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5-Axis In-line Measurement System for Laser Materials Processing

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Abstract

The dimensional and positional information is very important for laser materials processing of components, especially for laser cladding-based additive manufacturing. Therefore, inspection of the component based on its original CAD model is essential to ensure the component meeting the geometrical requirements. In general, the processed component has to be dismounted from the laser fabrication system before it can be inspected, which is time-consuming and may introduce alignment error from datum.

In this paper, a 5-axis in-line measurement system is introduced, in which a non-contact laser measuring method along with CAD/CAM software is integrated to a laser materials processing system. An algorithm has been developed to automatically generate NC programs for measurement and comparison for outside features. Therefore, the inspection can be performed just after the component has been fabricated on the same system. Comparing to a 3-axis measuring system we reported before, the developed 5-axis in-line measurement system provides much more flexibility, accessibility and accuracy for performing measurement on site. The developed in-line measuring capability can extend the functionality of conventional laser materials processing system and significantly shorten inspection time.

Introduction

Laser cladding is the technology that uses laser beam, which has controlled orientation and focal point, to melt injected powder (or wire) to deposit a solid line or layer at the desired position and motion speed. When repeating this procedure layer by layer, a functional component is able to be built without mold or die. The computer-aided manufacturing process is called Laser Consolidation (LC) [1]. The LC work presented in this paper was conducted using a proprietary LC system developed by NRC-London. The LC process is shown schematically in Figure 1.

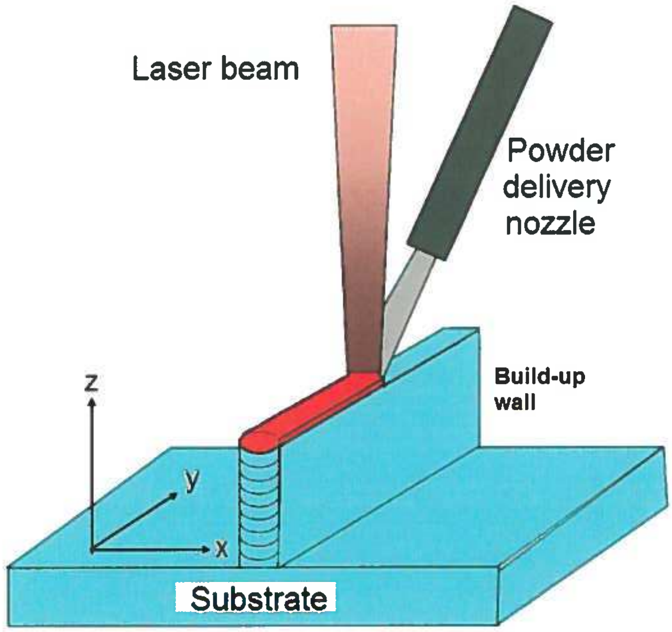


Figure 1: Principle of Laser Consolidation Process

Laser consolidation is composed of a powder feeder, a laser generator and a CNC motion table. LC system provides the flexibility to quickly change the design of the components. As a result, the lead time and cost to produce functional parts could be reduced significantly. Comparing to the conventional machining process, laser consolidation builds complete parts or features on an existing part by adding rather than removing materials. The parts built by the laser deposition process are metallurgically sound, free of porosity or cracks. Research work has been reported by various institutions using laser cladding based free-form fabrication technology on various alloys and steels [1-8]. Although the technology has a great potential for many industrial applications, concerns about the dimensional accuracy have been raised [9].

Dimensional inspection is the only methodology to know the actual dimension of the part. There are a lot of measuring tools for various geometries. Coordinate Measuring Machine (CMM) is the major measuring tool for free-form surface [10]. The typical CMM is composed of a touch probe and three axes, X, Y and Z, which are orthogonal to each other. Each axis has a scale system that indicates the location of the axis. The CMM will read the coordinates when the trigger signal from the touch probe is received. The machine then uses the (X Y Z) coordinates of each of these points to calculate size. Besides touch probe, a kind of optical probe, laser non-contact probes, has been integrated into CMMs [11]. The non-touch probe uses the principle of triangulation: A spot light from emitter is projected onto the work target; a portion of the light reflected by the target is collected through the lens by the detector. The distance from the sensor to the target is computed depending on the position of the beam on the detector by the electronic processor. Generally speaking, the former is more accurate, the latter is faster [12].

