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Real-Time Virtual Haptization of an Object Surface Measured by a High-Speed Projector-Camera System

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Abstract— **This paper reports real-time virtual haptization of, for example, a remote object surface based on high-speed 3D shape measurement. With this system, the operator feels sense of touch as if tracing the surface of an object. We use a high-speed projector-camera system to achieve high-speed measurement of the object surface so that high-frequency haptic feedback is maintained at a haptic device PHANToM. An actively directed structured light is projected so that the projected slit ray intersects with the haptic interaction point, which is determined by the stylus position of the haptic device. A camera image of this scene gives the positional relationship between the object surface and the haptic interaction point. We use this relationship to generate force feedback such that the haptic interaction point is pushed back to a point on the intersection of the slit ray and the object surface. Experimental results show that the proposed system displays an object shape correctly and that the high-speed measurement contributes to displaying smooth motion of an moving object.**

I. Introduction

Recently, there is emerging interest in user interfaces relying not only on the visual and auditory modalities but also on others, particularly in the fields such as human-computer interaction, virtual reality and entertainment. Haptics, among others, is gaining growing attention as a modality offering intuitive perceptual feedback to display shapes, motion and so on. A number of haptic feedback devices have been developed and some of them have been commercialized. One of the most popular uses of these devices is to display haptic sensation of virtual objects.

On the other hand, there have been efforts of displaying real object shapes that cannot be touched in ordinary ways [1], [2], [3], [4]. These technologies are expected to give users intuitive perception of untouchable objects because of their, for example, existing in remote sites, being preserved and protected, or being dangerous due to temperatures and toxicity.

In general, a haptic device should exert force at a high frequency such as 1000 Hz in order to maintain quality of offered sensation. Otherwise, impulsive forces caused by collision, for example, can not be displayed appropriately. When a system is to display haptic sensation of real objects instead of virtual ones, its measurement subsystem must be designed to operate at that high sampling frequency. Realization of 3D shape measurement at such a high frequency is, however, a hard burden, and thus its design requires some ingenuity and/or compromise.

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Owaki et al. [1] developed a system that displays shapes of objects captured by a high frame rate vision sensor. The system achieved 200-Hz haptic feedback, but captured and displayed shapes were only in 2D. Kouno et al. [2] used a stereo vision sensor to display 3D shapes, but its update frequency was 15 Hz and thus displaying a dynamic scene was difficult. Instead of using vision sensors, Nojima et al. [3] developed a haptic device whose tool tip can be equiped with various sensors, such as an electric conductivity sensor, to enable haptizing boundary surfaces of, for example, water and oil. Yano et al. [4] used a single-point laser range finder to give a 1-DOF haptic feedback to a thumb of a user.

In this paper, we propose a system to haptize an untouchable object using a high-speed projector-camera system. A structured light is projected onto an object surface and the reflected light is captured for 3D measurement. In order to achieve high-frequency measurement required for haptic feedback, we use a camera and a projector that operate in a high frame rate, and in addition, we control projected patterns dynamically so that only the point of interest is measured to achieve fast response. Unlike a single-point range finder, the proposed system can be extended to obtain more detailed information on the measured point, such as the normal vector.

II. 3D Measurement Subsystem

The measurement subsystem consists of a high-speed camera and a high-speed projector located side by side [5], [6]. The exterinsic and intrinsic parameters of the both are assumed to be known. The details from the hardware viewpoint are described in Section IV-A. The principle of the employed 3D measurement is the well-known light section method, where a slit ray is projected to the object and the image of the reflected slit light is captured by the camera, giving the 3D positions of the points on the intersection of the slit ray and the object surface. In our system, instead of scanning the slit ray over the whole scene, we control the slit ray direction so that the point of interest is measured immediately.

Actually, the projected pattern is a digital image consisting of two rectangular regions divided by a vertical boundary, namely a left white region with w-pixel width and a right region with $(1024 - w)$-pixel width. The boundary between the white and black regions forms the slit ray when the pattern is projected. The slit ray direction, designated by the variable w, is actively controlled.

