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A Visualization System of Scaler Stroke Motion

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Abstract: *Periodontitis is a dental disease from which many people suffer. The most effective treatment with it is to remove dental plaque and scale periodically by a scaler. For this purpose, those who wish to be a dentist or a hygienist must take training of scaling and root planing using a jaw model and a scaler. It is, however, difficult for a trainer to evaluate the scaler stroke motion of a trainee, since the end of the scaler in a mouth cannot be observed directly from out of the mouth. This paper proposes a novel method of visualizing the scaler stroke motion in the mouth three-dimensionally by the employment of a camera and a computer. The system is described and an experimental result is shown.*
Keywords *Dental training, scaling, augmented reality, mobile cameras, computer vision.*

1.Introduction

Periodontitis is a dental disease which many people suffer from. In order to treat the disease, a dentist or a hygienist removes dental plaque and scale of a patient periodically by use of a scaler. Those who wish to be a dentist or a hygienist must therefore take training of scaling and root planing using a jaw model and a scaler. Although a dental trainer is responsible for the training, it is actually difficult for a trainer to evaluate a trainee if he/she uses a scaler in an appropriate way. It is because the location and the motion of the end of a scaler in a mouth cannot be observed from the outside. Hence a system for visualizing the location and the motion of a scaler in a mouth is eagerly requested in the dental field. Realizing such a system will let the trainer evaluate a trainee's skill visually and, as one is able to save the end motion of a scaler by a series of three-dimensional (3-D) coordinates, the trainer can also evaluate a trainee's skill numerically. A trainee is as well able to use the system for his/her unsupervised training.

For overall assessment of the scaling skills, following items should be evaluated: (i) Operator's positioning to a patient; (ii) selection of a scaler with each tooth, (iii) selection of a working end of the selected scaler, and (iv) proper use of a dental mirror. The assessment method of these items are already proposed in the literature [1], though.

This paper proposes a method of visualizing the scaler stroke motion in a mouth in a 3-D way by the employment of a camera and a computer. The idea is to capture the movement of the scaler a trainee uses by a mobile camera, and to recover its 3-D posture/motion using the markers attached to the scaler. The recovered scaler posture/motion is superposed onto the training video image in the form of a virtual scaler so that the trainer may observe the motion on a display. A similar system is proposed and applied for a patent [2], but the method proposed in thist paper has some advantages over [2], which will be discussed in the next section.

2.Related Work

The scaler stroke display system proposed in [2] is briefly overviewed. There are some different points between [2] and the proposed method. The system in [2] employs a stereo camera system fixed on a frame and takes images of the motion of a scaler a trainee uses by illuminating the spot with two fixed lights. Three small markers are attached on the end of the scaler (opposite to its working end) and, by calculating their 3-D positions using the stereo cameras, the 3-D position of the working end of the scaler is calculated. The main drawback of the

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system is, however, that the trainee's head may sometimes occlude the scaler, since the fixed cameras look down the scaler.

The main superiority of the proposed method is that it employs a single mobile camera which a trainer can hold and move to the best position where it can observe the marker on the scaler well. The system doesn't need a light for illuminating the spot: The room light is enough for capturing images. The entire view of the proposed system is given in **Fig. 1**. Since the proposed system is equipped only with a single camera and a PC, the hardware is much simpler than [2]. Hence one may expect a cheaper system compared to [2].

3. Overview of the Entire System

3.1 The entire system

As shown in Fig. 1, the entire system is composed of a jaw model fixed on a table, a scaler with a polyhedral marker, a mobile camera and a PC. The camera takes motion of the scaler operated by a trainee.

A polyhedral marker is attached at the top of a scaler in the proposed system as shown in **Fig. 2a** and five star-shaped patterns as seen in Fig. 2b are drawn on each of its five facets to identify the facets. The marker is made of ABS resin, processed by a 3-D printer, and fixed symmetrically around the symmetric axis of a scaler. In this way, it is designed so that the marker may disturb the normal motion of the scaler a trainee makes to the least extent.

