Non-contact full field vibration measurement based on phase-shifting

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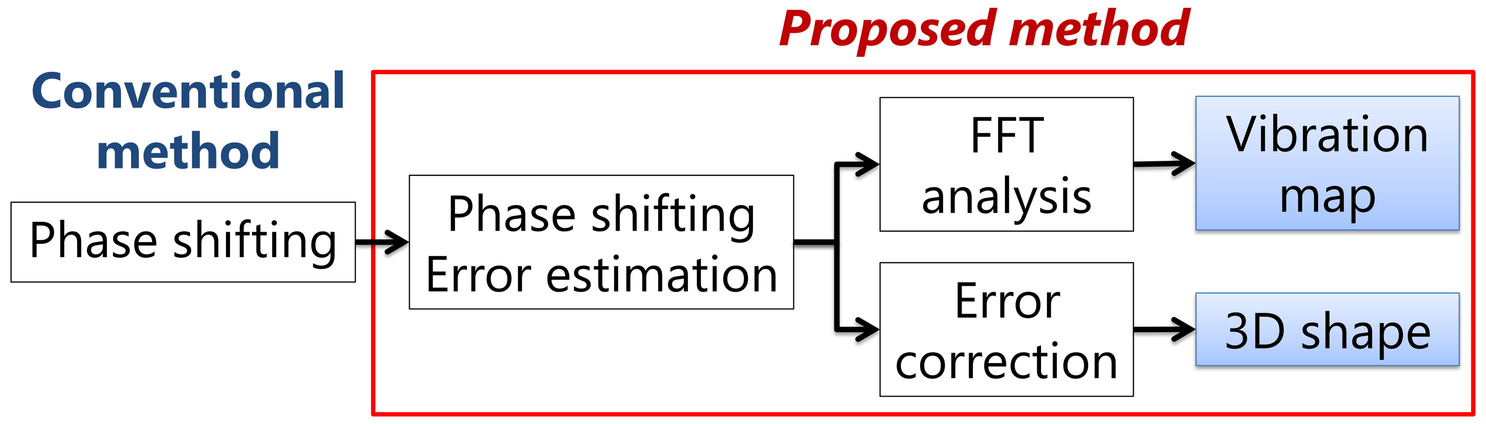
Objective

This paper present a novel, non-contact full field ***joint measurement*** technique both of ***vibrations*** and ***shape*** based on phase-shifting.

Main Idea

The main idea is to take phase shifting based structured light systems and derive a relationship between vibration of an object and errors in the predicted phase shift value. To estimates the phase-shift error by iterating frame-to-frame optimization and pixel-to-pixel optimization.



Phase-shifting Algorithm

I_n is the intensity at point (x,y). $B(x,y)$ is the intensity modulation, $A(x,y)$ is the average intensity and $\phi(x,y)$ is the phase

$$\begin{aligned} I_n(x,y) &= B(x,y) + A(x,y)\cos(\phi(x,y)+\phi_n) \\ &= B(x,y) + A(x,y)\cos\phi(x,y)\cos\phi_n \\ &\quad - A(x,y)\sin\phi(x,y)\sin\phi_n. \end{aligned} \qquad (1)$$

Eq.(1) can also be rewrite as follow:

$$I_n(x,y) = p(x,y) + q(x,y)s_n + r(x,y)t_n \qquad (2)$$

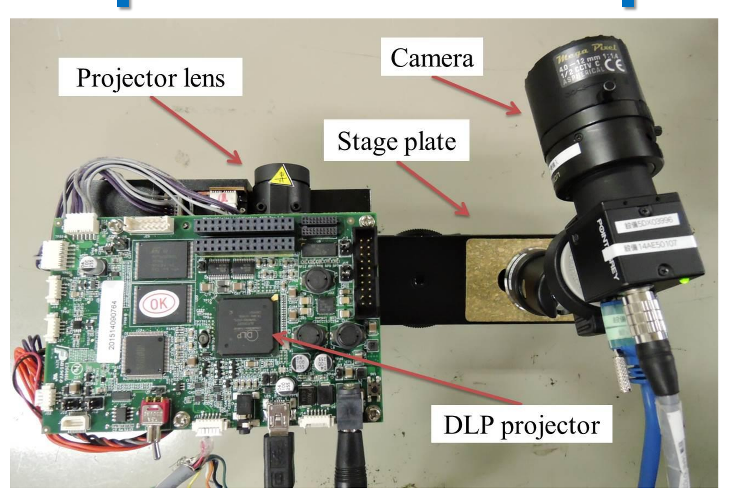
Solving eq.(2) using the least-squares algorithm, we obtain $\phi(x,y)$ as follows:

$$\phi(x,y) = tan^{-1}\left(\frac{-\sum_{n=1}^{N} I_n \sin(\phi_n)}{\sum_{n=1}^{N} I_n \cos(\phi_n)}\right) \qquad \phi_n = \frac{2\pi n}{N}$$

where ϕ_n is a phase-shifting offset. The phase residual is then defined as:

$$\Delta\phi_n(x,y) = \hat{\phi}_n(x,y) - \phi_n$$

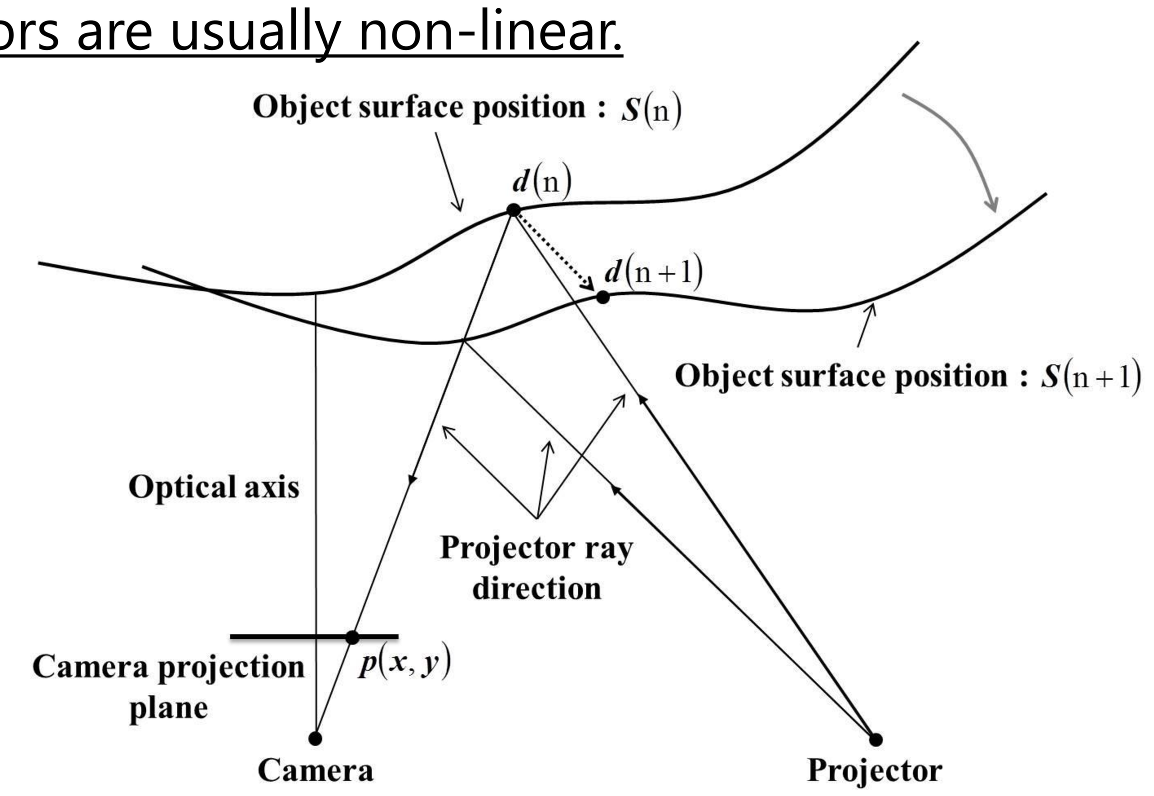
Experiment Setup



- Pattern rate: 100 Hz (8 bit)
- System size: 30 x 15 x 10 cm
- DLP projector (1140 x 912)
- 150 lumen
- CMOS camera (1328 x 1048)