The question left here is how the slit ray direction should be determined while the 3D position of the point of interest is unknown yet – which is exactly what we want as the result

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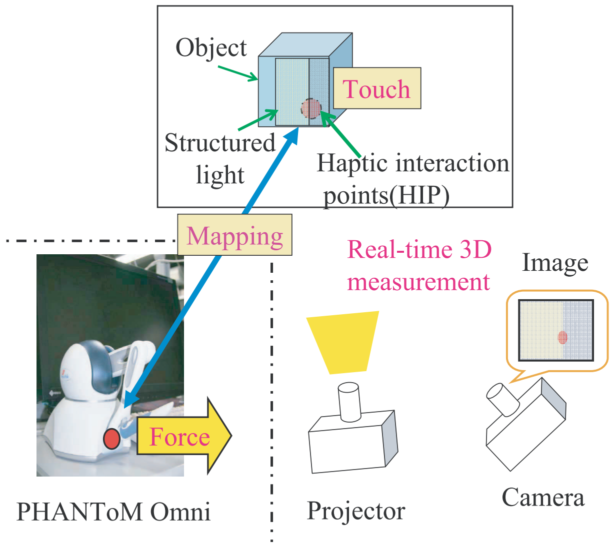


Fig. 1. Structure of the proposed system.

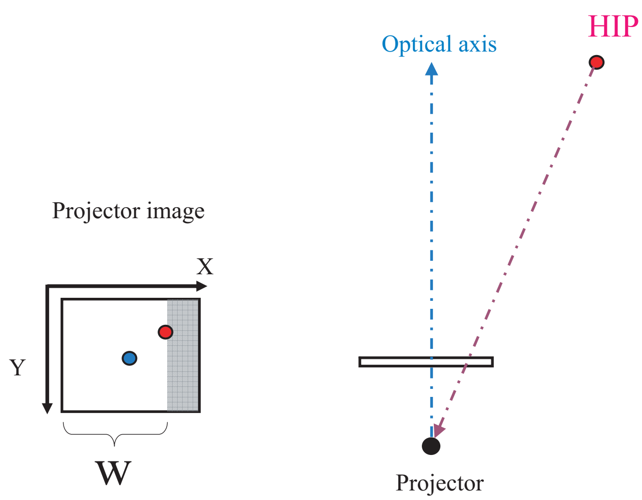


Fig. 2. Determination of the direction of the slit ray.