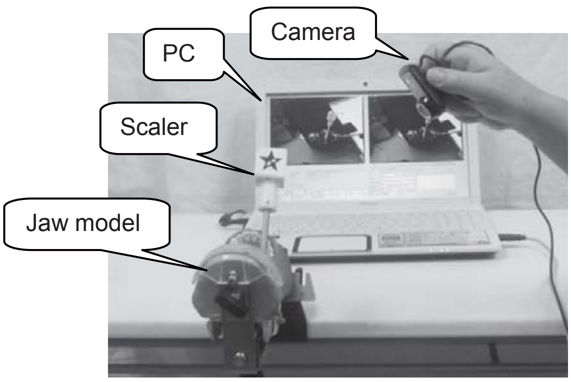
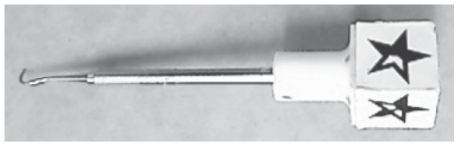
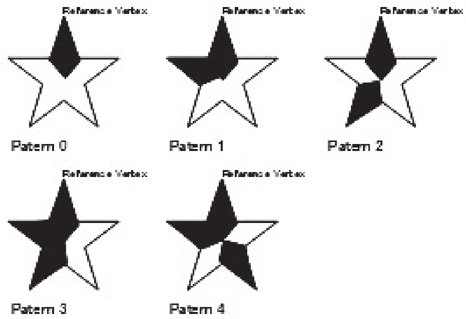


Fig. 1. Entire view of the proposed system. The camera is mobile held by a user. The display on the PC shows the original camera view on the left and the movement of a scaler model in a 3-D way on the right.



(a)



(b)

Fig. 2. A used scaler: (a) A polyhedral marker attached to the scaler, (b) five patterns on the facets of the marker.

The polyhedral marker attached to the scaler is not hidden by the trainee's hand, as the trainee holds the lower part of a scaler. The image of the marker is captured by the camera. By analyzing the appearance of a star-shaped pattern on the facet of the polyhedron, its posture recovers in a 3-D way.

3.2 Flow of the procedure

The entire procedure of the proposed system is illustrated in **Fig. 3** by a flowchart containing 8 steps. Each step is explained in the following:

(i) Input initial data & parameters:

The followings are fed into the developed program initially; camera inner parameters, the dimension of the used scaler with a polyhedral marker, shape of the star patterns, etc.

(ii) Input an image frame:

An image frame is fed into the program from a camera online.

(iii) Detect a star pattern by image preprocessing:

Several image processing techniques such as image binarization, labeling to extracted regions, contour tracing of the region, etc., are applied to the fed image frame to find a star pattern on the facet of the polyhedral marker.

Given a labeled region on the image frame, the contour on the region is traced to find convex/concave corners. If 5 convex corners and 5 concave corners are detected alternately on the contour, the region is recognized as a star pattern. The five star patterns are all different in shape as shown in Fig. 2. This difference can be known by examining pixel values on the line segment connecting the centroid of the star pattern and its 5 convex corners. The patterns differ from each other by the number and the order of black line segments and white line segments.

(iv) Compute the positions of the vertices on the star:

The image coordinates of the 10 corner points (vertexes) on the contour of the detected star pattern are initially obtained in (iii). The coordinates are, however, not very exact, since they are obtained while tracing the contour of the star pattern. Recalculation of the coordinates are therefore performed using the detected line segments on the contour in order to obtain the positions with higher precision.

(v) Compute the homography and camera parameters:

Once a star pattern is detected, the facet on which the pattern is painted on the polyhedral marker is identified. Then a homography matrix H relating the facet to its projected image on the image plane of a camera is calculated employing 10 pairs of corner correspondence between the two planes. Since matrix H represents the relation between the marker coordinate system and the camera coordinate system, a rotation matrix R and a translation vector $\boldsymbol{t}$ can be computed from H. The camera outer parameter matrix $M=(R\ \boldsymbol{t})$ is derived in this way.

