Sunlight Illumination Simulation for Archaeological Investigation -Case Study of the Fugoppe Cave-

Tomohito MASUDA† (tom@cvl.iis.u-tokyo.ac.jp) Yosuke YAMADA† (yamada@cvl.iis.u-tokyo.ac.jp)
Nobuaki KUCHITSU‡ (kuchitsu@tobunken.go.jp) Katsushi IKEUCHI† (ki@cvl.iis.u-tokyo.ac.jp)

†Institute of Industrial Science, University of Tokyo
4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan

‡National Research Institute for Cultural Properties, Tokyo
13-43, Ueno Park, Taitoh-ku, Tokyo 110-8713, Japan

Abstract

The Fugoppe Cave, located in northern Japan, is a natural cave in tertiary tufaceous rocks. Archaeologists believe that ancient painters and sculptors worked inside the cave using artificial lights such as torches. In contrast, we argue that there is a possibility that they used natural light such as sunlight, since an accumulation of soot, which is a side effect of using torches, is rarely found in the cave. However, our argument could be countered by the question of whether the natural light could enter and sufficiently illuminate the walls inside the cave. In order to verify our theory, we attempted to simulate how natural light might illuminate the interior walls by using a 3D model of the cave which we obtained from our proposed modeling system, and to examine the possibility that ancient painters and sculptors worked under natural illumination.

1 Introduction

Recently, many researchers have studied the measurement of 3D models of objects or scenes in the real world by using laser range sensors. The 3D models are useful, not only for the accurate record of object shapes, but also for the production of multimedia contents which allows us to observe an object from various viewpoints with less restriction. Moreover, by combining the 3D models and computer graphics techniques, it is also feasible to scientifically simulate phenomena that in the real world are difficult, if not impossible, to observe. One of the typical examples is lighting simulation. This simulation enables us to investigate the changes of the shadow and shading realistically according to the properties of the light sources. In this paper, our goal is to implement the simulation in order to analyze the natural lighting condition of a cave, which in our case, is Fugoppe Cave.

The Fugoppe Cave is a natural cave in tertiary tufaceous rocks located in the Yoichi town, Hokkaido, in northern Japan. The cave has a lot of petroglyphs (rock carving) of Zoku-Jomon period (A.D. 1C - 5C), and has been designated as a national historical site. Archaeologists often argue over how ancient sculptors created the carvings, since they usually imagine that it was dark inside the cave. The idea that ancient sculptors used artificial light sources has been considered; however, this is generally suspicious since there is no firm evidence of that. For example, the use of torches causes the soot on the wall and the ceiling, but almost no soot can be found there [1]. Thus, we consider that the natural light emitted by the sunlight could reach the interior of the cave. The reason is that the cave probably had the same entrance like the current entrance, which is large enough for the sunlight to pass through. In order to investigate how much the natural light comes in and whether it is sufficient for the ancient sculptor to work inside without an artificial light, we simulate it using computer graphics.

Inside the Fugoppe Cave, there was an observation room which consists of windowpanes until 2001. The windowpanes were temporally removed for reconstruction, and in that occasion we measured the 3D data inside the cave for the purpose of the preservation of the present condition. Later, the new windowpanes were built (Figure 1), and it became impossible to observe the natural light incidence in direct observation, since we began our project to solve the problem of the lighting inside the cave after the rebuilding. As a consequence, we required computer simulation by using the 3D data we have

Figure 1: Inside and outside the observation room of the Fugoppe Cave.

already obtained. In this paper, we take the correspondence between the 3D model of the cave and its position on the earth's surface, calculate the ecliptic at the latitude of the cave, and then reproduce the appearance change of the inside according to the position of the sun in our system coordinate. Finally, we describe the knowledge obtained from the simulation.

Caves are usually located under the ground, and it is hard to accurately recognize their relative positions with regard to the earth surface. A number of researchers have argued that the use of the 3D data is suitable for the investigation of the caves, and have proposed their 3D models[2][3]. Sellers et al.[4] measured the Kitley cave in England by using an ultrasonic sensor. Brown et al.[5] measured the frieze of the Cap Blanc in France, and Deblin et al.[6] used their data for the archaeological study. They restored the appearance under the torches inside the cave in order to investigate the shadow and shading motion and the visual effect resulting from the flames of the torches. Sandin et al.[7] developed the projection system, called "CAVE" in order to express the atmosphere unique to the inside space of the cave as virtual reality contents. However, to our knowledge, there is no previous work using computer simulation for illuminating a cave using natural light.

