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Development of Integrated Automatic System of Laser Cladding for Repairing of Polycrystalline Diamond Compact Bits

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Abstract: In order to improve the automatic level for laser-cladding repair of high value industrial equipment, such as polycrystalline diamond compact bit (PDC bit) applied in oil industry, a universal scheme of integrated automatic system for repairing is proposed in this paper, and the basic functional modules together with the executing order according to which each module runs are defined. There are two main technical points, i.e.,inspection and repairing, that need to be realized for such integrated automatic system. Therefore, according to the proposed scheme and the existing instruments, a dual-robot system, which includes two KUKA industrial robots, is adopted as the technological implementation, where one robot is used to carry a 3D scanner to reconstruct the PDC bit to realize inspection while the other is used to hold the laser to melt the special powder flowing to the damaged region of the bit to complete cladding. To realize automatic running of the whole integrated system, a hand-eye calibration method, namely three-point calibration, is then proposed, by which coordinates of point cloud of the damaged PDC bit detected by 3D scanner can be transformed to those of the coordinate system of the robot with the laser, so that the cladding path planned via cutting slice of the damaged region of the PDC bit in the upper computer software, the key of the integrated system developed by QT programming tool, can be tracked by laser head and then the damaged part of the PDC bit can be repaired. Finally, a laser-cladding experiment for repairing PDC bit is carried out and the feasibility of the proposed scheme of the integrated automatic system and the effectiveness of the dual-robot system implemented via KUKA robots are verified, According to existing literature, no papers about such integrated system for automatic laser cladding repair have been published.

Keywords: laser cladding; dual-robot system; 3D reconstruction; integrated automatic system

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1. Introduction

With the rapid developments of technology, more and more advanced equipment is applied in the modern manufacturing industry, and they significantly improve the production efficiency and product performance, as well as reduce the labor intensity of workers. As one of the most advanced repair technologies, laser-cladding technology [1] has been widely used in manufacturing industry in the last 20 years, with more than tens of thousands of research papers published in fields of intelligent manufacturing and materials sciences. Its most important application is to repair high-value equipment, which can greatly save cost compared to buying another brand new, and, at the same time, the repaired work piece has at least the same performance to the original. Therefore, laser-cladding technology can be used in repairing the hard facing of turbine blade [2–8], forging die [9–11], as well as in various material processing industries for complex curved surface generating [12–15], and repairs of rail-surface scratch [16], artificial joints in medical treatment [17], broken gears [18], and worn sprockets [19].

PDC bit, which is regarded as one of the products of the new technologies in the oil industry in the 1980s, have a huge cost and is often injured by erosion, chemical corrosion and other factors in the complex and harsh working environment, as shown in Figure 1.

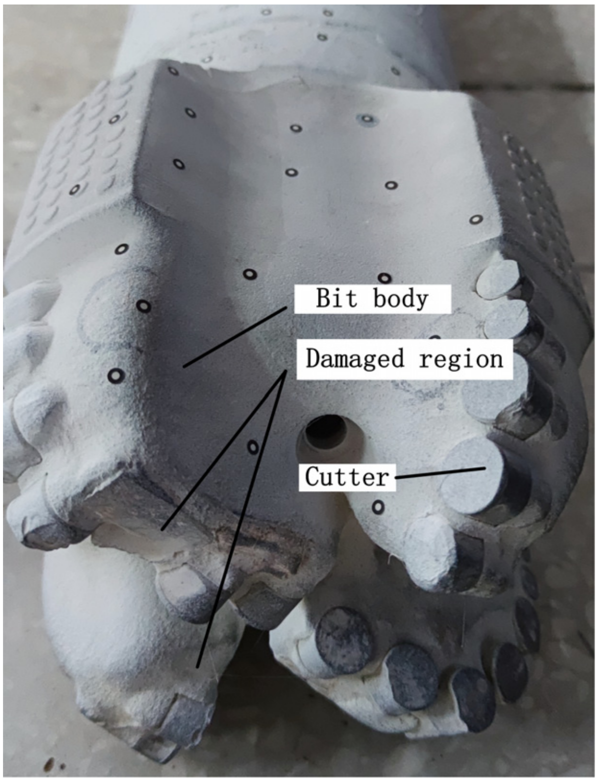


Figure 1. The PDC bit with some injuries.

The repair of PDC bit by laser cladding is more advantageous than that by traditional surface repairing technologies, such as arc welding, because the laser beam can heat the substrate of the bit and melt the coating powder flowing to the damaged region of the bit at the same time so that the powder and the substrate of the bit complete metallurgical bonding and the cladding coating is finally formed on the surface of the substrate, whereas the arc welding will cause the temperature of the local area of the bit to be too high, resulting in stress and affecting the service life of the bit, since the combination of there-welded hardened layer and the old one is not strong enough. Compared with microstructure layers repaired by other surface treatment methods, the one repaired by laser cladding is much denser, the residual stress is much lower, the chemical composition is more uniform, and the overall performance of the cladding layer is much better. Furthermore, accurate control of energy and quality can be achieved by laser cladding, with lesser heat-affected zones and lower coating dilution left on the substrate, and the coated layer would greatly improve the hardness, wear resistance and corrosion resistance of the substrate. The only disadvantage of laser-cladding repair is that its automation level is not as good as welding, in that laser cladding is a relatively new technology.

