Proceedings of the 2003 IEEE/ASME
International Conference on
Advanced Intelligent Mechatronics (AIM 2003)

A REAL-TIME OPTICAL SENSOR FOR SIMULTANEOUS MEASUREMENT OF 3-DOF MOTIONS

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ABSTRACT:

The need for simultaneous measurement of more-than-one degree-of-freedom (DOF) motions can be found in numerous applications such as robotic assembly, precision machining, optical tracking, wrist actuators, and active joysticks. Conventional encoders, though they are able to provide very high-resolution measurements (linear or angular), are limited to single-DOF sensing in motion control. The use of these single-DOF encoders for measuring 3-DOF motions in real time often requires additional mechanical linkages that often introduce frictions and backlashes. We present here a non-contact optical sensor for measuring multi-DOF motions.

This paper begins with the operational principle of a microscopic-surface-based optical sensor. The design concept and theory of a dual-sensor system capable of measuring a 3-DOF planar motion in real time is then presented. Along with a detailed analysis, the concept feasibility of a prototype 3-DOF dual-sensor system for measuring the instantaneous center of rotation and the angular displacement of a moving surface is demonstrated experimentally. It is expected that the analysis will serve as a basis for optimizing key design parameters that significantly influence the sensor performance.

1. INTRODUCTION

Optical gauging is a vision sensing technique for making displacement measurements based on the relative position of some types of patterns or features in the field of a vision sensor. These sensing methods have been used in many areas such as the alignment of contact lenses using fiducial marks, automobile wheel alignment, and alignment, docking and assembly tasks related to the construction of the International Space Station [McCarthy, 1998; Fernandez *et al.*, 1999]. In this paper, we offer an alternative design of an optical sensor for simultaneous measurement of three-DOF planar motions.

The use of single-axis encoders for measuring 3-DOF motions often requires a mechanism to constrain the device so that the 3-DOF motion can be deduced from the individual measurements of three orthogonal axes. The desire to eliminate the constraining mechanism, which introduces significant friction and inertia, has motivated Lee [1995] to develop alternative image-based methods for measuring the 3-DOF orientation of a spherical body. In order to overcome cycle-time limitations associated with traditional video-based vision system for machine applications, Lee and Blenis [1994] developed the design concept of a flexible-integrated-vision-system (FIVS) for motion control applications. Unlike conventional video-based systems that require pixel data of a full image frame to be stored in a video buffer before processing of pixel data can commence, the FIVS design provides an option to completely bypass the video buffer and thus offers a means to process and/or realize to store the digitized pixel data by directly transferring the ADC output to the DSP. Most recently, rapid increase in demands for high-performance pointing devices (such as a computer input mouse) for use with a personal computer has provided the incentives for the development of high-resolution optical sensors for measuring 2-DOF translational displacements [Bidlville, *et al.*, 1997]. The sensor for the pointing-device generates pulses proportional to the relative motion of the sensor with respect to a static surface. The number of pulses is derived from the detection of microscopic changes of surface-features between consecutive images; no engineered patterns (such as interferometer grating) are needed. These attractive features have provided the incentives for further development of an optical encoder, which can measure the instantaneous center of rotation and the angular displacement of a moving surface.

While the optical sensor for a pointing-device is capable to detect changes with a high imaging frame-rate in the order of 1,500 frames per second (fps), the sensor is indifferent to the rotation about its own optical axis. Moreover, since these optical sensors are primarily developed for use as a user-operated pointing device, there has been no design theory to help develop the sensor for use as a machine-operated motion sensor. For these reasons, we offer the followings:

(1) The operational principle of a microscopic-surface-based optical sensor, which leads to the design concept of a dual-sensor system capable of measuring a 3-DOF planar motion in real time.
(2) The development of a prototype dual-sensor system along with an experimental verification of its concept feasibility.
(3) A detailed analysis that offer an essential basis for optimizing the design for a given application.

2. OPERATIONAL PRINCIPLE OF AN OPTICAL SENSOR BASED ON MICROSCOPIC-FEATURES

Figure 1 shows the typical components making up of a basic imaging system, which consists of a photo-detector, a light source such as a light-emitting diode (LED) that illuminates the surface, and a lens collects the reflected light and forms an image on the photo-detector. The displacement of a moving surface beneath the sensor can be determined by analyzing the change in two consecutive images (I_{i-1} and I_i) as illustrated in Figure 2, where the black pixels represent the common area in both images; while hashed pixels are the intensity changes as detected by the sensor.

