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INTERNAL PROFILE MEASUREMENT USING ROTATING LASER-BASED SYSTEM

Masahito Tanaka
Graduate Student, Arizona State University, Tempe, Arizona, USA

Bharath Leeladharan
Graduate Student, Arizona State University, Tempe, Arizona, USA

Hongtao Wu
Post-Doctroal Fellow, Arizona State University, Tempe, Arizona, USA

Ampere A. Tseng
Professor, Arizona State University, Tempe, Arizona, USA

ABSTRACT
An automatic new system for measuring the complete inner profile of various structures has been developed. The system is compact and uses a point laser source passing through a rotating optical device fixed onto the top of the measurement device. To enhance the portability of the system, a handheld computer is selected to control the laser source and the rotating optical device. The information provided by this system is essential to construction industries for cost estimation and production as well as to speed up the delivery of customized windowpanes, woodwork, floor-tiles and ceilings. Applications of the system for measuring windowpanes and floor plans are demonstrated. The measurement accuracy is also evaluated and analyzed. Results have indicated that measurement accuracy can be achieved within 4% for typical window designs and floor patterns.

KEYWORDS
Automation, Floor Plan, Laser Measurement, Phase Difference Method, Profile Measurement

1. INTRODUCTION

A portable profile measurement system equipped with a laser-based device has been developed to quantify the inner profile of a structure being considered. A prototype of this measurement system has been built, and its accuracy and reliability were evaluated. This measurement system gives critical geometric information to the construction industry, including window and door builders, the glass, panel, board, and floor tile manufacturers, carpet vendors, and building contractors. The profile information obtained can be used for cost estimation and production control; furthermore, this system speeds up the delivery of products such as customized windowpanes, woodwork, floor-tiles and ceilings. This system also overcomes the problems caused by manual measurement, which are not only time consuming but also unreliable, and sometime less accurate.

The optical profiling system currently developed consists of a laser-based distance measurement meter, a rotating optical component that converts a series distance measurement into a profile measurement, and a handheld computer having a wireless communication capability. The software is developed to control the laser meter and rotating attachment, as well as to acquire measurement data. The rotating optical component is mainly composed of a rotating reflection prism, a motor, and a battery. The laser meter operates by emitting a collimated laser beam that is reflected from the target surface and collected by an internal sensor (Woodbury et al., 1993). Through RS 232 serial ports, the laser meter is connected to the hand held computer. By obtaining series of distance measurements between the source and target along the inner surface, the full shape of the profile can be constructed.

The most advanced profile measurement system currently available can only provide partial profile estimations. In those systems, the laser distance meter and rotational optical component are mounted in series on a base plate and the rotating mirror is located between the laser source and motor (Tseng et al., 2001). Consequently, the plate blocks the laser beam while the laser beam deflected by the rotating mirror is scanning across this plate. This design limits the scanning capability to only 180 degrees. In the system presently developed, the laser meter and the rotating component are attached in parallel, which enables a rotating laser beam to scan a 360-degree internal structure without hindrances or blockages. As a result, the present system is able to provide whole profile measurement, a complete 360-degree measurement for a given object.

The whole measurement system is very useful when a complete cross section area is in demand. An operation of this system is easy since it can be placed anywhere inside the structure. A partial profile measurement system generates a blind portion in the entire profile, where the laser beam is blocked. This may require additional scanning with a different setup to obtain complete geometrical information of the profile. Furthermore, the system presently developed is equipped with the wireless communication capability. It is capable of sending measurement data to manufacturers in real time through the Internet. Therefore, the presented system can significantly reduce a lead-time of a product delivery.

This paper starts with an introduction that is followed by design concept of the optical system, and the hardware and software description of the system. The prototype of the system has been used to demonstrate its reliability and accuracy of typical building windows and floor plans. The results are discussed and the accuracy of the system is specifically evaluated based upon various perspectives. Finally, suggestions for further refinement of the system are presented.

2. SYSTEM DESCRIPTION

The main application of the measurement system developed is in the construction industry. This requires the system to be lightweight and portable. The range of measurement needs to be from a fraction of a meter to ten meters with no significant loss of resolution. The mechanical integrity should sustain a normal drop impact. The measurement accuracy should not be significantly affected by naturally occurring variables, such as temperatures from –10 ^{o}C to 40 ^{o}C and variations in humidity. The measurement discrepancy should be less than 5% or ± 3 mm, which is within the specifications of most of the construction applications.

