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Encountered-type Visual Haptic Display Using Flexible Sheet

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Abstract— **An encountered-type visual haptic display using flexible sheet is proposed; it allows users to feel like seeing and pushing virtual soft objects directly. Both edges of a translucent flexible sheet such as rubber is attached to two manipulators. They apply bias tension to the sheet by pulling it from both sides, thus varying the sheet compliance. A user can feel the compliance of a virtual soft object by pushing the sheet with his finger directly. The motion of the finger tip is measured by stereo cameras. The manipulators also change the pose of the sheet along the object's surface together with the finger tip motion. The user can touch different points of the object and feel like stroking it with his finger. This sheet is also used as a rear projection screen. From the measured finger tip position, the deformation of the object is calculated by FEM. An LCD projector projects the CG image of the deformed object stereoscopically on the sheet from its back. The user can see the 3D image through stereoscopic glasses and touch the image directly. A method of correcting the CG image distortion caused by the movement of the sheet and the depression of the pushed sheet is proposed. A virtual soft cylinder is expressed by a prototype display: the stroking of the cylinder and the correction of its 3D image are evaluated.**

I. INTRODUCTION

In some virtual reality applications, it is important to display haptic sense when users touch virtual objects: shape, texture, hardness/softness, etc. In general the devices presenting virtual haptic sense are called "haptic devices" or "haptic displays" [1]-[4]. For example, haptic displays for medical training simulators simulate haptic sense in medical practices and present it to a trainee; he experiences virtual medical examination, palpation, surgery, and so on. In such applications, it is necessary that doctors can feel as if they treat real patients: they can feel like touching virtual patients' bodies directly with their hands/fingers, and the motion of them is not restricted. Not only haptic feedback but also visual feedback to the doctors are important. They should be able to see their hands/fingers touching the virtual bodies. The virtual objects to be presented in medical field are human bodies and organs, which are soft and flexible. Accordingly visual haptic displays of virtual soft and flexible objects are required.

In the present study, we propose an encountered-type visual haptic display using flexible sheet such as rubber; this is an improvement of our previous study[5], [6]. Both edges of a translucent flexible sheet is attached to two manipulators. They apply bias tension to the sheet by pulling it from both sides, thus varying the sheet compliance in the normal direction. A user can feel the compliance of a virtual soft object by pushing the sheet with his finger directly. The motion of the finger tip is measured by stereo cameras. The manipulators also change the pose of the sheet along the object's surface together with the finger tip motion. The user can touch different points of the object and feel like stroking it with his finger. From the measured finger tip position, the deformation of the object is calculated by FEM. An LCD projector projects the CG image of the deformed object stereoscopically on the sheet from its back. The user can see the 3D image through stereoscopic glasses and touch the image directly. A method of correcting the CG image distortion caused by the movement of the sheet and the depression of the pushed sheet is also proposed. A virtual soft cylinder is expressed by a prototype display: the stroking of the cylinder and the correction of its 3D image are evaluated.

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II. VISUAL HAPTIC DISPLAY USING FLEXIBLE SHEET

We already proposed a visual haptic display using translucent flexible sheet[6]. This display allows users to feel like seeing and pushing virtual soft objects directly with their fingers.

- For haptic display, the sheet compliance in the normal direction is varied by changing the bias tension applied to the sheet. A user feels compliance of a virtual object by pushing this sheet with his finger directly. The bias tension is applied to the sheet by pulling and fixing its edge using position-controlled actuators; we pull 4 corners of the square sheet with 4 motors.
- For visual display, the sheet is used as a rear projection screen. Two cameras extract the tiny mark attached to the finger tip. The position and deformation of the point pushed by the finger on the sheet are measured by stereo vision. Then the deformation of the virtual object is calculated by FEM, and the 2D CG image of the deformed object is generated by OpenGL. An LCD projector projects this image on the sheet from its back. The user directly sees both the object image and his own finger pushing it.

This display have the following problems:

1) The pose of the sheet is fixed. Thus the user can touch a virtual object only at the limited points or areas which are in contact with the sheet. He cannot feel the shape of the object by active touch.
2) The sheet is depressed when it is pushed; it distorts the CG image projected on the sheet.
3) The displayed image is 2 dimensional.