Typically, to inspect a part using a CMM, the part has to be uninstalled from the machine that it is fabricated, installed and aligned on the CMM. This procedure is time-consuming. We develop a low-cost measuring modular that can be attached to an existing 5-axis laser consolidation system so that the LC system can be used as a "CMM". Comparing to a 3-axis measuring system we reported before [13], the 5-axis in-line measurement system provides much more flexibility, accessibility and accuracy for performing measurement on site. This portable modular can be integrated into any CNC motion system through the RS232 port and M function channels when needed. The structure proposed system is much simpler than that mentioned in [14]. The benefits of this modular are: (1) to simplify the procedure of inspection. (2) to shorten the time of measurement. (3) to eliminate the error of coordinate systems.

Steps of building a part using Laser Consolidation

To build a functional part by LC system, there are following main steps related to the geometry:

(1) Design of shape: Usually a CAD model of the part is provided by clients. Otherwise the CAD model must be designed by us.
(2) Design of tool path: Look for the feasible tool path considering the characteristic of a LC system.
(3) Generation of NC program: Convert desired tool path into motion system (NC) program.
(4) Inspection of dimension and position: Check the geometry quality of the part.

Obviously, if the part is fail in inspection, the modification/compensation in geometry is the simplest solution. The geometry modification could correct the positional errors and the geometry compensation could improve the dimensional accuracy. The method of successive approximations is shown in Figure 2. The loop breaks until all errors are within tolerances.

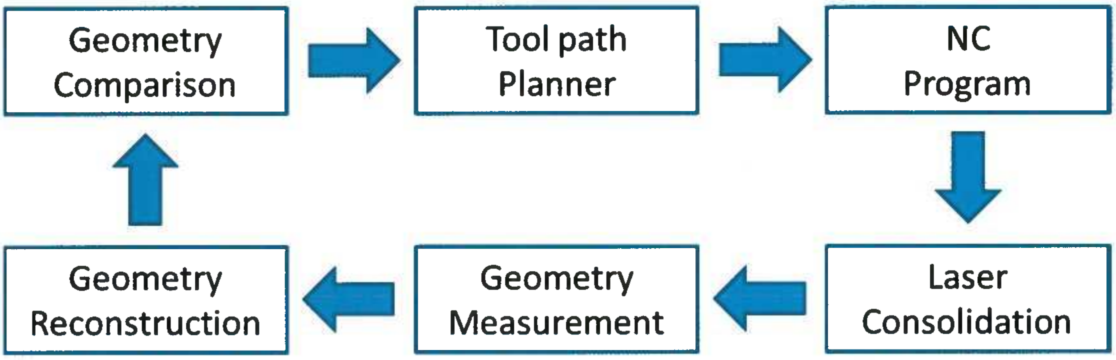


Figure 2: Iteration of Geometrical Error Control

To do so, an in-line measuring modular (system) is one of the options. The system must have the following two features: (1) Share motion table with LC system. It helps to reduce cost of inspection and to eliminate error from different coordinates systems. (2) Can be integrated into various LC motion control systems. It helps to increase the usage of this modular.

Measuring System Structure

An in-line measuring system is composed of a probe, motion table and measuring controller. There are two kinds of probes: mechanical touch probe and optical non-contact probe (laser sensor). Touch probes have high accuracy (with a resolution of less than 1 μm) but have low data acquiring rate. The 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 sensors). Among the non-contact sensors, laser displacement sensors have the advantages of low cost and high accuracy. Proposed system shares the motion table with laser consolidation system. Usually, the motion table for laser consolidation is designed as a 5-axis tilt-rotary table. A laser processing head and laser sensor are installed on the Z axis. Both aim down to the table vertically. There are a large number of benefits that 5-axis machining can bring to the laser consolidation. The rotary axis can be used for "revolved" geometry such as a cylinder to minimize radial error. The tilt axis can be used for building a side features without re-position or re-fixture. A 5-axis motion table provides the ability to build complex parts that are not otherwise possible. The 5-axis motion table can also provide benefits to the measuring system: (1) Measuring a surface along with its normal will receive a minimized measuring error. (2) Measure some features that only can be measured under 5-axis table. For example, a cylinder can be built using only a 3-axis table. However, to measure its roundness and height, a 5-axis table has to be used. Our 5-axis measuring system is shown in Figure 3.

