ON-LINE THREE-DIMENSIONAL LIGHT SPOT TRACKER AND ITS APPLICATION TO CLINICAL DENTISTRY

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ABSTRACT

The therapy of masticatory disorders is in its childhood since the diagnostic tools and methods are not universally accepted. One method of diagnostic consists in the characterization of abnormalities in the chewing function through the interpretation of the movements of the mandible. This paper presents a system which records on-line the six degrees-of-freedom of the lower jaw relative to the head with accuracy. Some typical results are shown which prove its usefulness for clinical dentistry.

INTRODUCTION

Great attention is paid in biomechanics to the study of the movements of anatomical limbs and joints. Kinzel (1983) gives a review of the various studies and the different joint models used. He points out the difficulty to obtain accurate measurements without interfering with the motion being measured.

The need of accurate jaw motion measurements is very important in clinical dentistry for two main reasons:

- For diagnostic of temporomandibular joint (TMJ) disorders (i.e. joint clicking) which may be caused by an incorrect position of the condyle in the fossa;
- For automatic production of posterior dental restorations (Rekow 1985) in order to determine the position of the cusp tips.

Little is known about the three-dimensional movement of the mandible and the condyle. Most of the diagnostical examinations of the TMJ require fluoroscopic studies, which are not harmless for the patient and which do not give a quantitative information about the condylar pathes. Furthermore, these fluoroscopic studies which are quite long and must be repeated in order to observe an evolution due to the therapy cannot be made with certain patients (i.e. pregnant women).

The task of measuring the three-dimensional motion of any point of the mandible consists in acquiring the six degrees-of-freedom of the mandible (considered as a rigid body) in respect to the head. As mentioned by Kinzel (1983), one of the problems of anatomical relative motion recording is to mark references on the member of interest. However in the case of the mandible there is direct access to the upper and lower jaw through the mouth.

Pioneering work on the method of measuring the six degrees of freedom of the mandible has been performed by Cannon (1964). The patient wears two intra-oral clutches fixed to the uppper and lower jaw. These clutches are attached to two extra-oral facebows. Six linear optoencoders are placed between the two facebows. The disadvantage of this set-up is the non-negligible weight of the lower facebow which might interfer with the motion to be measured. Numerous studies have been performed with this system which is still in use at the University of Florida.

The motivation of the present development was to improve the measuring method by reducing at the extreme the hinderance of the marking system to the normal chewing function.

We conducted (Mesqui 1984) a prototyping study based on a approach proposed by Erdman (1975). Erdman fixed two target frames containing each three light emitting diodes (LED) to the upper and lower jaw of the patient and recorded the motion of the six LED on film. Through the knowledge of the spatial coordinates of the six LED one is able to derive the six degrees-of-freedom of the lower jaw in respect to the maxilla. Instead of using film as recording medium (which has first to be processed and then manually analyzed) we recorded the motion of the LED with a commercially available optoelectronic system (Selspot I). Furthermore, in order to increase the redundancy we used target frames with each four LED. The system showed many disadvantages, which were limiting factors for its use in a clinic. The optoelectronic system furnished noisy positions of the light spots on the sensors, due to the dependence of the measured locations to the light amount of the spots on the sensors. The three-dimensional reconstruction with the DLT (Abdel-Aziz 1974) was computed off-line. The six degrees-of-freedom were determined by the least-square technique published by Spoor (1980). These off-line computations were too time-consuming to be acceptable for a clinical diagnostic. On the other hand the system had to be precalibrated before each measurement, which is again time-consuming and not practical in a clinical environment.

Since the principle of measuring was working well, we devised a new system keeping a simplified version of the method in order to make it acceptable for a clinic. The design criteria included following goals:

- no calibration. The system has to be calibrated once in order to be movable in the clinic without recalibration;
- on-line computation of the six degrees-of-freedom. The trajectory of the point of interest on the mandible has to be computed in real-time. This goal is imperious so that the clinician can observe the location of the condyle during mandible reposition treatments;
- easy preselection of the point of interest. The preselection has to be performed on the patient;
- stand-alone and transportable.

Last but not least, the system has to be easy to use by non technician.

These design criteria imposed severe restrictions on the technical choices and everything had to be kept as simple as possible. The system is composed of three subsystems namely a three-dimensional light spot tracker, a trajectory computation unit and a 3D display unit. The light spot tracker computes on-line the spatial location of the LED and the trajectory computation unit derives from the locations of the LED the six degrees-of-freedom of the mandible and computes the three-dimensional trajectory of a preselected point. In the preselection modus, this unit computes the location of the point of interest. The 3D display unit shows in real-time a perspective view of the trajectory on a CRT-screen.