In order to restore the 3D appearance of the object with computer graphics, three factors are required. The first factor is geometrical information, which represents the 3D shape. The second factor is photometric information, which is identical to the color information. We describe how to obtain the geometrical information by using the 3D data measured by a laser range sensor and how to texture the 3D data with 2D color images captured by a digital camera in Sections 2 and 3, respectively. The appearance of the object depends upon its environment. Thus, environmental information is required as the third factor. In Section 4, we explain how to obtain it by adjusting the surface, direction, altitude, latitude and longitude of the cave. We describe the method and the result of the simulation, the conclusion and the future work of our study, in Sections 5, 6 and 7, respectively.

2 Acquisition of Geometrical Information

2.1 3D Shape Measurement

The entire 3D shape of the Fugoppe Cave is measured by using two types of laser range sensors: the CYRAX 2500 and the VIVID 900. The CYRAX 2500 is a time-of-flight type sensor, which can obtain the distance between the sensor and the object surface by calculating the time during which the emitted laser ray returns into the sensor after being reflected from the object. The VIVID 900 is a triangulation type sensor that can measure the distance by calculating the difference of the position at which the laser ray, emitted from the sensor as a slit light and reflected against the object to the sensor, is observed in the CCD. The former can cover a wide area, but cannot guarantee a highly accurate measurement: it cannot capture the carving on the wall. The latter covers a much narrower area, but can measure the 3D shape with much higher accuracy than the former. We therefore measured the whole shapes and the carving areas by using the CYRAX 2500 and the VIVID 900, respectively, and then integrated two types of the measured data.

Figure 2: Carvings inside the Fugoppe Cave.

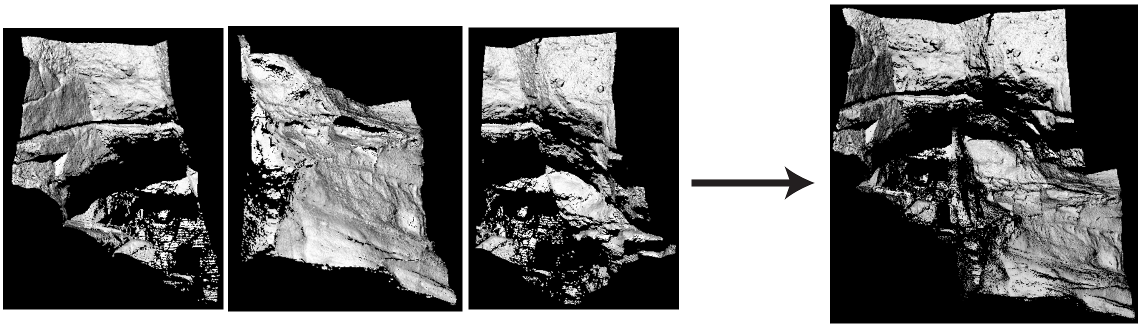


Figure 3: Alignment. Alignment can restore the relative position and posture between each corresponding pair of range images (left) as shown in the right illustration.

2.2 Registration

The laser range sensors cannot scan the whole target in one measurement because of their range limitation. To resolve it, multiple measurement is applied, which, as a consequence, requires the registration of the data (Figure 3). In the 3D data registration, the Iterative Closest Point (ICP) [8] is commonly used. The conventional registration method based on ICP is a sequential technique which handles only one pair of data per one registration[9]. If the number of data consisting of the whole shape is small, the accumulation error of the registration can be ignored; however, if the number is large, the registration of the whole shape tends to fail. Oishi et. al. developed the registration method, which can evenly distribute the accumulation error by registering all data simultaneously [10]. This method produces more accurate shape restoration than the sequential one. As a matching unit of our registration, the distance between the point and the plane is used in order to increase the accuracy of the registration. In Addition, to reduce the outlier effect, our method uses a thresholding for the correspondence, by considering the distance between the corresponding points and the measurement error. The search for the corresponding point is usually expensive computationally, yet our method can reduce the computational cost drastically, since its search computation mainly depends on the graphics hardware.

2.3 Merging

As the last step of the 3D shape restoration, the registered multiple data is integrated into a single mesh (merging) (Figure 4-(1)). This is performed by calculating the signed distance between the center of the lattice and the object surface on each lattice. Calculated signed distance fields are converted into a single mesh model by using the marching cubes method[11].