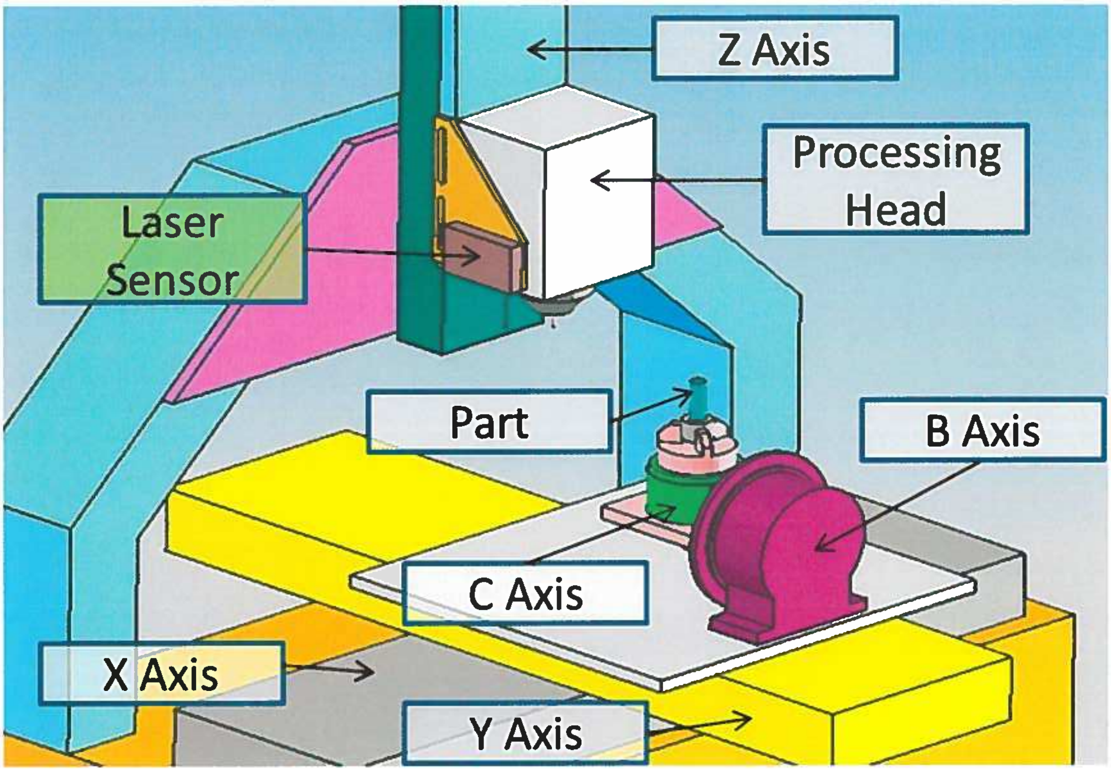


Figure 3: Integrated 5-axis Laser Consolidation System

Measuring controller plays a key role during inspection. It not only controls each axis' motion including position and speed but also acquires and processes data. A master-slave structure is design for the measuring system as shown in Figure 4. This structure has a clear boundary between motion controller and measuring controller. The measuring controller does not need to "break-in" the motion controller such as reading axis' encoders. Measuring controller (Master) generates G-code and M-code commands based on the requirements of measurement (measuring plan). The motion controller in an existing laser consolidation system runs on a "Slave" mode. In other words, the motion controller does only three things: listen, action and report. The "listen" means monitoring I/O port to get a command. The "action" means that motion controller executes the received command so that the motion table will move to desired position. The "report" means sending a feedback to Master when the "action" is finished. The digital I/O channels are used to communicate each other. The measuring controller is also in charge of acquiring the data from sensor, filtering measuring noise and transforming the data into a standard format.

