

Surface Contour Measurement Using a Short Range Laser Displacement Sensor

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Reviewed, accepted September 18, 2009

Abstract

Non-contact freeform surface measurement is widely used in industry. To acquire the surface data, a laser displacement sensor and a motion system are typically used. One of the factors that affect the measuring accuracy is the sensor's resolution. A high resolution sensor usually has a short measuring range. However, an unknown component's profile with a large peak-to-valley height variation can not usually be measured using a short range sensor.

We designed and developed a measuring system based on an existing 3-axis motion system with a laser displacement sensor mounted on its Z axis. This measuring system can be easily integrated to an existing laser processing system by standard communication ports to extend its applications into tool path planning, in-line inspection and monitoring. With the developed system, the real-time distance from the sensor to the component surface is acquired, and used as a feedback signal to control the sensor's position on the Z axis to automatically maintain its distance with a given value.

Through this development, the measuring range of the system is extended from the sensor's measuring range up to the Z axis travelling range of the motion system so that a surface with large peak-to-valley height variation can be easily measured by a short range sensor with substantially improved accuracy.

Introduction

Laser cladding is a material depositing method by which injected powder material is melted by a focused laser beam and resolidifies to form a coating on a substrate. A recent paper has reviewed laser cladding of various metals [1]. This technology has been used to repair damaged parts by adding desired material onto the worn-out areas [2-3]. To increase the productivity, improve the quality and decrease human mistakes, the repair automation is desired, which may consist of several steps: (1) measuring the worn out part, (2) creating the patch geometry model, (3) generating cladding tool path, and (4) performing laser cladding repair. Several papers have been published in this area. J. Zheng et al [4] and J. Gao et al [5] focused on the broken geometry reconstruction of worn-out components, while C. Bremer [6] developed a web-based data management system for automated repair of turbine components.

The nominal CAD model of a component does not represent the worn out component anymore and can not be used directly for the repair [5]. Therefore, the first step in the repair procedure is to extract the actual geometry of the components. Many research activities have been focused on finding a better approach to acquire the geometry data and a review paper on the free-form surface inspection techniques was published by Y. Li et al. [7]. There are many ways

to extract the free-form geometry. Among them, touch probe [8], non-contact laser sensor [9-12], CCD camera [13-14] and other optical sensors [14-15] or hybrid sensor are widely used. Touch probes are very accurate (with a resolution of less than 1 μm) but have low data acquiring rate. The CCD cameras have very high data acquiring rate (that may not be necessary for the surface reconstruction [16]) but have low accuracy (resolution greater than 50 μm). Non-contact laser sensors have middle range but acceptable accuracy (resolution between 10 μm and 50 μm for most models). Non-contact laser sensors have been widely used in the past decade. There are various types of non-contact laser sensors for surface contour measurement, including multiple-points sensors (such as line sensors), and single-point sensors (such as displacement sensor). Among the non-contact sensors, laser displacement sensors have the advantages of low cost and high accuracy.

Typical setup for a contour measurement system usually consists of a 3-axis motion table and a sensor, as shown in Figure 1. The table is able to move in a horizontal plane (X-Y plane) in a coordinated manner. A component to be measured is mounted on the table. The sensor is installed on the Z-axis motion table at a position over the component surface, with the sensor aiming at the X-Y plane of the motion table at a normal angle. The Drive Unit, Motor, Encoder and PC form a closed-loop position control system. The Encoder converts the angular position of the motor to digital code, which relates to the current position of the table, and the code is sent to a PID regulator built in the PC. Comparing to the desired position, a drive signal from the PID regulator is sent to the Motor through the Drive Unit to eliminate or reduce the position error. By controlling relative movement between the sensor and the component using the X-Y table, the laser sensor, at predetermined sampling points (x, y), acquires the distance (z) information between the sensor and the measured surface of the component. After scanning the entire interested area, the surface contour is constructed and represented by a group of 3D coordinates (x, y, z).