Since each piece of measured data has random measurement error which can affect the final results, the consensus

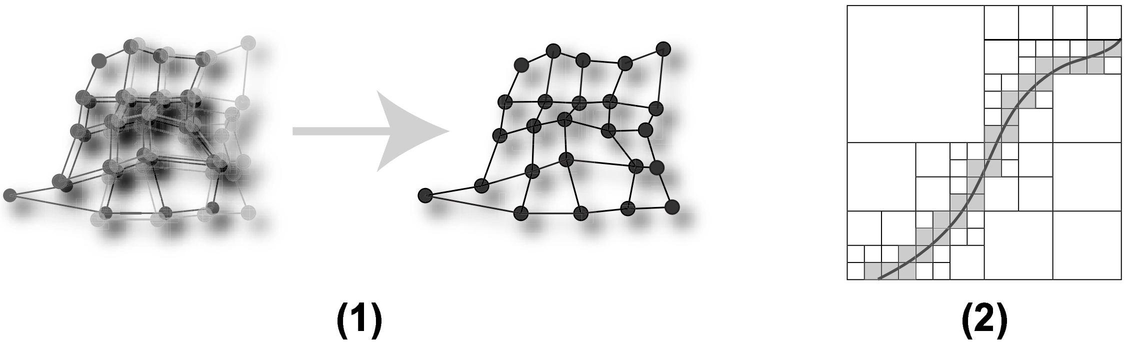


Figure 4: (1) Merging. Merging can integrate multiple aligned images (left side) into the single image (right side). (2) Voxel division by octree. Octree provides the effective merging because voxel division is adaptively performed only where the object surfaces exist.

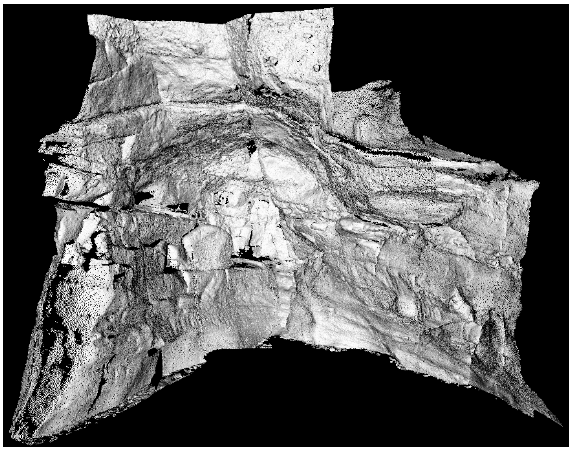


Figure 5: Acquired whole shape of the Fugoppe cave in our modeling system.

is taken among the multiple measured data representing the same surface [12]. Moreover, the octree representation is employed to adaptively and effectively divide the lattice unit which covers only the object surface (Figure 4-(2)).

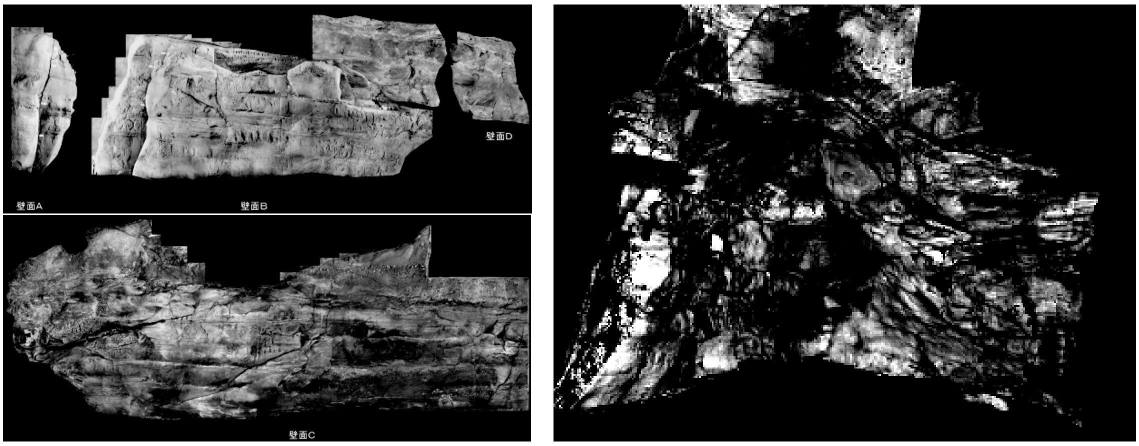
Figure 5 shows the acquired whole shape of the target. In this measurement 18 pieces of data were obtained. The measurement error of the depth was less than $\pm 5mm$. The registration didn't need much time, since it was accelerated by the hardware-dependent implementation. The merging took about three hours to accomplish.