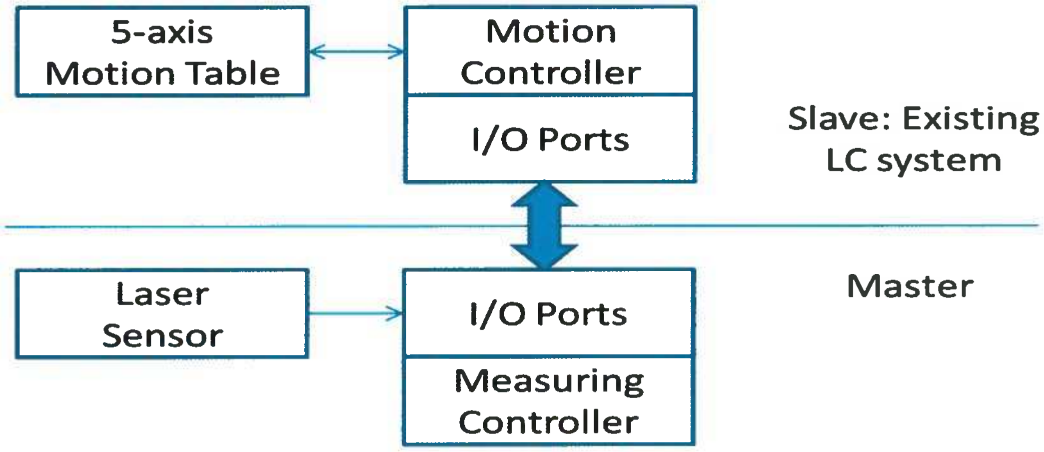


Figure 4: Master-Slave structure of measuring system

Kinematic chain of motion system

The 5-axis motion system usually has 3 translation axes and 2 rotation axes. It can be treated as a kinematic chain from work piece to tool no matter the setting up of the 5 axes [15]. The chain of our system in Figure 3 is shown in Figure 5.

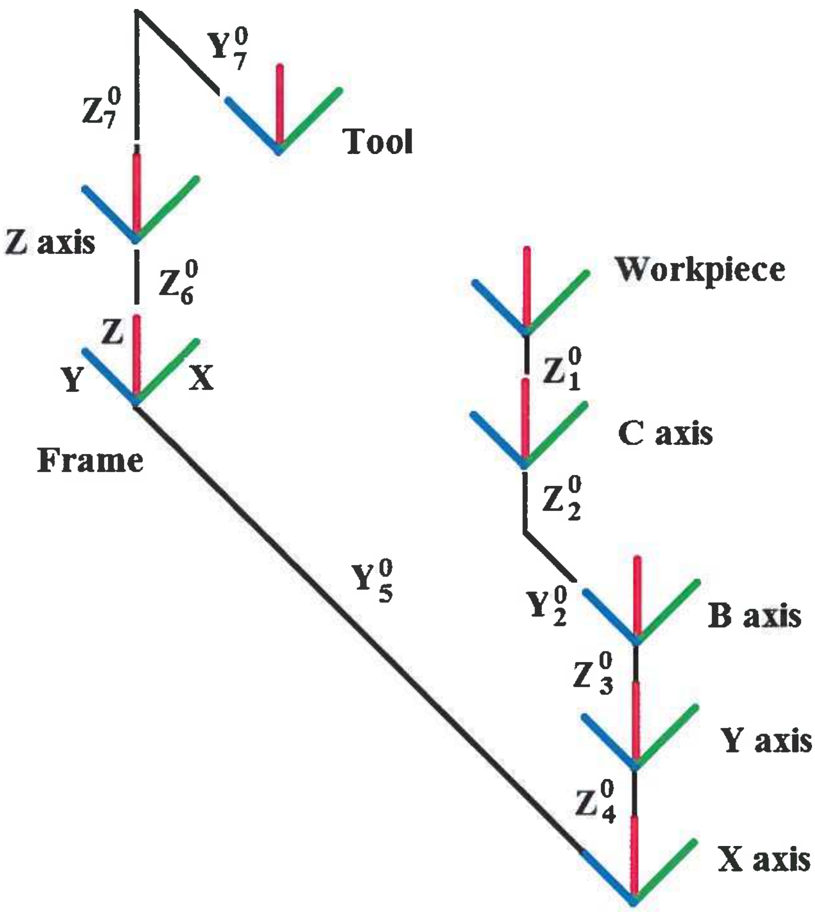


Figure 5: Kinematic Chain of a 5-axis Motion System

In mathematics, any transformation (translation or rotation) between two coordinate systems could be represented by a 4×4 homogenous transformation matrix, T. In homogeneous coordinates, the concatenation of transformations can be carried out with matrix multiplications, which is still a homogenous transformation matrix. For example, the transformation matrices in Figure 5 are:

- The transformation matrix from the C axis coordinate system to the Workpiecs coordinate system:

$$T_1 = \begin{bmatrix} \cos C & \sin C & 0 & 0 \\ -\sin C & \cos C & 0 & 0 \\ 0 & 0 & 1 & -Z_1^0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where C is the angle of C axis. Rotation of a positive angle is defined to be counter clockwise around the positive direction of the C axis.

- The transformation matrix from the B axis coordinate system to the C axis coordinate system:

$$T_2 = \begin{bmatrix} \cos B & 0 & -\sin B & 0 \\ 0 & 1 & 0 & -Y_2^0 \\ \sin B & 0 & \cos B & -Z_2^0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where B is the angle of B axis. Rotation of a positive angle is defined to be counter clockwise around the positive direction of the B axis.

- The transformation matrix from the Y axis coordinate system to the B axis coordinate system:

$$T_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -Y \\ 0 & 0 & 1 & -Z_3^0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where Y is the position from Y axis origin. A positive offset is defined to be the positive direction of the Y axis.

- The transformation matrix from the X axis coordinate system to the Y axis coordinate system:

$$T_4 = \begin{bmatrix} 1 & 0 & 0 & -X \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -Z_4^0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where X is the position from X axis origin. A positive offset is defined to be the positive direction of the X axis.

- The transformation matrix from the machine frame coordinate system to the X axis coordinate system:

$$T_5 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -Y_5^0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- The transformation matrix from the Z axis coordinate system to the machine frame coordinate system.

$$T_6 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & Z + Z_6^0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where Z is the position from Z axis origin. A positive offset is defined to be the positive direction of the Z axis.

- The transformation matrix from the Z axis coordinate system to the tool coordinate system:

$$T_7 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -Y_7^0 \\ 0 & 0 & 1 & -Z_7^0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation matrix from workpiece coordinate system to tool coordinate system is:

$$T = T_1 * T_2 * T_3 * T_4 * T_5 * T_6 * T_7$$

$$= \begin{bmatrix} \cos C \cos B & \sin C & -\cos C \sin B & M_{14} \\ -\sin C \cos B & \cos C & \sin C \sin B & M_{24} \\ \sin B & 0 & \cos B & M_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots\ldots(1)$$

where

$M_{14} = -X \cos C \cos B + (-Y - Y_7^0 + Y_5^0 - Y_2^0) \sin C - (Z + Z_7^0 + Z_6^0 - Z_4^0 - Z_3^0) \cos C \sin B$

$M_{24} = X \sin C \cos B + (-Y - Y_7^0 + Y_5^0 - Y_2^0) \cos C - (Z + Z_7^0 + Z_6^0 - Z_4^0 - Z_3^0) \sin C \sin B$

$M_{34} = -X \sin B + (Z + Z_7^0 + Z_6^0 - Z_4^0 - Z_3^0) cosB - Z_2^0 - Z_1^0$

Assuming that the origins and directions of the tool coordinate system and the workpiece coordinate system are overlapped (that is, T = identity matrix) at the initial state (X=0, Y=0, Z=0, B=0, C=0) of the kinematic chain, then:

$$\begin{cases} Y_2^0 + Y_7^0 = Y_5^0 \\ Z_1^0 + Z_2^0 + Z_3^0 + Z_4^0 = Z_6^0 + Z_7^0 \end{cases} \quad \ldots\ldots(2)$$

