International Journal of Advances in Computer Science and its Applications – IJCSIA
Volume 4 : Issue 1 *[ISSN 2250 – 3765]*
Publication Date : 09 January 2014

Development of 3D measurement system using phase-shift digital holography

[Qiyue Yu, Ryo Taguchi, Masahiro Hoguro, Hideyoshi Horimai and Taizo Umezaki]

***Abstract*—We propose a digital holography reconstruction method using convolution approach rather than the conventional Fresnel approach. Simultaneously, we propose a 3D measurement system of phase-shift digital holography using principle of light detector. Using proposal method, we develop a compact 3D measurement system of phase-shift digital holography with low price and high measurement accuracy.**

***Keywords*—3D measurement, phase-shift digital holography, optical system**

I. Introduction

In these years, demand for 3D measurement technology is higher. However, in many of conventional 3D measurement methods, such as the method using phase-shift patterns projection, it is difficult to measure shape of specular reflective and transparent objects, because power of reflected light is too high from specular reflective objects or too low from transparent objects, so that information of reflected light cannot be acquired accurately by a digital camera. Digital holography technology has been used for resolving this problem. In conventional digital holography, interference fringe of object light wave and reference light wave is recorded by a digital camera. Using Fresnel diffraction principle, phase information of object light wave can be calculated and shape of object can be calculated using interferometry. It can be used for 3D measurement of reflective and transparent objects, but as the principle of Fresnel diffraction, DC and conjugate components exist in calculated phase information of object as noises[1], so accuracy of 3D measurement is lower. For imp-roving the measurement accuracy, research on phase-shift digital holography is actively carried out[2]. In phase-shift digital holography, first, four phase-shift interference fringes are captured by a digital camera, while the optical path difference between object light wave and reference light wave is shifting 1/4 times laser wavelength by piezoelectric stage. Then, using the four phase-shift interference fringes, DC and conjugate can be removed directly by phase-shift method. At the end, by reconstructing the object light wave using Fresnel transform, phase distribution of object light wave can be calculated, and 3D shape can be measured using interferometry. However, for generating four phase-shift interference fringes, control of piezoelectric stage is necessary, so control accuracy of piezoelectric stage affects measurement accuracy. Moreover, price of piezoelectric stage is high, so that price reduction of measurement system is difficult.

In this letter, according to the principle of light detector, we propose a new phase-shift generation method using low-priced polarizer to take place of expensive piezoelectric stage. Simultaneously, we propose a new digital holography object wave light's reconstruction method using convolution approach rather than the conventional Fresnel approach[3]. Using proposal method, we also develop a compact 3D measurement system using phase-shift digital holography with low price and high measurement accuracy.

Qiyue Yu, Ryo Taguchi and Taizo Umezaki
Nagoya Institute of Technology
Japan
yuqiyue@ume.mta.nitech.ac.jp

Masahiro Hoguro
Chubu University
Japan

Hideyoshi Horimai
Holymine Cooperation
Japan

II. Proposal system

A. Overview

Structure of proposal system is shown as Figure 1. First, after passing through the half wavelength plate, laser beam is split to two beams by polarization beam splitter. Then, one laser beam reflected from object becomes object light wave, the other laser beam reflected from mirror becomes reference light wave. At the end, after passing through light-detector, object and reference light waves produce an interference fringe on surface of CMOS sensor. Here, by rotating of the polarizer four times, four phase-shift interference fringes are captured by CMOS sensor. Flow chat of 3D measurement processing is shown as Figure 2.

