Real-time close-range 3-D motion measurements for dental medicine

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ABSTRACT

Dental medicine needs to observe the motion of the jaw with respect to the skull in three dimensions. This represents, therefore, a problem domain in which one has to observe, in real-time, the motion of one three-dimensional body in 3-D space (the jaw) with respect to another three-dimensional body in 3-D space (the skull) which both may move independently.

This paper discusses an innovative solution to this requirement. The solution is implemented on a personal computer and is based on light-emitting diodes that are attached to the two moving 3-D objects. The innovation has been granted patent protection[2]. An element of the solution is the hand-held 3-D cursor whose position is also trackable as a separate three-dimensional body in 3-D space and allows the user to identify the XYZ coordinates of any point by a free-hand pointing action.

Applications of this real-time 3-D measurement system are not only in dental medicine but may extend to mechanical engineering, medical gait analysis and other applications where 3-D motions need to be tracked in real time.

1. INTRODUCTION

The need to observe three-dimensional bodies in 3-D space and to determine their position and orientation in real-time, i.e. about 30 times per second, exists in several fields of science and engineering. We had a requirement to develop a system in which the motion of the jaw could be tracked in real-time with respect to a coordinate system that is attached to the skull of a patient. The problem poses itself, therefore, as observing in 1/30 of a second the position and attitude of the jaw in a moving coordinate system.

We solved this problem by developing MANDARS (Mandibular Analysis and Recording System). This system incorporates a number of innovations that have been protected by the granting of a U.S. patent. The system is based on single image photogrammetry by determining and observing a bundle of rays whose vertex is at the center of a photo-detector and the base of each ray is at the center of a light-emitting diode. Figure 1 illustrates how a patient is equipped with a set of diodes that are attached to the head and a second set of diodes that are attached to the jaw. Two photo-detectors observe the two sets of diodes and each observation is performed in a fraction of a second. The measurement concerns the direction of the ray from the LED to each of multiple photo-detectors.

Given the fact that the relative distances between the LEDs are known, a single photo-detector can be used to determine the position of the jaw and the skull. The second photo-detector is therefore used only to ensure proper redundancy and conditioning.

We will describe in the following the concept of the 3-D real-time measurement of motion and explain its application in dental medicine. We also report on some experiences and accuracy assessments, illustrating a positional error of less than ±1mm in a volume of 3m x 3m x 3m.

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1. Currently with Starplus Software, Inc., Oakland, California
2. Patent number #4836778

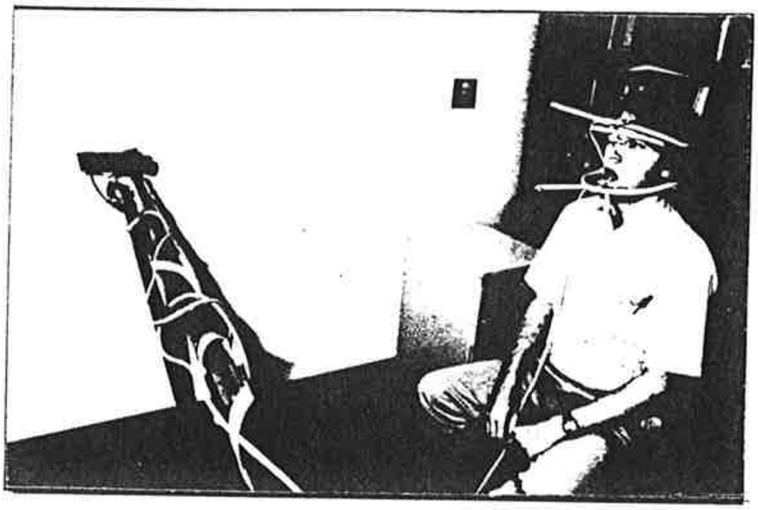

Figure 1: A patient with a set of LEDs to measure jaw motion in a coordinate system attached to a moving skull.

The implementation of the theoretical concepts has been completed and a number of systems have been built and put to clinical evaluation. At the current time this evaluation is still ongoing and the expectation exists that the real-time 3-D measurements of the motion of the jaw with respect to the skull will be beneficial in diagnosis of temporo-mandibular joint (TMJ) dysfunction and orthodontic work.