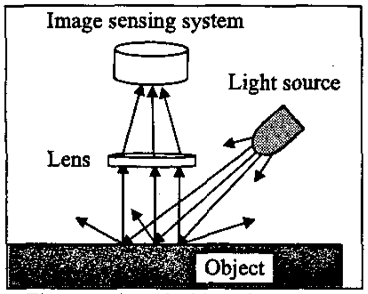


Figure 1: A typical imaging system

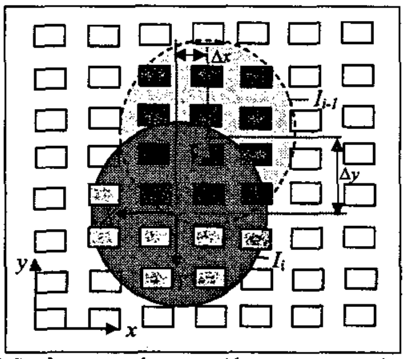


Figure 2 Surface moved captured by two consecutive images

In Figure 2, the reference frame XYZ is located at the optical center of the imaging sensor, while xyz is fixed on the moving surface. The directions of (X, Y) and (x, y) are assigned such that as viewed by the fixed sensor, the displacements of the moving surface and the fixed sensor have the same sign algebraically. The instantaneous velocity of the moving surface at a particular time instant can be expressed as

$$\mathbf{v} = v_x\hat{x} + v_y\hat{y} \tag{1}$$

And

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \frac{1}{t_c}\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \frac{1}{C_i t_c}\begin{bmatrix} C_x \\ C_y \end{bmatrix} \tag{2}$$

where $\hat{x}$ and $\hat{y}$ are unit vectors of the x and y axes defined in Figure 2; t_c is the cycle time; C_i is the counts per inch for the sensor; and $(\Delta X, \Delta Y)$ and (C_x, C_y) are the incremental distance traveled and the corresponding sensor output (in number of counts) within a cycle. A single optical sensor, however, is indifferent to the rotation about its own optical axis. Thus, more than one sensor is needed in order to measure the angular rotation of a plane.

Consider the k^{th} sensor that is fixed with respect to the XYZ reference frame as shown in Figure 3. The plane beneath the k^{th} sensor moves at a velocity $\mathbf{v}_o$, and rotates at an angular velocity ω about the z-axis. Thus, the velocity of the point beneath the origin O of the XYZ frame is given by

$$\mathbf{v} = \mathbf{v}_0 + \mathbf{r}\times\boldsymbol{\omega} \tag{3}$$

where

$$\boldsymbol{\omega} = \omega\,\hat{z} \tag{4}$$

and $\hat{z}$ is the unit vector along the z axis.

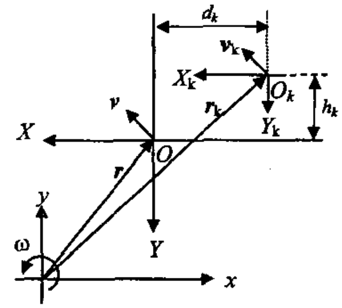


Figure 3 Sensor coordinates

The instantaneous motion of the surface can be broadly classified into the following cases:

<u>Case 1</u>: 1-DOF rotation (v_o=0 and r =0)

The surface beneath the k^{th} sensor rotates about the Z axis. The instantaneous angular velocity is given by

$$\omega = \frac{2}{d_k}|v_k|\hat{Z} \tag{5}$$

where $d_k \neq 0$. The angular velocity can be determined using one sensor.

<u>Case 2</u>: 2-DOF translation (ω=0)

The surface beneath the k^{th} sensor translates in both X and Y directions. The instantaneous velocity of the surface, as seen by the sensor, is given by Equation (2). The corresponding displacements in X and Y directions can be found by integrating the respective velocity components over time.

