMark. The source of the Z-axis error has been concluded as ArrayMark's smaller reference point detection. Distinguishing the reference point size is problematic in low-contrast images, as shown in Figure 12.

An improvement in image contrast or adjustments in the design of a reference point is needed to improve the in-plane direction measurement accuracy.

Table 1: Accuracy results of position and attitude measurement

a) Image-capturing locations

No.	Distance [mm]	Attitude [deg]	
		Pitch (X)	Yaw (Y)
1	300	0	0
2		5	0
3		-5	0
4		0	5
5		0	-5
6	400	0	0
7		5	0
8		-5	0
9		0	5
10		0	-5

b) Difference between results obtained using ArrayMark and those obtained by the degree of movement of the monitor camera

No.	Position [mm]			Attitude [deg]		
	X	Y	Z	X	Y	Z
1	-0.3	0.3	0.1	0.0	0.1	0.0
2	-0.8	0.3	0.3	-0.2	0.6	0.0
3	-0.2	0.5	1.3	0.2	-2.7	-149.8
4	-0.2	0.6	1.0	0.0	0.6	0.1
5	0.4	1.1	1.8	-0.3	-0.4	-0.1
6	1.9	-0.8	-1.3	0.0	0.1	0.1
7	2.2	-0.6	-3.5	-0.3	0.4	0.0
8	1.7	-0.2	0.1	0.1	-0.1	0.0
9	1.1	-0.8	-0.1	0.1	0.9	0.2
10	2.0	-0.3	0.7	0.4	0.3	0.4

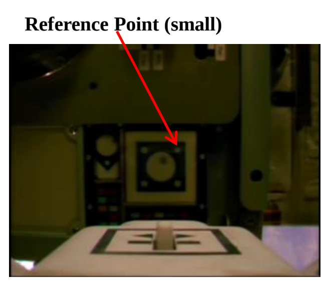


Figure 12: Example of a low-contrast image

4.2 Change in Optical Properties of Sample Kit by Space Environment Exposure

Temporal change in the sample kit's optical properties is due to exposure to AO and UV. The total AO dose from a six-month exposure is assumed to be approximately $0.8*10^{20}$ atoms/cm^2. Similarly, the total UV dose from a six-month exposure is assumed to be approximately 5 ESD [10].

The space environmental tolerance of the sample kit's marker was verified using contrast, saturation, and hue as optical properties. It was discovered that the reduction in contrast was mainly due to AO exposure by the results of the on-ground environmental test [11]. Similarly, it was found that increased saturation was mainly due to UV exposure by the results of the on-ground environmental test. Furthermore, we evaluated the sample kit’s discoloration due to UV exposure by hue.

Contrast of the center circle area of ArrayMark was measured using the captured images from the first and second observations. First, the captured color image was converted to an 8-bit (256 steps) gray-scale image. Then, the gray-scale value on the white area was measured in the center circle via image processing. Similarly, the gray-scale value of the dot of moiré in the center circle was measured. We defined the gray-scale value measurement result of the white area in the center circle as the luminosity of ArrayMark and defined the contrast as the difference between the luminosity values of the white area and the dot of the moiré.

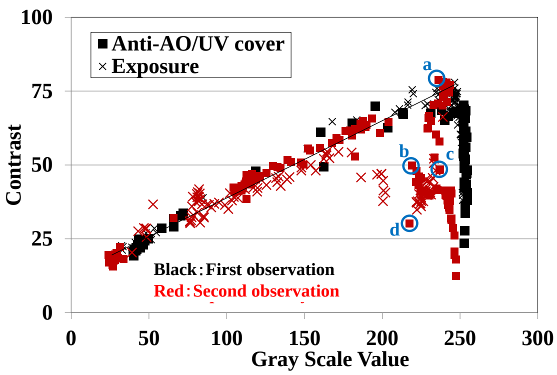


Figure 13: Contrast measurement results.

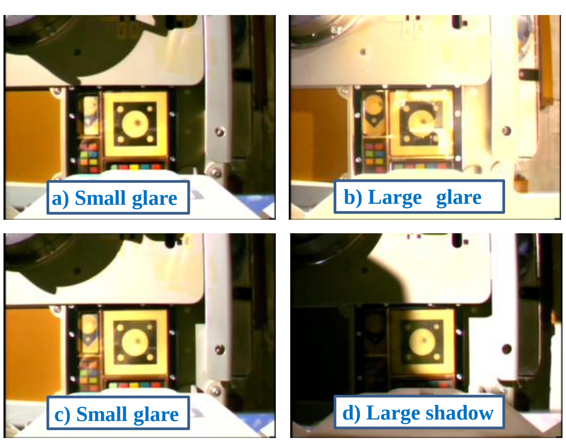


Figure 14: Example of glare or shadow on ArrayMark.