(vi) Compute the scaler position:

By detecting a star pattern, the marker coordinate system is localized and the posture of the scaler is also localized on the marker coordinate system. It is then described by the camera coordinate system using the matrix M and finally by the world coordinate system.

(vii) Display the result:

A scaler model described by the camera coordinate system is displayed over the real scaler on the video in real time.

(viii) Continue or not:

The entire procedure from (ii) to (vii) is repeated every frame till the final frame of the video is processed.

3.3 Camera calibration and an undistorted camera

For the calibration of the camera employed in the system, a board with checker pattern is used. By finding correspondence of the points on the checker pattern whose 3-D coordinates are known with their projected points on a camera image, the 3×3 camera inner parameter matrix A' and the distortion coefficients κ of the camera are calculated. Then an undistorted camera, which was not considered in [3], is defined: Its inner parameter matrix A (a 3×3 matrix) is calculated from A' and κ.

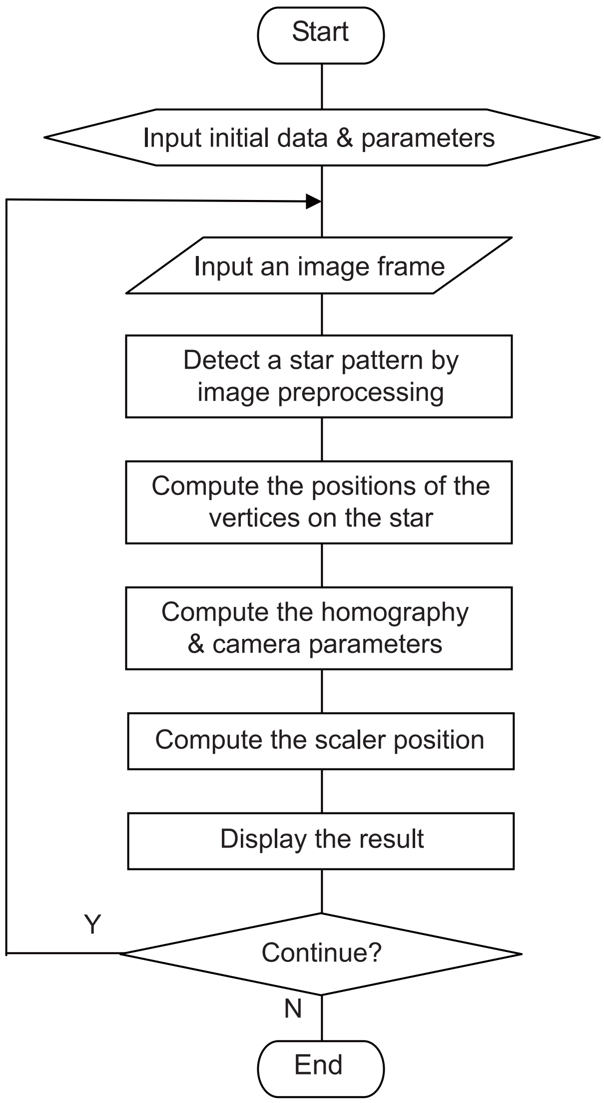


Fig. 3. Flowchart of the procedure.

3.4 Computational procedure

Let us denote an inner camera parameter matrix by A and the outer camera parameter matrix by M (a 3×4 matrix) which relates the camera coordinate system (O_C-$X_CY_CZ_C$) to the marker coordinate system (O_M-$X_MY_MZ_M$). The outer camera matrix M is further written as $M=(R\ \boldsymbol{t})=(\boldsymbol{r}_1\ \boldsymbol{r}_2\ \boldsymbol{r}_3\ \boldsymbol{t})$ where R is a rotation matrix and $\boldsymbol{t}$ is a parallel translation vector between the two coordinate systems.