Although the introduction of new equipment has lifted the level of repairing technology, it has also brought out an outstanding problem, i.e., how to integrate these devices together to accomplish a specific task. For instance, with the development of industrial robot, the carrier for laser has been changed from CNC machine [20] to robot [12]. Even so, in order to safeguard their own commercial interests, robot manufactures refuse to provide the basic registers of the robots to ordinary customers. Therefore, there is not a united communication protocol or function interface for developing such an integrated automatic system, because different brands of robots have different hardware structures. In [3], the KUKA robot is used to carry the laser, in [5] the ABB robot is used, and in [9] the FUNAC robot is used, which means such integrated automatic system is difficult to realize by using a different robot.

It is unrealistic to develop a set of upper computer software suitable for all robots. Therefore, a general integrated framework for a laser-cladding repair robot system is proposed, which points out the basic modules and the key functions that need to be realized. In this paper, KUKA robots are applied to realize such framework for repairing PDC bits, which is an implementation of the proposed scheme. In such scheme, there are two main modules to be developed for laser-cladding repair: one module, i.e., inspection, is to detect the injured PDC bit to obtain the location information and geometric information of its damaged parts; the other is to carry laser to repair the damaged regions. On inspection, with the development of optical technology, non-contact measuring instruments such as structural light 3D scanner [5–8,19], stereo vision sensor [9,21], and 3D laser vision [12,16,20,22], become the first choice. Then, the 3D point cloud of the damaged parts of the bit can be obtained by using such non-contact measurement, with a file in STL (stereolithography) format [2] being exported in most cases. One can compare the exported STL file, which approximates the real scanned damaged part, with the standard one of the same part to obtain the damaged region that needs repairing by simple collection operation [5,7,16,18,19,21]. For repairing modules, there are also two tasks that need to be carried out. Firstly, the location of the damaged parts of the PDC bit in world coordinate system is necessary, without which failure would occur because one cannot transport the alloy powder used for cladding repair to the right position. The coordinate information of the damaged part of the PDC bit can be obtained through the "eyes" of the integrated system, i.e., the 3D scanner, and a key technology, namely, hand-eye calibration, is touched on, by which the coordinates of the damaged parts of the bit captured by the scanner can be transformed to that used in the coordinate system of robot. There is also several papers regarding hand-eye calibration, which suggest many methods for obtaining intrinsic and external parameters of cameras [23–25], and the latest trend is to use fewer reference objects or reference points while driving the camera to make the motion certain to realize calibration [26–29]. In the scheme, a simple method similar to three-point hand-eye calibration is proposed. Secondly, the path for industrial robot is planned, so that the robot can hold the laser to clad the powder into the whole damaged area of the PDC bit. Zheng [3,23] studies the path planning for laser cladding on complex spatial surface, in which he optimizes the model parameters affecting the model error according to the PSO method; however, he obtains the STL data directly from the CAD model without locating the damaged parts. Similarly, Liu [13] obtains the optimal cladding path of complex surface by adjusting the distance between adjacent section points, also without the locating step. Li [17] plans a path for laser cladding on artificial joint surface through the arch height error method, without locating. Liu [12] uses a 3D laser scanner to inspect an entire spatial curved surface and obtains the path for laser cladding via slicing method according to the STL file, without locating. In order to express the curved surface accurately, Wang [14] exports NURBS surface from point cloud data inspected by 3D scanner and then obtains the optimal path by the arch height error method, without locating.

Finally, upper software, the key to the integrated automatic system, is developed by a QT programming tool and then deployed in desktop computer. Thanks to such software, the KUKA-dual-robot system can be integrated together with the laser-cladding system and 3D scanning system. It also realizes two main modules, i.e., inspection and repairing, defined by the proposed scheme. The best benefit of this work is that a feasible scheme to build up an integrated automatic platform for a laser-cladding system can be used as reference, by which a custom-made platform or additional functions according to his or her own tasks can be realized without being limited by commercial software [10,11,18].This automatic system can be extended to laser-cladding repair for turbine, rail, and other objects, while it is necessary to add guide rails to move the robots and enhance processing capacity of point cloud data registration for the scanner, as the operating range increases.

According to the existing literatures on laser cladding, most of them are related to material science, whereas a few relate to automation-related issues and mainly focus on path planning for 3D printing of surfaces. Although the pictures in their articles show that various robots are used, the interaction between the inspection system, robot system and upper computer program, and hand-eye calibration, which is the sign to realize automatic laser-cladding repair, is not mentioned. Therefore, this article is mainly about integrating these systems to realize automatic repair by dual-robot system and show all necessary links.

The remaining sections are arranged as follows: the scheme of integrated automatic system and their main modules and functions is described in detail in Section 2; the specific implementation of each module of the scheme is then shown in Section 3; in Section 4, a repairing experiment of the damaged PDC bit is demonstrated; and Section 5 is the conclusion.

2. Scheme of Integrated Automatic System for Laser-Cladding Repair

This section starts from the abstract conceptual design, and then expands to the concrete physical realization.

2.1. Damage Analysis for Equipment That Needs Repairing

The first work is to assess the injured degree of the equipment to be repaired, as the criterion for damaged equipment is whether it can be repaired and whether the profit from repairing is more than the cost. From the long-term experience in PDC bit repairing, the injured degrees of the equipment can be roughly divided into four types: compact wear, slight body wear, severe body wear and scrap. In addition, the performance of the damaged equipment with compact wear or slight body wear can recover well after repairing with low cost, while the cost of the equipment with severe body wear is high, and the scrapped one cannot be repaired at all. Fortunately for the bit-repairing profession, most of the wears belong to the former two, which means that the repair work of bits has great economic and social benefits.