Based on these results, it was found that contrast increased with luminosity. However, contrast abruptly decreased when the luminosity reached approximately 240 digits or more, caused by the overexposure to the dot of moiré. The contrast of ArrayMark with the anti-AO/UV cover did not decrease after a six-month exposure. However, the contrast of exposed ArrayMark decreased during its six-month exposure, as shown in Figure 13. It was inferred that the low contrast of ArrayMark with the anti-AO/UV cover in the second observation (blue circle in Figure 13) was caused by glare or shadow on the sample kit, as shown in Figure 14.

Table 2: Average of saturation measurement results

Average saturation (Luminosity 150-220 digit)	First observation	Second observation
Anti-AO/UV cover	73	157
Exposure	85	188

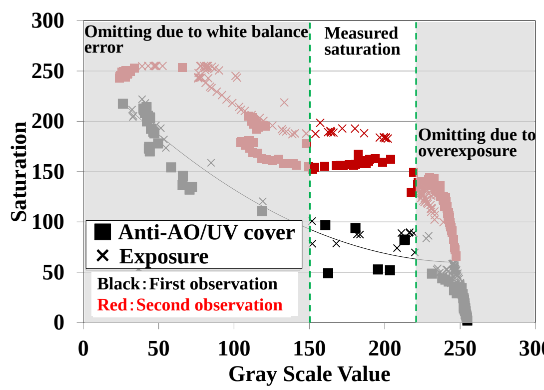


Figure 15: Saturation Measurement results.

Saturation was measured using ArrayMark center circle’s white area. First, the captured color image was converted to an HSV color space and then saturation was measured when the luminosity of ArrayMark ranged from 150 to 220 digits. Saturation measurement was omitted when the luminosity of ArrayMark ranged from 220 to 255 digits due to overexposure. Similarly, saturation measurement was omitted when the luminosity of ArrayMark ranged from 0 to 150 digits due to white balance error in the color temperature of the lighting device. (Table 2 and Figure 15)

From these data, it is apparent that saturation increased due to the six-month exposure. In addition, the saturation increase in an exposed ArrayMark was greater, compared with ArrayMark with the anti-AO/UV cover. This increased saturation is caused by the discoloration of the sample kit when exposed to the space environment.

Hue was measured using the ArrayMark center circle’s white area and color pattern. In the second observation, the hue of the ArrayMark’s white area was approximately 45°. Approximately 45° of hue value displayed yellow or orange. By measuring hue, it was confirmed that the yellowing of the sample kit was a result of the six-month exposure in the space environment, as shown in Figure 16.

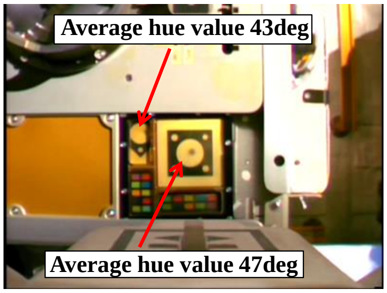


Figure 16: Measurement of hue value in ArrayMark's white area.

Similarly, we confirmed the discoloration of color pattern by hue value. Discoloration was considerable in blue and purple hues in color pattern. On the other hand, discoloration was slight in yellow and red hues in color pattern, as shown in Figure 17. From these results, it was inferred that the cause of the color pattern's hue value change to be yellowing from exposure to the space environment.

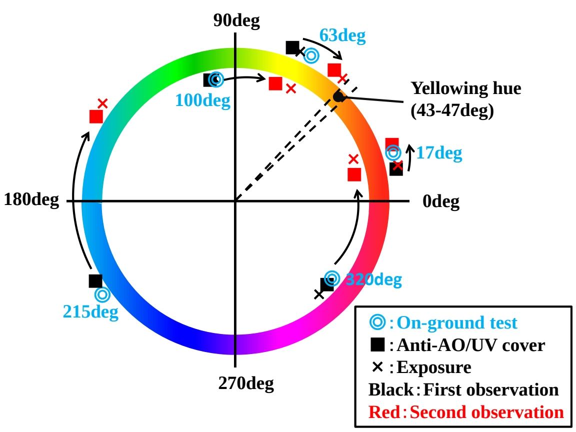


Figure 17: Example of hue value change in color patterns from exposure to the space environment.

From above results, the change of sample kit was mainly yellowing from the space environment. It is apparent that the yellowing of sample kit was caused by mainly UV light. However, the composition of the yellowing material cannot be inferred from captured images by the on-orbit experiment. Only after final analysis of the sample kit, that identification of the yellowing material will be made.