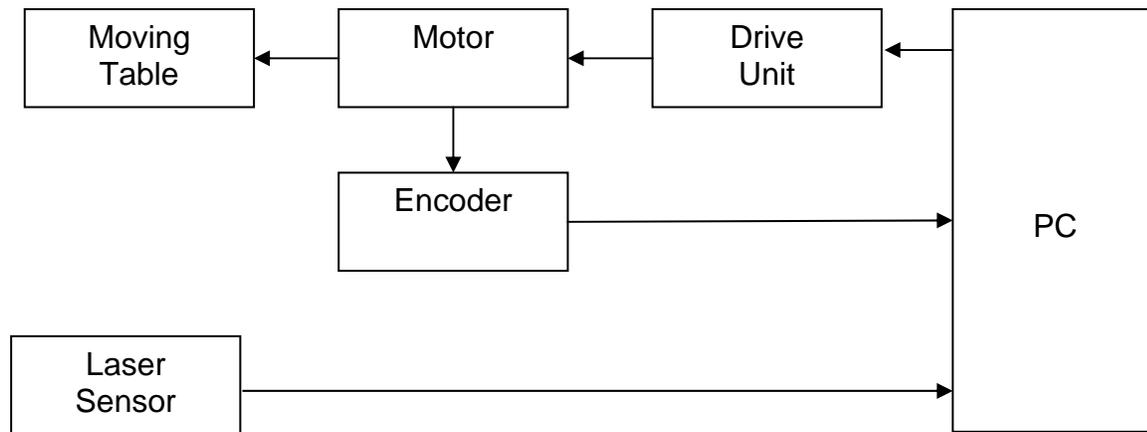


Figure 1: Typical structure of a surface contour measurement system

In this paper, we have designed and implemented an automated measurement system with an improved structure. In the system, a short range sensor is used to measure the surface contour with large peak-to-valley height variation.

Measurement System Structure and Method

The operation of a laser displacement sensor is mainly defined by two parameters: measurement range (or called Depth of Field), R , and standoff distance, L , as shown in Figure 2. The measurement range, R , defines the maximum distance that the sensor can accurately detect, while standoff, L , is the distance from the sensor to the center of the measurement range. In order to measure the surface contour of a component, the sensor must be properly set up so all the target points on the surface are within the sensor's measurement range [10, 11, 15, 17].

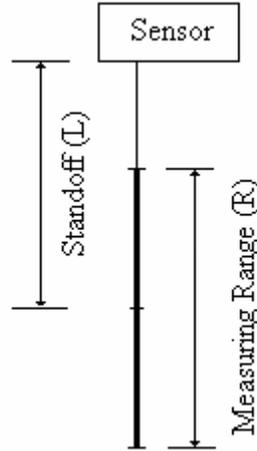


Figure 2: Measurement range and standoff distance of a laser displacement sensor

H. Qiu et al [9] designed an autonomous freeform measurement system on a machining center using a short range laser sensor. In this system, two sensors (laser displacement sensor and linear encoder) are installed on the nut of a ball screw which is attached to spindle axis in the machining center. However, this modification involves high cost in terms of components and time.

As a part of the laser cladding system, our proposed measuring system must be embedded into an existing motion control system by its predesigned input/output (I/O) communication ports. Therefore, our measurement system is designed as a master-slave structure, as shown in Figure 3. In the system, the sensor is installed on the end plate of a Z motion axis in a 3-axis motion system and its position along the Z-direction is dynamically controlled based on available surface geometry information in such a way that the target point being measured on the component surface is always kept within the sensor's measurement range. After a scanning request (such as scanning area) is inputted through the user's interface, the measurement controller (in Master) automatically generates a measuring plan. It includes the sampling points, path and corresponding motion control commands (G-Code). The commands are sent to the motion controller (in Slave) and then to be executed automatically in Slave. The distance, Z , between the sensor and the component is acquired by the sensor at each sampling point.