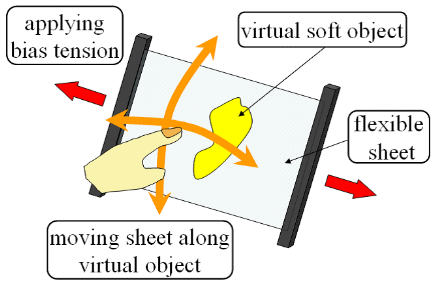


Fig. 1. Basic idea of encountered-type visual haptic display using flexible sheet

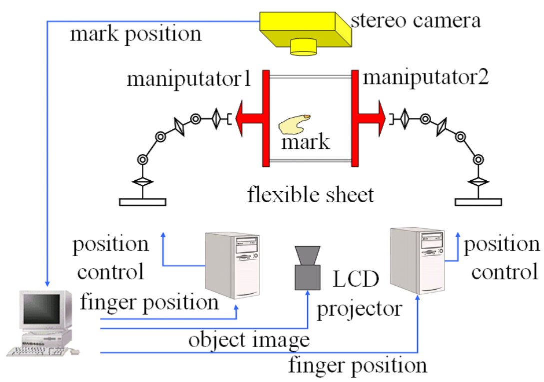


Fig. 2. System configuration of Encountered-type display

III. Improvement into Encountered-type Display

A. System Configuration

In order to overcome the above-mentioned problems, we improve this visual haptic display into encountered-type.

As shown in **Fig. 1**, a flexible sheet can generate variable compliance by changing the bias tension applied to it. Thus a user feels the compliance of a virtual soft object by pushing the sheet directly. If this sheet is moved along the shape of the virtual object, the user can touch different points of the object and feel the shape of the object by stroking it.

We propose to attach both edges of a translucent flexible sheet to two manipulators. **Fig. 2** shows the system configuration. They apply bias tension to the sheet by pulling it from both sides, thus varying the sheet compliance in the normal direction. The finger tip motion is measured by stereo cameras. The manipulators also move the sheet along the surface of the virtual object together with the finger tip motion. An LCD projector projects the CG image of the deformed object stereoscopically on the sheet from its back. The user can see the 3D image through stereoscopic glasses and touch the image directly.

B. Encountered-type Haptics and Active Touch

The proposed display is classified into encountered-type. As shown in **Fig. 3**, the manipulators move the sheet so that it may be the tangential plane of a virtual object coordinating with the finger tip motion. Once the finger tip moves away from the object, the tip touches the object again at different point. Thus the user can touch different points of the object.

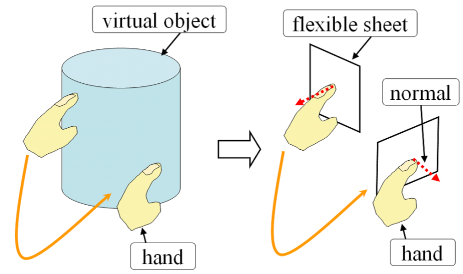


Fig. 3. Encountered-type haptics

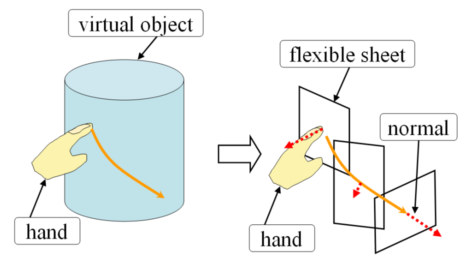


Fig. 4. Active touch

When humans recognize the shape of an object, they combine the information of cutaneous sensation that their fingers are touching the object and the information of motion sensation that their fingers are moving along the shape of the object. This function of humans is called "active touch"[7]. As shown in **Fig. 4**, the proposed display can realize active touch: the manipulators control the pose of the sheet along the surface of the virtual object while the finger is always touching the sheet. As a result the user can feel like stroking the object with his finger.

The proposed display makes use of the advantages of the flexible sheet. The compliance and the shape of a virtual object is presented separately: the compliance is presented by applying bias tension to the sheet, and the shape is by moving the sheet. We do not have to detect whether the finger is touching the sheet or to measure the force applied to the sheet. The manipulators are position-controlled, not force-controlled.