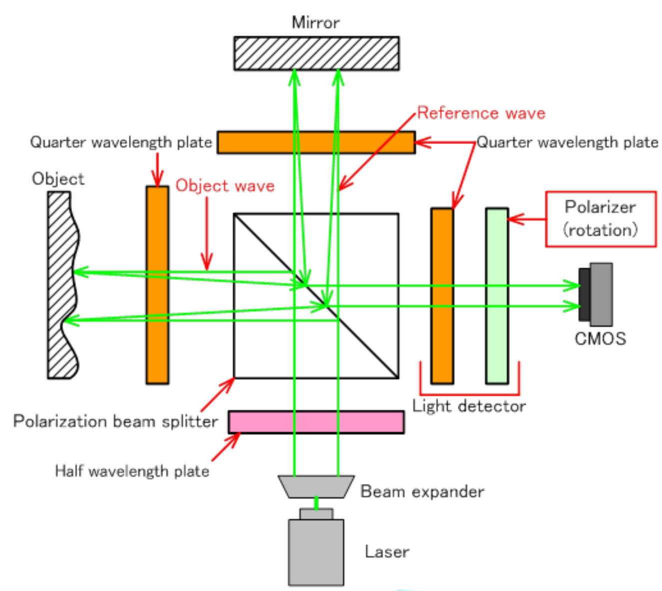


Figure 1. Conceptual diagram of proposal system.

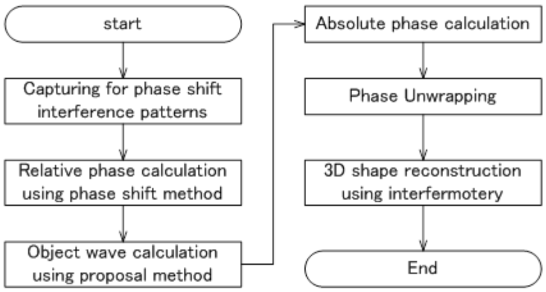


Figure 2. Flow chat of proposal 3D measurement processing.

B. ***Generation of phase-shift interference fringes***

Polarization states of light waves in proposal system when laser irradiating are shown as Figure 3. In order to increase 3D measurement range, laser beam is expanded by beam expander. The expanded laser beam passes through the half wavelength plate and irradiates the polarization beam splitter. By rotating the half wavelength, intensity of object and reference light waves can be adjusted. Laser beam is split into two beams having different polarization plane by the polarization beam splitter. P-polarized laser beam is emitted toward the mirror, respectively S-polarized laser beam is emitted toward the object. Thereafter, S-polarized and P-polarized laser beams become two circularly polarized beams having difference directions of optical rotation after passing through the quarter wavelength plate, and irradiate the mirror and object.

After laser irradiating, polarization states of light waves in proposal system when laser reflecting are shown as Figure 4. Circularly polarized object light wave reflected from surface of object becomes P-polarized light wave after passing through the quarter wavelength plate, and irradiates the polarization beam splitter. On the other hand, Circularly polarized reference light wave reflected from mirror becomes S-polarized light wave after passing through the quarter wavelength plate, and is reflected by the polarization beam splitter. Here, object light wave and reference light wave propagate toward CMOS sensor together, but since polarizations are orthogonal, at output of the polarization beam splitter, interference phenomenon does not occur. Thereafter, the object light wave and reference light wave having orthogonal polarizations become two circularly polarized light waves having difference directions of optical rotation after passing through the quarter wavelength plate of light detector. Because only linearly polarized component of light wave predetermined by the polarization plate can pass through the light detector, phase-shift interference fringes of object and reference light waves can be captured by CMOS sensor by rotating the polarization plate 45-degree four times. Using a mirror as measurement object, principle verification result of phase-shift interference fringes' generation is shown as Figure 5. According to the luminance change of one line in captured images shown in Figure 5, it can be confirmed that phases of interference fringes are changed by 90-degree by rotation of the polarizer.