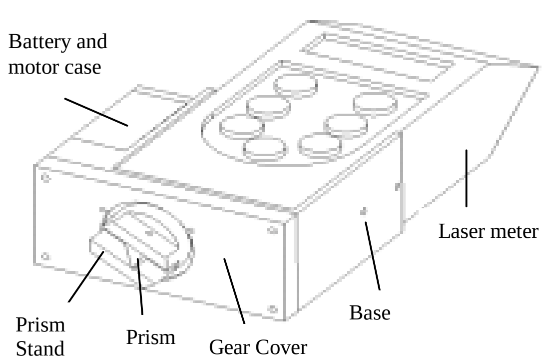

Figure 1: Schematic of Laser-Based Full Profile Measurement System

The present system is an open-loop system. It includes the laser distance meter, a rotating optical attachment, and the associated software. As shown in Fig. 1, the rotating optical attachment comprises a prism, a motor with a gear head, a battery inside a battery box, a gear train, a controlling circuit, a base and top cover and a prism stand. The prism acts as a reflecting mirror and is driven by a battery powered motor through a gear train. In this way, there is no hindrance of the laser beam while scanning is conducted. The handheld computer used for control is not shown in the figure.

The laser beam is emitted from the laser meter and enters into the prism, where the beam is reflected to 90 degrees. A motor through a gear train rotates the prism for scanning or sweeping the whole inner surface of a cross-section of a structure. The beam is diffused from the target surface, and a portion of the beam enters back into the prism. A detector, inside the laser meter receives the reflected beam through the same prism, and the phase change of the emitting and incoming signals is evaluated to determine the distance of each measurement.

In operation, the measurement system should be located inside the structure, normally near the center of the inner structure. The beam moves along the target surface of the structure until data have been recorded for an entire profile of the cross-section. The measurement starts at a user's request and stops as soon as the required location is reached. The distance data measured by the system is saved in the computer in the form of a spreadsheet. The software retrieves the data from the spreadsheet, and the profile is drawn after some computations on the data. Three major components of the system, namely the laser distance meter, the optical attachment, and the software, will be discussed further in the following sections.

2.1 Laser Distance Meter

DISTO Pro®, a model manufactured by Leica Geosystems AG of Heerbrugg, Switzerland (www.leica-geosystems.com/usa), was found to be suitable for the present application, as a result of a survey of modern laser measurement devices. The light source of the DISTO Pro® is a visible laser at 635 nm wavelength having a spot size changing from 6 to 60 mm for measurement distances increasing from 10 to 100 meters. It is a hand held device and capable of connecting to a PC through RS232 serial port for instantaneous data transfer and receive the operations. The measuring range for Model DISTO Pro is from 0.3 to 100 meter, and the measurement accuracy of ±1.5 mm.

The DISTO Pro meter® is based on the phase difference technique to estimate the distance. The general principle of this technique and its comparisons over other contemporary methods like triangulation method or time of flight method can be found from various sources including Burnside (1991) and Rüeger (1996). A brief description on the principle and evaluation of the phase difference measurement technique is given in this section.

With a phase difference distance laser meter, an emitted laser beam is modulated on the carrier wave at a particular frequency; the modulated beam travels to the target and is reflected or scattered from the target. The relative modulation phases of the emitted beam and the received light from the target can be evaluated and the phase difference of these two signals can be used to estimate the distance between the meter and the target. One of the major advantages of the phase difference technique is that the phase difference between two modulated signals of the same frequency is time independent; therefore, one can measure the phase difference over a time period much longer than the real time measurement required by other distance measurement methods. The distance between the laser meter and the target (S), which is one half of the total travel distance, can be computed as follows (Rüeger, 1996):

$$S = m\,(\lambda/2) + (\Delta\phi/2\pi)(\lambda/2) \tag{1}$$

where m is the (integral) number of full wavelengths over the measuring distance; λ is the modulation wavelength of the laser beam; and $\Delta\phi$ is the phase difference in radian. Here, $(\lambda/2)$ is also known as the unit length of the measurement device.