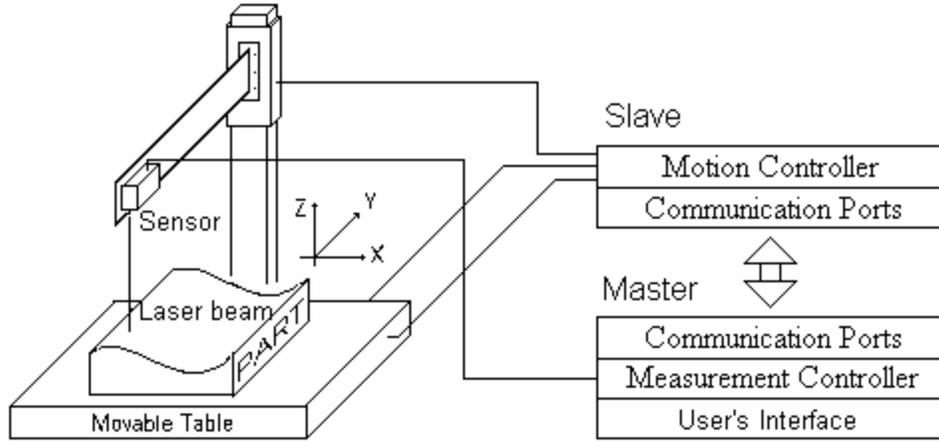


Figure 3: Improved structure of a surface contour measurement system

When using a laser displacement sensor to measure surface contour, the measurement accuracy depends strongly on the resolution of the sensor. Generally speaking, the resolution of a laser displacement sensor is inversely proportional to its measurement range. This poses a challenge to design a high accuracy system for measuring surface contours of components with a wide range of depths. For example, short range sensors can produce higher measurement accuracies. However, they can only be applied for measuring components with relatively shallow features. On the other hand, in order to measure components having deep and steep features, a long measurement range sensor must be used. In such cases, accuracy has to be compromised. It is thus highly desirable to develop a system that does not have restrictions on the maximum measurement depths and at the same time can provide high accuracy.

Suppose that a bounded surface can be represented by the function, $z = f(x, y)$, where $(x, y) \in D$, as shown in Figure 4(A). Within the measurement region, the surface must have at least a maximum, $z_{\max} = \max_D(f(x, y))$, and a minimum, $z_{\min} = \min_D(f(x, y))$. The necessary condition that the measurement can be implemented is defined by

$$R \geq P, \quad \dots \dots (1)$$

Where $R > 0$ is the sensor's measurement range and $P = z_{\max} - z_{\min} \geq 0$ is the maximum of the peak-to-valley height variation within the sampling area.

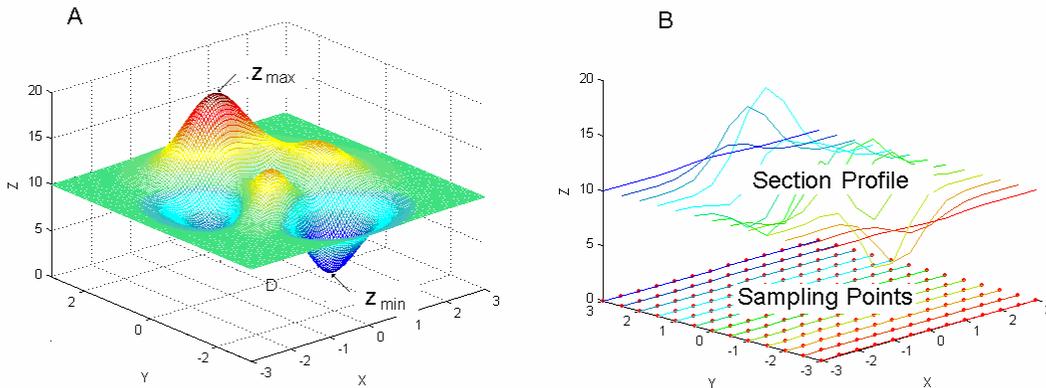


Figure 4: Schematic representation of a component surface for a surface contour measurement

To conduct a contour measurement, the component is mounted on the X-Y table of the motion system. Then, sampling along the X-axis is performed at successive offset values of the Y axis, $y=y_i$ ($i=1,2,\dots,m$) (Figure 4(B)), obtaining a group of 2D curves for sections of the contour along the scanning paths at $y=y_i$.