Substituting (2) into (1), then T=

$$\begin{bmatrix} \cos C \cos B & \sin C & -\cos C \sin B & -X \cos C \cos B - Y \sin C - (Z + Z_1^0 + Z_2^0) \cos C \sin B \\ -\sin C \cos B & \cos C & \sin C \sin B & X \sin C \cos B - Y \cos C + (Z + Z_1^0 + Z_2^0) \sin C \sin B \\ \sin B & 0 & \cos B & -X \sin B + (Z + Z_1^0 + Z_2^0) cosB - (Z_2^0 + Z_1^0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Considering that X, Y and Z in Equation (3) are the length of "links" in the kinematic chain, they are constants. Assume X=0, Y=0 and Z=0 without loss of generality, then

$$T = \begin{bmatrix} \cos C \cos B & \sin C & -\cos C \sin B & (Z_1^0 + Z_2^0) \cos C \sin B \\ -\sin C \cos B & \cos C & \sin C \sin B & (Z_1^0 + Z_2^0) \sin C \sin B \\ \sin B & 0 & \cos B & (Z_1^0 + Z_2^0) cosB - (Z_2^0 + Z_1^0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots\ldots(4)$$

Assuming the workpiece coordinate system is fixed, any point $\begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix}$ in the tool coordinate system can be transformed to the workpiece coordinate system by:

$$\begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} = \begin{bmatrix} \cos C \cos B & \sin C & -\cos C \sin B & (Z_1^0 + Z_2^0) \cos C \sin B \\ -\sin C \cos B & \cos C & \sin C \sin B & (Z_1^0 + Z_2^0) \sin C \sin B \\ \sin B & 0 & \cos B & (Z_1^0 + Z_2^0) cosB - (Z_2^0 + Z_1^0) \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x_t \\ y_t \\ z_t \\ 1 \end{bmatrix} \quad \ldots\ldots(5)$$

Equation (5) could be used to map the measuring results into the workpiece coordinate system for geometry reconstruction.

The sampling position, denoted by the vector $[x_t \quad y_t \quad z_m \quad B \quad C]$ in measuring plan, can be obtained from the inverse kinematics or from commercial CAM software. The laser sensor is setup as a tool. The center point of the measuring range of the sensor is setup as zero point of output and the origin of tool coordinate system. At each sampling point, the actual height at the sampling point is $z_m = z_t - r$, where r is the reading from the sensor.

Case Study: Fabrication and measurement of cold spray nozzles

A 500 W or 1 kW Lasag Nd:YAG laser coupled to a fiber-optic processing head was used for the experiments. The laser was operated in a pulsed mode with an average power ranging from 20 to 300W. A SULZER-METCO 9MP powder feeder was used to simultaneously deliver metallic powder into the molten pool through a proprietary nozzle with the powder feed rate ranging from 1 to 30 g/min. The laser beam and the powder feed nozzle are moved following a predesigned laser path that is generated directly from a computer aided design (CAD) model, creating a bead of molten material on the substrate, which solidifies rapidly to form the first layer. The traveling velocity is ranging from 2 to 10 mm/s depending on the material deposited and component geometry. The second layer is deposited on the top of the first layer. By repeating this process, a solid thin walled structure is built. A 5 axis computer numerical control (CNC) motion system was used for the laser consolidation work, while processing was conducted in a glove box, in which the oxygen content was maintained below 50 ppm during the process [16].

Cold spray is a solid-state coating process in which small solid particles are accelerated and deposited onto a surface by impinging. Currently, the most commonly used cold spray nozzle has a round shape in the cross-section. Round nozzles are easy for manufacturing, but the thickness of a single-track coating is not uniform. Another type of commonly used cold spray nozzle has a rectangular cross-section. To improve the cross-section thickness uniformity of single-track cold spray coatings, the new nozzle is designed and manufactured shown as in Figure 6.