<u>Case 3</u>: 3-DOF planar motion v_o=0 and $\mathbf{r} \neq 0$

There are three unknowns in the 3-DOF planar motion measurement; namely, the instantaneous center of the rotation (x, y), and the angular velocity about the z-axis. Two sensors are needed and thus we consider here two identical sensors (k=1 and 2) in the following discussions. As shown in Figure 4, the velocity of a point directly below O_k on the moving surface is given by

$$\mathbf{v}_k = \boldsymbol{\omega}\times\mathbf{r}_k \tag{6}$$

or

$$\mathbf{v}_k = \begin{bmatrix} -\omega(y+h_k) \\ \omega(x+d_k) \end{bmatrix} \tag{7}$$

where

$$\mathbf{r}_k = (x+d_k)\hat{x} + (y+h_k)\hat{y} \tag{8}$$

The instantaneous velocity of the surface (as viewed by the dual-sensor system that is fixed) is given by Equation (2) and thus Equation (7) can be written as

$$\frac{1}{t_c}\begin{bmatrix} \Delta x_k \\ \Delta y_k \end{bmatrix} = \begin{bmatrix} -\omega(y+h_k) \\ \omega(x+d_k) \end{bmatrix} \tag{9}$$

For a dual-sensor system, it can be shown that only three of the four equations given by Equations (9) where k=1, and 2 are independent since both sensors will have a same reading in the direction along the line connecting the optical center. For simplicity, we let $h_1 = h_2 = 0$ which implies that the two identical sensors are mounted on the X-axis and hence

$$\Delta x_1 = \Delta x_2 \tag{10}$$

The angular velocity ω is then given by

$$\omega = \frac{\Delta y_1 - \Delta y_2}{(d_1 - d_2)t_c} \tag{11}$$

and the instantaneous center of rotation, (x, y) is at

$$x = \frac{1}{2}\left[\frac{\Delta y_1 + \Delta y_2}{\omega t_c} - (d_1 + d_2)\right] \tag{12}$$

and

$$y = \frac{-\Delta x_k}{\omega t_c}. \tag{13}$$

The angular displacement of the surface can then be calculated from the following integral:

$$\theta = \int_0^{nt_c} \omega dt \approx \left(\frac{1}{d_1 - d_2}\right)\sum_{i=1}^{n}(\Delta y_1 - \Delta y_2) \tag{14}$$

3. EXPERIMENTAL PROTOTYPE

An experimental prototype has been developed to demonstrate the concept feasibility of the dual-sensor system for measuring 3-DOF planar motions.

3.1 Optical Sensor Assembly

Figure 4 shows an exploded view of a typical sensor assembly that consists of an optical sensor [Agilent, 2001], an LED, and lenses. An assembly view showing the light paths of the optical sensor is shown in Figure 5.

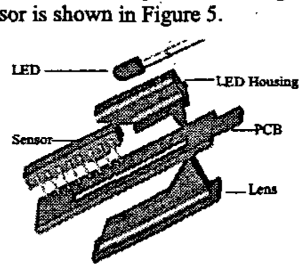


Figure 4 Exploded view of an optical sensor

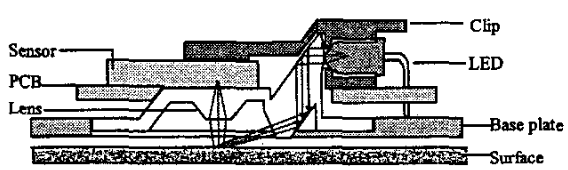


Figure 5 Assembly view illustrating the principle

A block diagram that shows the signal processing of the optical sensor is given in Figure 6. The optical sensor outputs two pairs of quadrature signals: (XA, XB) and (YA, YB) to a decoding circuit designed at Georgia Tech to facilitate the communication between an optical sensor and an external microcomputer. The decoding circuit as shown in Figure 6 consists of a pair of HP HCTL-2000 chips [Agilent, 1999] and a Keithley KPCI-3130 digital I/O card [Keithley, 2000]. The 12-bit output data of each decoder is organized in two bytes (eight lower and four higher bits), which are read by the eight digital lines of the Keithley digital I/O card via the digital control signals SEL, OE and $\overline{\text{RST}}$.