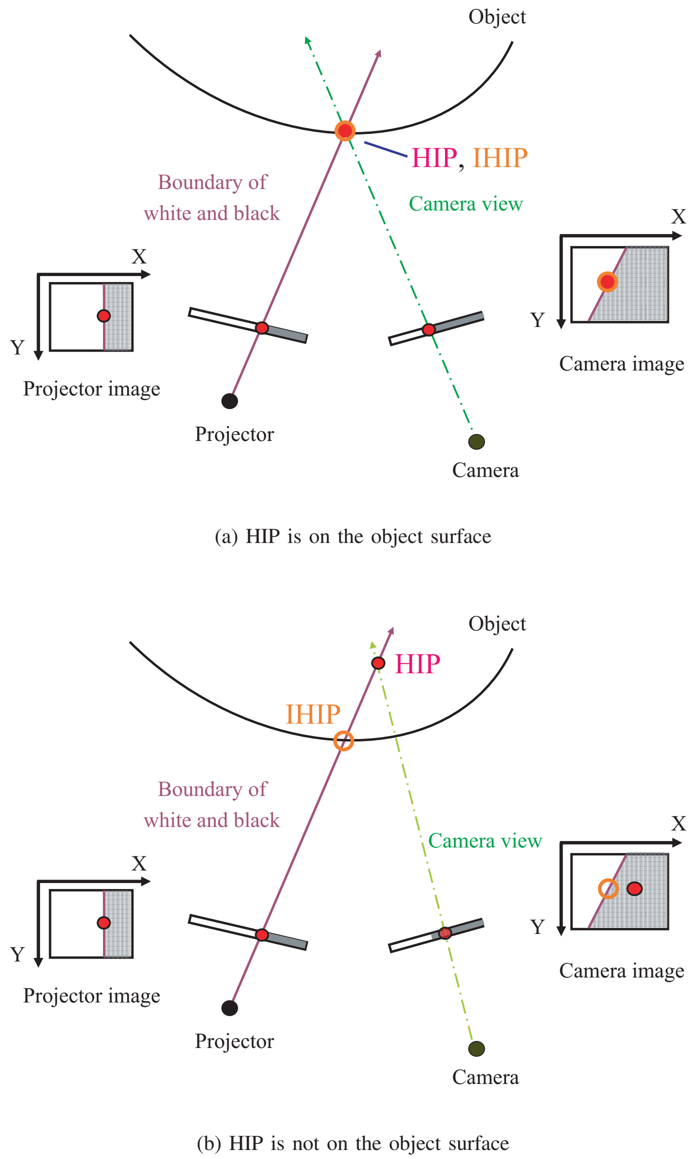


Fig. 3. Difference of camera images with respect to the HIP position.

of measurement. One possible way is to introduce a feedback control of the ray direction so that the slit ray can include the point of interest. Inoue et al. [6] achieved tracking of the object point that is the nearest to the camera, where three adjacent slit rays, instead of only one, are used to enable efficient local search of the nearest point.

III. Haptizing of a Measured Object

The structure of the whole system is shown in Fig. 1. As a haptic display, PHANToM Omni developed by SensAble Technologies is used. A one-to-one correspondence is made between the PHANToM stylus tip workspace and the measured space. When the stylus position is transformed into the measured space, the point is referred to as the haptic interaction point or the HIP. When the HIP touch the surface of an object, haptic sensation is given to the user.

The force applied to the stylus is calculated based on the invasion of the HIP from the surface of an object, as is usually done in the literature [7]. One popular choice in the case of haptization of a virtual object is to find the nearest point to the HIP on the surface, often referred to as the intermediate HIP or the IHIP, and generate the force $\boldsymbol{f} = k\boldsymbol{x}$ where $\boldsymbol{x}$ is the vector from the HIP to the IHIP. Here, a virtual spring whose natural length is zero is assumed to exist between HIP and IHIP.

In our case, however, it is impossible to determine the nearest point to the HIP on the surface immediately, because we do not have a complete map of the object shape. Our choice is to direct the slit ray toward the HIP and select a point on the intersection of the slit ray and the object surface as the IHIP, as shown in Fig. 2. This is done by backprojecting the HIP position onto the projector image plane and letting the boundary of the black and white regions include the backprojected point. When this scene is observed from the camera, the black and white boundary will be found somewhere close to the point corresponding to the HIP in the image. If the HIP is on the surface of an object, the black and white boundary will include the HIP image, and otherwise the boundary will not, as shown in Fig. 3.

We still have one degree of freedom left to determine the IHIP, and our choice is to select the point with the same y coordinate as the backprojected HIP in the camera image plane. Obviously, this is not the optimal choice, but as long as the feedback system works well and the invasion is sufficiently small, its adverse effect will be also small. It should be noted that the popular choice of the nearest point to the HIP as the IHIP is not always optimal [7].

The detailed procedure is as follows:

1) the HIP is backprojected onto the projector image plane, and the projected pattern is determined so that the black and white boundary includes the backprojected point.
2) An image is captured by the camera, and local search for the black and white boundary within the horizontal line is carried out around the point corresponding to the HIP in the camera image plane.
3) For accurate calculation of the 3D position, a third-order polynomial is fitted to multiple points on the black and white boundary, and the IHIP in the image plane is determined with subpixel accuracy. The IHIP position in the 3D space is accordingly determined.
4) When the HIP is further than the IHIP from the camera image plane, the system decides that the HIP and an object collide with each other, and generate the force according to the virtual spring model.

With our choice of IHIP, the force is generated only within the plane that passes through HIP and the camera optical center and is parallel to the camera X axis. Fig. 4 shows the cross section made by this plane, where the local object surface is approximated by a plane. Within this cross section, the angle made by the projector ray and the object surface lines is θ, and the small invasion of HIP from the object surface is d_0. When we assume that the correct force should be generated in the direction perpendicular to the object surface line within this cross section (note that even this direction is not optimal), the error from this correct force is expressed as $kd_0/\tan\theta$. Fig. 5 shows an example relationship between the error force and the angle θ. Obvisously, the error takes its minimum value at $\theta = \pi/2$, and becomes larger as θ approaches 0 or π. When the error force is large, the approximation of the object surface by the plane will no longer be appropriate, which makes the situation worse.