Comparing to the system described in reference [9], the structure of our system is simplified significantly. The system can be integrated to any existing motion system easily with standard I/O ports.

Surface Contour Tracking

Now, consider the scanning of one contour section profile along the X axis at a given Y offset value, $y=y_i$, as shown in Figure 5. Assume that X coordinates at two adjacent target points on the component surface, A and B, are X_k and X_{k+1} . Z_k denotes the distance from the sensor to the home position of the Z axis of the motion system at point A ($x=X_k$) and is set/controlled by the motion control system. S_k denotes the distance from the sensor to the target point, A, which can be obtained by reading the sensor if the target point is within the sensor's measurement range, $[L-R/2, L+R/2]$. Thus, the height of target point A on the component surface as measured from the motion table surface can be calculated by

$$H_k = M - S_k - Z_k \quad \dots \dots (2)$$

where constant M is the distance from the home of the Z axis of the motion system to the top surface (Reference Zero) of the X-Y motion table. Obviously, if the target point A is in the center of the measuring range, the S_k equals to the constant L , which is an ideal distance between the sensor and the target point for getting best measurement results (Note: L is relevant to the sensor, see Figure 3).

After measuring the height at the point A, the X-Y motion table is shifted along the X direction by a predetermined distance ΔX , so that the sensor will aim at the next target point, B ($x=X_{k+1}=X_k+\Delta X$). The sensor is moved vertically at point B to a new position according to the offset at the previous target point A:

$$Z_{k+1} = Z_k - U_k, \text{ where } U_k = (L - S_k) \quad \dots \dots (3)$$

Assume that the $|S_k - L| \leq R/2$ holds at the target point A. If the $|H_k - H_{k+1}| \leq R/2$, then at the target point B, the $|S_{k+1} - L| \leq R/2$ holds ($k=1,2, \dots, n$). That means as long as at the initial step ($k=1$), the target point is within the measurement range, the all successive steps ($k=2, 3, \dots, n$) are within the range. This will be proved by Equation (5) in next section. The H_{k+1} can be obtained by Equation (2) while $k=k+1$.