THE THREE-DIMENSIONAL LIGHT SPOT TRACKER

We opted for an optoelectronic system whose principle had been successfully applied by Fuchs (1978), Yamashita (1982) and Macellari (1983). The system consists in three one dimensional linear cameras. In each camera a cylindrical lens forms an image line from a point light source on a photosensitive linear sensor. The sensor consists of 2048 photosensitive diodes accurately disposed in a line. The location of the image line on the sensor is determined by the number of the diode in the array which delivers the maximal video signal. By combining three such cameras in a convenient and fixed geometry (see figure 1) the 3D reconstruction of the coordinates of a light spot is easy to perform. As a matter of fact the three-dimensional coordinates of a light spot are computed in 800 µs. This time is less than the time needed to "read" out serially the 2048 photodiodes (2 ms). The system has a field of view of 14 cm and a theoretical spatial resolution of about 0.07 mm (140mm/2048). An accuracy test gave an error less than 0.1 mm (Mesqui 1985). The calculations are performed by a 16 bit microprocessor and a 64 bit Multiply and Divide Unit (MDU). The computed coordinates are available for long time storage and off-line processing on a separate computer.

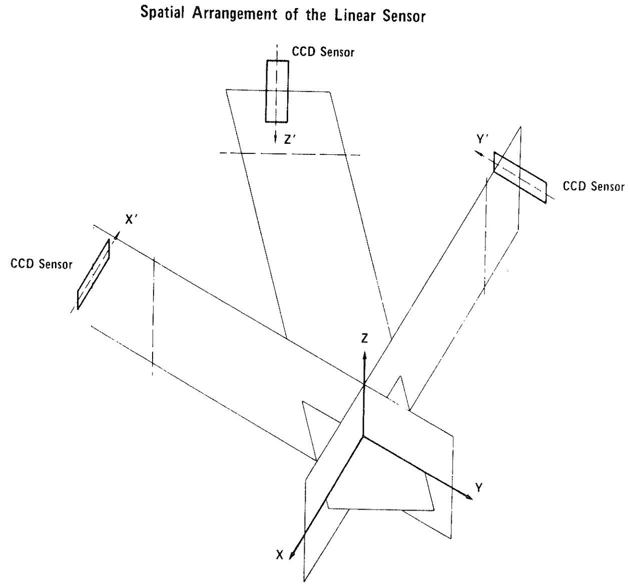
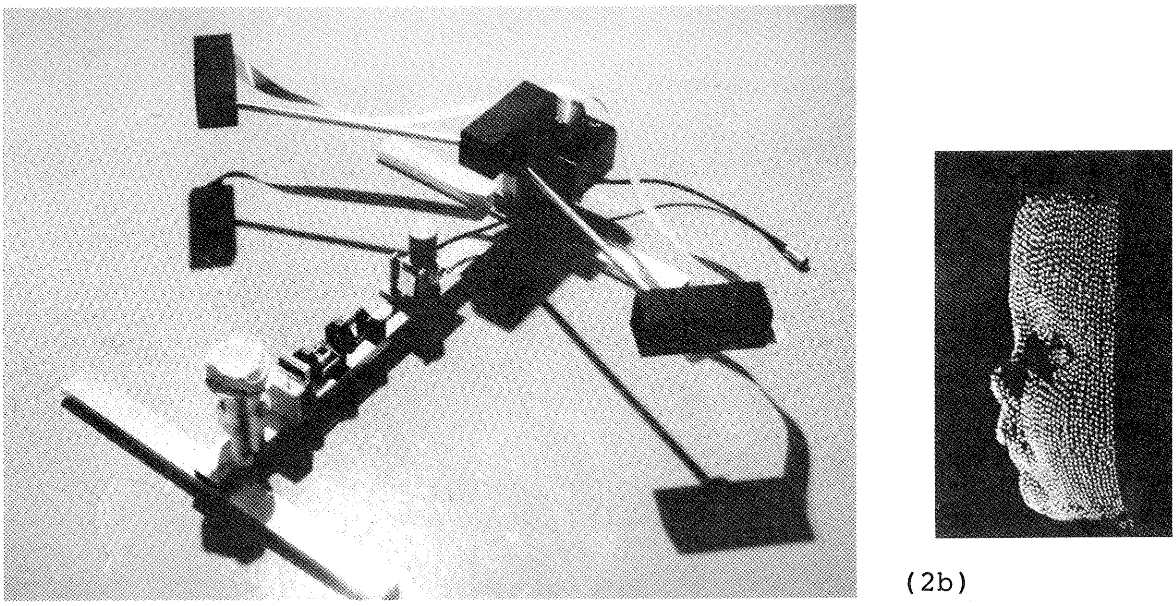


Fig. 1: Fixed geometry of the 3D spot tracker

A first application of this three-dimensional light spot tracker consisted in digitizing surfaces (Fischer 1985). A laser beam is deflected vertically by means of rotating mirror and produces a spot on the surface of an object placed in the field of view of the measuring system (see figure 2a). The objects rotates step by step when the vertical scanning is finished. Figure 2b shows typical pseudo 3D views of the head of a doll digitized by the system.