Because we fit a third-order polynomial to the measured boundary points around the IHIP, we can draw more detailed geometric information about the surface around the IHIP. Actually, since we can obtain the slope of the tangent at the IHIP in the camera image plane, the normal vector of the surface is perpendicular to the intersection line of the slit ray and the plane including both the tangent line in the camera image and the camera optical center. If another constraint is available, for example, by introducing another pattern with boundaries with two different directions, the surface normal is determined and more sophisticated force generation will be possible.

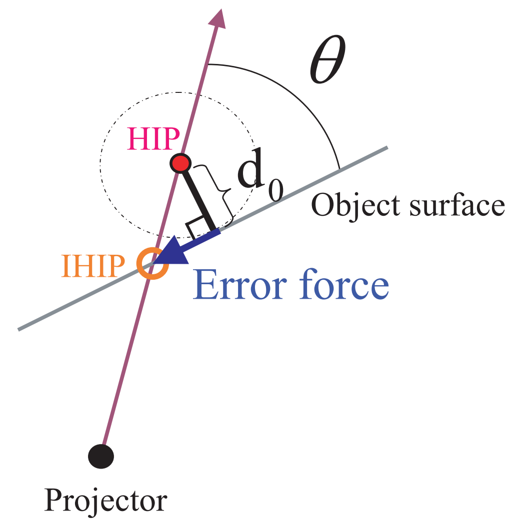


Fig. 4. Cross sectional view around HIP.

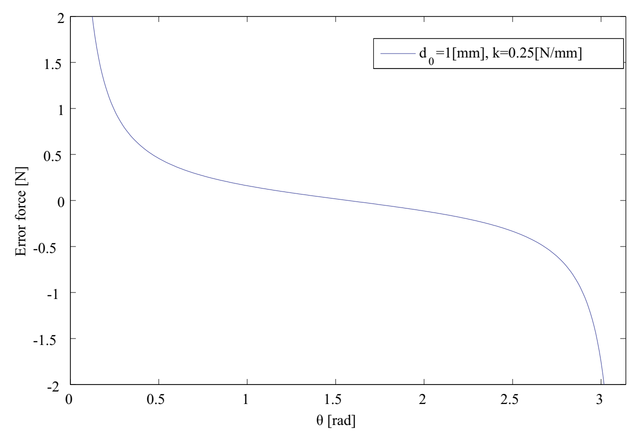


Fig. 5. Relationship between the error force and the angle θ.

Despite the subpixel accuracy estimation of the IHIP position, vibration due to inaccurate image measurement was not sufficiently removed. To subdue this vibration, in the following experiments, a two-frame simple moving average is applied to the calculated force.

IV. EXPERIMENTS

A. Experimental Equipments

The developed system consists of a high-speed projector-camera pair, a haptic display, and a PC with dual Intel Xeon 2.8-GHz CPUs, which controlls all the components of the system.

The high-speed projector in the proposed system consists of a Texas Instruments Digital Micromirror Device [8] (DMD

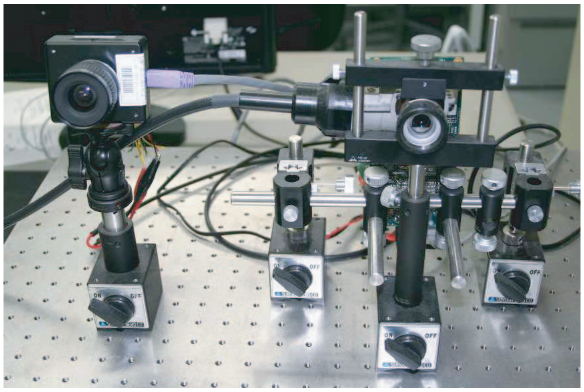


Fig. 6. High-speed projector-camera system.