2. THE REAL-TIME 3-D MEASUREMENT SYSTEM

The basic concept to measure 3-D motion of a body in 3-D space is to attach to the body light emitting diodes. A minimum of three diodes is required to uniquely determine the position and attitude of the object. Each diode transmits light visible to a photo-detector. Note that a photo-detector is not a camera, but a device that is capable of very accurately determining the position of a light source with respect to an optical axis. The photo-detector is only capable of measuring the center of a single light source in its field-of-view. Therefore, the three light-emitting diodes need to "fire" one at a time and the photo-diode only sees the center of one LED at any given time.

The photo-diode itself creates an electric signal that needs to be digitized and entered into a personal computer. The PC software will control the configuration giving signals to the LEDs to fire and will receive the angle that the photo-detector has measured for the single firing LED. With a minimum of three LEDs in place one has about 1/30 of a second to fire all three LEDs in sequence to measure the direction to the LEDs as seen from the photo-detector. Figure 2 explains the geometric concept.

Clearly if three LEDs need to be attached to the object as a minimum, it is necessary and meaningful to use actually an overdetermined system of four or more LEDs. Also because of signal-to-noise relationships, one may not want to fire an LED only one time per observation, but fire it several times in a sequence to ensure that the signal is strong with respect to the background noise. Given the ambient light in an office environment, it is advantageous to not use visible light but infrared LEDs. In order to also minimize the effect of spurious motion of the object while the LEDs are firing, it is important that a single cycle of LED observations is not 1/30 of a second but much shorter. In a realistic implementation, we found that to track the rapid motion of the jaw, it is necessary to make a full observation of at least 4 measurements of 12 LEDs that are attached to the head and jaw in about 12 milliseconds. The remainder of a cycle is used for previous cycle display, so the time resolution for display is 1/30 of a second.

Since the observation of the motion is of no interest in an absolute coordinate system in which the photo-detector may be placed, but instead in a coordinate system that is attached to another moving body, it is necessary for the second moving body to also have a minimum of three (preferably four to six) LEDs attached to it. The basic principle, therefore, is to track two sets of six LEDs each whereby each group of LEDs is attached to one moving body. In a fraction of a second, therefore, a sequence of 12 LEDs or more may be fired and observed by a single photo-detector and it becomes subsequently simply a matter of the proper single image photogrammetry to determine the position and attitude of both objects and compute the motion of one object with respect to the other.

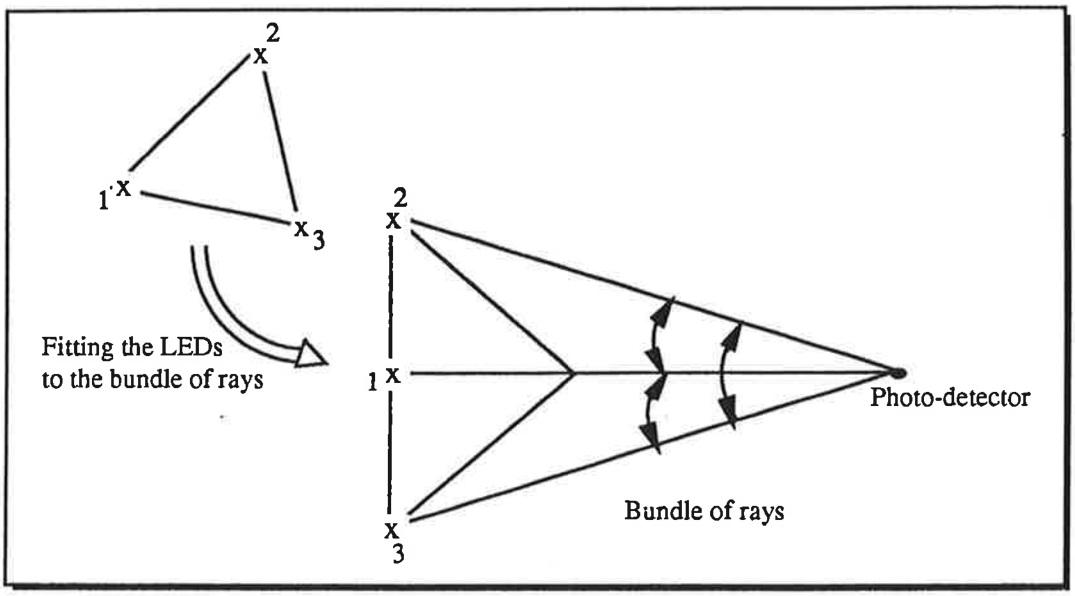

Figure 2: Resecting the position and attitude of an object using LEDs and a photo-detector (Resection-in-space).