C. Correction of CG Image Distortion

1) Image distortion: We use the sheet as a rear projection screen. It is normally assumed that the screen is flat and fixed. In our system the sheet is depressed when it is pushed, and the pose of the sheet is changed by the manipulators. Thus, if the CG image is projected normally, the image on the sheet is distorted. **Fig. 5** explains the reason why this distortion occurs. V is the user's point of view, P is the position of the light source of the projector, A is one of the points of the virtual object model, the actual screen is the flexible sheet, and the imaginary screen is placed where the proper (undistorted) image is projected without correction. We define the intersection of the line V-A with the imaginary

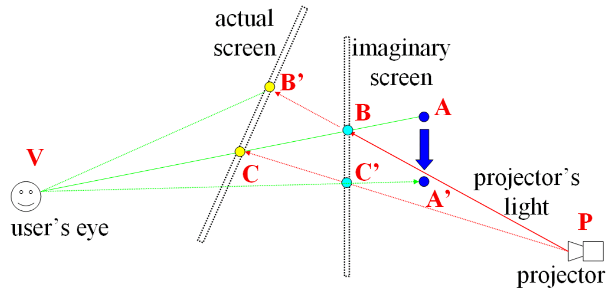


Fig. 5. Image correction algorithm

screen as the point B. Normally the projector emits a light beam toward the point B so that the user can see the point A at correct position on the imaginary screen. Thus, if the actual screen coincides with the imaginary screen, the user sees the undistorted image. But, if not, the light beam is projected on the point B' on the actual screen. Accordingly the user sees the point A at wrong position, thus seeing the distorted image.

2) Image correction algorithm: To solve this problem, we propose a method of correcting the CG image distortion caused by the movement of the sheet and the depression of the pushed sheet. In order for the user to see the point A at correct position on the actual screen, the point A has to be projected on the point C which is the intersection of the line V-A with the actual screen; the projector must emit a light beam toward the point C. By the way the projector assumes that the screen is placed at the imaginary screen. Hence the projector has only to emit the light beam toward the point C' which is the intersection of the line C-P and the imaginary screen. Finally, in order for the projector to emit the above-mentioned light beam, the point A of the virtual object model should be shifted to the point A'; this point is the intersection of the line V-C' with the plane which is parallel to the imaginary screen and includes the point A. Now we formulate the above algorithm. The following variables are defined:

$\boldsymbol{r}_o$: position vector of imaginary screen
$\boldsymbol{n}_o$: normal vector of imaginary screen
$\boldsymbol{r}_s$: position vector of actual screen
$\boldsymbol{n}_s$: normal vector of actual screen
$\boldsymbol{r}_p$: position vector of projector P
$\boldsymbol{r}_v$: position vector of user's eye V
$\boldsymbol{r}_a$: position vector of point A
$\hat{\boldsymbol{r}}_a$: position vector of point A'
$\boldsymbol{r}_c$: position vector of point C
$\hat{\boldsymbol{r}}_c$: position vector of point C'

First the point C is on the actual screen.

$$(\boldsymbol{r}_c - \boldsymbol{r}_s)^T \boldsymbol{n}_s = 0 \quad (1)$$

It is also on the line V-A.

$$\boldsymbol{r}_c = s_1 \boldsymbol{r}_v + (1 - s_1)\boldsymbol{r}_a \quad (2)$$

where s_1 is an unkown parameter. From these two equations, we can obtain s_1 and $\boldsymbol{r}_c$. In the same way, the point C' is on the imaginary screen and on the line C-P.

$$(\hat{\boldsymbol{r}}_c - \boldsymbol{r}_o)^T \boldsymbol{n}_o = 0 \quad (3)$$

$$\hat{\boldsymbol{r}}_c = s_2 \boldsymbol{r}_c + (1 - s_2)\boldsymbol{r}_p \quad (4)$$

where s_2 is an unknown parameter. From these two equations, we can obtain s_2 and $\hat{\boldsymbol{r}}_c$. Finally, the point A' is on the plane which is parallel to the imaginary screen and includes the point A.

$$(\hat{\boldsymbol{r}}_a - \boldsymbol{r}_a)^T \boldsymbol{n}_o = 0 \quad (5)$$

It is also on the line V-C'.

$$\hat{\boldsymbol{r}}_a = s_3 \boldsymbol{r}_v + (1 - s_3)\hat{\boldsymbol{r}}_c \quad (6)$$

where s_3 is an unknown parameter. From these two equations, we can obtain s_3 and the position $\hat{\boldsymbol{r}}_a$ of the shifted point A'. Using these formula, we shift all points (vertex of polygons) on the surface of the virtual object, draw the object by OpenGL and project the image on the sheet from its back. Then the user can see the proper 2D image of the virtual object from the point of view V.