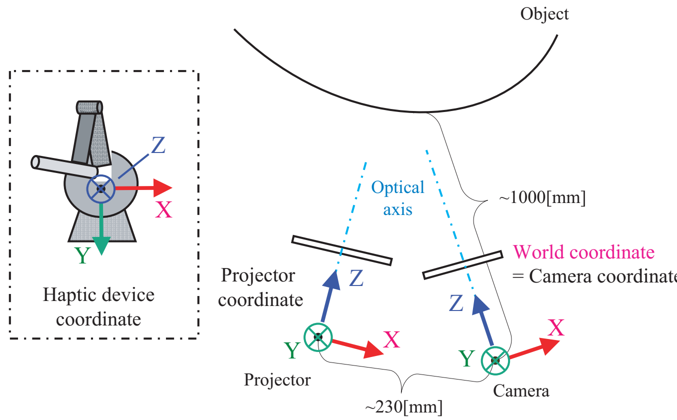


Fig. 7. Experimental setup and the coordinate systems. The positive senses of the camera and the projector coordinates are downward, respectively. The coordinate system of the haptic device is a left-handed system. The world coordinate system coincides with the camera coordinate system.

0.7XGA 12DDR), its starter-kit controller board DMD Discovery 1100, and a ViALUX ALP-1 [9] pattern storage board. $1,024 \times 768$ pixels binary images can be projected at 8,000 fps at maximum. The DMD reflects light from a Dolan Jenner Fiber-Lite MH-100 metal halide illuminator to a projection lens whose focal length is 27 mm.

In typical usage of the pattern storage board ALP-1, a fixed pattern sequence is stored in the storage memory and the sequence is projected repeatedly, while our system requires adaptive pattern projection instead of fixed sequence projection. Adaptive pattern projection is implemented by storing many sequences each of which contains only a single pattern and selecting an arbitrary pattern to be projected in real time through a USB 2.0 link, as done in our previous work [6].

Because the maximum number of patterns that can be stored is only 2,730, variety of the projected patterns is strictly limited. This is the main reason that the projected pattern is restricted to the very simple one with black and white rectangles. More flexible and informative measurement will be enabled when this hardware limit is overcome[1].

A 640×480 pixels gray scale image of the scene is captured by a Point Grey Research Dragonfly Express high-speed camera equipped with an imaging lens whose focal length is 6 mm, and is transferred through an IEEE 1394 link to the PC.

The employed haptic device is, as described in Section III, a SensAble Technologies PHANToM Omni connected to the PC through an IEEE 1394 link. The workspace is $160 \times 120 \times 70$ mm and the nominal position resolution is 0.055 mm. The maximum force is 3.3 N.

B. Displaying a Static Shape

The first experiment was to verify whether the proposed system correctly generate force feedback so that the stylus tip can trace the surface of a static shape. The experimental setup and the coordinate systems are shown in Figs. 7, 8 and 9.

[1]For example, the newest DMD Discovery Kit from Texas Instruments includes an on-board FPGA and pattern storage memories.

Fig. 8. Measured space with a hemisphere and a white planar board.

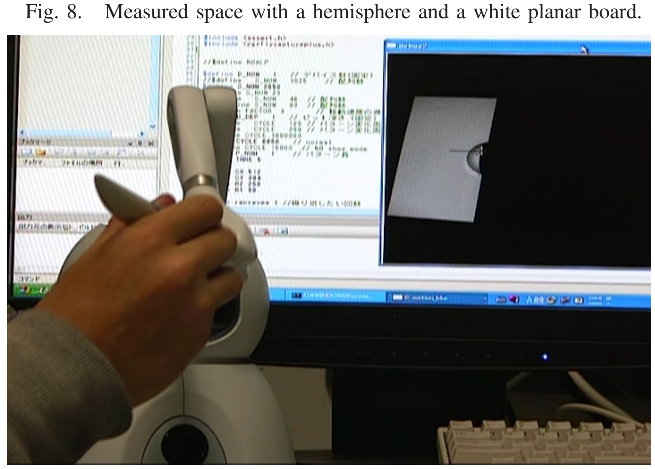


Fig. 9. Measurement and haptization of a hemisphere.