In order to preserve the principle of redundancy, not a single photo-detector is used, but actually two. A single personal computer, therefore, will read the observations by two photodetectors.

3. HARDWARE ISSUES

A system that implements the basic concept described in the previous section consists of components as described in Figure 3:

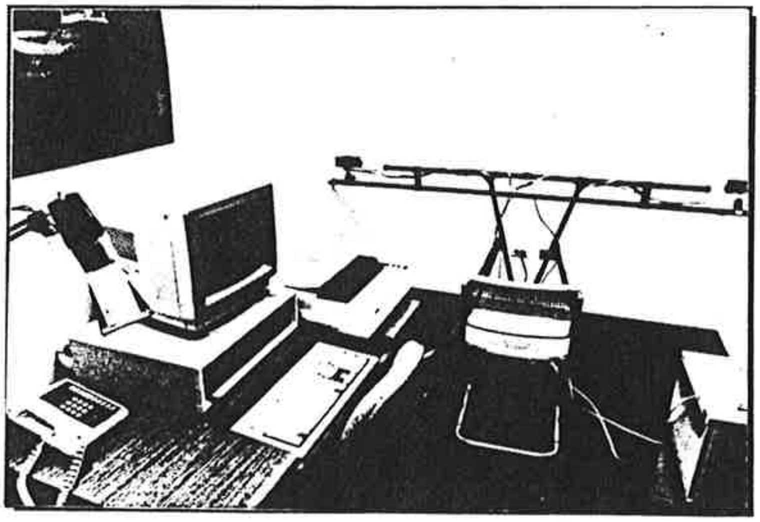

Figure 3: System configuration for the three-dimensional measurements

(a) a personal computer; the current implementation is on a PC 386 running MS/DOS;

(b) an analog to digital converter printed circuit board to digitize the output from the photo-detector into 12-bit digital signals;

(c) two detectors that are in fixed preset positions to continuously sense, using photo-voltaic cells, the XY positions of each of the LEDs as the LEDs are pulsed;

(d) amplifiers, which are used to improve the signal to noise relationship of the signals coming from the detectors. The amplifiers are attached to the photo-detectors to avoid any signal loss in the cables from the photo-detectors to the PC;

(e) LEDs, which are used to transmit infrared light upon a signal received from a PC;

(f) LED sequencer, a device that controls the firing of the LEDs based on software commands emanating from the PC. The firing of the LED needs to be precisely time-synchronized with the receipt of signals from the two photo-detectors.

(g) LED mounts; each object whose position and attitude needs to be tracked needs to carry a minimum of three, more preferably six, LEDs. The attachment of the LEDs to the object is by means of a harness;

(h) a photo-detector mount stand, to be used primarily in the form of a single bar that is mounted horizontally and at its two ends carries one photo-detector each. That bar can be mounted on a tripod or on the wall and holds the cameras at a distance sufficient to fill a 3-D space of 3m x 3m x 3m.

It is useful in the tracking of anatomical objects, such as in dental medicine, to have an auxiliary device that lets one create "virtual LEDs". This can be accomplished by marking up an arbitrary point on the object using a hand-held pointer. As the pointer is pointing towards a specific location on an object (which at this point is not marked by an LED), the position of the pointer is sensed by the photo-detectors and by some simple geometric manipulations, the XYZ coordinates of that feature are computed in a coordinate system of those LEDs attached to the object of interest. Note that we are describing a general purpose three-dimensional digitizing cursor whose XYZ position is known at all times by observing another set of 6 LEDs attached to the pointer (see Figure 4).

Figure 4: The hand-held 3-D pointer. Note that the pointer carries also multiple LEDs which need to be in the field-of-view of one or both of the photo-detectors.