2.2. The Scheme and Its Construction

As shown in Figure 2, a simple scheme of an integrated automatic system about laser-cladding repair, which has nothing to do with concrete hardware implementation, is provided. Then, in next subsection, the existing equipment is assembled as a complete integrated system according to the blueprint.

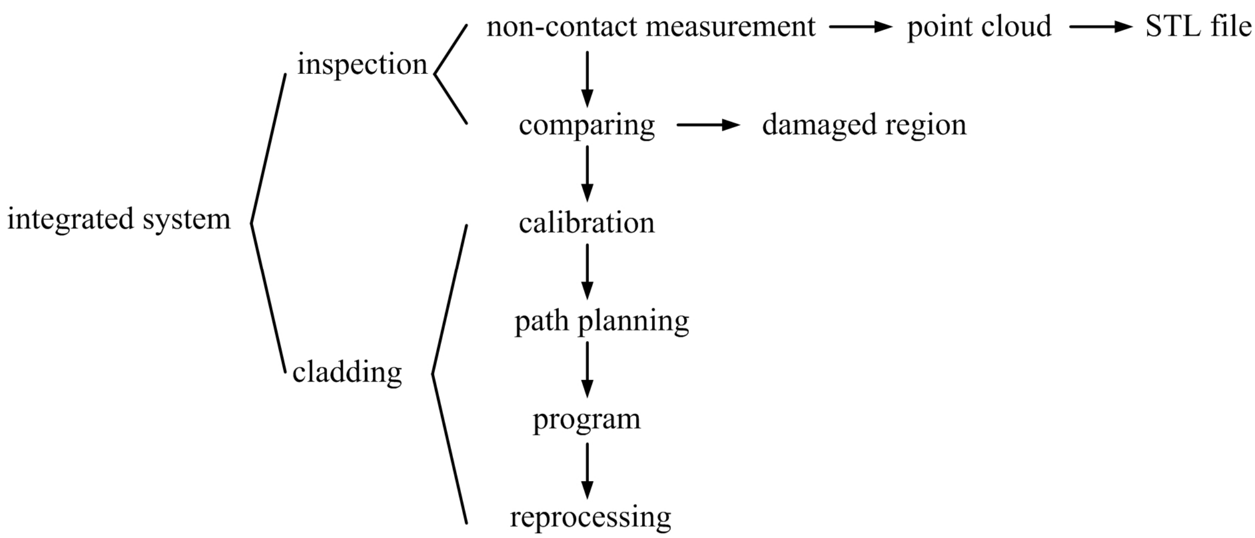


Figure 2. A scheme of a laser-cladding integrated automatic system.

Figure 2 demonstrates that the whole integrated automatic system mainly contains two modules: inspection and cladding. The inspecting process, which is used to obtain the location information and geometric information, should be fulfilled before cladding. On inspection, there are also two main function modules that need to be realized, that is measurement and comparing. For measurement, optical non-contact measurement such as structural light 3D scanner is popular. The 3D point cloud data of the PDC bit to be repaired is then captured by the 3D scanner and transformed into a file in STL format, which approaches the contour of the object. Then, on comparing module, the transformed STL file should be compared with the intact one provided by manufacturer, with damaged regions of the equipment obtained. On cladding, there are four main function modules that need to be realized: calibration, path planning, program, and reprocessing. Calibration, which transforms the coordinates in the 3D scanner frame to those in the robot frame, is very important for repair because the robot must know the location and geometric information of the damaged parts of the equipment. This is quite different from 3D printing, as the designed object in 3D printing can be printed no matter where it is located. Path planning provides the robot an entire trajectory to hold the laser to traverse the damaged areas, and the general repair region of the damaged PDC bit is always blocky, so that the planned path is generally a broken line, which is quite different from the literature regarding surface repair. For the program module, the nodes of the planned path need to be transmitted to the robot in order, i.e., forming the program's positional variables of the robot. Finally, the extra materials need to be removed after repairing, as indicated by the reprocessing module.

2.3. An Implementation of the Proposed Scheme

As shown in Figure 3, an implementation of the scheme is proposed based on the existing equipment and technology accumulation, which just provide a plane layout because there is so much equipment that their relationships cannot be described clearly all in one photo. Then, a view of the whole platform is demonstrated in Figure 4, with some important devices be found.