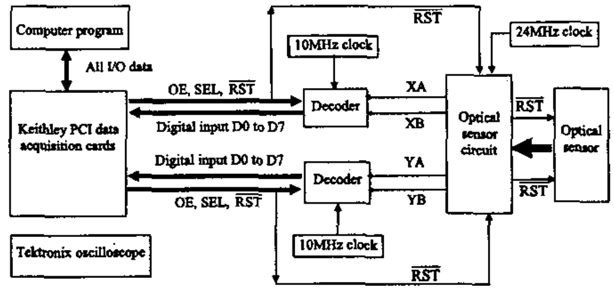


Figure 6 Schematics showing signal processing of the sensor

3.2 Dual-sensor System

For a dual-sensor system design, two identical sensor assemblies are housed in parallel in a holder as shown in Figure 7, which constrains the relative position between two optical sensors. For simplicity, we choose

$h_1 = h_2 = 0$ and $d_1 = -d_2 = \frac{d}{2} = 14.38\,\text{mm}\,(0.575\,\text{inch})$.

$$\omega = \frac{C_{y1} - C_{y2}}{dC_i\, t_c} \tag{15a}$$

$$x = \frac{1}{2}\left[\frac{C_{y1} + C_{y2}}{\omega t_c C_i}\right] \tag{15b}$$

$$y = \frac{-C_{x1}}{\omega t_c C_i} \tag{15c}$$

For an optical sensor with a linear resolution of 500cpi, the resolution of the angular displacement with a cycle time t_c is in the order of 0.1° for a given d of 30mm.

The dual-sensor system uses four decoders to convert four pairs of quadrature signals to two sets of x and y displacements. Each of the decoders requires eight digital data lines and three digital control signal lines ($\overline{\text{RST}}$, SEL and OE). Two Keithley KP-3130 cards are needed to accommodate the 44 digital lines; one of these provides (4x8) 32 digital I/O data and the other is used to send signals for data-reading control.

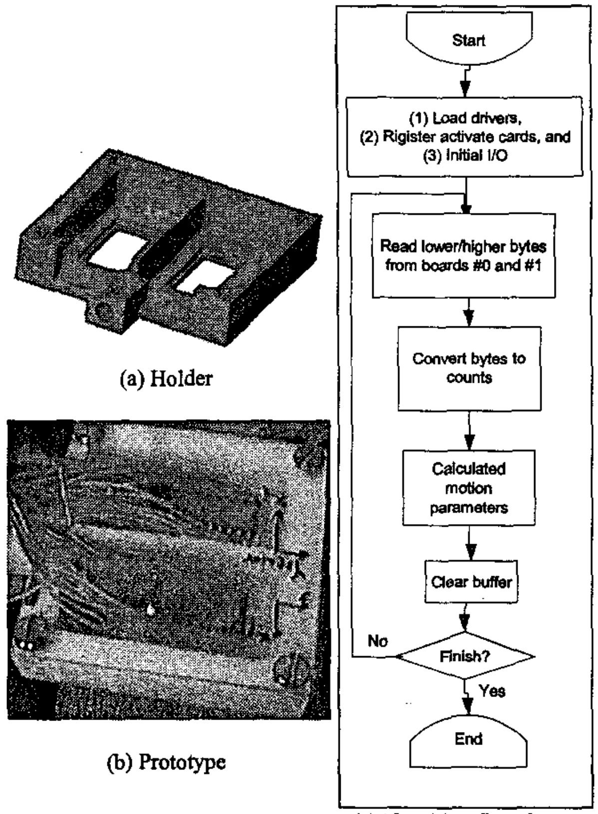
3.3 Software

For the breadboard configuration, software was written using MS C++ for executing the following tasks:

(1) Send digital control signals data-reading and clearing.
(2) Read the two-byte data from the decoders.
(3) Convert the two-byte data to x and y counts, C_{xk} and C_{yk}
(4) Calculated the motion variables, x, y, and ω.
(5) Save and display data for debugging.

The flowchart of the computer program is shown in Figure 7(c). The drivers of the DI/DO cards are first loaded. The I/O cards registered in the computer are then checked and initialized by setting $\overline{\text{RST}} = 0$. Meantime, each of the cards and their DI and DO channels are assigned a unique address.

The digital signals ($\overline{RST}$, OE, SEL) are set to (1, 0 0) for reading the lower byte and (1, 0, 1) for the higher byte, which are then converted counts (256*H_byte+L_byte) with an overflow check using an IF-THEN function. The motion parameters are then computed using Equations (15a)-15(c). With a 650MHz Pentium III PC, the computation cycle-time including data saving and display is in the order of 4ms.