3 Acquisition of Photometric Information

Besides 3D shape, to restore the 3D appearance of the object, color information on the object surface (texture) is needed. Texture images are captured separately from the 3D data, so the registration between 3D data and texture is required. Here we use the method which matches the characteristic property of 2D texture image and the edge of reflectance image subsequently obtained from the laser range sensor[13][14].

The reflectance image represents the reflection intensity of laser light on each measurement point, and they are measured simultaneously by the same laser range sensor; thus, the reflectance image coincides with the 3D measured data.

The reflectance image and color image have similar characteristic with the respect that they affect the material, shape and color of the object surface. The Cyrax 2500 uses a green laser diode; in this wavelength, the reflectance changes according to the difference of surface color and material, so their boundary is shown as the edge in the reflectance image. On the other hand, the color image has similar boundary edges, since the different material generally has the different color. The jumping edge and contour are similarly shown in both images.



(2)

Figure 6: (1) Color images of the Fugoppe Cave, used as the texture. (2) Acquired whole shape of the Fugoppe Cave with texture.

The registration between 3D shape data and 2D color image is performed by iteratively minimizing the squared sum of the corresponding edge of the reflectance and the color image in 3D coordinate. In order to reduce the influence of the outliers, this iterative minimization is implemented by using conjugate gradient method and maximum likelihood method whose distribution function is Lorentz function.

For the texture of the cave, we used the pictures acquired by the Yoichi Town Board of Education (Figure 6-(1)). They are captured by a camera made by HASSELBLAD, inc. with the strobe light and the illumination. Figure 6-(2) shows the result of the texture mapping as explained above.

4 Acquisition of Environmental Information

4.1 Correspondence between 3D Model and its Position on Earth's Surface

In order to restore the interior appearance of Fugoppe Cave under sunlight, the correspondence between 3D model and its position on the earth's surface has to be taken. The surface registration of the cave model is performed by using principal component analysis for the estimation of the cave surface data which is extracted from the whole 3D model (Figure 7-(1)). The direction registration is performed by using multiple reference points, including the 3D model, where the latitude, longitude, and altitude are known (Figure 7-(2)).

4.2 Orbit and Light Source of the Sun

The ecliptic is assumed here to be a simple circular orbit which is defined from the gradient of the earth axis, the latitude and the earth position in the revolution surface. The circular orbit is translated according to the earth's position in the revolution, the season (Figure 7-(3)). In order to simplify the time setting of a day, the mean solar time is adopted. The sun always crosses the meridian at noon under the mean solar time.

In existing computer graphics techniques, the sunlight is usually assumed to be parallel light rays. However, to be more physically correct, the sunlight should be represented as the skylight. The skylight is the hemispheric light of infinite radius as the collection of surface light patches changing the brightness distribution according to the position of the sun, since the rays emitted from the sun are diffused because of the floating matter in the atmosphere and such diffused light is regarded as the indirect light from the entire celestial sphere. Perez proposed the ALL-WHEATHER MODEL in which all the sky models were classified into eight categories[15].

The skylight changes according to the season, time of the day and the state of the atmosphere. The International Commission on Illumination (CIE) defines the typical brightness distribution of the skylight as "CIE Standard Sky Luminance