3) Approximate correction for pushed sheet: When the finger tip is away from the sheet or is slightly touching the sheet, the sheet can be regarded as a flat screen. The pose of the sheet (its position vector $\boldsymbol{r}_s$ and normal vector $\boldsymbol{n}_s$) is controlled by the manipulators. Thus we can apply the above-mentioned image correction algorythm directly. When the sheet is pushed by the finger, it is depressed; it cannot be regarded as one flat screen. Exact correction requires accurate measurement of the shape of the sheet, but real-time measurement is difficult. Hence we approximate the depressed sheet by 4 flat triangles: each triangle is defined by the pushed point and two neighboring corners of the sheet. The position of the pushed point (common vertex of the triangles) is measured by stereo cameras. This is the common position vector $\boldsymbol{r}_s$ of the triangles. The positions of 4 corners of the sheet (the other vertex of the triangles) are calculated from the poses of the manipulators. Then the normal vectors $\boldsymbol{n}_{si}$ $(i = 1, \cdots, 4)$ of 4 triangles are obtained. For each point of the object, we examine the triangle which the point belongs to and switch the normal vector $\boldsymbol{n}_{si}$, thus generating the corrected image of the object.

4) Stereoscopic Image: Changing the point of view V in the image correction algorithm, we generate the corrected 2D images of the virtual object seen from right and left eyes, respectively. If we present the 2D image for the right eye to the right eye and that for the left eye to the left eye through stereoscopic glasses, the user can see the proper (undistorted) stereoscopic image of the object.

IV. Experimental System

Fig. 6 shows the experimental setup.

- Translucent flexible sheet: urethane rubber, 240[mm]×240[mm]×1[mm].
- RV-1A (MITSUBISHI. Inc.): two 6-DOF manipulators whose ends are attached to the both sides of the sheet.

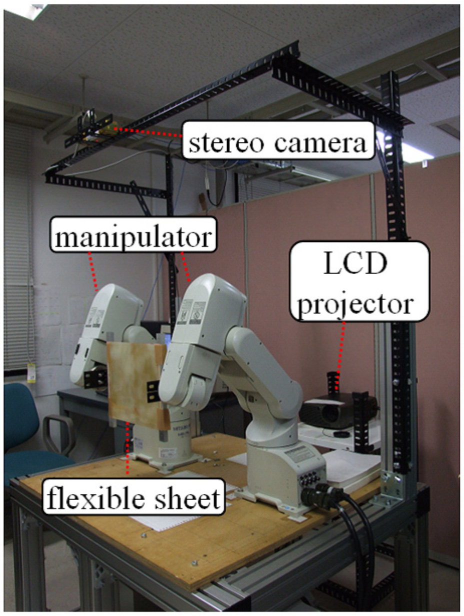


Fig. 6. Experimental setup

- BumbleBEE (Point Grey Inc.): a stereo camera.
- DepthQ (InFocus Inc.): an LCD projector.
- CrystalEyes (Stereo Graphics Inc.): stereoscopic glasses.
- One main computer generates the sheet motion, calculates the deformation of a virtual object and generates its CG image. Two computers control the manipulators. These are connected through the network.

The manipulators have two functions: applying the bias tension to the sheet by pulling it from both sides, and changing the pose of the sheet. A tiny mark is attached to the user's finger, and the stereo camera measures the position of this mark. The measured finger tip position is sent to the main computer. It generates the sheet motion and send it to the computers of the manipulators. Then the manipulators moves the sheet coordinating with the finger tip motion. From the measured finger tip position, the main computer also calculates the deformation of the object by FEM and generates the corrected CG image of the deformed object. The LCD projector projects this image stereoscopically on the sheet. The user sees the stereoscopic image through stereoscopic glasses, while touching it on the sheet.