4. PHOTOGRAMMETRIC CONSIDERATIONS FOR A REAL-TIME 3-D MEASUREMENT SYSTEM

If it is necessary to track an object in real-time, we need to have a system in place that can compute both the position and the attitude of an object in less than 1/30 of a second. If, furthermore, not only one but several objects need to be tracked, then the time available to compute the position and orientation of a single object may just be a fraction of 1/30 of a second.

The desire exists to use very simple computing tools, in particular a personal computer operating under the MS/DOS operating system. An analysis shows that a real-time implementation is feasible for a described problem domain. A harness can be attached to the object in such a manner that the relevant positions of the individual LEDs on a harness are calibrated and known. The photo-detector, therefore, determines a bundle of rays to a set of LEDs whose relative positions are well established. The problem, therefore, exists to find that position and attitude of the LED harness that is consistent with the bundle of rays observed by the photo-detector. An expression for tracking an LED array device center using this approach is:

$$[x,y,z,\omega,\phi,\kappa]^T_{i+1} = f(L_i^{\alpha},[x,y,z,\omega,\phi,\kappa]^T_i)$$

where: $[x,y,z,\omega,\phi,\kappa]$ = positional and rotational coordinates in a right-handed system,

L_i^{α} = (x,y) measurements for LEDs α at time series instant i,
$\alpha = 1,2, ..., 12,$

$i = 0,1,...,N,$

N = # elements in time series

The functional relationship implied by f above is complex; example for the recursive computation of the x-coordinate follows:

$$x_{i+1} = [\{L_i^2(x)\}(z_i + a\alpha_{31} + b\alpha_{33}) + \{L_i^3(x)\}(z_i - a\alpha_{31} + b\alpha_{33}) - 2p_a b\alpha_{13}]/(2p_a)$$

where: $L_i^2(x)$ = x-component of L_i^2, LED #2 at time i,

z_i = z-component at time series instant i,

a,b = harness constants derived from geometry,

p_a = principal distance of primary detector,

α_{kj} = (k,j) element of rotation matrix using (ω,ϕ,κ) angles at time series instant i,

$\alpha_{13} = \sin(-\omega)\sin(-\kappa) - \cos(-\omega)\sin(-\phi)\cos(-\kappa)$

$\alpha_{33} = \cos(-\omega)\cos(-\phi)$

$$\alpha_{31} = \sin(-\phi)$$

With the above formulation, we can track the harness attached to a single object in a coordinate system determined by the optical axes of the photo-detectors. If we want to use another reference coordinate system, particularly one related to another moving body such as a skull, then that position and attitude need to be determined independently and then the two coordinate systems need to be related so that the position and rotation of one object with respect to the other is computed.

5. ISSUES OF IMPLEMENTATION

The implementation of a real-time 3-D measurement system implies that both hardware and software are operating in concert. The need to precisely coordinate the firing of LEDs and the reading of photo-detector voltages is based upon a proprietary sequencer device as an attachment to the PC. A major difficulty is the signal-to-noise ratio of the observations done in the photo-detector. This has been a persistent problem and was solved by firing the actual LEDs at a frequency of at least 4,000Hz or more (currently 24KHz) and thereby obtaining high multiplicity of individual observations and averaging of those observations over time.

A second problem is certainly the loss of signal from the photo-detector on its way to the analog-to-digital conversion board in the PC. To avoid that loss of signal, analog signals are amplified directly at the location of the photo-detector and then sent from the photo-detector to the A/D card at the PC.

The number of LEDs necessary to reliably track a single object is, of course, minimally three. A higher number than three is desirable to be certain that at least three, preferably four, LEDs are in the field-of-view of a photo-detector at all times. Figure 1 explains the design of the harness and that design reflects the need of insuring full visibility of at least three LEDs from one photo-detector position even if the object moves and rotates significantly, so that some of the six available LEDs are not in the photo-detector's field-of-view.

The issue, of course, also exists of how to present the observations to the user. In the medical field, the user will certainly not want to be concerned with photogrammetry and will demand that a very simple interface exists that shows the information of relevance to the doctor. We have implemented a user interface that displays the motion of the LEDs and the motion of the bodies in absolute 3-D space as well as the motion of one body with respect to another. Since motion is in three dimensions and a user video-display only offers two dimensions, there is an issue of projecting three-dimensional real-world situations into two dimensions. It is not uncommon in medical fields to decompose a 3-D situation into frontal, sagittal and coronal planes. In engineering we often call this front view, side view and top view. In the particular applications, it has become important to have the motions of the objects displayed by means of a stick figure that represents the jaw moving with respect to the skull. The skull is considered to be fixed in that coordinate system, but in reality the patient does not have to keep the head motionless.