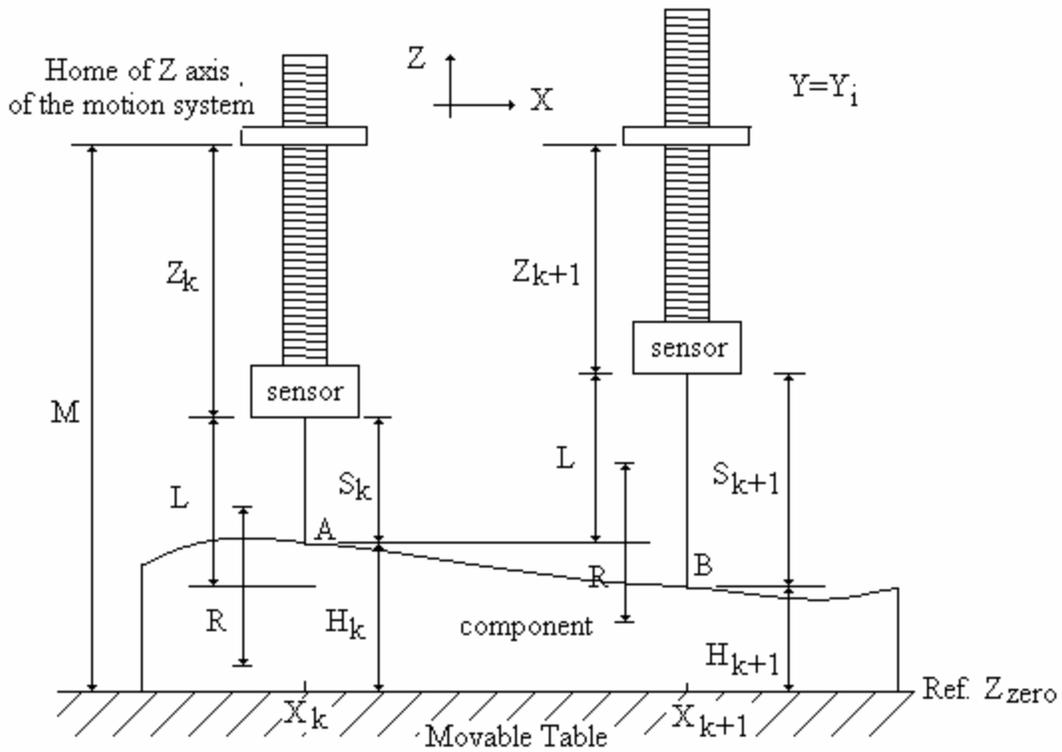


Figure 5: Tracking procedure

Repeating the above procedures, the data sets representing the whole surface contour as measured at all $y=y_i$ planes are obtained:

$$\{(X_k, Y_i, H_{k,i}); k=1,2,\dots,n; i=1,2,\dots,m\}$$

For a typical surface contour measurement system, the measuring error depends on the maximum of component's peak-to-valley height variation because the error increases as the sensor's measuring range increases. In our system described above, the error is independent of the maximum of component's peak-to-valley height variation, which can significantly improve measurement accuracy using high accuracy but short range laser sensors. Meanwhile, all laser sensors also have linearity error, which is regularly about $\pm 0.1\%$ - 1.5% in full scale. The measuring inaccuracy from this error can be minimized if our suggested surface contour track is applied since only a subinterval of the measurement range is used. In addition, our suggested surface contour track tries to keep the measurement point close to center of the measurement range as possible, where the diameter of laser beam spot is much smaller than that in the ends of the span. The smaller the spot is, the higher the resolution of the contour's features. Therefore, tracking the surface contour not only enlarges the measurement range, but also significantly improves the measurement results. Compared to the sensor's error, the mechanical system error can be ignored because the later is much smaller than the former.

Computer Simulation

The effectiveness of the proposed measurement method described above has been demonstrated through many measurement applications in our lab. The following is a brief theoretical analysis on its effectiveness.

From the formula (2), the contour's height difference at points X_{k+1} and X_k is

$$H_{k+1} - H_k = (M - S_{k+1} - Z_{k+1}) - (M - S_k - Z_k) \quad \dots \dots (4)$$

Substitute equation (3) into (4)

$$H_{k+1} - H_k = L - S_{k+1} ; k = 1, 2, \dots, n$$

Therefore

$$|S_{k+1} - L| = |H_{k+1} - H_k| \leq N \quad \dots \dots (5)$$

where $N = \max_{k=2}^n (|H_k - H_{k-1}|)$, the maximum height difference of the contour between two adjacent target points. Obviously, $0 \leq N \leq P$.

At any $k > 1$, the distance from the sensor to the target point on the surface is kept within the interval $[L - N, L + N]$. Hence, the necessary condition for successfully measuring the surface contour using a laser displacement sensor having a measurement range, R , is

$$N \leq R / 2. \quad \dots \dots (6)$$

The Figure 6 shows computer simulation results of the sensor's position during a contour measurement process. The following parameters were assumed in the simulation: sensor's measurement range $R = 100$ mm; the section curve to be measured satisfies the Equation (6); sensor's standoff distance $L = 150$ mm; the distance from Z axis home to the motion table $M = 600$ mm, the initial sensor's position $Z_1 = 225$ mm; the measuring results at all target points are assumed as 175, 150, 100, 150, 200, 150, 100, 100, 100, 100, 200, 200, 200, 200, 150, 150 mm, respectively.

When $k = 2$, $Z_2 = Z_1 - (L - S_1) = 225 - (150 - 175) = 250$ mm, so that sensor moves down (negative) 25 mm ($L - S_1 = 150 - 175 = -25$ mm). The measuring result at second target point is 150 mm in our previous assumption. The height of the target point is $M - Z_2 - S_2 = 600 - 250 - 150 = 200$ mm. Continuing this procedure, the height of all target points can be obtained as 200, 200, 250, 250, 200, 200, 250, 300, 350, 400, 350, 300, 250, 200, 200, 200 mm, respectively. Please note that for this surface profile, the maximum of peak-to-valley height variation is $P = 400 - 200 = 200$ mm, which is outside of the measurement range of the sensor ($R = 100$ mm). Therefore the curve can't be measured using this sensor with the conventional method (without contour tracking).