(2b)

(2a)

Fig. 2: (a) Set-up for surface data acquisition. The object (foreground) rotates in the field of view of the three cameras (background). The laser beam deflecting unit is located between them. (b) Perspective view of a head of a doll digitized with the system.

In order to overcome the difficulty of finding out which LED produces which line on the sensor each LED is fired sequentially. After one LED has been fired and after the video information has been read out of the CCD its three-dimensional location is computed. When all LED have been fired (one cycle) the video information without any LED is stored for subsequent substraction from the next CCD video readouts (static background cancellation).

THE TARGET FRAMES

The patient wears two extra-oral target frames fixed on the labial faces of two teeth of the upper and lower jaw. The weight of the triangular frames (see figure 3) is negligible (2 g each including fixation). The intra-oral part has to be made for each patient in order to respect the natural lips closure. The target frames contain each three LED, which is the minimal number of reference points to characterize the six degrees-of-freedom of a rigid body. The intended abandonment of redundancy (in the prototyping version the target frames contained four LED) has following reasons:

- the target frames are more difficult to be constructed if the LED are not coplanar;
- if the LED are not coplanar, the probability of one LED being not detectable by one camera becomes greater;
- the algorithms are more complicated and therefore more time-consuming thus either reducing the temporal resolution of the system or having to be performed off-line, which is not acceptable.

Fig. 3: Patient wearing the target frames

The upper and lower target frames define each a coordinates system. The task of monitoring the position of an arbitrary point whose coordinates are known in the lower system reduces to the transformation of its coordinates in the upper system. The reason of introducing the upper target frame is twofold: first to define the anatomic planes (horizontal, frontal, sagittal) in which the trajectory will be computed and then to measure the movements of the head which is not restrained.

THE TRAJECTORY COMPUTATION UNIT

The trajectory computation unit performs two main tasks:

- in the preselection modus, it computes the location of the point of interest on the lower jaw in the coordinates system defined by the target frame fixed on the mandible (referred to later as lower system);
- in the normal modus, it computes the spatial trajectory of the point of interest in the head related coordinates system defined by target frame fixed on the maxilla (referred to late as upper system).

This unit has to compute the orientation matrix and the translation vector describing the position of the upper system in the global measurement system and the same matrix and vector for the lower system. The three LED are mounted on the frames as vertices of a rectangular triangle. The orientation matrix is easy to determine by taking the normed vectors along the two perpendicular edges as first two columns and computing the third as cross-product of the two first. The translation vector is composed of the coordinates of the vertex of the right angle in the global coordinates system. The trajectory of the point of interest is then easy to compute by standard coordinates transformation techniques using the matrices and the vectors and knowing its position in the lower system. These operations are the limiting factor for the temporal resolution of the system. They are performed by a 16 bit microprocessor and a floating point co-processor.

In the preselection modus, the computation unit performs the inverse operation. The preselection device consists of a handle on which two adapters fit. The first one is for intra-oral use and has three extra-oral LED attached to an intra-oral pointer, whose coordinates are known in the LED system. By pointing at the point of interest the system transforms the coordinates of the end of the pointer in the lower coordinates system so that the system knows which point of the jaw should be tracked. The second adapter consists of a single LED and is used to mark the location of the condyle or any point which is not reachable with the first adapter. The clinician can also reenter manually the coordinates of a point preselected in a former session.

THE 3D DISPLAY UNIT

The 3D display unit, which is a very important feature of the system, allows the clinician to see on-line the trajectory of the preselected point. As mentioned above this feature is imperious in case of repositioning of the jaw because the clinician has to see the location of the condyle while the patient is instructed to perform some jaw movements. The 3D display unit is based around two analogic hardware modules commercially available (OEI, Model 6104 and 6134) which permit at extreme low cost a convenient perspective representation. The image may be continuously rotated or zoomed.

RESULTS

Figure 4 shows a complete view of the system, which can be easily moved in the clinic. A plotter can be hooked to the system to provide quantitative plots of the trajectories measured. A typical plots shown in figure 5, where the trajectory of the condyle is sumperimposed by crosses indicating the presence of a joint clicking.