In Eq. (1), both m and $\Delta\phi$ are unknown and can normally be solved by introducing more than one modulation frequency in the measurement (Querzola, 1979; Hamada and Ohtomo, 1981). The highest frequency gives the shortest wavelength; its corresponding unit length is called the main unit length and is used for the fine measurement of the distance. The DISTO Pro® meter uses two frequencies of 50.0 MHz and 1.042 MHz. Using a speed of light of 3.00 $\times 10^8$ m/s, this yields corresponding wavelengths of 6.00 m and 288 m, and the main unit length of 3.00 m and second unit length of 144 m, respectively. As mentioned earlier, the meter is designed to be able to measure up to 100 m at 1 mm resolution; this requires a display of up to five significant digits; therefore, the maximum value of 99.999 should be displayed in this meter. The main unit length of 3 m is used to determine the precision, i.e., the last three digits and the second unit length of 144 m is used for determining the integer parts of the reading.

2.2 Rotating Optical Attachment

The rotating optical attachment is designed to convert the distance measurement into a 2-D profile measurement. This attachment consists of a DC motor, battery, gear head, gear train, prism, and covers. A voltage regulating circuit is linked to the battery to supply a constant voltage to drive the motor rotating constantly. The DC motor is 0.5 Watt at 60% efficiency having no-load speed at 16,000 rpm. The DC motor/gear head assembly is relatively small: 50 mm in length and 12 mm in diameter. The DC motor is attached to a spur gear head so that it can rotate at a desirable range of the rotation speed that is used to rotate the prism.

A 9-volt DC battery through the electric circuit drives the motor. An MC50 motor speed control card by Instech Laboratories (Plymouth Meeting, PA) was used for outputting a voltage. This card is used to maintain a constant output voltage as the source voltage drops due to drainage of the battery. The control card has a rated output load current of 50 mA for a supply voltage from +6 to +18 VDC. An Additional 10 kΩ potentiometer was used for adjusting the output voltage, thus changing a rotation speed of the prism. The board dimension is small (45 mm by 23 mm) so that it is uncomplicated to package into the system. The DC motor, speed control card, and battery are placed inside the motor and battery case and mounted in parallel on the side of the laser meter (Fig. 1). In this manner, the laser beam's path is not hindered by the motor attachment. A 1219-006G model DC motor was assembled with a spur gear head made by MicroMo Electronics (Clearwater, FL). With the typical load in the system the rotating speed can be regulated within a range from 0.5 to 2 rpm.

Reflecting prism is to reflect the laser beam emitted by laser measurement meter by an angle of 90 degrees. The surface of the prism should be large enough to receive enough reflected laser light from the target to be detected. An experiment for measuring a target covered with a white paper has been conducted to find the proper size of the prism. Two right angle prisms made of Schott BK7 glass by Linos Photonics® of Milford, MA, having surface areas of 10×10 mm and 20×20 mm were tested, and the target distance was changed from 0.5m to 6 m. The experimental results with 10×10 mm indicate that the measurement error can be within 3 % when the distance is within 1.5 m. When a 20×20 mm prism was used, the range increases to over 6m. The prism coated with a broadband antireflective coating of ARB2 by Linos Photonics yields better accuracies; thus, a coated 20×20 mm prism was chosen for this system.

3. SYSTEM SOFTWARE

Software has been developed for the control of the motor and the laser meter and the calculation of the actual distance and the numerical and graphic output of the 2D profile. A handheld computer, Palm VIIx, made by Palm Inc. (Santa Clara, CA) is used to host the software developed. The handheld computer communicates to the DISTO Pro laser meter through an RS 232 port. The software controls the location of the laser beam by regulating the motor in the rotating attachment. In operation, software sends commands to the motor and laser meter through the RS 232 interface and the computer receives the measurement data from the laser and stores these data and the corresponding time for every measurement. Then the computer uses these data to calculate the position of the target being observed by the laser, and the final profile of the structure is stored.

3.1 Profile Composition

In profile measurements, the software sends a command to the laser meter to take measurements in continuous mode. By specifying the rotation speed, ω, and the distance between the prism and the laser meter L_p, the time required for whole measurement (360º) is calculated. If the time at that instant (t_i) is less than calculated time T_m ($=360/\omega$), then loop is continued; otherwise a graph is plotted with the values from the data sheet to obtain the profile of the internal structure. The software program can be exited at any point, and also the restart button takes back loop to the start of the program at any time inside the loop. The system is an open looped system with no other sensor feedback to verify the locations of each target point measured or the profile constructed.