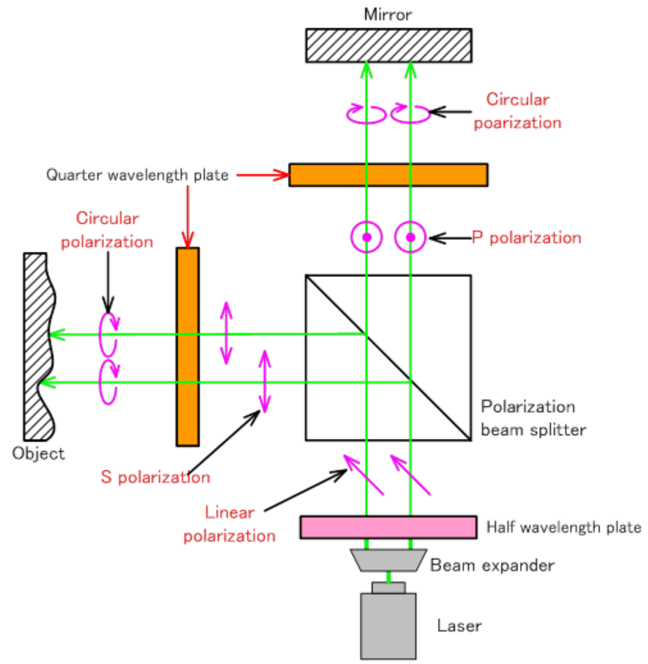


Figure 3. Conceptual diagram of proposal system when laser irradiating.

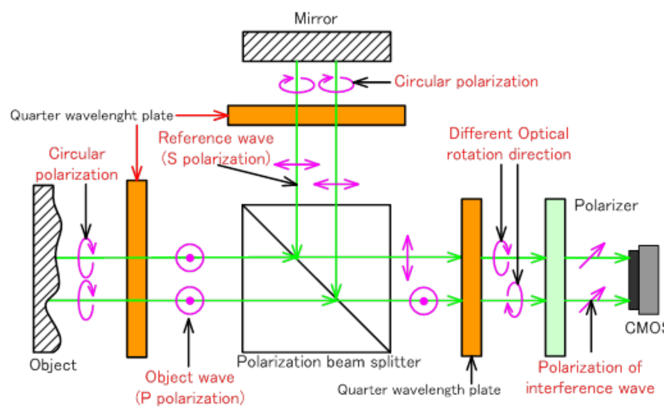
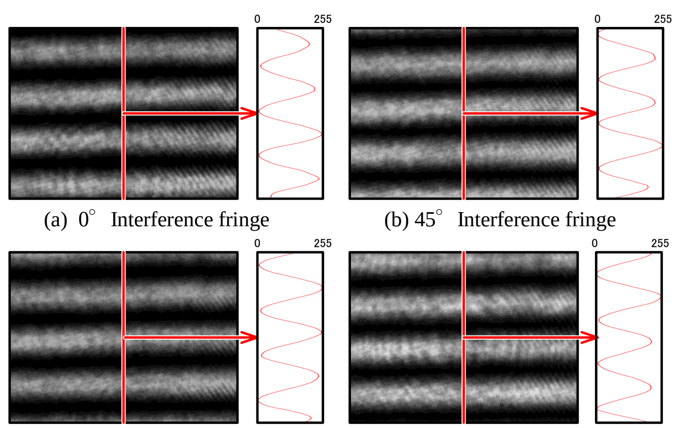


Figure 4. Conceptual diagram of proposal system when laser reflecting.



(a) 0° Interference fringe (b) 45° Interference fringe

(c) 90° Interference fringe (d) 135° Interference fringe

Figure 5. Phase-shift interference fringes.

C. *Setup of proposal system*

Appearance of proposal system is shown as Figure 6. In proposal system, solid-state laser with 532 [nm] wavelength is used as light source, pixel size of CMOS sensor is 3.54 [μm], measurement range is 7×7 [mm], size of system is 83×40 [mm]. Price comparison of automatic rotation used in proposal system and piezoelectric stage used in conventional system is shown in TABLE I.