The system can be hooked to an external computer for research purpose and further off-line analysis of the results. We use an IBM-PC AT to collect the 3D locations of the LED. The ultimate goal of this off-line analysis is to compute an invariant describing the motion of the jaw. A lot of work has been performed on this topic (Kinzel 1983). Woltring (1985) analyses the difficulty of estimating the helical axis of motion from noisy landmarks measurements. The first use of this invariant for dental purpose in-vivo has been published by Lupkiewicz (1982). First attempts of estimating the helical axis of motions showed the sensitivity of the determination of the helical of motion to noise and the difficulty of its interpretation in a clinic.

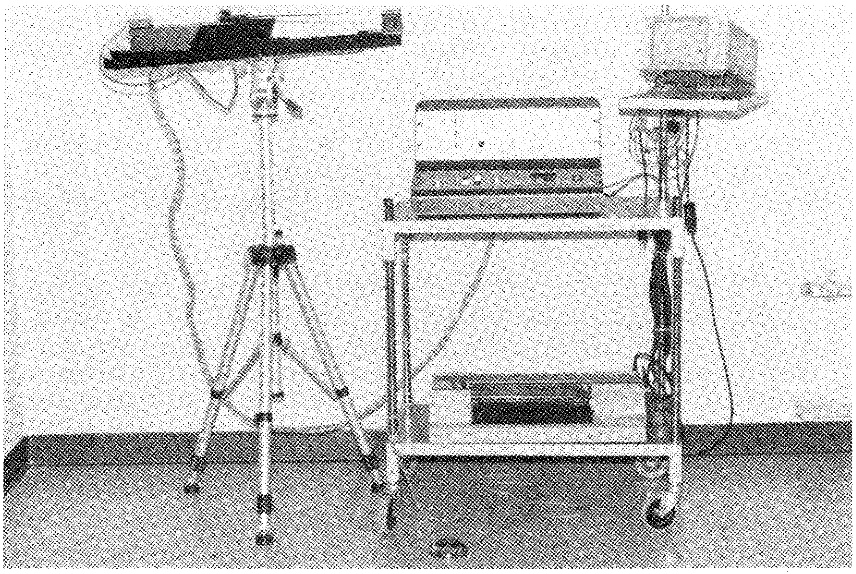
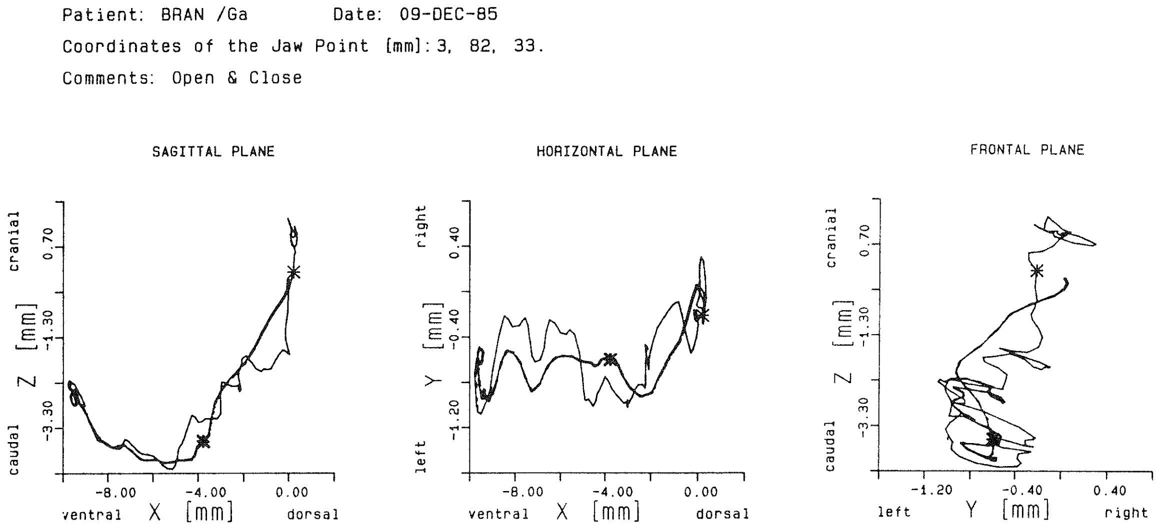


Fig. 4: Complete system for jaw motion monitoring. The three cameras are located at the left. The CRT is on the right of the Control Unit. A plotter is located under the Control Unit.



Patient: BRAN /Ga Date: 09-DEC-85

Coordinates of the Jaw Point [mm]: 3, 82, 33.

Comments: Open & Close

Fig. 5: Plot of the projections of the trajectory of the TMJ during normal opening and closing. The thicker line occurs during closing. The two crosses correspond to joint clicking.

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