(a) Holder

(b) Prototype

(c)Algorithm flowchart

Figure 7 Dual-sensor system

4. EXPERIMENTAL RESULTS

Experimental setups have been developed for the following experiments:

(1) Identify key parameters that significantly influence the performance of the 3-DOF optical sensor.

(2) Verify the concept feasibility of the dual-sensor system for measuring the 3-DOF planar motion; namely, the center of rotation and the angular velocity.

4.1 Effects of Surface Property on Resolution

In order to determine the resolution and to study the effects of the surface property on the resolution and the repeatability of the optical sensor, a 1-DOF experimental setup was developed.

As shown in Figure 8, the experimental setup consists of a precision NSF ball-screw and a beam, on which the optical sensor is mounted. The 1-DOF translational motion of the sensor is measured by means of an LVDT and a micrometer-depth-gauge that has a resolution of 0.025mm (or 0.001 inch).

Table 1 compares the resolutions in counts per inch (cpi) for several different surface properties. As expected, surfaces that are characterized by its high irregularities (such as a photocopy of a sand paper) are more desired (than uniform surfaces such as a white paper) as the sensor detection is based on microscopic changes of the surface. Figure 9 plots the reading of the optical sensor manually moved over a photocopy of a sand paper (Aluminum Oxide 220grit manufactured by Ali-Gator-Grit), for which the resolutions in both X and Y directions were determined to be 495cpi.

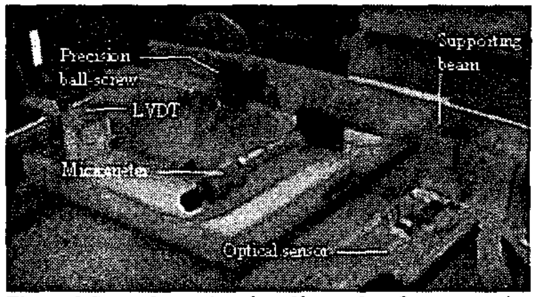


Figure 8 Setup for testing the effects of surface properties

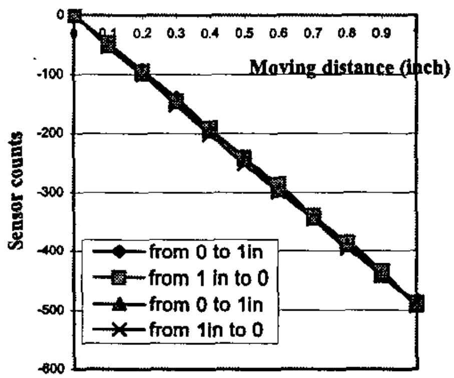


Figure 9 Test results of sensor repeatability (C_r=495cpi)

4.2 Effects of Sensor-surface Spacing on Accuracy

Figure 10 shows an experimental setup for evaluating a dual-sensor system given in Figure 7(b). The setup consists of a DC motor-tachometer speed-servo, which rotates a planar surface about the motor shaft. The DC motor is controlled by a Copley Motion Controller, the speed of which is measured by the tachometer and is digitized using a Keithley ADS1602 [Keithley, 1998] so that comparisons between the tachometer readings and those measured using the optical dual-sensor system can be made. The signal generated by a Tecktronix TM504 Signal Generator is taken as a reference input for the speed servo.

An experiment was set up to study the effect of the spacing between the sensor and the rotating surface on the sensor errors. The sensor-surface spacing is monitored by a micrometer dial gauge that has a resolution of 0.001 inch as shown in Figure 12. For a given sensor-surface spacing, the dual-sensor system measures the displacements of the rotating surface over a specified number of rotations. It has been observed that the maximum number of sensor counts for a specified angular displacement occurs when the spacing between the sensor and the rotating surface is in the neighborhood of 2.4mm, which represents a minimum loss in counts. Relative errors at other distances are computed using the following equation

$$\text{Relative errors} = \frac{|\text{actual counts - counts at 2.4mm}|}{\text{counts at 2.4mm}} \tag{15}$$

The results are summarized in Figure 12.