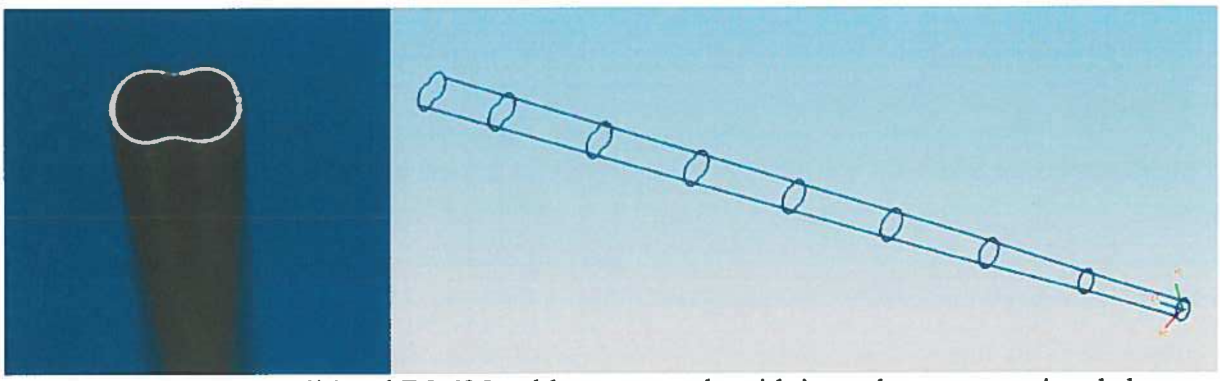


Figure 6: Laser-consolidated IN-625 cold spray nozzle with irregular cross sectional shapes

To get best spray result, the nozzle has stringent dimension tolerance. However, the cross-section of the nozzle is irregular shape (non-circle and non-square) and varies to nozzle's elevation. It is impossible to be measured precisely using traditional measuring tool such as a caliper.

The integrated 5 axis laser consolidation system is used to build and measure these nozzles. To conduct the measurement, the following steps are taken:

- Create measuring plan using CAD software at CAD/CAM work station. This plan includes the position of sampling points, laser beam's orientation at sampling points shown in Figure 7.

- Generate measuring input-data file using CAM software: based on the setup of motion system, convert the measuing plan into a text file.
- Transfer the file to measuring controller.
- Load and run measuring programs which read from the input-data file and send G-code commands to motion controller.
- The motion controller executes the commands and meanwhile the sensor acquiring the "distance" between the sensor and the target point.
- Transform the raw data into workpiece coordinate system using Equation (5).
- Save measuring results as a output-data file.
- Transfer the output-data file back to CAD/CAM station.
- Reconstrctruct and compare to its original CAD model. The results reconstructed in CAD are shown in Figure 8.

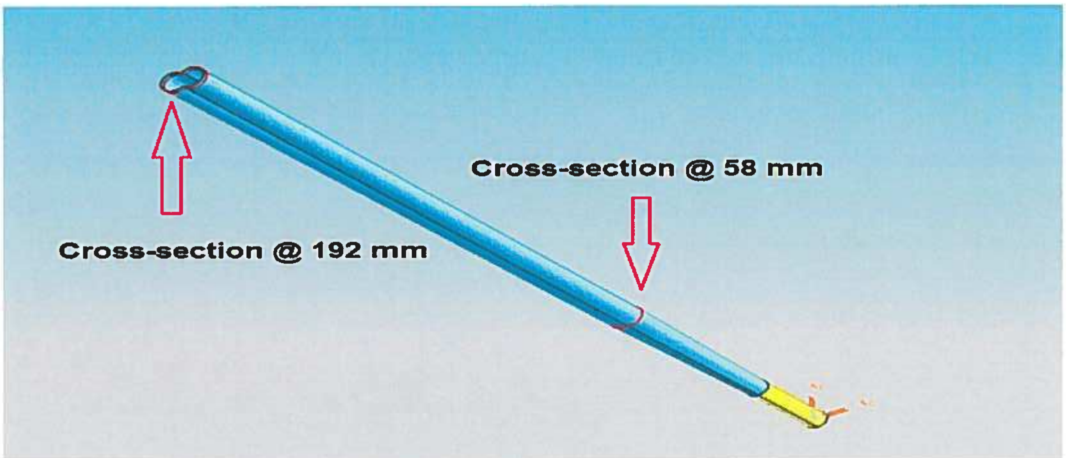
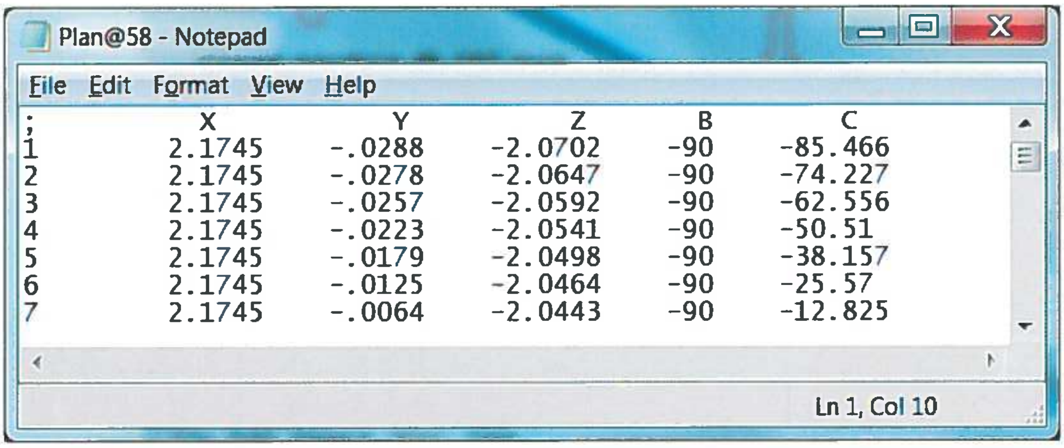