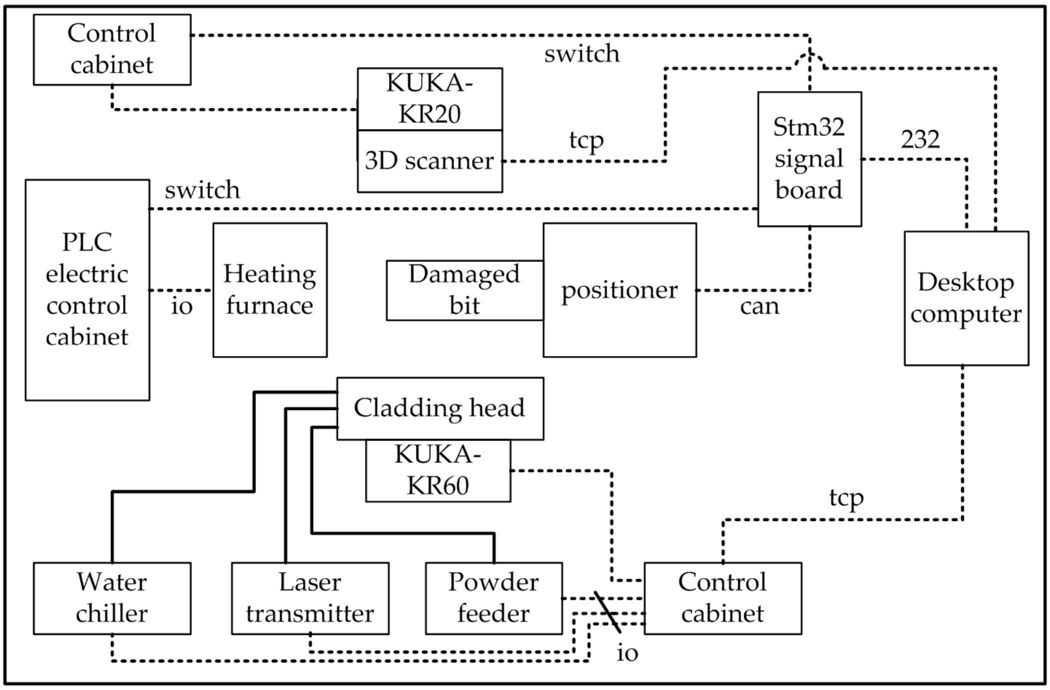


Figure 3. An implementation of an integrated automatic system about laser-cladding repair according to the scheme.

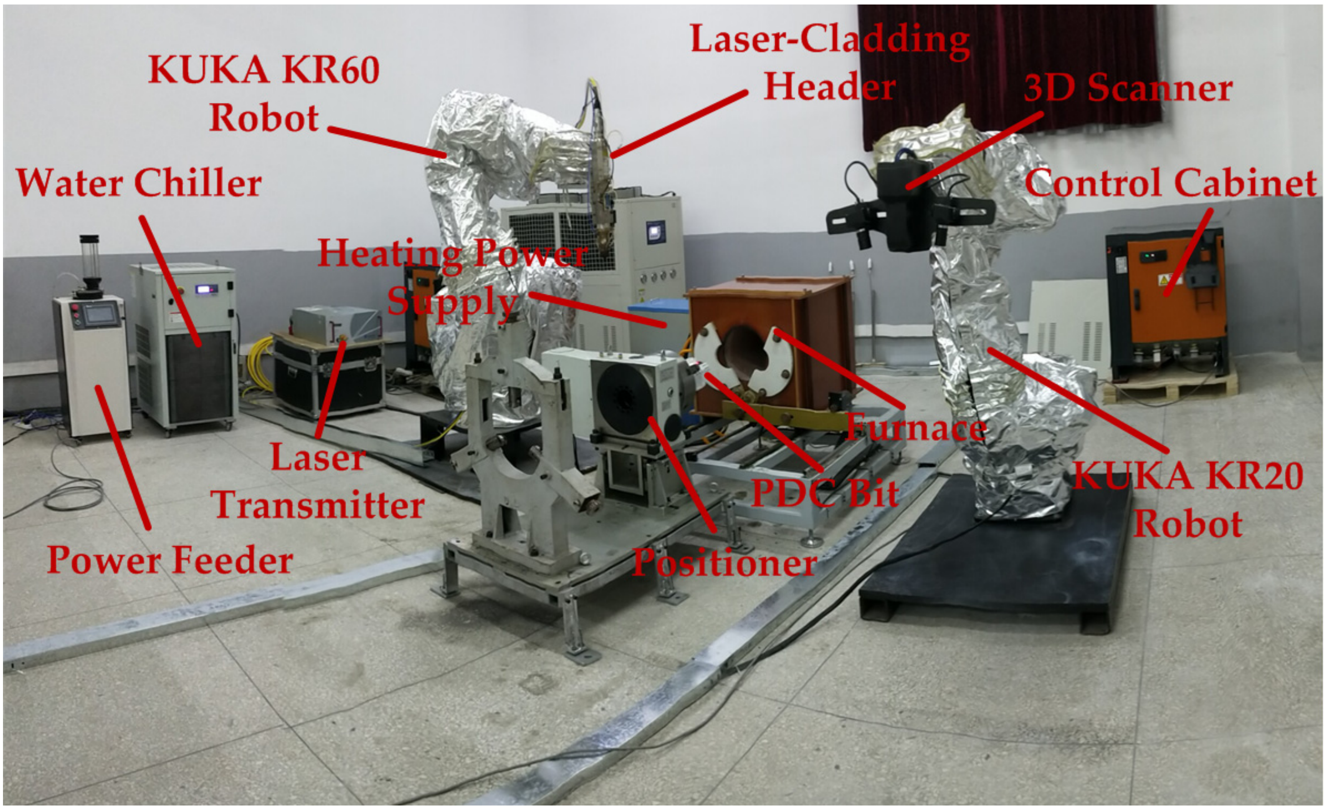


Figure 4. Main equipment of the experimental platform.

It can be seen in Figure 3 that the platform can be divided into four parts by relevancy: i.e.,KUKA-KR20 robot with 3D scanner (abbreviated as KR20), KUKA-KR60 robot with laser (abbreviated as KR60), positioner and heating furnace (abbreviated as positioner), and desktop computer. Dotted lines between devices are used to indicate the transmissions of signals as well as solid ones indicate those of matter or energy.