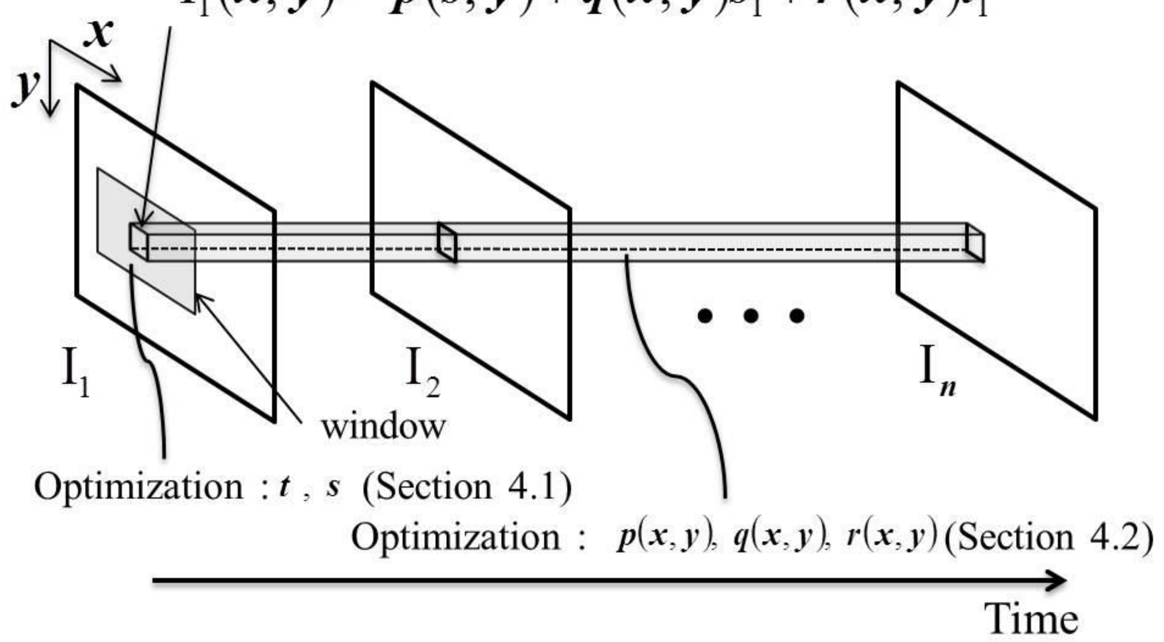
Non-linear Correction of Phase Error

Phase-shift errors caused by object or projector movement during measurement. **Problem:** <u>These errors are usually non-linear.</u>



Iterative optimization performed **frame-to-frame** in the ROI image and optimization **pixel-to-pixel** in images.

$$I_1(x,y) = p(s,y) + q(x,y)s_1 + r(x,y)t_1$$



☐ Pixel-to-pixel optimization

The optimization of common variables <u>at each pixel</u>.

$$\begin{bmatrix} 1 & s_1 & t_1 \\ \vdots & \vdots & \vdots \\ 1 & s_n & t_n \end{bmatrix} \begin{bmatrix} p(x,y) \\ q(x,y) \\ r(x,y) \end{bmatrix} = \begin{bmatrix} I_1(x,y) \\ \vdots \\ I_n(x,y) \end{bmatrix}$$

Where $p(x,y)$, $q(x,y)$ and $r(x,y)$ are wrapped phase, DC component and AC component of intensity, respectively.