V. Experiment of Stroking Virtual Cylinder

A. Sheet Control for Stroking Virtual Cylinder

Initially the user's finger tip position measured by the stereo camera is away from the virtual cylinder. As shown in **Fig. 7(a)**, we consider a line between the finger tip and the center of the cylinder O, and obtain the intersection A of this line with the cylinder surface. The manipulators are controlled so that the sheet may be a tangential plane of the cylinder surface at the point A. Then the finger tip comes in contact with the cylinder surface (thus the sheet) at the point A. We define the point on the sheet at this initial touch as A'; initially A' equals A.

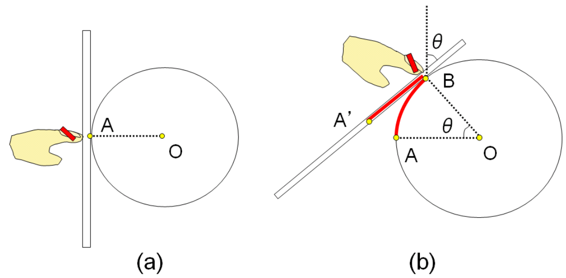


Fig. 7. Sheet control for stroking virtual cylinder

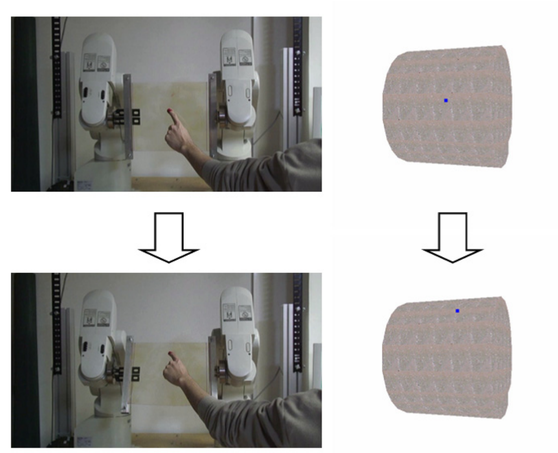


Fig. 8. Experiment of stroking virtual cylinder

Next the finger tip strokes the virtual cylinder surface. We measure the current finger tip position B. As shown in Fig. 7(b), the circular arc AB is the distance along which the finger tip moves on the cylinder surface. The length A'B is the distance along which the finger tip moves on the sheet. Accordingly the manipulators control the sheet so that the circular arc AB may be equal to the length A'B and that the sheet may be a tangential plane of the cylinder surface at the point B. As a result, the user can feel as if he is stroking the surface of the virtual cylinder.

B. Experiment Method

The diameter of the virtual cylinder is $50\sqrt{2}$[mm], and its height is 120[mm]. It is laid in front of the user. A mark representing the current finger tip position is drawn on the CG of the cylinder surface. A target mark is also displayed; the user moves his finger so as to follow this mark. If the CG image is projected on the sheet from its back, the user cannot see these marks because they are behind the finger. Thus, in this experiment, the CG image is presented on the CRT display placed near the sheet. The user moves his finger while seeing this image.

Fig. 8 shows the scene of the experiment. The sheet is inclined, as the mark representing the current finger tip

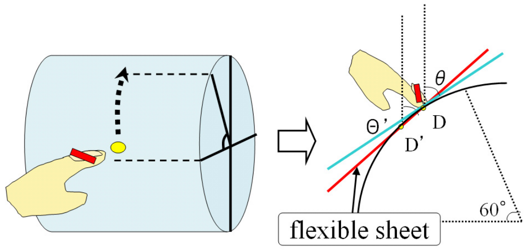


Fig. 9. Estimation of position and angle errors in stroking experiment

TABLE I
POSITION AND ANGLE ERRORS IN STROKING EXPERIMENT

Moving time	10[s]	30[s]
Average of Δd	0.443[mm]	0.277[mm]
Average of $\Delta\theta$	0.359[deg]	0.225[deg]
Standard deviation of Δd	0.0330[mm]	0.0221[mm]
Standard deviation of $\Delta\theta$	0.267[deg]	0.179[deg]

position moves together with the movement of the finger.