The distance measurement from the meter location to the target, D_i, at time, t_i, obtained from the laser meter and computer clock, are all recorded in the form of a spreadsheet in the computer. Then the time interval between the last measurement and the current measurement, Δt_i, and the angular increment, $\Delta\theta_i$ (= $\omega\Delta t_i$) and θ_i (= $\theta_{i-1} + \theta_i$), are estimated by including the effect of time delay, i.e., $\Delta t_i = \alpha\Delta t_{i-1} + (1-\alpha)(t_i - t_{i-1})$, where θ_i is the summation of the angles measured untill that instant (t_i). The α is the weighting parameter for considering the time delay in recording the measurement time t_i.

The weighting parameter, α, is changed from 0 to 1 depending upon the time delay that might have occurred in taking the readings. The α parameter in some respects resembles the weight factor used in time interpolation in finite-difference approximations of the parabolic partial differential equations (Jaluria and Torrance, 1986). If there is no delay in recording time, α equals 0, and this number is also used as default. It should also be noted that at i =1, $\Delta t_1 = (1-\alpha)\, t_1$. Thus the corresponding Cartesian co-ordinates, x_i and y_i, are calculated, and stored in the spreadsheet, where $x_i = (D_i - D_p) \cos\theta_i$ and $y_i = (D_i - D_p) \sin\theta_i$.

3.2 Data Communication

To speed up the product delivery to the field location, such as the construction site, the prompt transfer of the measurement data to the manufacturer or company data center is essential. In fact, the wireless communication capability was one of the major reasons in selection of the handheld computer, Palm VIIx, for this measurement system. Palm VIIx is capable of accessing the Internet. Therefore, the geometrical information obtained by this measurement system is ready to be directly sent to manufacturers or corporation data center. This should shorten the lead-time for product delivery. The schematic for the wireless communication is illustrated in Fig 2.

4. MEASUREMENT RESULTS

The prototype system has been tested to determine the reliability and accuracy of the profile measurement. The internal profiles consisting of a window shape and a floor plan of a room. The window shape is a typical aluminum rectangular frame. The size of the floor is much larger compared to the other two shapes. The weighting parameter discussed earlier has been tested to assess the effect of the time delay. The measurement results are also analyzed.

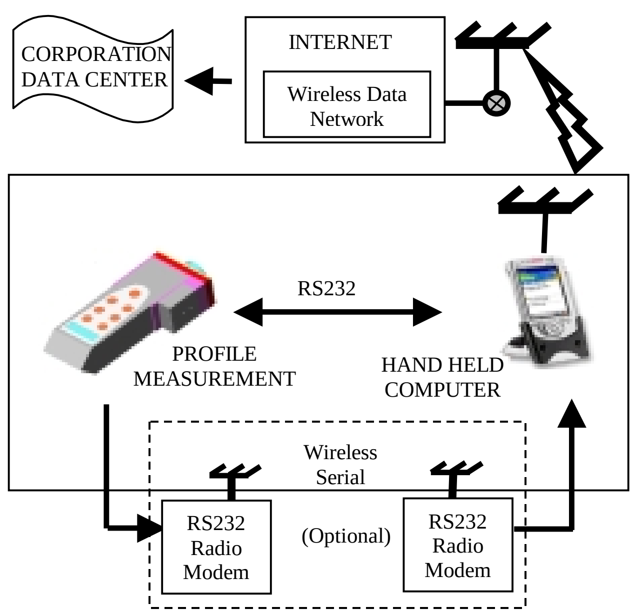

Figure 2: Schematic of Wireless Communication with Laser-Based Measurement System

4.1 Rectangular Frame

The measurement profile of the rectangular aluminum window frame is shown in Fig. 3. The figure also shows the measurement starting point, the prism location, which is normally near the center of the window frame. The measurement was done at a speed of 1 rpm (6 degrees per second) with a complete 360-degree sweep. It is observed that the number of measurement points is significantly reduced, or the time to take a measurement is much longer when an incident angle becomes larger than 45 degrees.