☐ Frame-to-frame optimization

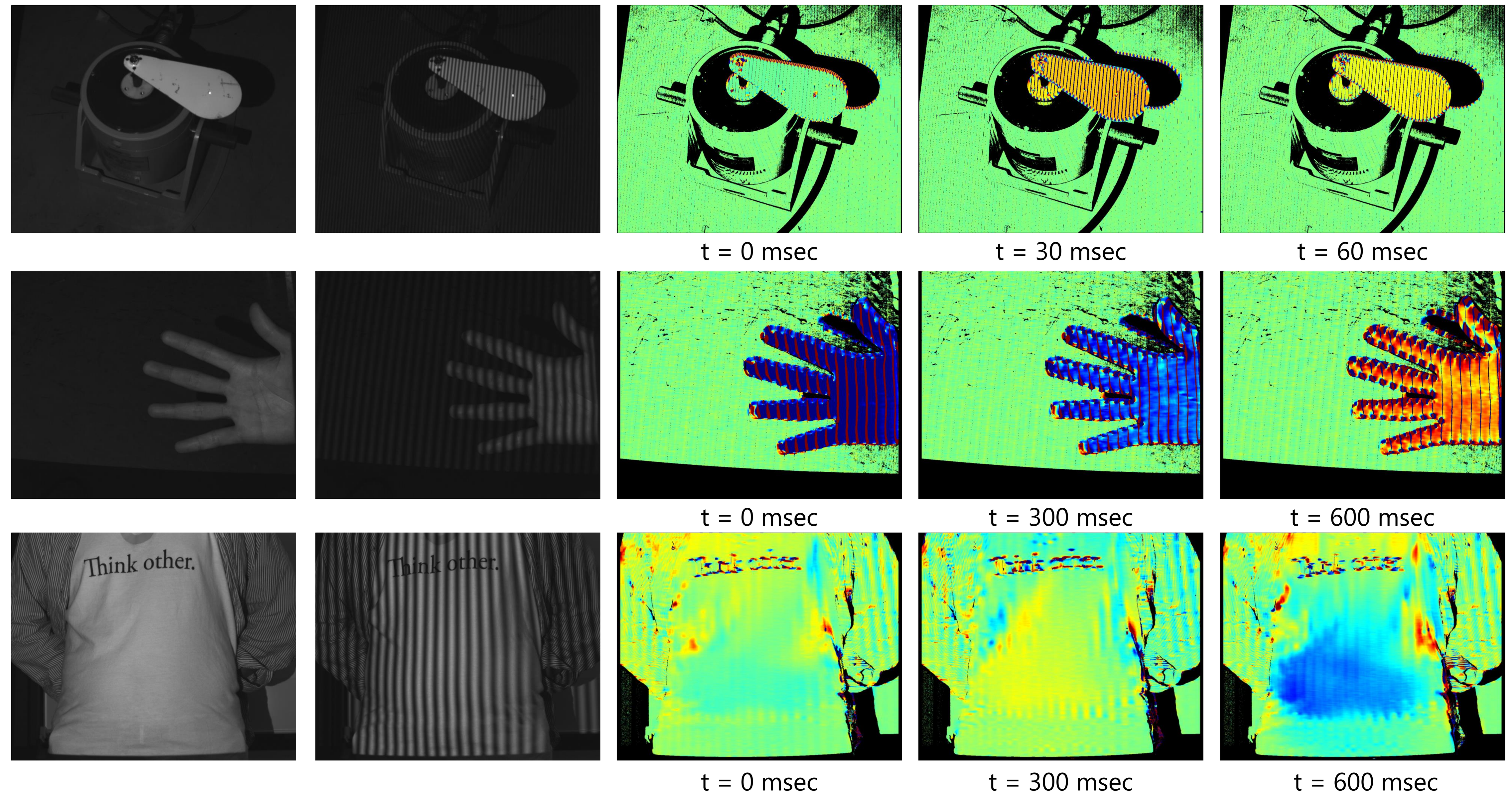
The optimization of common variables <u>in an images</u>.

$$\begin{bmatrix} q_1 & r_1 \\ \vdots & \vdots \\ q_l & r_l \end{bmatrix} \begin{bmatrix} s_n \\ t_n \end{bmatrix} = \begin{bmatrix} I_1 - p_1 \\ \vdots \\ I_l - p_n \end{bmatrix} \qquad (s_n)^2 + (t_n)^2 = 1.$$

Where s_n and t_n which are the phase shifted value of each image. l is the number of pixels in the ROI image.