C. Error Estimation

After the finger tip position is measured, the sheet is moved to the ideal position calculated by the above-mentioned method. This time delay causes an error between the measured finger tip position and the position which the sheet presents. In **Fig. 9**, the following variables are defined:

- D : finger tip position which is measured by camera
- D' : finger tip position which the sheet presents
- θ : angle of tangential plane of the virtual cylinder at the point D
- θ' : angle of tangential plane of the virtual cylinder at the point D'
- Δd : position error ($= |D - D'|$)
- $\Delta\theta$: angle error ($= |\theta - \theta'|$)

The accuracy of this sheet motion when the finger moves at two different speeds is evaluated. The finger moves from the initial position to the 60[deg] position. The target mark is displayed on the surface of the cylinder, and users move their finger to follow this mark. The position error of the stereo camera near the sheet is 2.95[mm].

Tabel.I shows the results. Both the position and angle errors of 30[s] stroking are smaller than the errors of 10[s] stroking. In both cases, the motion accuracy of the sheet is smaller than the finger size and the measurement accuracy of the stereo camera.

VI. Experiment of Correcting Image Projected on Sheet

A. Experiment method

Initially the sheet is set perpendicularly to the ground and coincides with the imaginary screen. The user's viewpoint is at a horizontal distance of 400[mm] from the center of

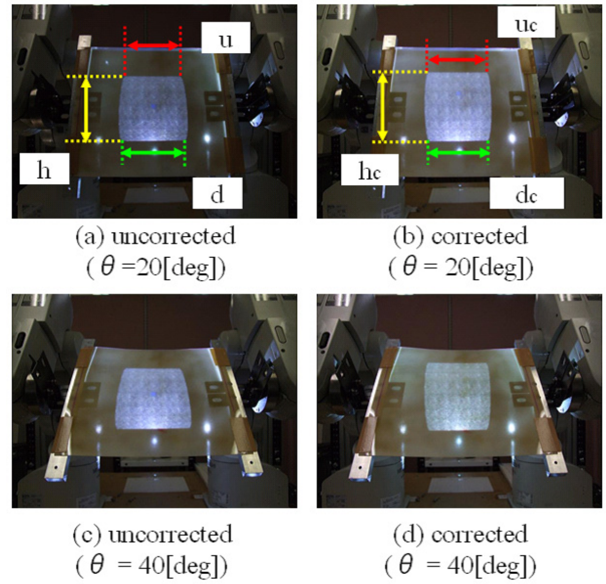


Fig. 10. Experiment of correcting image projected on inclined sheet

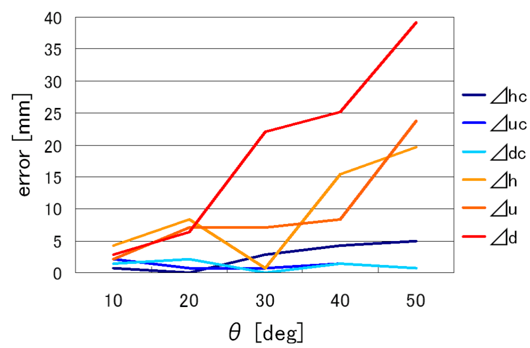


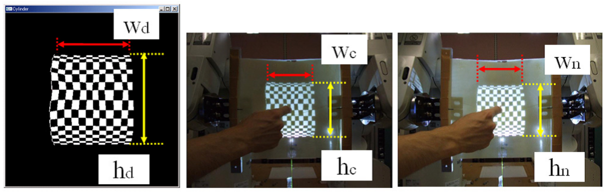
Fig. 11. Error of image projected on inclined sheet

the front side of the sheet, and the LCD projector at a horizontal distance of 1000[mm] and a downward distance of 250[mm] from the center of the backside. The displayed virtual object is a cylinder: its diameter is $50\sqrt{2}$[mm] and height is 120[mm]. Its central axis is set horizontally, and its side surface touches the sheet. It is confirmed that the cylinder image is projected on the sheet in the proper size when the sheet coincides with the imaginary screen.

A measurement camera is fixed at the user's viewpoint. It takes the pictures of the uncorrected and corrected images projected on the sheet and seen from the viewpoint. Then the errors between these images are evaluated.