If we denote an arbitrary point in the marker coordinate system by $\boldsymbol{P}$ and its homogeneous form by $\tilde{\boldsymbol{P}}$, and its projected point on an image by $\boldsymbol{p}$ and its homogeneous form by $\tilde{\boldsymbol{p}}$, the following relation holds;

$$\lambda\tilde{\boldsymbol{p}} = AM\tilde{\boldsymbol{P}} = A(R\ \boldsymbol{t})\tilde{\boldsymbol{P}} = A(\boldsymbol{r}_1\ \boldsymbol{r}_2\ \boldsymbol{r}_3\ \boldsymbol{t})\tilde{\boldsymbol{P}}. \quad (1)$$

Here λ is a scaling constant. R is written by components as R=($\boldsymbol{r}_1$ $\boldsymbol{r}_2$ $\boldsymbol{r}_3$).

If a point $\boldsymbol{P}_0$ on the top face of the marker is chosen, its coordinate is written as $\tilde{\boldsymbol{P}}_0=(X_i, Y_i, 0, 1)^T$, since $Z_M=0$. This expression can be reduced to $\tilde{\boldsymbol{P}}_0 = (X_i, Y_i, 1)^T$. Then, from Eq.(1), we have

$$\lambda\tilde{\boldsymbol{p}}_0 = A(\boldsymbol{r}_1\ \boldsymbol{r}_2\ \boldsymbol{t})\tilde{\boldsymbol{P}}_0. \quad (2)$$

Equation (2) expresses the relation between two planes in the 3-D space, i.e., plane $Z_M=0$ and an image plane in a camera. The relation is described by a 3×3 homography matrix H as follows;

$$A(\boldsymbol{r}_1\ \boldsymbol{r}_2\ \boldsymbol{t}) = H. \quad (3)$$

Hence, once the homography matrix H is computed, the rotation matrix R=($\boldsymbol{r}_1$ $\boldsymbol{r}_2$ $\boldsymbol{r}_3$) and the translation vector $\boldsymbol{t}$ are determined by

$$(\boldsymbol{r}_1\ \boldsymbol{r}_2\ \boldsymbol{t}) = A^{-1}H,\quad \boldsymbol{r}_3 = \boldsymbol{r}_1 \times \boldsymbol{r}_2. \quad (4)$$

The obtained matrix R is further tuned using the singular value decomposition in order to satisfy $R^TR=RR^T=I$.

3.5 Graphical display

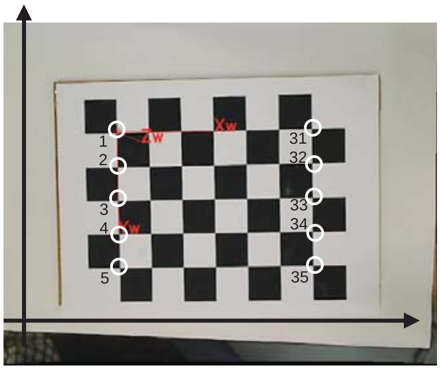
Once the matrix M has been derived from the procedure stated in 3.3, we get a projection matrix M_p and a model view matrix M_{mv}, respectively, from A and M. These matrices are employed for displaying a virtual scaler on the original image so as to be superposed on the real scaler.

4. Experimental Results

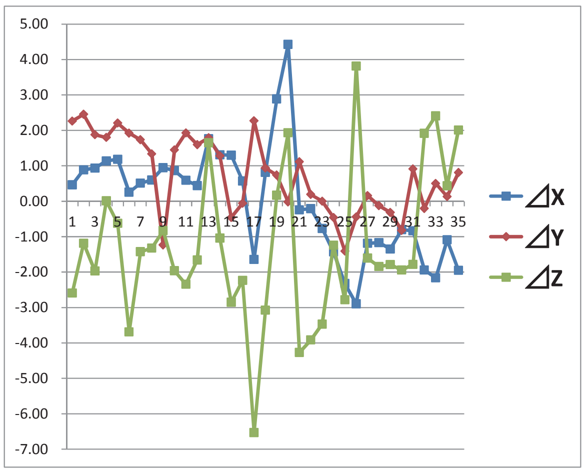
4.1 Examination of the precision

In order to examine the precision of the developed system, 3-D point recovery on a checker pattern board shown in **Fig. 4a** was performed. Figure 4b gives 35 points on the board which are the joint points of two diagonally adjacent black squares: They are numbered from 1 to 35 and the first and the last vertically aligned points are indicated by white circles with numbers. The coordinate system is also shown in the figure and the 35 points recover their 2-D coordinates with respect to the coordinate system.