In the KR20 subsystem, a blue-ray 3D scanner designed by TECHLEGO is fixed on the end link of the robot (shown in Figure 4), the using of which the point cloud data of the damaged bit can be obtained. The scanner has an accuracy of 0.005 mm, a capture time of less than 0.3 s, and a blue light as the light source to avoid interference of the ambient light effectively.Starting or stopping is determined by a switch value sending to/from the control cabinet of the robot (shown in Figure 3). The measurement module, as well as its subsequent modules, i.e., point cloud module and STL file module, of the inspection module (shown in Figure 2) is realized in the KR20 subsystem.

KR60 subsystem consists of a KUKA-KR60 industrial robot, coaxial powder feeding cladding header, powder feeder, semiconductor laser transmitter, and industrial water chiller (shown in Figure 4). LDM4000-100 laser(a semiconductor laser produced by Laser-line), which belongs to diode laser, is selected as the core of the cladding system. It has a long service life, stable performance, an energy utilization rate that can reach more than 40%, and the laser gate that can be opened and closed by IO port of KUKA-KR60 robot (shown in Figure 3). In order to avoid the high temperature under which the laser cladding cannot work normally, a special water chiller for laser transmitter is equipped, with a stable cooling water of which the temperature can be adjusted accurately while being supplied. At the same time, it can also provide cooling water with suitable temperature for the cladding header. It is important that the powder feeding rate that is determined by the feeding equipment is uniform, and can be precisely set up by the digital display control system, with a range of 0–25 g/min. Furthermore, the control signal, including cladding path, from desktop computer to the control cabinet of KUKA-KR60 robot is transmitted through Ethernet based on TCP protocol (shown in Figure 3). Meanwhile, the other devices of KR60 subsystem, such as powder feeder, laser transmitter, and water chiller, are controlled by IO outputs of the control cabinet of KUKA-KR60 robot through the ordinary conductor (shown in Figure 3). The calibration, path planning, and program of the cladding (shown in Figure 2) are acting on the KR60 subsystem while the data come from desktop computer subsystem.

The positioner and heating furnace (shown in Figure 4) are mainly in the positioner subsystem. CNC vertical rotary dividing head is used in positioner subsystem, and the clamping device holding the damaged PDC bit is driven to rotate by CNC servo motor, which can be cooperated with the KR20 subsystem to realize a better camera scanning for the damaged region of the bit. Medium-frequency power is used to provide energy for the heating furnace, in which the bit is heated to exceed 700 °C and then taken out before laser cladding starts. If the temperature of the carcass of the bit is lower than 600 °C, the repairing process is terminated, and the bit is reheated by furnace to exceed 700 °C again. The servo controller of the positioner can be driven based on the CAN bus, and the heating furnace with medium-frequency heating power supply is controlled by IO ports of the PLC from the PLC electronic control cabinet, and the PLC is controlled by the switch values from the desktop computer. The positioner subsystem is just an auxiliary unit to construct the inspection module as shown in Figure 2.

The desktop computer subsystem, including a personal computer and a signal board developed by STM32 chip, is the control center of the whole platform. The signal board obtains the command from the computer through a serial port based on RS232 protocol, and then sends instructions to KR20 subsystem, PLC control cabinet, and positioner accordingly (shown in Figure 3). The personal computer receives the point cloud data from the scanner through the USB3.0 interface, and sends data to, as well as receives data from, the KR60 subsystem through Ethernet based on TCP protocol (shown in Figure 3). The comparing module, as well as its subsequent damaged region module, of the inspection module (shown in Figure 2) is realized here. The data of the cladding module (shown in Figure 2) sending to or receiving from other subsystems are mainly generated in the desktop computer subsystem, and the upper computer software is developed by QT programming tool.

The main repairing process according to the scheme in Figure 2 and the implementation in Figure 3 can be described as follows:

(a) Measurement: Desktop computer starts the whole process by sending commands via STM32 signal board to KUKA-KR20 robot, and the robot drives the scanner to several positions in turn to capture the bit in multiple views.
(b) Comparing: Different point cloud set obtained by scanner from different perspectives is uploaded to desktop computer, and the image processing software provided by TECHLEGO can be used to organize the whole point cloud sets into the final one to complete a PDC bit by matching the same feature points of the bit among different sets. Compared to the final point cloud of the PDC bit with the standard one by point cloud processing software, i.e., Geometric Studio, the damaged region of the bit that needs repairing can be obtained.
(c) Calibration: The key to hand-eye calibration lies in establishing the transformation matrix from scanner coordinate frame to robot coordinate frame. The most direct way is to let the scanner and robot detect the same points in the space, obtain the coordinates under their coordinate systems respectively, and then calculate the transformation matrix between the two coordinate frames, which is the basic principle of three-point calibration method proposed in this paper.
(d) Path planning: Using transformation matrix that is obtained in advance in (c), the three-dimensional coordinate of any point in the damaged region of the bit that obtained in (b) in scanner coordinate system can be transformed into that in the coordinate system of KUKA-KR60 robot. Then, a fold line with width property can be planned to cover the whole damaged region of the bit in the robot coordinate system.
(e) Program: Finally, the desktop computer sends each endpoint of the fold line in turn as the repair-path to the KUKA-KR60 robot via TCP protocol, as well as operating

command for powder feeder, laser transmitter, and water chiller. Then, the robot drives the cladding header to complete repair by traversing the planned path.

(f) Reprocessing: After cladding, there will be redundant materials left on the wound surface, and they can be removed by machining. In Figure 3, the proposed implementation does not contain machining equipment, and such a module can be completed independently in other factories.

2.4. The Interface of Upper Computer Software

As shown in Figure 5, an integrated automatic system is developed by QT programming tool.