Figure 7a: Measuring plan of the nozzle (CAD)



Plan@58 - Notepad

File Edit Format View Help

;	X	Y	Z	B	C
1	2.1745	-.0288	-2.0702	-90	-85.466
2	2.1745	-.0278	-2.0647	-90	-74.227
3	2.1745	-.0257	-2.0592	-90	-62.556
4	2.1745	-.0223	-2.0541	-90	-50.51
5	2.1745	-.0179	-2.0498	-90	-38.157
6	2.1745	-.0125	-2.0464	-90	-25.57
7	2.1745	-.0064	-2.0443	-90	-12.825

Ln 1, Col 10

Figure 7b: Measuring plan of the nozzle (position & orientation)

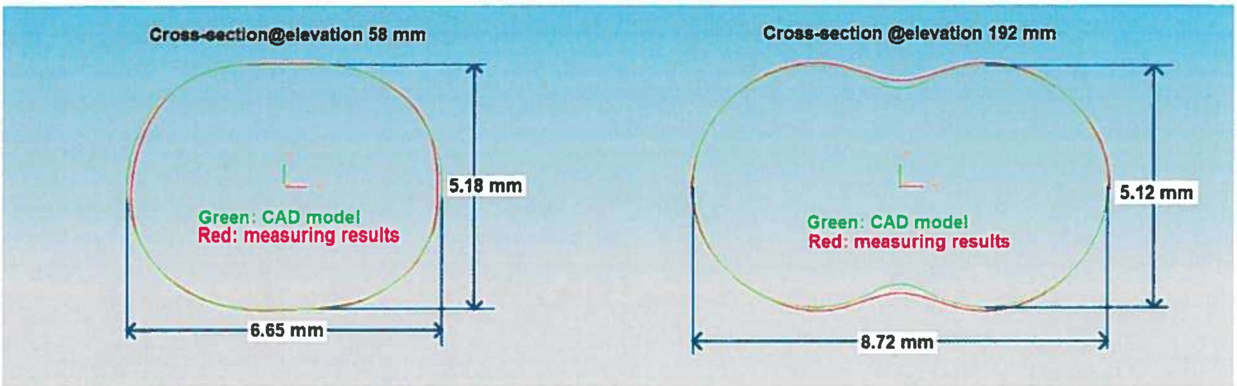


Figure 8: Comparison of the measuring results and its original CAD model

Conclusions

Obviously, without changing setup of a part, A 5 axis motion system could provide the 5 measurable-sides (top, left, right, front and back) but 3-axis system provides only one side (top). Proposed 5 axis integrated in-line measurement system is able to save the leading time of measurement and eliminate the errors between the fabrication coordinate system and measurement coordinate system. The measurement system extends the functions of laser consolidation system with high cost-efficiency. This system has been successfully used in our projects for dimension compensation and repair of parts.

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