In the measured space, which is approximately 1 m distant from the camera, a white hemisphere of 100-mm diameter was attached on a white planar board. The spring constant k

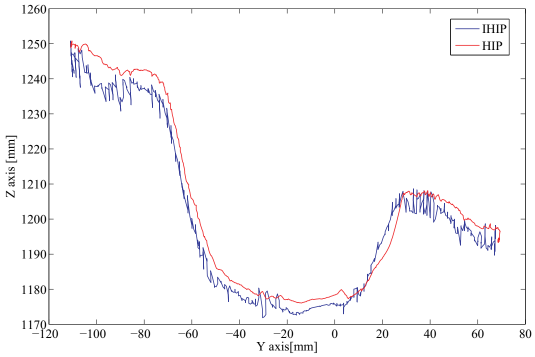


Fig. 10. Trajectories of the HIP and IHIP when a hemisphere surface was traced.

for force generation was set to 0.25 N/mm, which was also employed in the second experiment. In this experiment, the whole system ran at about 144 fps.

An operator was asked to hold the stylus of the haptic device and trace the perceived surface at a constant speed without being too tense, starting from a point on the planar board above the hemisphere in the downward direction.

Figure 10 shows the trajectories of the HIP and IHIP projected in the Y-Z space, where the Z axis coincides with the camera optical axis and the positive sense of the Y axis is downward. The red and blue lines show the HIP and IHIP trajectories, respectively.

It is observed that the hemisphere of 100-mm diameter was almost correctly displayed. While the IHIP trajectory sometimes exhibited strong vibration, the HIP trajectory, and thus the stylus trajectory was relatively smooth. This can be explained by the fact that IHIP is directly computed through image processing whereas HIP is determined by the resultant force fenerated by the haptice device and the human operator. The vibration in the IHIP position possibly caused by the image measurement error is filtered out by the dynamics of the haptic device and the human operator.

It is also observed that the red HIP line is below the blue IHIP line around $Y = 20$, meaning that the stylus was temporarily floating when it was moved from the hemisphere surface to the planar board.

C. Displaying a Moving Object

In the second experiment, we verify the usefulness of the proposed high-speed measurement system in displaying haptic sensation of a moving object. It is well known that high frequency haptic rendering is vital particularly in displaying high stiffness. However with our system, stiffness cannot be correctly evaluated because the employed haptic device is a low-cost model that compromises in its kinematic stiffness. Another aspect that will be affected by the display frequency is the perceived smoothness of the motion of an object, which was evaluated in this experiment.

In this experiment, a white planar board that is almost perpendicular to the camera optical axis at the distance of about 1 m. A subject was asked to point the stylus virtually on the planar board surface. Then, the board was moved about 100 mm within about 1 s at almost constant speed by an experimenter manually so that it came closer to the camera, and thus virtually to the subject. The subject was asked to follow the motion of the haptically displayed object without being too tense. Figure 11 (a), (b) and (c) show the examples of the relations of the HIP and IHIP positions and the generated force when the feedback frequency was 144, 66 and 33 fps, respectively.

For each trial, the subject was asked to report how smooth the motion was. The smoothness was reported as a subjective score, where 100 corresponds to the case that the motion was completely smooth and 0 corresponds to the case that the motion was ridiculously bumpy. This process was repeated for different system operating frequencies of 22, 33, 66 and 144 fps, in a randomly generated order. Neither the experimenter nor the examiner knew this order. Before the experiment, the subject was given an about 5-minute practice time to be accustomed to the experiment procedure with 66-fps haptic feedback.

TABLE I

THE SCORES REPORTED BY THE SUBJECTS FOR SMOOTHNESS OF MOTION OF A MOVING OBJECT.

Haptic feedback frequency [fps]	144	66	33	22
Subject 1	75	75	55	45
2	50	60	50	45
3	80	70	65	30
4	70	60	70	60
5	100	95	90	70
6	80	65	75	80
7	90	98	92	80
8	90	75	85	70

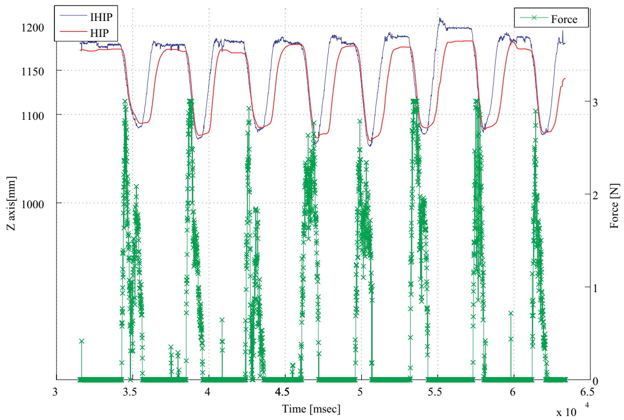
The scores reported by eight human subjects (male students, aged 21 to 28) are summarized in Table I. It is observed that the trials with higher feedback frequencies tend to result in higher scores.