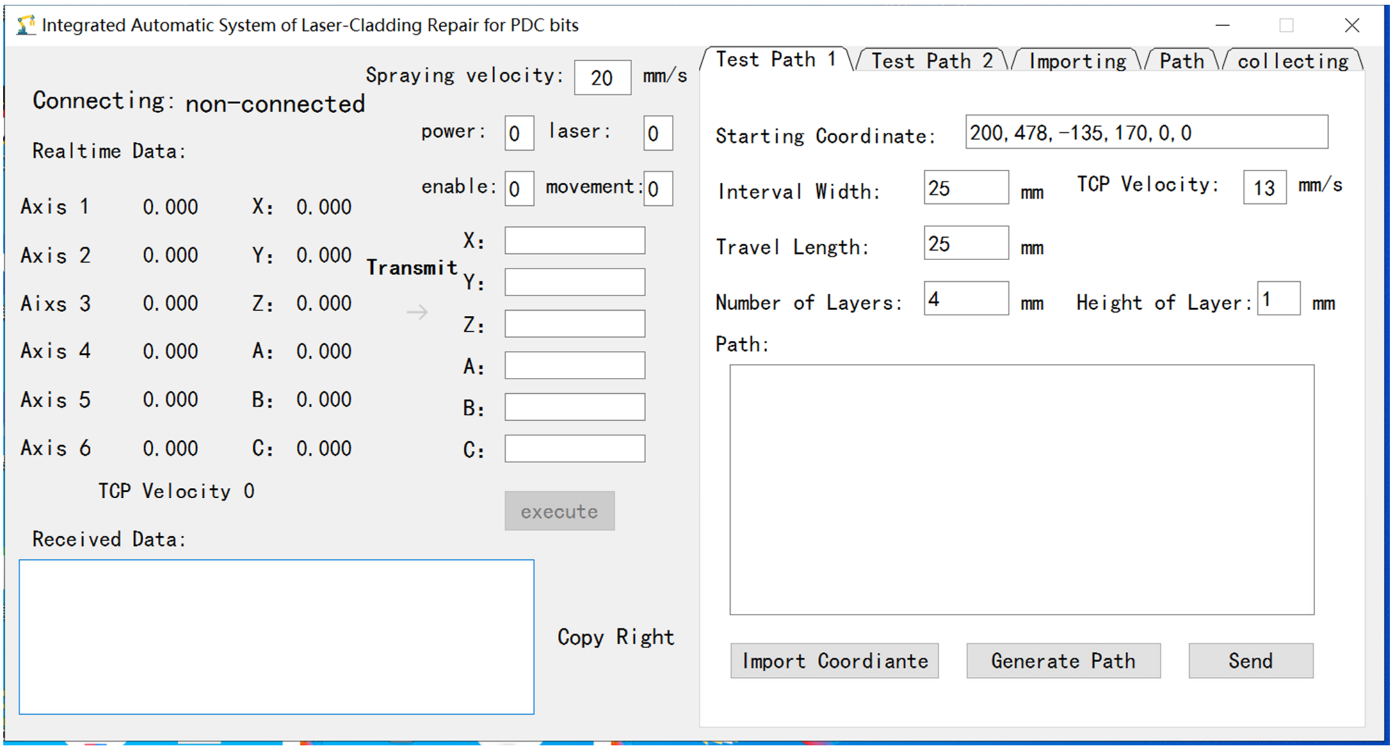


Figure 5. An upper computer software of integrated automatic system developed by QT programming tool.

Such software is running in a desktop computer, and its interface can be divided into left and right parts as shown in Figure 5. The left part shows the basic status of KUKA-KR60 robot, as well as that of laser header. The right part takes Table Widget module of QT programming tool, with one interface shared by five tables and only the activated table displayed on the interface. There are two groups of data under label "Real Time Data": one group, which is marked as "Axis 1", "Axis 2", "Axis 3", "Axis 4", "Axis 5", and "Axis 6", represents the coordinates in joint coordinate frame of KUKA-KR60 robot, the other group, marked as "X", "Y", "Z", "A", "B", and "C", represents the coordinates in the workspace coordinate frame of KUKA-KR60 robot. These data are uploaded to such software in real time from the KUKA-KR60 robot via Ethernet protocol. On the right side of label "Transmit", there are also same labels "X", "Y", "Z", "A", "B", and "C", of which the function is to transmit the values typed in the vacancy from desktop computer to KUKA-KR60 robot to test robot to move to the specify position. Table "Test Path 1" that tests straight line path, is used to obtain the optimal process parameters, i.e., laser power, powder feeding rate, and moving velocity of laser-cladding header, as shown in Figure 6a and Table 1."Test Path 2" is used to test Program module shown in Figure 2, i.e., to test transmissions of the planned path for KUKA-KR60 robot before robot can carry the laser header to clad the corresponding curves, as shown in Figure 6b.

(**a**) (**b**)

Figure 6. Simple path test experiments of laser cladding: (**a**) Straight line path test to obtain the optimal process parameters; (**b**) Curve path test to test the program module.

Table 1. The optimal process parameters of laser-cladding repair in such project.