5 CONCLUSION

This study described the on-orbit experiment of the new 2D color marker for space applications. The sample kit for the on-orbit experiment comprises two ArrayMarks and two color patterns for the high-function 2D marker. To date, the sample kit is being exposed to the space environment for a one year period, and the on-orbit experiment is ongoing. The impact of a six-month exposure on the sample kit was verified using images captured in the space environment.

In the space environment, ArrayMark demonstrated sufficient measurement of position and attitude. However, adjustments in the design of ArrayMark's reference points, as shown in Figure 18, will be of value to improve the position and attitude measurement accuracy in low-contrast images.

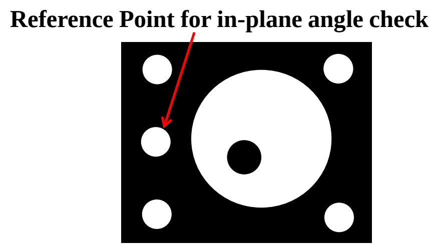


Figure 18: Suggested new ArrayMark design to improve position and attitude measurement accuracy in low-contrast images.

In addition, the study confirmed the contrast of ArrayMark with anti-AO/UV cover was remained consistent after a six-month exposure. However, changes in the color pattern, i.e. yellowing, in markers with an anti-AO/UV cover, were confirmed as due to UV exposure. The impact of yellowing was less significant in hues of red or yellow. Improvement of UV tolerance is required for definitive recognition of hues in the color spectrum. Therefore, a high UV tolerance material will be required to realize high functionality in the 2D color marker.

In future research, we will verify temporal changes after a one-year period of exposure and further verify in detail the space environmental tolerances by analyzing the sample kit upon its repatriation to Earth.

Acknowledgement

The on-orbit experiment for the high-accuracy 2D color marker was performed using ExHAM and JEMRMS-SFA. We would like to thank the parties involved in the development and operation of the ExHAM project.

References

[1] Ueno H, Doi S, Morimoto H and Wakabayashi Y (2008) JEMRMS on-orbit task scenario and operation plan. In: *proceedings of 26th*

international symposium on space technology and science (ISTS), Hamamatsu, Japan, 2008-h-19.
[2] Kitajima Y, Hattori H, Ueno H and Doi S (2010) Development and realtime monitor of JEM robotics operation ground observatory (ROGO). In: *proceedings of the international symposium on artificial intelligence, robotics and automation in space (i-SAIRAS)*, Sapporo, Japan, pp.851-858.
[3] Inaba N, Oda M and Hayashi M (2003) Visual servoing of space robot for autonomous satellite capture. *Trans. Japan Soc. Aero. Space Sci.* 46(153):173-179.
[4] Bondy M, Krishnasamy R, Crymble D and Jasiobedzki P (2007) Space vision marker system (SVSN). In: *proceedings of AIAA SPACE 2007 Conference & Exposition*, Long Beach, California.
[5] Tanaka H, Sumi Y and Matsumoto Y (2012) A high-accuracy visual marker based on a microlens array. In: *proceedings of 2012 IEEE/RSJ international conference on intelligent robots and systems (IROS)*, Vilamoura, Algarve, Portugal, pp. 4192-4197.
[6] Kamimura H and Nishida S (2004) Three dimensional color marker for on-orbit assembling using space robot. In: *proceedings of 55th international astronautical congress 2004 (IAC)*, Vancouver, Canada.
[7] Ueta A, Watanabe K, Suzuki S, Takei Y and Tanaka H (2014) A high-accuracy 2D color marker for dexterous manipulation in space. In: *proceedings of 65th international astronautical congress 2014 (IAC)*, Toronto, Canada.
[8] JAXA. Exposed Experiment Handrail Attachment Mechanism (ExHAM). Available at: http://iss.jaxa.jp/en/kiboexp/ef/exham/
[9] Wakabayashi Y, Morimoto H, Satoh N, Hayashi M, Aiko Y, and Suzuki M (2002) Performance of Japanese robotic arms of the international space station. In: *proceedings of 15th triennial world congress (TWC)*, Barcelona, Spain.
[10] Furuta H, Kitazawa S, and Imamura S (2015) Space environmental testing of PEEK and PFA. In: *proceedings of 59th the space sciences and technology conference*, Kagoshima, Japan. (in Japanese)
[11] Ueta A, Watanabe K, Takei Y, Suzuki S and Tanaka H (2014) A high-accuracy 2D visual marker for dexterous manipulation robot in space. In: *proceedings of the international symposium on artificial intelligence, robotics and automation in space (i-SAIRAS)*, Montreal, Canada.