Theoretically, in a perfect surface, if the incident angle is other than zero, the reflected light that returns to the originated point of the incident light is zero. If a senor is located at the originated location will have no response, because no reflected light is received. Fortunately, no surface is perfect, and it always has certain amount of light or photons that reflects back to the original point of source because of the diffusion of reflection caused by the irregularity of surface. Normally, the higher the surface roughness, the higher the diffusion is. The photodiode inside the laser meter presently considered has to receive enough amount of reflected light or photons to estimate the phase difference. Since the reflectivity of the aluminum frame studied is relatively high or the surface roughness is relatively low, the intensity of the reflected beam is strong along the direction of the angle of the reflection, but only a smaller amount of light or photons are diffused and returned back to the photodiode in the laser meter. As a result, the photodiode in the laser meter will need a longer time to receive enough intensity of light or photons to react and determine the distance.

The errors of the measurement of the aluminum frame have been quantified in Fig. 4, where the error is defined as 100 × |Actual distance – Measured distance| / Actual distance. The effect of the weighting parameter, α, on the measurement errors is also studied. Results based on two values of α, 0.0 and 0.3, are presented for comparison. At $\alpha = 0$, the majority of the errors obtained are less than 2%; however, in some cases the error can be as high as 4%.

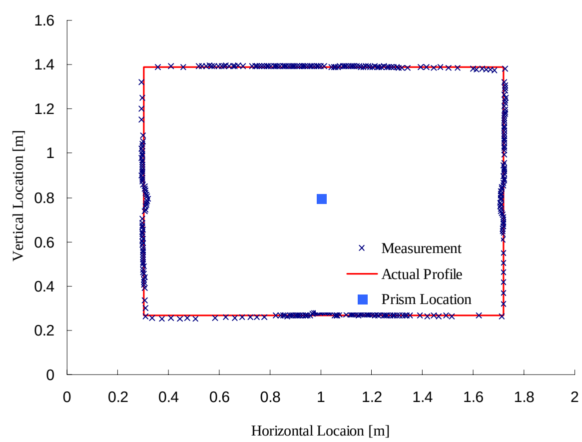

Figure 3: Measurement of an Aluminum Rectangular Frame at 1 RPM

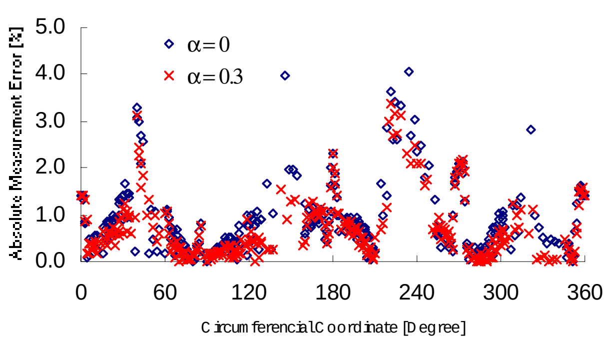

Figure 4: Measurement Errors of an Aluminum Frame for α = 0 and 0.3

With α = 0.3, the maximum error is reduced to 3.5%, which indicates that implementing the weighting value can reduce the errors, but not too much. Further study of the weighting parameter on reducing the error should be encouraged.

In Fig. 3, some bumps are also noticeable where the incident angle of the laser beam is close to zero, i.e., the laser beam is perpendicular to the target surface. Furthermore, these data points in Fig. 5 plotted in the vicinity of the angles at 0, 180, 270, and 360 degrees are not significantly affected by the weighting parameters. This indicates that the cause of these errors is not due to time delay of the measurement. The reasons for these bumps are not known yet, and it leaves room for further investigation.

4.2 Room Floor Shape

An experiment was conducted to measure the cross section of a rectangular room. The profile measurement device was again situated around the center of the room. The distance readings along with the wall of the room for the speed of 1 RPM are shown in the Fig. 5. Though the measurement distances were much greater than the previous inner structures considered, they are still in good agreement with the actual profile. The corresponding error estimations for α = 0.0 and 0.3 are shown in Fig. 6, in which percentage error is plotted against the polar angle based on laser beam. As shown, the absolute percentage errors for the weighting value of 0 are over 6%, but the majorities are below 3%. When choosing a weighted value of 0.3, these errors decrease and fall below 4%. This again provides support that the weighted parameter can be used to reduce the measurement error caused by the delay in recording the measuring time and α = 0.3 is the optimum for the current system.