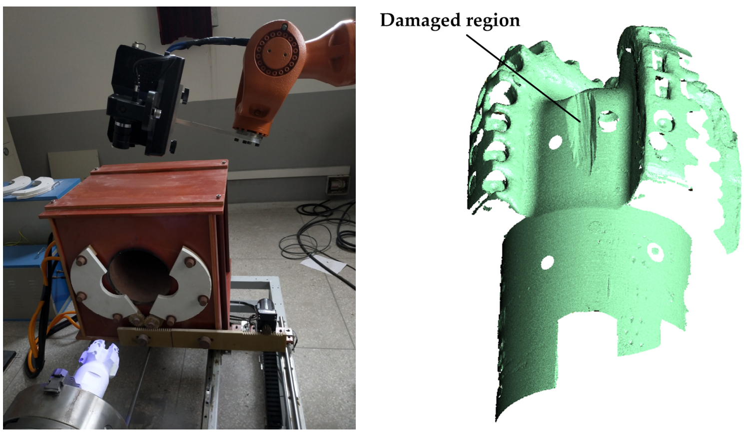
Laser Power	Powder Feeding Rate	Movement Velocity of Laser Header	With of Path	Height of Path
2.2 kW	5 g/min	20 mm/s	2 mm	1 mm

From an engineering perspective, these two test tables of the software can be carried out in advance.

3. Specific Realization of Each Functional Module of the Scheme

3.1. Non-Contact Measurement and Damaged Regions Identified by Comparing

As seen in Figure 2, module Measurement and module Comparing constitute the whole inspecting system. Measurement is carried out by 3D scanner (as shown in Figure 7a), and the process can be regarded as a kind of three-dimensional reconstruction, based on which the point cloud of injured PDC bit can be captured by the binocular camera of the scanner. Then, the point cloud data is transmitted from scanner to desktop computer via USB3.0 protocol. The corresponding software that is provided by scanner manufacturer receives all the data, and then saves them as the file in STL format, which can be processed by Geometric Studio, as shown in Figure 7b.



(**a**) (**b**)

Figure 7. Inspecting by 3D scanner and its processing of data: (**a**) An injured PDC bit captured by 3D scanner; (**b**) The point cloud data that are uploaded to upper computer and processed by Geometric Studio.

Compared the point cloud of damaged bit with that of standard one provided by bit manufacturer, the point cloud of the damaged regions of the bit can be obtained by Boolean subtraction operated in Geometric Studio (shown in Figure 8) and can be saved in the file in STL format at final, which is just the aim of Comparing module.

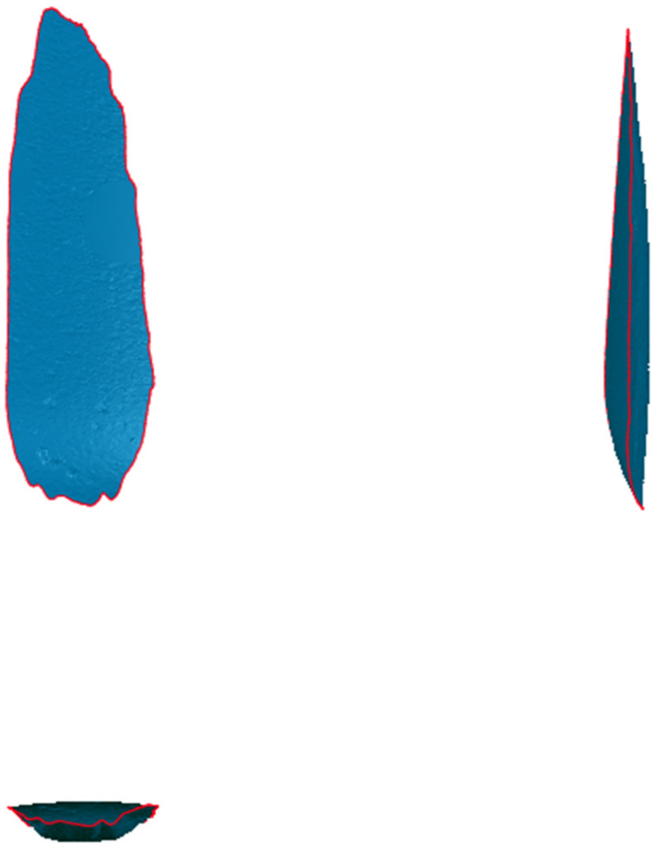


Figure 8. Three views of the damaged region of the PDC bit processed in Geometric Studio (the red lines are boundaries generated automatically).

3.2. Hand-Eye Calibration via Three-Point Method

The geometric information of the damaged region obtained as in Figure 8 cannot be used for laser-cladding repair directly, because the coordinate of each point on the body, such as in Figure 8, is expressed in the scanner coordinate system rather than in the KUKA-KR60 robot coordinate system on which the laser header is fixed. Therefore, the mapping relationship between the two coordinate systems should firstly be obtained, and the coordinates of the points in scanner coordinate system can be then transformed to those in the KUKA-KR60 robot coordinate system, which is also the aim of the calibration module. In the proposed implementation, the commercial 3D scanner is used to help determining the mapping relationship of coordinates between the same points in space.

As shown in Figure 9, the three points not on a line are arranged at first, and then the tip of the laser header is selected as the tool center point of the KUKA-KR60 robot. Finally, the robot is operated to move the tool center point onto each point to obtain the three-dimensional coordinate by reading the teaching device of the KUKA-KR60 robot. The three points can be also captured by the scanner, and the three-dimensional coordinate of each point can be finally obtained by processing software.