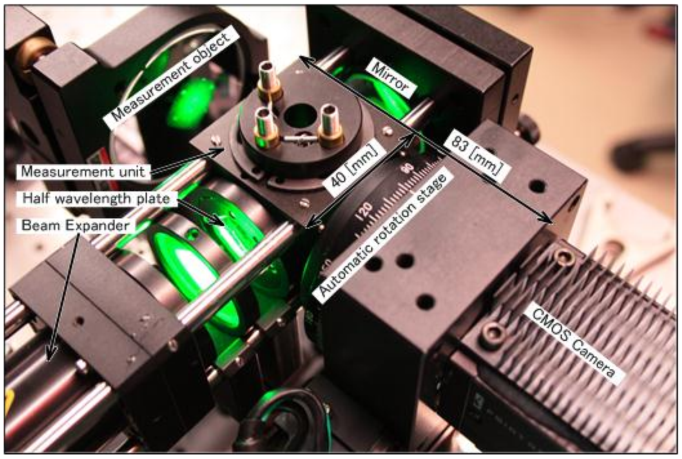


Figure 6. Appearance of proposal system.

TABLE I. PRICE COMPARISON OF AUTOMATIC ROTATION STAGE AND PIEZOELECTRIC STAGE

	Automatic rotation stage	Piezoelectric stage
Model number of stage	FPW06360	SFS-H40Z(CL)
Model number of controller	DS102	FINE-01γ
Total price	JPY 284,000	JPY 570,000

According to the size of proposal and price comparison shown in TABLE I, it can be considered that realization of compact 3D measurement system with low price is possible.

III. Proposal Method

In this letter, we propose a new object light wave's reconstruction method using phase-shift digital holography with convolution approach rather than Fresnel transformation in conventional method. In proposal method, first, the DC and conjugate components, which are difficult to remove using single interference fringe, are removed directly using four phase-shift interference fringes and phase-shift method. Then, object light wave is reconstructed using convolution approach, and phase distribution is calculated from the reconstructed object light wave. At the end, the phase distribution of reconstructed object light wave is unwrapped by quality map method[4], and 3D shape of object is calculated using interferometry from the unwrapped phase distribution.

A. *Phase-shift method*

For removing effects of DC and conjugate components on measurement accuracy, phase-shift method is used to calculate relative phase of object light wave and reference light wave. The phase-shift method is shown in (1).

$$\Delta\varphi(x,y) = \tan^{-1}\left\{\frac{I_4(x,y)-I_2(x,y)}{I_1(x,y)-I_3(x,y)}\right\}. \quad (1)$$

$I_1(x,y) \sim I_4(x,y)$ are four phase-shift interference fringes captured by CMOS camera. (x,y) is coordinates of captured image. $\Delta\varphi(x,y)$ is the relative phase of object light wave and reference light wave.

According to (1), the calculated phase distribution is the phase of object light wave relative to the phase of reference light wave. For calculating absolute phase distribution of object light wave, reconstruction process of object light wave is necessary.

B. *Reconstruction using convolution method*

Using phase-shift method, relative phase of object light wave can be calculated, so the complex amplitude of object light wave having relative phase can be described as in

$$E_O(x,y) = e(x,y)\exp\{\, i\Delta\varphi(x,y)\},$$
$$e = \sqrt{(I_4-I_2)^2+(I_1-I_3)^2}. \quad (2)$$

$E_O(x,y)$ is the complex amplitude, e is amplitude, $\Delta\varphi(x,y)$ is relative phase calculated using phase-shift method.

By substituting the complex amplitude of object light wave having relative phase in Fresnel transform, complex amplitude of object light wave on object surface as point light source can be described as in

$$E_O(x,y) = \frac{i}{\lambda}\iint \Gamma(\xi,\eta)\frac{\exp(-i\frac{2\pi}{\lambda}\rho)}{\rho}d\xi d\eta,$$
$$\rho = \sqrt{(x-\xi)^2+(y-\eta)^2+d^2}. \quad (3)$$

$E_O(x,y)$ is the complex amplitude having relative phase of object light wave, $\Gamma(\xi,\eta)$ is the complex amplitude of object light wave on object surface. (ξ,η) are coordinates of object plane shown in Figure 7. (x,y) are coordinates of image captured by CMOS sensor, d is distance between sensor plane and object plane. λ is laser wavelength.