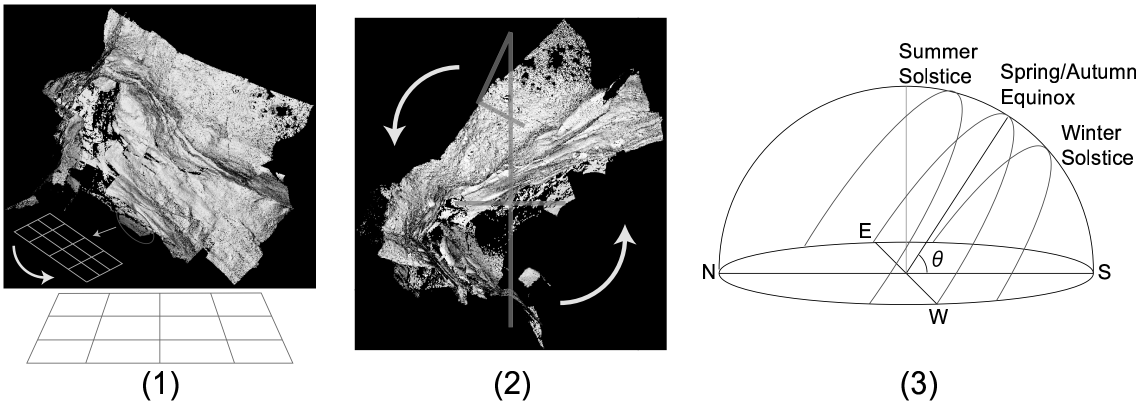


Figure 7: (1) Registration of the ground surface. (2) Registration of the direction. (3) Ecliptic according to the season and the time.

Distribution”. This distribution is determined by the direct horizontal irradiance as the irradiance of the direct light and the diffuse horizontal irradiance as that of the indirect light, the light diffused by the floating matter in the atmosphere.

4.3 Light Interreflection

The cave is illuminated by the direct sunlight and the indirect light which is reflected by the surfaces inside the cave. In computer graphics, the indirect light is usually created by the radiosity method which considers the interreflection of the light among the objects. In the radiosity method, the illumination brightness of the object surface, which is assumed to be the Lambertian surface, is calculated as the sum of the brightness of the direct sunlight and the indirect light from other surfaces.

In this paper, we first assume the parallel and direct light; and later, we relax the assumption by using the skylight and the entire light including the indirect light. In our simulation that considers the indirect light as well, we use the radiance[16] which enables the radiosity method. While, in the real world, the indirect light is reflected repeatedly; by using the radiance, this is approximated by the gradual radiosity method that set the number of interreflections of the light. In this method, one or two interreflections are enough for the creation of the shadow and shading, and more than four interreflections are needed for the illumination calculation. In our simulation, we use four interreflections.

5 Appearance Simulation of Cave under the Sunlight

We reproduce the appearance inside the Fugoppe Cave under the above conditions with the computer graphics. Here we consider the following issues.

- the appearance changes of the cave under the sunlight at each equinox and solstices.
- the shadow movement of the sculptor standing against the south wall and the west wall.

In this paper, we describe how we first observe the shadow cast by using the direct light and assuming that the sunlight is a parallel light source. We ignore the changes of the luminance and the spectrum of sunlight. The region, which the direct light reaches, is shown by its color obtained as the photometric information, and other regions by black. We use a proper 3D human model created by CAD for the shadow movement simulation of the sculptor.

The simulation results under the above conditions are shown in Figure 8 and 9. We first observe the deepest part of the south wall inside the cave. At the winter solstice, the direct sunlight does not reach the wall during the daytime (Figure 8-(1)). At the spring/autumn equinox, it reaches the wall at 6:00 a.m., but it soon becomes dark (Figure 8-(2)). On the other hand, the sunlight reaches the wall from 4:00 a.m. to 9:00 a.m. during the summer solstice (Figure 8-(3)). In summary, the direct sunlight reaches even the deepest part of the cave during fine weather for over half of a year, especially for about five hours per one day at the summer solstice. Moreover, even if a sculptor stands there under the direct sunlight, the shadow does not cast on the wall, and has no effect on his/her working (Figure 9).

The simulation result under the interreflected light as well as the direct light is shown in Figure 10. This result shows that it is sufficiently bright to sculpt inside the cave.

6 Consideration of Simulation Result

From this simulation, it is known that the direct sunlight reaches the deepest part inside the Fugoppe Cave at a certain time. But this simulation is based on the current conditions of the cave, and it is possible that the ancient conditions were different.

It is too difficult to accurately estimate the ancient condition. The Fugoppe Cave probably had the similar entrance in the same direction as the present, since the ancient cave dwellers are imagined to pass through the entrance, judging from the distribution of the excavated relics. First, the floor of the cave is presumed to be lower than in the current condition because there are a lot of carvings nearby the floor, so it would have been brighter ancient times. Second, the width of each wall would be different from the present condition since the carvings remain nearby the current entrance. Third, the current ceiling may be higher than the ancient because of its crashes, but the shadow, cast in the deepest part before and after the direct sunlight reaches, results from the wall, so the ancient illumination condition would be almost the same as the present as far as the height of the ceiling doesn't change so much.