(a)



(b)



(c)

Fig. 4. Examination of the precision: (a) A checker pattern board, (b) chosen 35 points, (c) distribution of the displacement.

The 3-D positions of these 35 points are calculated using transformation matrices. Let us denote the relation between the world coordinate system and the camera coordinate system by a 4 by 4 matrix E_W and the relation between the marker coordinate system and the camera coordinate system by E_M. They contain a rotation matrix and a parallel translation vector, respectively. Let us also denote a point P in a 3-D space described by the world, camera and marker coordinate system by $\tilde{\boldsymbol{P}}_W, \tilde{\boldsymbol{P}}_C, \tilde{\boldsymbol{P}}_M$, respectively. Here, in general, a point $\boldsymbol{P} = (x, y, z)^{\mathrm{T}}$ is described by a homogeneous form $\tilde{\boldsymbol{P}} = (x, y, z, 1)^{\mathrm{T}}$. Then the following relations hold;

$$\tilde{\boldsymbol{P}}_C = E_{\mathrm{W}} \tilde{\boldsymbol{P}}_W, \quad \tilde{\boldsymbol{P}}_C = E_{\mathrm{M}} \tilde{\boldsymbol{P}}_M. \tag{5}$$

Hence we have

$$\tilde{\boldsymbol{P}}_W = E_{\mathrm{W}}^{-1} E_{\mathrm{M}} \tilde{\boldsymbol{P}}_M. \tag{6}$$

In practice, as the tip end of the scaler is given by $\tilde{\boldsymbol{P}}_M = (0, 6, -173.9)^{\mathrm{T}}$, it is substituted into Eq.(6) and its location in the world coordinate system recovers.

The result of the precision examination is shown in Fig. 4c, in which the abscissa is 35 points and the ordinate is the displacement from the true position in millimeters. The displacements with respect to the three axes, $\Delta X, \Delta Y, \Delta Z$ are shown in blue, red and green lines, respectively. The statistical values of the displacement are given in **Table 1**.

Table 1. Statistical values on the displacement.

Displacement [mm]	ΔX	ΔY	ΔZ
Average	0.00	0.74	- 1.30
Variance	3.02	1.17	4.66
Standard deviation	1.74	1.08	2.16

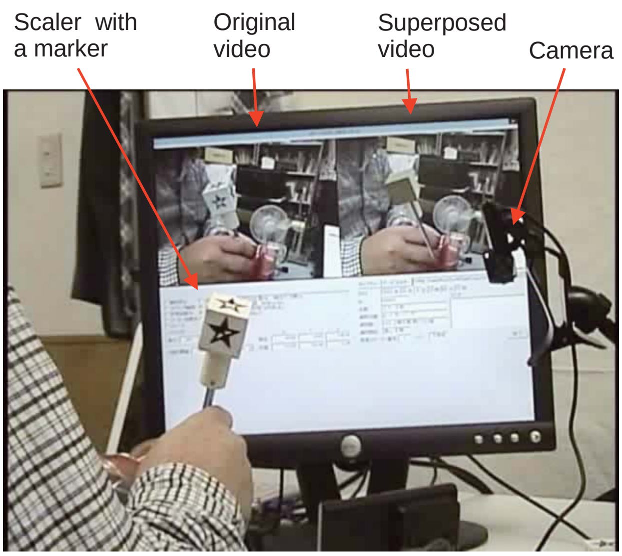


Fig. 5. The developed visualization system.