Fresnel transform can be described as (4) with a factor $g(\xi,\eta,x,y)$ shown in (5).

$$E_O(x,y) = \frac{i}{\lambda}\iint \Gamma(\xi,\eta)g(\xi,\eta,x,y)d\xi d\eta, \quad (4)$$

$$g(\xi,\eta,x,y) = \frac{i\exp(-i\frac{2\pi}{\lambda}\rho)}{\lambda\rho},$$
$$\rho = \sqrt{(x-\xi)^2+(y-\eta)^2+d^2}. \quad (5)$$

According to the convolution principle, (4) can be described by (6) using Fourier transform.

$$\Im\{E_O(x,y)\} = \Im\{\Gamma(\xi,\eta)\}\times\Im\{g(\xi,\eta,x,y)\}. \quad (6)$$

$\Im$ is Fourier transform.

According to (6), the complex amplitude and phase distribution of object light wave on object surface can be calculated using (7).

$$\Gamma(\xi,\eta) = \Im^{-1}\left\{\frac{\Im\{E_O(x,y)\}}{\Im\{g(\xi,\eta,x,y)\}}\right\},$$

$$\varphi(\xi,\eta) = \tan^{-1}\left\{\frac{\mathrm{Im}\{\Gamma(x,y)\}}{\mathrm{Re}\{\Gamma(x,y)\}}\right\}. \quad (7)$$

$\Im^{-1}$ is inverse Fourier transform, Im and Re are imaginary part and real part of the complex amplitude respectively.

Because object light wave on object surface can be considered as point light source, phase distribution $\varphi(\xi,\eta)$ in (7) is absolute phase distribution of object light wave. For instance, calculated absolute phase distribution using proposal method from four interference fringes shown as Figure 5 is shown as Figure 8.

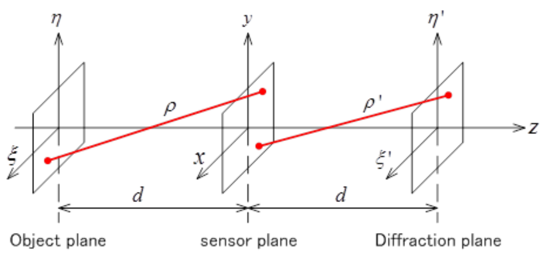


Figure 7. Coordinate relations of object, sensor and diffraction plane.

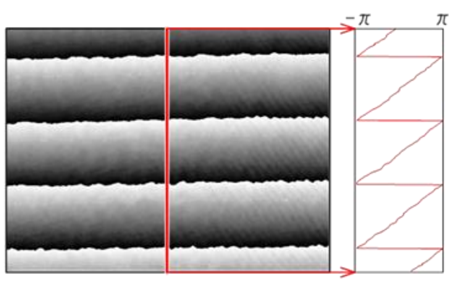


Figure 8. Absolute phase distribution of object light wave.

C. *Interferometry*

Interferometry is used to calculate 3D shape of object from absolute phase distribution. However, range of absolute phase value is [-π, π] since tan2() function of C++ language in computer. Therefore, phase unwrapping process is necessary before calculation of interferometry. In this letter, quality map method is used in phase unwrapping process.

After unwrapping absolute phase distribution of object light wave, 3D shape of object can be calculated using interferometry shown in (8).

$$X = \frac{\lambda d}{W\Delta x}x, \qquad Y = \frac{\lambda d}{W\Delta y}y, \qquad Z = \frac{\lambda}{2\pi}\varphi. \quad (10)$$

(*x*,*y*) are coordinates of image captured by CMOS sensor. *X*,*Y* and *Z* are coordinations of object's 3D shape. Δx and Δy are pixel size of CMOS sensor., *W* and *H* are width and height of image. φ is unwrapped absolute phase distribution. λ is laser wavelength. d is distance between object plane and sensor plane.