Then we consider the outside obstacles for the sunlight. On the east of the Fugoppe Cave,there is no high mountain which can obstruct the sunlight; instead, there is hill of $\pm 50m$ altitude, which does not yield a shadow inside the Fugoppe Cave, judging from the numerical analysis of the data on the map. It is difficult to know the ancient vegetation, but the entrance would not be covered by some plants similarly in the present condition since the ancient vegetation is consider to have been similar to the present one[1]. Therefore we think that the ancient illumination condition of the cave would be almost the same as the simulation result.

In other words, we consider that the direct sunlight would reach inside of the Fugoppe Cave also at the ancient era at a certain season or time, although the simulation may not be exact, because of the subtle difference of the ancient conditions. Moreover, the simulation, which considers the interreflected light, shows that it would be so bright inside the cave.

From the above consideration, we can assert, against the established theory of the carving with an artificial light, the possibility that the ancient sculptors worked inside the cave under the sunlight if they could choose the optimum season and time for working.

Finally, we consider the distribution of the carvings according to the shadow effect of the sculptor in working. As shown in Figure 9-(1), the shadow of the sculptor standing against the south wall would have been cast on the right side. If he/she were to be right-handed, the illumination condition would be better for him/her to be there . In the case of the west wall, it would have been worse because the shadow would have been cast just at the front as shown in Figure 9-(2). Actually, more carvings remain on the south wall than on the west, and this fact coincides with our theory.

7 Conclusion and Future Work

In this paper, we describe how we restored the sunlight illumination condition inside the Fugoppe Cave which, in the real world, is impossible to observe directly. We were able to do this by using its 3D model created from the 3D measurement data of the laser range sensor. From this illumination simulation, we verified the possibility that the ancient sculptors worked inside the cave without an artificial light by choosing the optimum season and time for their working. In the future, we also intend to investigate the other typical tumuli in order to consider their illumination condition in the same way and thus acquire novel archaeological knowledge.

Acknowledgement

This work was supported in part by Japan Science and Technology Cooperation (JST) under the CREST program, and we thank the Yoichi Town Board of Education for their cooperation of our work concerned about the Fugoppe Cave.

References

[1] Otaru City Board of Education. *Symposium on Temiya Cave(in Japanese)*. Otaru City Board of Education, 1997.

[2] W. I. Sellers, R. Orton, and A. T. Chamberlain. Computer-aided visualisation of archaeological caves. http://www.shef.ac.uk/˜capra/3/sellers.html, 2001.

[3] M. Roe. The brighter the light the darker the shadows: how we perceive and represent underground spaces. http://www.shef.ac.uk/˜capra/2/roe.html, 2000.

[4] W. I. Sellers and A. T. Chamberlain. Ultrasonic cave mapping. In *Journal of Archaeological Science*, pp. 283–289, March 2001.

[5] K. A. Robson Brown, A. Chalmers, T. Saigol, C. Green, and F. d'Errico. An automated laser scan survey of the upper palaeolithic rock shelter of cap blanc. In *Journal of Archaeological Science*, pp. 867–873, September 1998.

[6] K. Devlin, A. Chalmers, and D. Brown. Predictive lighting and perception in archaeological representations. In *UNESCO World Heritage in the Digital Age 30th Anniversary Digital Congress*, October 2002.

[7] C. Cruz-Neira, D. J. Sandin, and T. A. DeFanti. Surround-screen projection-based virtual reality: The design and implementation of the cave. In *Proceedings of SIGGRAPH 1993*, pp. 135–142, August 1993.

[8] P.J. Besl and N.D. McKay. A method for registration of 3-d shapes. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 14, No. 2, pp. 239–256, February 1992.

[9] G. Turk and M. Levoy. Zipped polygon meshes from range images. In *ACM SIGGRAPH Proceedings*, pp. 311–318, July 1994.

[10] Fast Simultaneous Alignment of Multiple Range Images Using Index Images(in Japanese). Takeshi oishi, atsushi nakazawa, katsushi ikeuchi. In *Meeting on Image Recognition and Understanding 2004*, July 2004.

[11] B. Curless and M. Levoy. A volumetric method for building complex models from range images. In *Proceedings of ACM SIGGRAPH 96*, pp. 303–312, August 1996.

[12] R. Sagawa K. Nishino, M.D. Wheeler, and K. Ikeuchi. Parallel processing of range data merging. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Vol. 1, pp. 577–583, October 2001.

[13] R. Kurazume, M.D. Wheeler, and K. Ikeuchi. Mapping textures on 3d geometric model using reflectance image. In *Data Fusion Workshop in IEEE International Conference on Robotics and Automation*, May 2001.