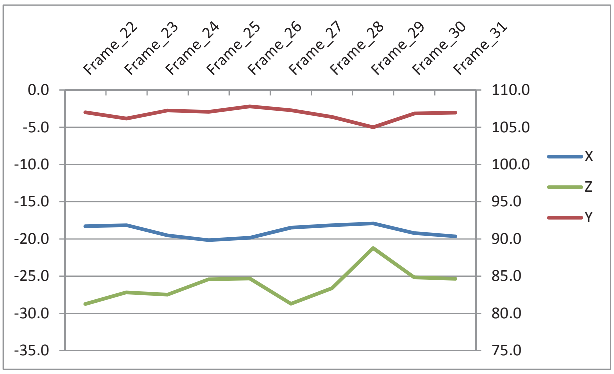
4.2 The developed system

The developed visualization system is shown in **Fig. 5**. A subject is applying a scaler with a polyhedral marker to a jaw model on this side: It is taken a video by a camera on the right-hand side (fixed in this particular experiment): The video is shown at the upper left side on a display: The video in which a virtual scaler is displayed over the real scaler is given at the upper right side on the display.

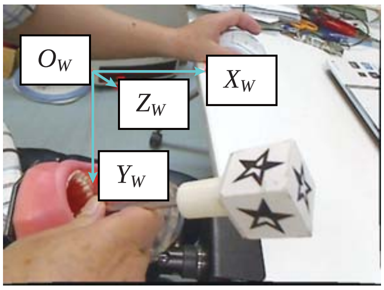
One of the experimental results is explained here. The result of 3-D recovery of the tip end position of a used scaler is given in **Table 2**, in which the coordinates (X,Y,Z) are listed from frame 22 to frame 31. Their numerical changes with respect to the frame number are also illustrated in **Fig. 6(a)**. Figure 6(b) shows the location of the world coordinate system O_W-$X_W Y_W Z_W$. The frames 22-30 are given in **Fig. 7**. With each frame in Fig. 7, the upper image is the original image, whereas the lower image contains a superposed virtual scaler. Although the motion of the scaler is small, its movement is seen in Fig. 7. (See more explanation in the figure.)

Table 2. Recovered 3-D coordinates of the tip end position over 10 successive frames.

Tip End Position	X mm	Y mm	Z mm
Frame_22	-18.3	107.0	-28.7
Frame_23	-18.2	106.2	-27.2
Frame_24	-19.5	107.3	-27.5
Frame_25	-20.2	107.1	-25.4
Frame_26	-19.9	107.8	-25.3
Frame_27	-18.5	107.3	-28.7
Frame_28	-18.1	106.4	-26.6
Frame_29	-17.9	105.0	-21.2
Frame_30	-19.2	106.8	-25.2
Frame_31	-19.6	107.0	-25.4



(a)



(b)

Fig. 6. 3-D recovery of the tip end position: (a) Graph of the recovered coordinates w.r.t. frames 22-31, (b) Location of the world coordinate system.

It is noted that, although the proposed system visualizes the tip end of a scaler in a 3-D way and it is the position where the tip end hits in the mouth, the proposed system does not provide the position in the mouth directly. To do so, the model of a jaw and teeth must be included in the proposed system.

5.Conclusion

The paper proposed a method of visualizing scaler stroke motion by a camera-computer system. The method displays the motion of a virtual scaler superposed onto a real scaler in a video in real time. The method therefore enables a trainer to evaluate the scaler stroke motion of a dental student in training by observing the motion of the virtual scaler on a PC display. The trainer can also evaluate the stroke motion numerically as the result of 3-D recovery of the tip position of a scaler.

This method differs from the existent method in that it employs a hand-held, *i.e.*, mobile camera for video image taking. Therefore a user can bring the camera to the best position for observing the scaler motion.

The requirement on the precision of 3-D recovery is 0.5 mm or less practically. Since the proposed system still contains slightly larger recovery errors as shown in 4, further improvement needs to be done with the present method to achieve higher precision.