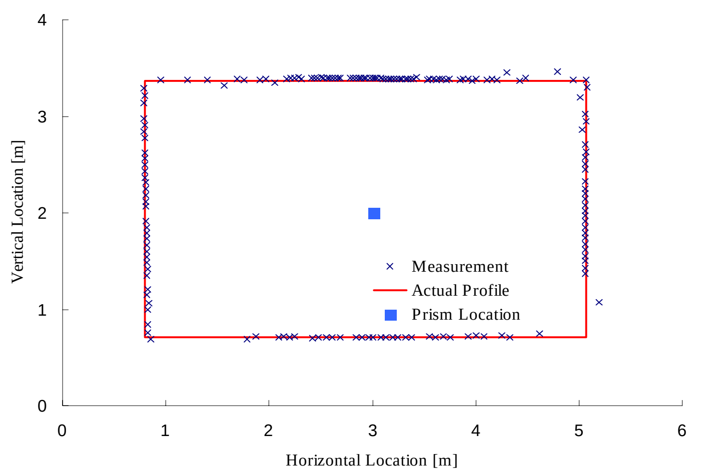

Figure 5: Measurement of a Rectangular Room

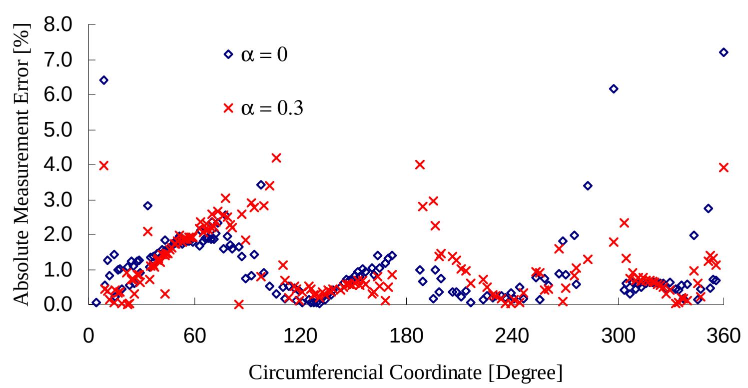

Figure 6: Measurement Errors of a Rectangular Room for α = 0 and 0.3

5. CONCLUDING REMARKS

A laser-based profile system has been designed and built to measure the complete cross-sectional profile of various internal structures. The application of this system in measuring the shapes of window frames and floor plans has been successfully demonstrated. The system reliability and measurement accuracy have been evaluated and studied. Experimental results have proved that the measurement accuracy of 4% for the typical structures considered can be achieved.

The estimation of time delay effects by employing a weighting parameter, α, on the measurement accuracy are studied. The results indicate that an appropriate value of α contributes to reducing high error points. Since the frame tested for the current study is only a rectangular shape, further investigation employing different frame shapes is needed for validity as well as optimization of this parameter.

The present study of the design also revealed that when the incident angle to the target increases to more than 45 degrees, the time to perform the measurement by the laser meter becomes slow for an aluminum material and measurement accuracy may be deteriorated marginally. In fact, the reflected light is weaker as the incident angle increases. Dependent mainly on the roughness of the target and the sensitivity of the receiving sensor in the laser meter, the reflect laser light becomes too weak to be detected, when the incident angle is larger than a threshold value.

In the future, efforts to further develop the hardware and software of the system are recommended to improve measurement accuracy. Some of the improvements that could be done include upgrading the IC circuits used in the laser meter to increase measurement speed and thereby to obtain more data-points at faster processing speeds. In software development, the measurement accuracy near the corners of rectangular frames can be improved by applying artificial intelligence techniques to use less data to construct the shape of the internal structures. The use of a stepping motor instead of a DC motor will also result in more control, reducing the errors caused by the target movement. Statistical methods like use of standard deviation can be applied in eliminating those random “high-error” points; observed particularly for an aluminum frame. Then the averages can be taken for the plots to obtain better results because most of the points are centered on the actual profile or distance.

7. ACKNOWLEDGEMENTS

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