Table 1 Effect of surface properties on C_i

Surface property	Counts per inch
White copier paper	0
Glossy metallic painted finish	23
Black characters on white paper	120
Table surface	335
Dot pattern cloth	495
Photocopy of a sand paper	495

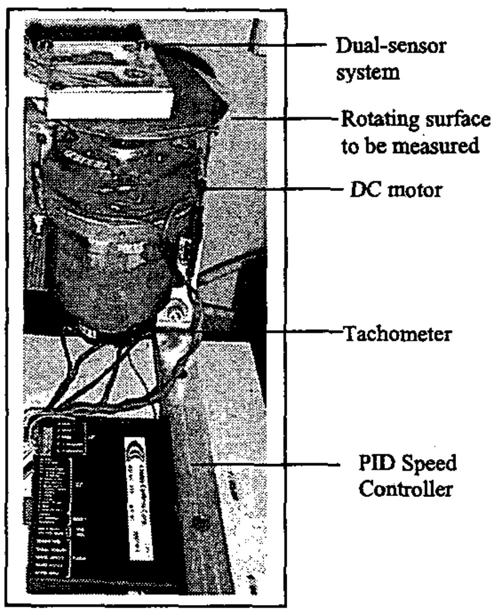


Figure 10 Experimental setup of a dual-sensor system

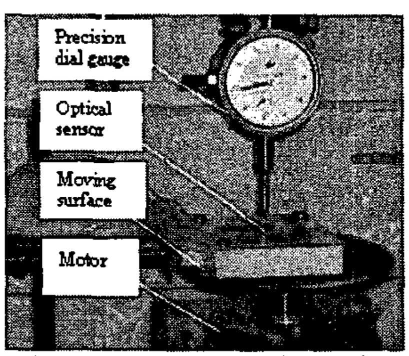


Figure 11 Test of sensor-surface spacing

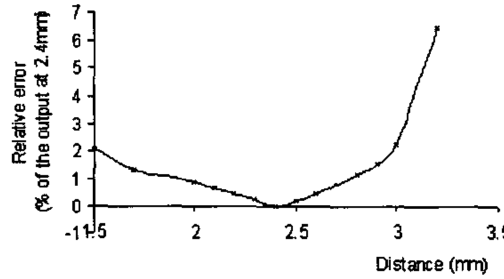
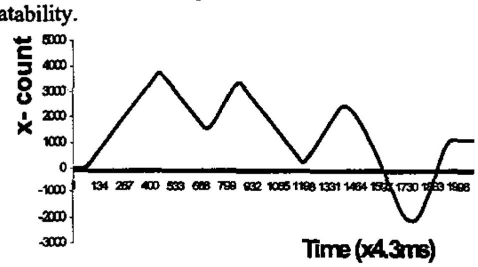


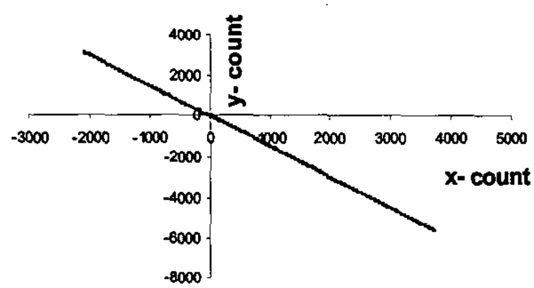
Figure 12 Effects of sensor-surface spacing

4.3 Test of Repeatability

To examine the repeatability of the optical sensor, we registered the x and y counts of the sensor as the surface is rotated arbitrarily back and forth with respective to the fixed sensor. Figure 13(a) show the typical x-counts as a function of time. The locus of a point passing beneath the optical center is essentially part of a circle with respect to the rotating axis (or the motor shaft). However, as perceived by the optical sensor that provides incremental readings, the points passing below the optical center will appear as a straight line relating the x and y counts as shown in Figure 13(b). The slope of this straight line is proportional to the inclination of the sensor coordinate frame from the line connecting the optical center and the axis of rotation. As shown in Figure 13(a), a point corresponding to x=2000counts passes the optical center 6 times and consistently yields y =–3000 counts as shown in Figure 13(b), which demonstrates that the optical sensor exhibits an excellent repeatability.



(a) x-counts for an arbitrary trajectory



(b) Local (x- and y-counts) as viewed by the sensor

Figure 13 Test results of repeatability

4.4 Measuring the Three-DOF Planar Motions

To validate Equations (15a)-(15c) that the sensor has the ability to measure the angular speed of the rotating surface, and the instantaneous center of rotation, experiments were conducted to compare the digital readings of the dual-sensor system against those measured by the tachometer.