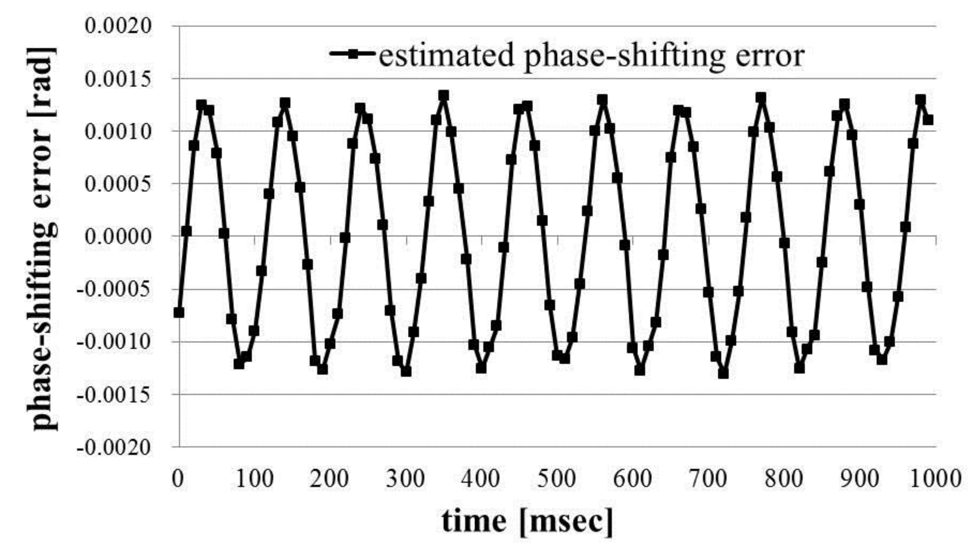
Results

1. Estimate phase shift error



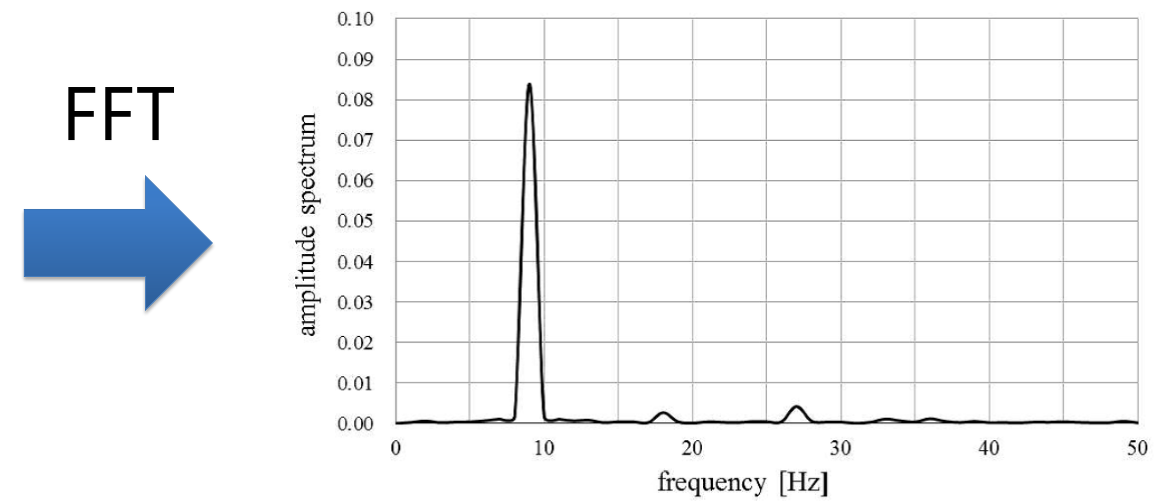
Vibration measurement results for a vibrator (top), a hand (middle) and human breathing (bottom) (color bar range from blue (-0.005) to red (0.005))

2. Frequency from FFT analysis



Cross section of the estimated phase-shift errors at a point of interest (frequency of vibration: 10 Hz)

FFT

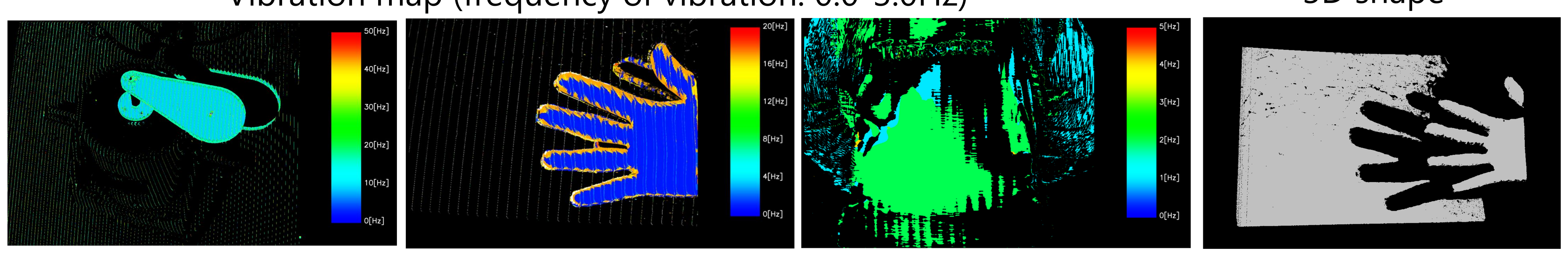


FFT analysis results at a point of interest on the vibrating surface.

3. Vibration map and 3D reconstruction

Vibration map (frequency of vibration: 0.0-3.0Hz)

3D shape



Conclusion

The proposed system can perform high accuracy vibration(0-10 Hz) measurement and reconstruct a 3D shape. This paper presents an active-lighting approach to measuring a 2D frequency map of vibrating surfaces. Our system is the same as that used for measuring a 3D shape using phase-shifting.