[14] R. Kurazume, Z. Zhang K. Nishino, and K. Ikeuchi. Simultaneous 2d images and 3d geometric model registration for texture mappint utilizing reflectance attribute. In *Proceedings of Fifth Asian Conference on Computer Vision*, pp. 99–106, January 2002.

[15] Perez R., Seals R., and Michalsky J. All-weather model for sky luminance distribution - preliminary cofiguration and validation. *Solar Energy*, Vol. 50, No. 3, pp. 235–245, 1993.

[16] Ward Gregory J. The radiance lighting simulation and rendering system. In *Proceedings of SIGGRAPH 1994*, pp. 459–472, July 1994.

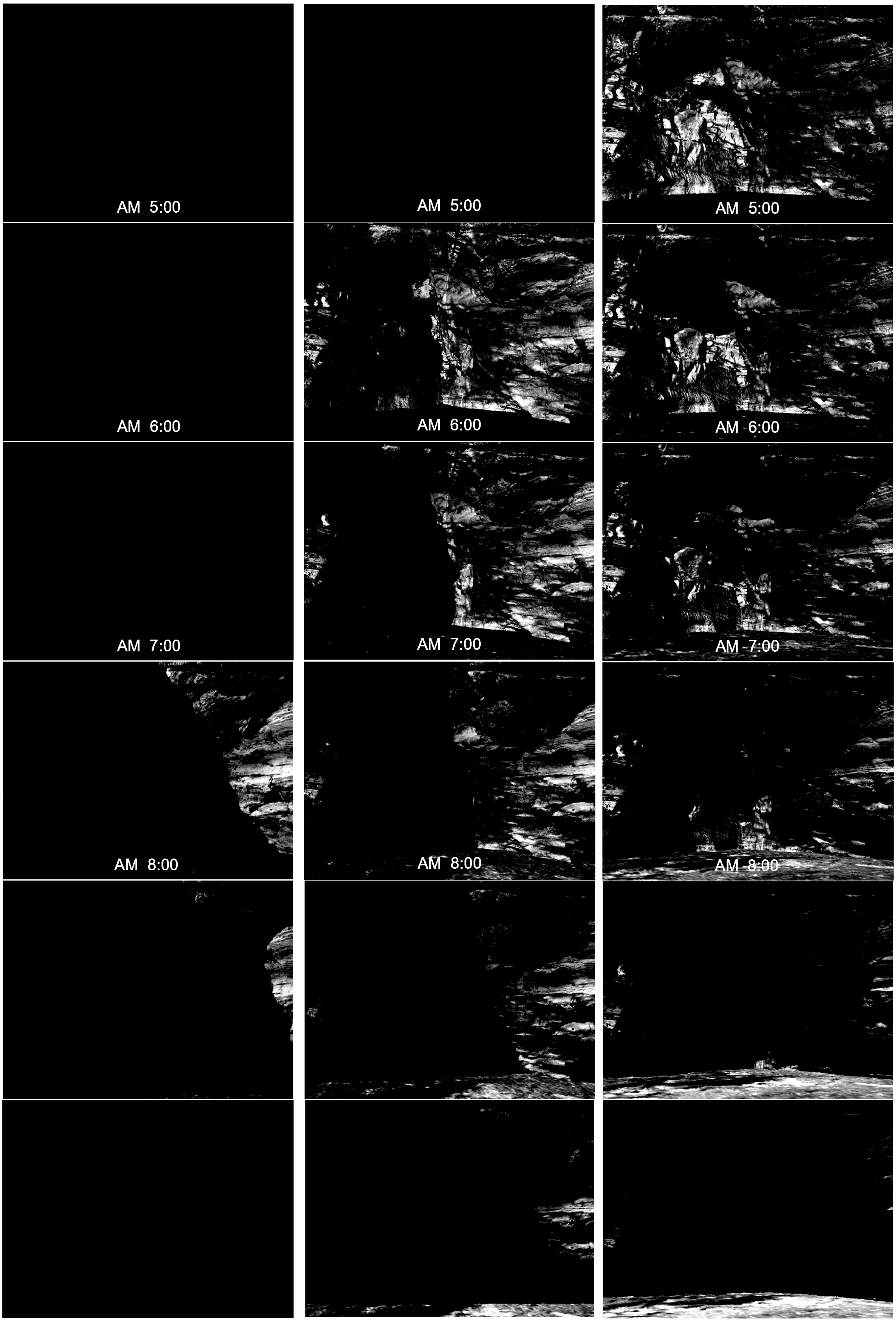


Figure 8: Simulation results. As the season changes from winter to summer, the direct sunlight reaches the walls for more hours.