Figures 14 and 15 compare the measurements for two different types of input to the DC motor; namely, a sinusoidal wave and a square wave. Each of these inputs is superimposed with the same offset. In these measurements, the relative position of the sensor with respect to the motor shaft remains fixed. As shown in Figures 14(a) and 15(a), the angular speeds computed by the dual-sensor system closely agree with those obtained using the tachometer.

Since Equations 15(b) and 15(c) that compute the x and y coordinates of the axis of rotation is sensitive to the difference of the two sensor readings, the computed data of the x and y coordinates are somewhat noisy. These noises are filtered using a digital filter. As compared in Figures 14(b) and 15(b), the filtered x and y coordinates of the shaft axis are identical regardless of the input wave forms.

5. CONCLUSIONS

The design concept and analysis of a dual-sensor system capable of measuring three-DOF planar motions in real time has been presented. The dual-sensor system, which detects microscopic changes in consecutive images, computes the angular displacement of a moving surface and the instantaneous center of rotational axis.

An experimental prototype has been developed and tested. The concept feasibility of the dual-sensor system for measuring 3-DOF planar motions has been demonstrated experimentally. A detailed experimental analysis has been presented, which not only help to provide a better understanding of the sensor but also identify key design parameters that significantly influence its resolution and repeatability.

It is expected that the prototype dual-sensor system has an immediate application in measuring the three-DOF orientations of a spherical motor.

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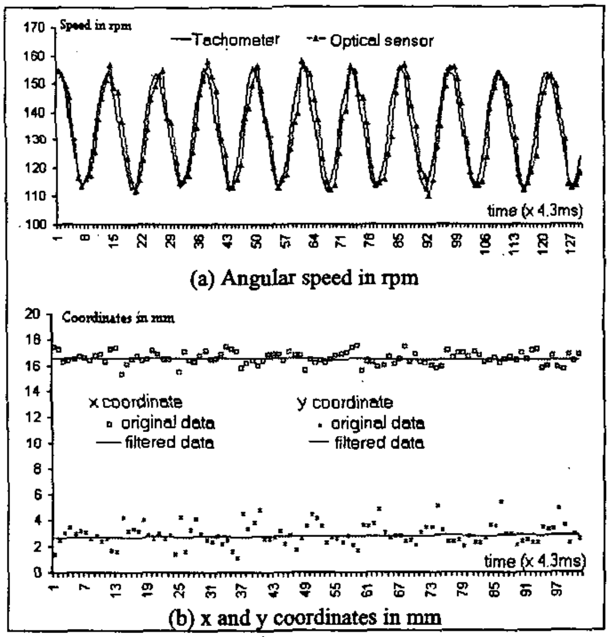

Figure 14: 3-DOF Sensor response to sinusoidal input

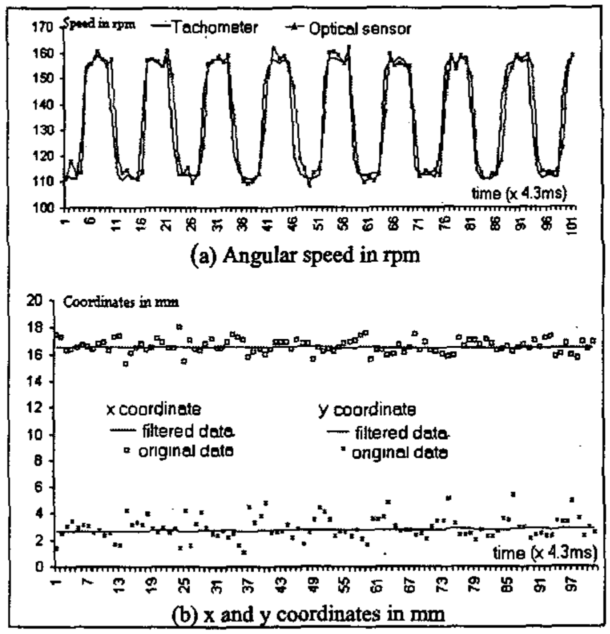

Figure 15: 3-DOF Sensor response to sinusoidal input