Clearly with the rapid changes in the computer offerings it is desirable to be able to use computers at various clock rates and with various operating systems. The implementation of the system has been done in such a way that clock rates can be used as they are being offered (16Hz, 20Hz, 25Hz, 33Hz, etc). The current implementation is based on the heavy use of color graphics on a VGA-compatible color monitor.

6. EXPERIENCES AND TEST RESULTS

With two photo-detectors that are about 1.14 meters apart, the field-of-view of each photo-detector encompasses a volume of 3m x 3m x 3m. Depending on the type of calibration that has been performed, only a subset of the $27m^3$ volume will really be meaningfully available to the 3-D measurements. In the past, a volume of 1/3m x 1/3m x 1/3m has reliably been made available to the user. At the current time, a number of systems are in clinical testing at academic dental research centers. While the clinical relevance of mandibular motion measurements may be of little interest in the current context, it is certainly of interest to assess the geometric accuracy of the approach that has been described here.

A number of tests have been performed to ascertain the accuracy in position and angle. Table 1 provides a summary of the positional and angular test statistics. Note that relative accuracy is accomplished of at least 1 in 1,000. A real issue exists in assessing the accuracy of a system like this because the assessment implies that a second method exists of measuring the motion, position and attitude of an object that is an order of magnitude more accurate than that which needs to be tested. In the current case a calibration rig was built and two harnesses were moved known distances and rotated by known angles; the measurement of those distances and angles was obtained from the 3-D measurement system. Reality and measurement were compared and are the basis of Table 1.

	R.M.S Absolute	**R.M.S. Relative Error Type I (%)**	**R.M.S. Relative Error Type II (%)**	**Comment**
X	0.81 mm	1.54	0.08	2" movement
Y	1.35 mm	2.57	0.14	90 mm movement
Z	1.14 mm	2.16	0.11	2" movement
ω,ϕ,κ	1.14 mm	3.28	N/A	30° movement

Table 1: Positional accuracy obtained using 5 measurements for each of two positional settings for each of three coordinates (X,Y,Z). Angular accuracy obtained using two measurements for one angular setting for each of three angles (ω,ϕ,κ). "Relative Error Type I" refers to the ratio between the absolute error and the true value. Note that "true value" is obtained from a fairly crude calibration rig which itself may have an error of ±1 to ±2 mm. In photogrammetry, "relative accuracy" is often expressed as dimensional error in the object divided by the distance between the camera and object. Since the camera is about 1 meter from the object, relative coordinate accuracy is about 1:1,000 (Relative Error Type II).

7. CONCLUSIONS

The described system has two interesting central aspects:

(a) A capability has been developed to accurately measure 30 - 100 times per second the position and attitude of several 3-D objects in 3-D space, with an accuracy of 1 part in 1,000.

(b) In addition, a 3-D pointing device has been perfected that can serve as a general purpose 3-D digitizer. In the current context, that pointer primarily serves to define virtual LEDs. It may very well be possible that applications are developed for a 3-D pointer that allow one to digitize the 3-D shape of arbitrary objects in 3-D space using free-hand motion.

In the medical fields, 3-D motion is typically not measured directly; instead 2-dimensional motion is measured. Such measurements are made by tracking a metallic object in a magnetic field or by tracking a single sound transmitting device with the use of two or more sound-sensitive membranes. Our system represents an improvement since it utilizes 3-D motion, not a 2-D projection. In the non-medical field, 3-D shape is typically measured rather than 3-D motion. Shape measurements themselves are often obtained from laser scanning devices. Such measurements are very accurate but slow and expensive. Also, the size of the object has to be reasonably small so that the laser scanning device can successfully describe the shape of the object. Our hand-held 3-D pointer represents an improvement since it is expected that an LED-photo-detector system can conceptually cover much larger volumes at much lower cost than the laser scanning device will be able to do.

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