Regarding the reported scores as in an ordinal scale, we tested by the U test a null hypothesis that there are no differences between the reported scores for different haptic feedback frequencies. As the result, the null hypothesis was rejected at 0.5-% significance level for the pairs of 144 and 66 fps, 66 and 33 fps, and 33 and 22 fps, meaning that the proposed high-speed measurement subsystem was effective in displaying moving objects.

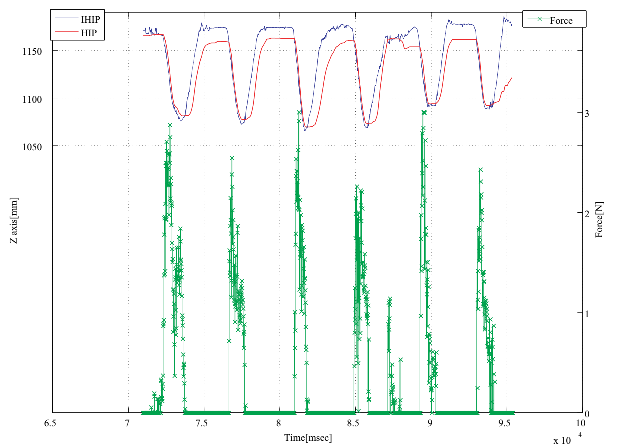
Some of the subjects reported that they sometimes felt unnatural force in wrong directions, particularly in the case when the planar board was not completely perpendicular to its moving direction. This phenomenon can be explained by the analysis described with Figs. 4 and 5. It is expected that this unnaturalness will be reduced if the normal of the surface is measured and the feedback force is accordingly generated.

V. Conclusions

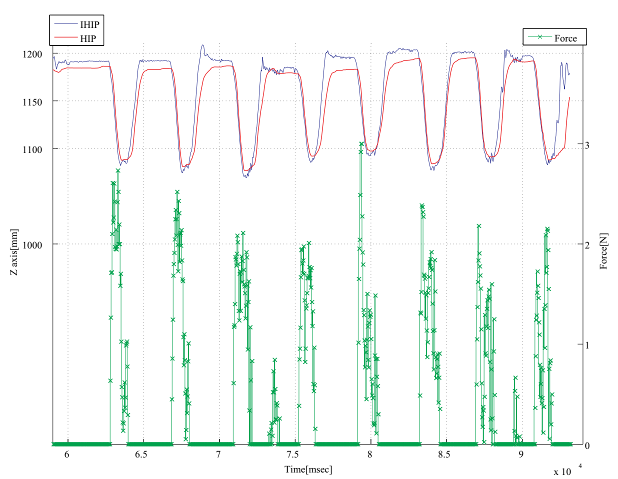
In this paper, we described a system for real-time virtual haptization of a real object, where the object shape is measured in a contactless manner. To achieve a high-speed feedback frequency, which is required for high-quality haptic sensation, a high-speed projector-camera system has



(a) 144-fps feedback



(b) 66-fps feedback



(c) 33-fps feedback

Fig. 11. Relations between the HIP and IHIP positions, and the generated force.

been introduced and adaptively-controlled structured light 3D measurement is implemented. It was proposed to direct the slit ray projection so that the ray includes the HIP and the IHIP is chosen from the points on the slit ray image. The experimental results show that a shape of a static object was able to be displayed almost correctly, and that the high-speed measurement subsystem contributed to displaying smooth motion of a moving object.

The 144-fps haptic feedback by our system was not sufficiently high to render the sense of the impulsive force made by collision between HIP and a moving object. The feedback rate of our current implementation is limited by the time required for the image processing and the camera frame rate. For better displaying of such sensation, a higher frame rate camera should be introduced with further optimized image processing.

Future work will include removal of the unnatural force that is sometimes generated by measuring the normal of the surface as well. The presented system still suffers from image measurement errors and reducing them for better haptic feedback will be also important.

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