In summary, using the proposal method, DC and conjugate components can be removed directly, and relative phase distribution of object light wave can be calculated using phase-shift method. Moreover, calculation of absolute phase distribution of object light wave with convolution approach is possible, and 3D shape of object can be calculated using interferometry from absolute phase distribution after phase unwrapping process.

IV. Measurement accuracy

In order to evaluate measurement accuracy, 1 [μm] step place on the step master(Mitutoyo NO. 616-498) is measured by 10 times. Using 3D shape of the step master measured by proposal system, step value is calculated as the measurement value. In addition, the same step place is measured by touch probe coordinate measuring machine(Dektak 150 surface profiler), and the result of measurement(1.040 [μm]) is used as the true value. Average error between the measurement value and the true value is calculated as result of measurement accuracy evaluation shown as Figure 9. According to the result of measurement accuracy evaluation, we can confirm that the measurement average error of the proposal system is 7.1 [nm].

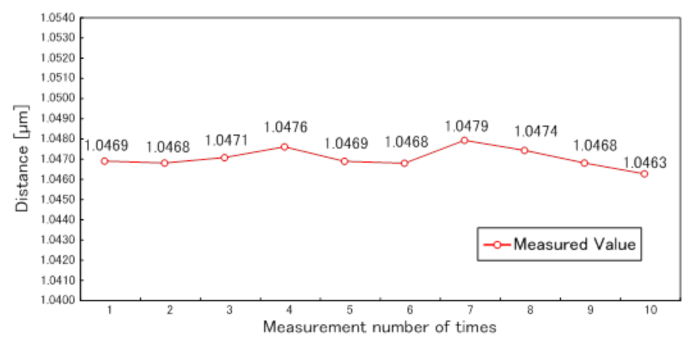


Figure 9. Measurement values of 1 [μm] step place on the step master.

V. Measure Experiment

In almost conventional 3D measurement methods, such as the method using phase-shift patterns projection, it is difficult to measure shape of specular reflective and transparent objects. For emphasizing the advantage of proposal system, in measure experiment, we measured the surface of an aluminum board and a mirror coated with oil as specular reflective objects. Simultaneously, we also measured the surface of a lens as transparent object. The results of measure experiment are shown as follows. According to the results of measure experiment, it can be considered that 3D measurement for specular reflective and transparent objects is possible using proposal system.

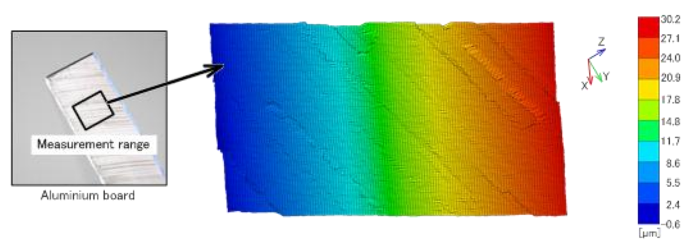


Figure 10. 3D shape of aluminum board's surface.

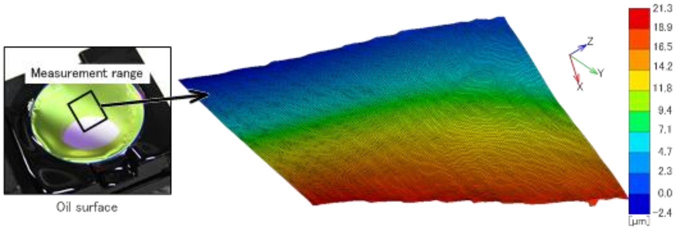


Figure 11. 3D shape of oil's surface.