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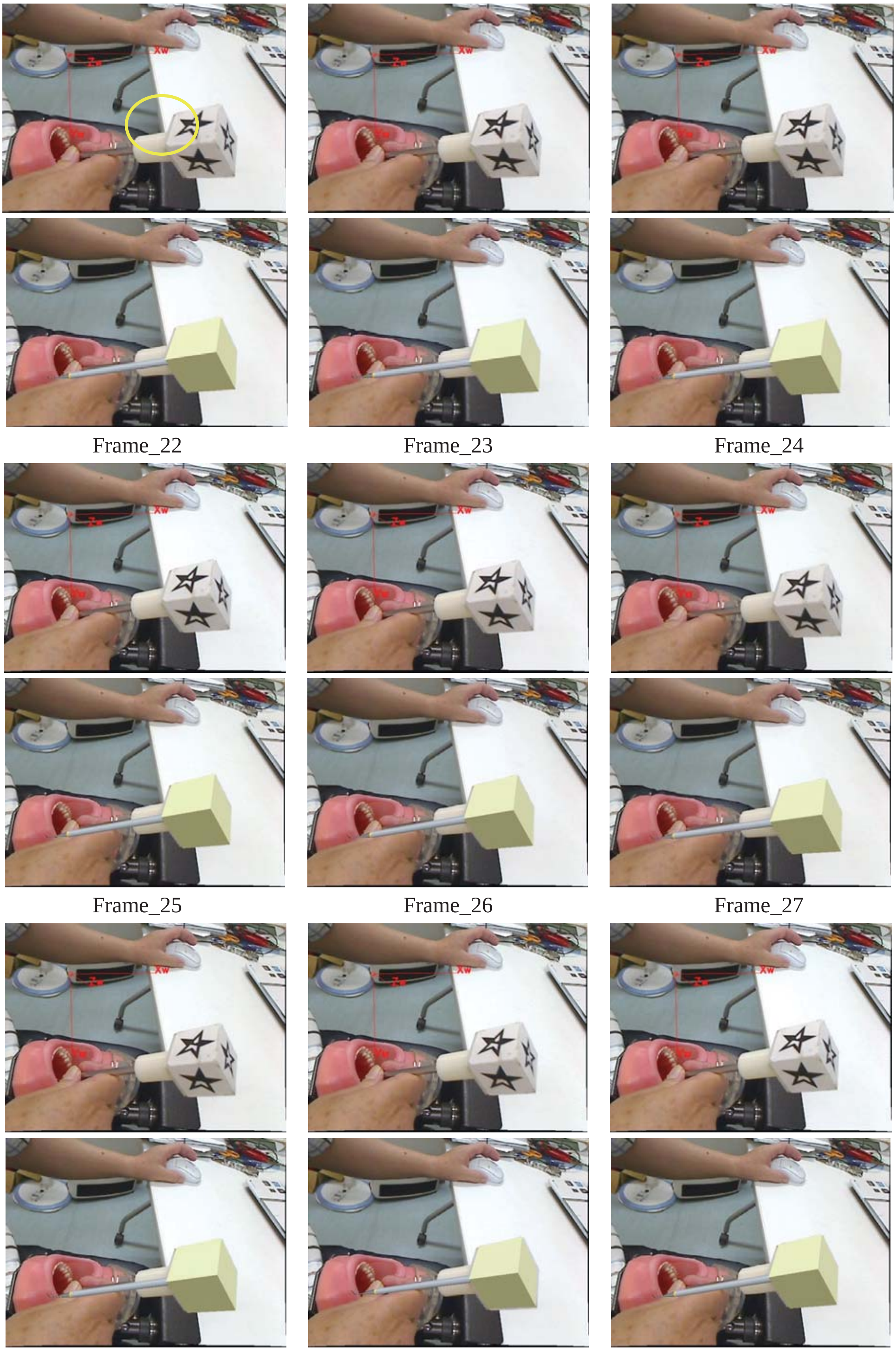

Fig. 7. Performance of the developed system. With each frame, an upper image is the original image, whereas the lower image shows the virtual scaler superposed onto the real scaler. Though the scaler motion is small, it may be observed if one looks at the position indicated by a yellow circle throughout the 9 images.

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