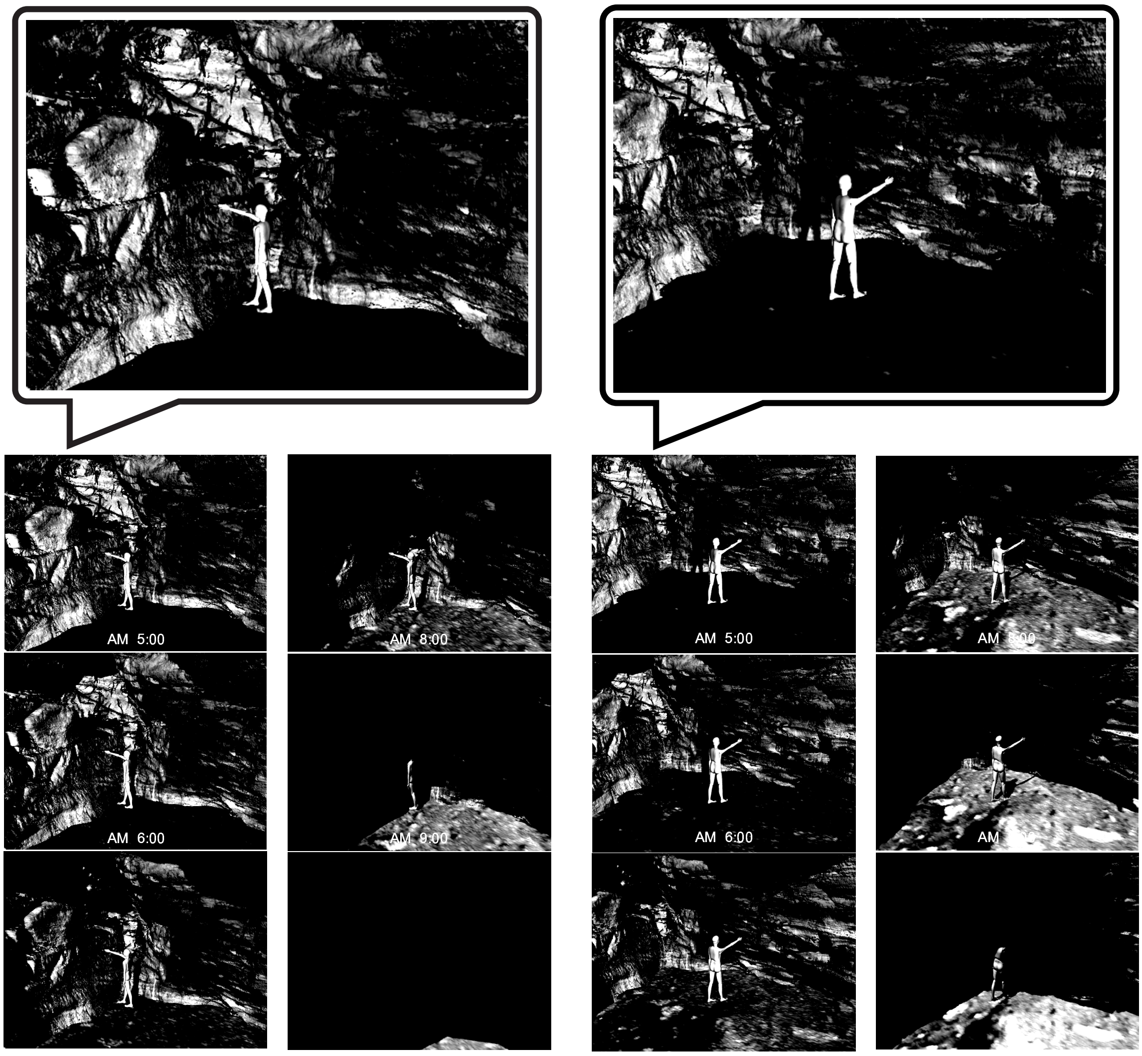


Figure 9: Simulation result on the summer solstice with a man standing against the wall. This shows the sculptor's shadow doesn't darken his/her working space.

Figure 10: Simulation result considering the sunlight interreflection. This result shows the inside is brighter than it is expected.