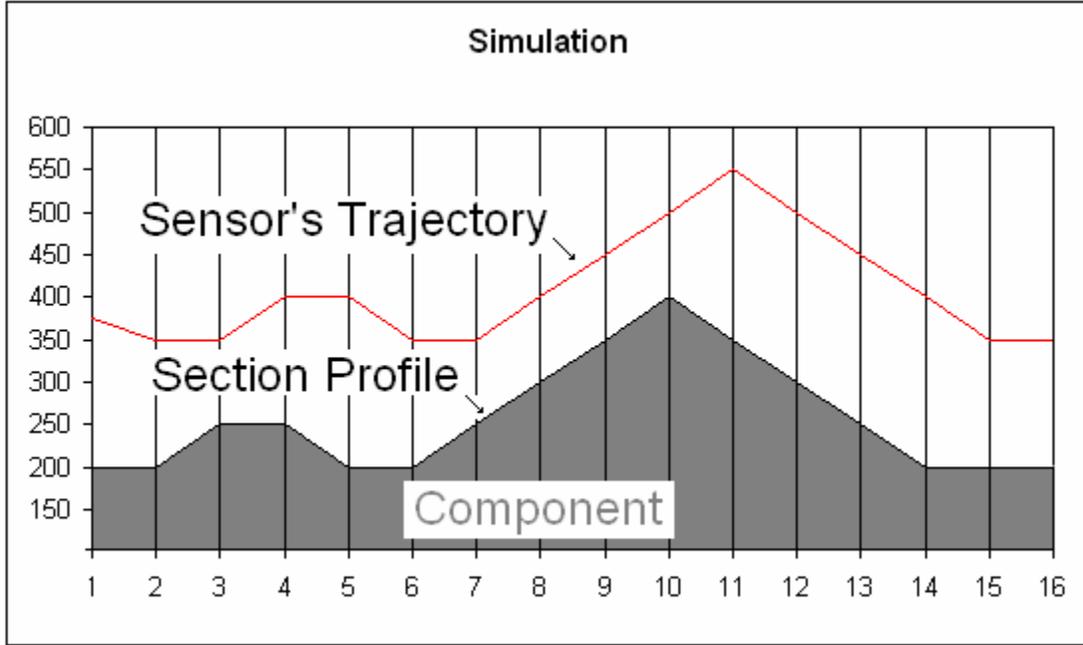


Figure 6: A simulation example showing the effectiveness of the current method.

Comparison of Applicability

As mentioned earlier, for a given surface $z = f(x, y)$, the condition defined by Equation (1) has to be satisfied over the whole region during the measurement when using the conventional method [11]. However, using the method described here, this condition is changed to Equation (6), i.e., the surface contour of a component can be measured as long as the maximum height difference between any two adjacent target points falls within the measurement range of the sensor. The height difference can be reduced by shortening the sampling step length for any continuous surface (almost all engineering surfaces are continuous in practice). This means, there always exists a sampling step length $\Delta X > 0$ at and/or below which Equation (6) is satisfied. Therefore this method is applicable to any continuous surfaces even if Equation (1) is not satisfied over the whole measurement area.

For a bounded discontinuous surface (such as stairs), the N may not be reduced to small enough for the condition in Equation (6) to be satisfied even if the ΔX approaches zero. To analyze such situation, two variables, α and β , are introduced here. Let

$$N = \alpha P \quad \dots \dots (7)$$

and

$$P = \beta R \quad \dots \dots (8)$$

where N , P and R are defined in Equations (6) and (1), respectively. From Equation (7), $0 \leq \alpha \leq 1$ must hold.