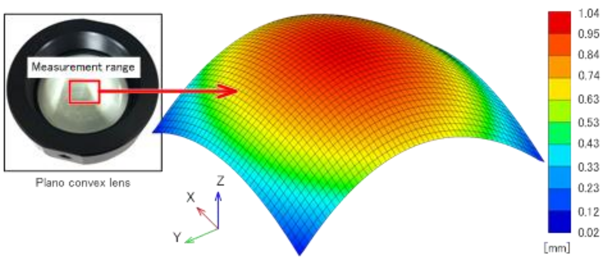


Figure 12. 3D shape of lens' surface.

VI. Conclusion

In this letter, we proposed a digital holography reconstruction method using convolution approach rather than the conventional Fresnel approach. Simultaneously, according to light detector principle, we also developed a compact 3D measurement system using phase-shift digital holography with low price. According to the result of measurement accuracy evaluation, the average measurement error is 7.1 [nm], so we concluded that the high accuracy 3D measurement is possible using proposal method. According to the results of measure experiment, we concluded that 3D measurement for specular reflective and transparent objects is possible using proposal system.

References

[1] Goodman JW, Lawrence RW : Digital image formation from electronically detected holograms, Appl Phys Lett 11, pp.77-79, 1967.

[2] Yamaguchi, Zhang t: Phase-shifting digital holography. Optical letter, vol.22, no.16, pp1268-1270, 1997.

[3] Kronrod MA, Merzlyakov NS, Yaroslavski LP : reconstruction of hologra ms with a computer, Sov Phys-Tech USA 17(2), pp.333-334, 1972

[4] Yuri Barseghyan, Hakob Sarukhanyan: Laplacian Based LF Quality Map for Phase Reconstruction. CSIT 2009.

About Author (s):

Qiyue Yu received the B.E. degree in Information Science and Technology from Qingdao University of Science & Technology, China, in 2007, the M.E. degree in techno-business administration from Nagoya Institute of Technology, Japan, in 2012. Currently, he is Ph.D. candidate in computer science and engineering at Nagoya Institute of Technology, Japan. His research interests are image processing technology and 3D measurement. He is a member of IPSJ.

Ryo Taguchi received the B.E., M.E. and Ph.D. degrees from Toyohashi University of Technology, Japan, in 2002, 2004 and 2008. He has been an assistant professor at Nagoya Institute of Technology since 2008. He received the JSAI best paper award 2010. His research interests are conversation with robot and language acquisition. He is a member of JSAI, IPSJ, RSJ and ASJ.

Masahiro Hoguro received the B.E. and M.E. degrees in electrical engineering from Chubu University, Japan in 1993 and 1995. He joined DDS Inc. in 2002. He received the Ph.D. in computer science and engineering at Nagoya Institute of Technology. He has been an associate professor at Chubu University since 2010. His research interests are speech and image processing. He is a member of IEICE and JSWE.

Hideyoshi Horimai received the B.E. and M.E. degrees from Toyohashi University of Technology, Japan, in 1982 and 1984. He has been engaged in advanced technology development of optical disc field at SONY from 1984 to 1996. He established Optware Ltd. in 1999, and is researching on 3D display. He was a committee of council for science and technology policy during 2002-2004. He has been a visiting professor at Toyohashi University of Technology, Japan, from 2006. He has been a part-time lecturer at Nara Institute of Science and Technology from2009.

Taizo Umezaki received the B.E. and M.E. degrees from Toyohashi University of Technology, Japan, in 1982 and 1984. He received the Ph.D. degree from Nagoya University, Japan, in 1987. He was an assistant at Nagoya University. In 1990 he was a lecture and in 1992 an assistant professor at Chubu University. During 1993-1997 he was a visiting scholar at Carnegie Mellon University. He has been a professor at Chubu University in 1999. Since 2003, he has been a professor at Nagoya Institute of Technology. His research interests are speech and image processing, education for deaf children and welfare robot. Dr. Taizo Umezaki received the best paper award from JSWE in 2003, and won the Good Design Award 2006, and received science and technology policy minister award of industry-academia-government collaboration merit award in 2008. He is a member of IPSJ, ASJ, IEICE, JSWE, HIS of Japan, JSMBE, RSJ and JSPE.