B. Experiment of inclined sheet

When a user strokes the side surface of the virtual cylinder with his finger, the sheet is inclined so as to be the tangential plane of the cylinder. We define the angle of inclined sheet by θ. **Fig.10** shows the uncorrected and corrected images when θ=20[deg] and 40[deg]. From these pictures, we measure the following size of the cylinder by pixel unit:



(a) proper (S = 30 [mm]) (b) corrected (S = 30 [mm]) (c) uncorrected (S = 30 [mm])

Fig. 12. Experiment of correcting image projected on pushed sheet

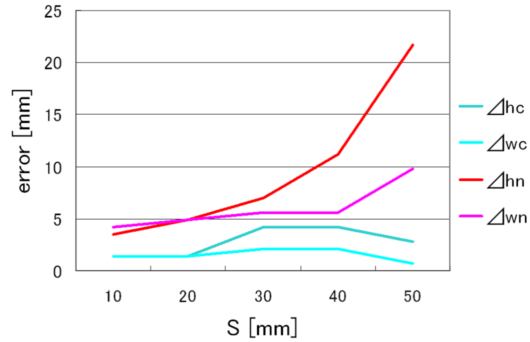


Fig. 13. Error of image projected on pushedsheet

h_c : height of corrected cylinder
u_c : upside width of corrected cylinder
d_c : downside width of corrected cylinder
h : height of uncorrected cylinder
u : upside width of uncorrected cylinder
d : downside width of uncorrected cylinder

1[pixel] of the image corresponds to 0.7[mm] on the imaginary screen. Ideally the image should be seen unchanged regardless of θ. Hence we define the absolute errors Δh_c, Δu_c, Δd_c, Δh, Δu and Δd between the images when the sheet is inclined and the proper image when the sheet is not inclined. **Fig.11** shows these errors when θ is changed from 10[deg] to 50[deg] by 10[deg]. The maximum Δu_c and the maximum Δd_c are 2.1[mm], and the maximum Δh_c is 4.9[mm]. The average Δu_c and the average Δd_c are 1.1[mm], and the average Δh_c is 2.5[mm]. When θ=50[deg], the average error of three sizes of the uncorrected image is 27.5[mm] but that of the corrected image is 2.1[mm]. Thus the error is reduced to 7.6% by our image correction algorithm.

C. Experiment of pushed sheet

The center of the side surface of the virtual cylinder, thus the center of the sheet, is pushed by a finger. Then the image of the deformed cylinder is calculated and projected. We define the depth of pushing by S. **Fig.12** shows the images when S=30[mm]: (a) is the proper image, (b) is the corrected image, and (c) is the uncorrected image. From these pictures, we measure the following sizes of the cylinder by pixel unit:

h_d : height of proper cylinder
w_d : width of proper cylinder
h_c : height of corrected cylinder
w_c : width of corrected cylinder
h_n : height of uncorrected cylinder
w_n : width of uncorrected cylinder

1[pixel] of the image corresponds to 0.7[mm] on the imaginary screen. **Fig.13** shows the errors $\Delta h_n = |h_n - h_d|$, $\Delta w_n = |w_n - w_d|$, $\Delta h_c = |h_c - h_d|$ and $\Delta w_c = |w_c - w_d|$ when S is changed from 10[mm] to 50[mm] by 10[mm]. The maximum Δw_c is 2.8[mm], and the maximum Δh_c is 4.2[mm]. The average Δw_c is 1.7[mm] and the average Δh_c is 2.8[mm]. When S=50[mm], the average error of two sizes of the uncorrected image is 15.8[mm] but that of the corrected image is 2.1[mm]. Thus the error is reduced to 13% by our image correction algorithm.

VII. Conclusion

We proposed an encountered-type visual haptic display using flexible sheet and made a prototype display. This display can present

- the compliance of a virtual soft object by applying the bias tension to the sheet using two manipulators,
- the shape of the object by controlling the pose of the sheet using the manipulators, and
- the CG image of the object stereoscopically projected on the sheet from its back using the LCD projector.

The accuracy of the sheet motion when stroking a virtual cylinder is evaluated. It is verified that the CG images of the cylinder seen from the user's viewpoint are corrected when the sheet is inclined and pushed.

In the future, we will present the shape of other objects and combine the feeling of stroking with that of pushing.

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