For the conventional method, Equation (1) must be satisfied, i.e., $\beta \leq 1$. Therefore, the necessary condition of the conventional method being able to work is $\beta \leq 1$ and $0 \leq \alpha \leq 1$, which is shown by the shaded area in Figure 7 (A).

Substituting Equations (7) and (8) into Equation (6) gives

$$\beta \leq 1/(2\alpha)$$

This is the condition under which our new method is applicable. Therefore, the necessary condition of the new method being able to work is $\beta \leq 1/(2\alpha)$ and $0 \leq \alpha \leq 1$, which is shown by the shaded area in Figure 7 (B).

Comparing Figures 7(A) and 7(B) shows that our proposed new method is applicable in wider ranges of β values than the conventional method. However, in the variables region of $\beta \leq 1, \beta > 1/(2\alpha)$ and $\alpha \leq 1$, the proposed method may not be applicable while the conventional method will be suitable. For example, assuming $\beta = 1$ (that is, $R = P$, the conventional method can work properly), however $N > R/2$ because $\alpha > 1/2$. Under such situations, our proposed method can be converted to the conventional method by simply setting $U_k = 0$, ($k = 1, 2, \dots, n$) (cancelling the tracking function) in Equation (3). Thus, the proposed method is essentially an extension of the conventional method, offering more flexibility and better accuracy for surface contour measurement.

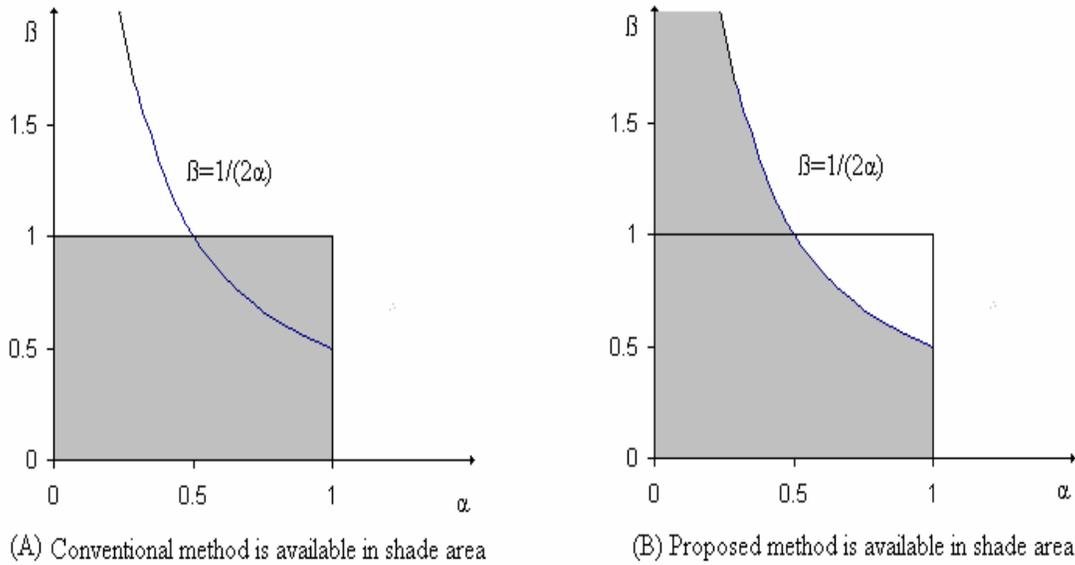


Figure 7: Comparison of applicability of (A) the conventional method and (B) the proposed method for contour measurement of discontinuous surfaces

Conclusions

A new method has been presented for surface contour measurement using a short range laser displacement sensor. The sensor is installed on the Z axis of a 3-axis CNC motion system. During measurement, the position of the sensor along the Z-axis is dynamically adjusted to closely follow the surface contour so that target points on the component surface are kept within the sensor's measurement range. By applying the proposed method, steep surfaces and surfaces having greater overall height difference than the sensor's measurement range can be measured with significantly improved accuracy. This method can also be used to various motion systems, such as a 4 axis (X, Y, Z and C) motion system, to measure a cylinder-like surface.

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