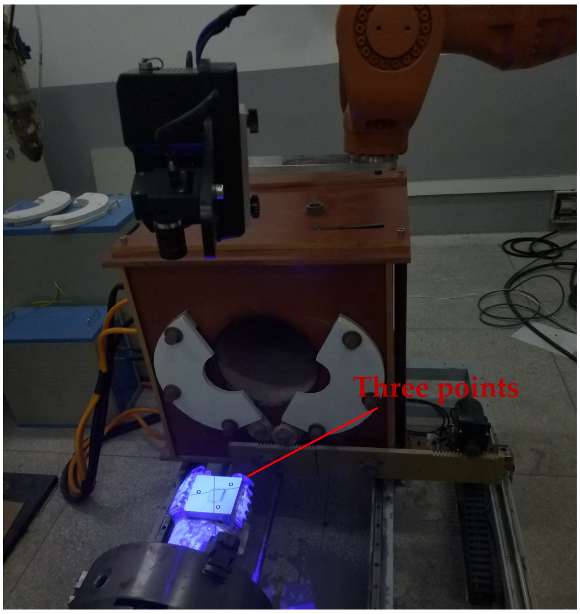


Figure 9. Hand-eye calibration for laser-cladding repair system by three-point method.

If the coordinate of each point that captured by scanner is recorded as x_{ci} (where i = 1, 2, 3) and which is shown on the KUKA-KR60 robot's teaching box is y_{ri} (where i = 1, 2, 3), then the transformation relationship between two coordinate systems can be determined by

$$\begin{bmatrix} y_{ri} \\ 1 \end{bmatrix} = \boldsymbol{H} \begin{bmatrix} x_{ci} \\ 1 \end{bmatrix},\ i\ =\ (1,2,3) \tag{1}$$

where $\boldsymbol{H} \in \mathbb{R}^{4\times4}$ means homogeneous transformation matrix and is easy to be solvedby combining the three Equation (1) with the induced one, that is:

$$\begin{bmatrix} y_{r1} & y_{r2} & y_{r3} & y_{r1} + (y_{r2} - y_{r1}) \times (y_{r3} - y_{r1}) \\ 1 & 1 & 1 & 1 \end{bmatrix} = \boldsymbol{H} \begin{bmatrix} x_{c1} & x_{c2} & x_{c3} & x_{r1} + (x_{r2} - x_{r1}) \times (x_{r3} - x_{r1}) \\ 1 & 1 & 1 & 1 \end{bmatrix} \tag{2}$$

where "×" denotes the cross product of the two vectors, and y_{r1} + (y_{r2} — y_{r1}) × (y_{r3} — y_{r1}) and x_{r1} + (x_{r2} — x_{r1}) × (x_{r3} — x_{r1}) mean the coordinates expressed in two coordinate systems from the same point, which is induced by three points. As shown in Figure 10, the induced point is obtained by computing the cross product of the three points rather than linear combination, so each matrix in Equation (2) is nonsingular, and the homogeneous transformation matrix $\boldsymbol{H}$ can be calculated.

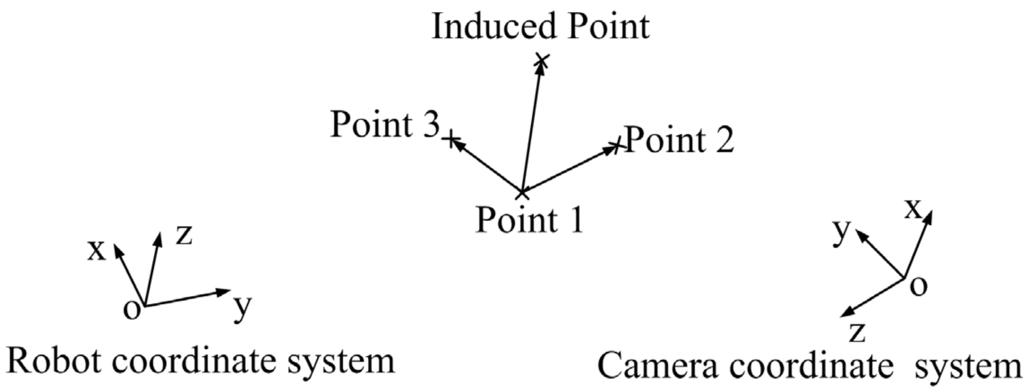


Figure 10. The induced point in the three-point method.

In the proposed implementation, the transformation matrix is finally obtained as

$$H = \begin{bmatrix} 0.1018 & 0.9680 & -0.2295 & 245.8351 \\ 0.9723 & -0.0480 & 0.2289 & 334.3406 \\ 0.2106 & -0.2464 & -0.9460 & 383.4096 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

3.3. Path Planning for Repair and Program Generating for KUKA-KR60 Robot

After data processing in Geometric Studio, the damaged body of the bit can be obtained(shown in Figure 8), which is lastly saved in STL format file, with coordinates of the points all expressed in the scanner coordinate system. As shown in Figure 5, the STL file is then loaded into the integrated software by using table "Importing", and the matrix obtained by the proposed hand-eye calibration method can be used to transform coordinates of the points of the damaged body in the scanner coordinate system into those in the KUKA-KR60 robot coordinate system, within which the planned path can be executed by the KUKA-KR60 robot.

The cladding path, or the path of the tool center point of the KUKA-KR60 robot, can be planned within the damaged body of the bit in the robot coordinate system and such a task is carried out in table "Path" in the integrated software in Figure 5. In order to explain the whole path planning process, a diagram is drawn as Figure 11. First, the damaged body can be cut with a set of parallel planes, of which the height between any adjacent two is equal to the height of the cladding alloy, and then in each plane a group of parallel line segments can be planned with the same width to the cladding alloy to fill up the whole area within the boundary.

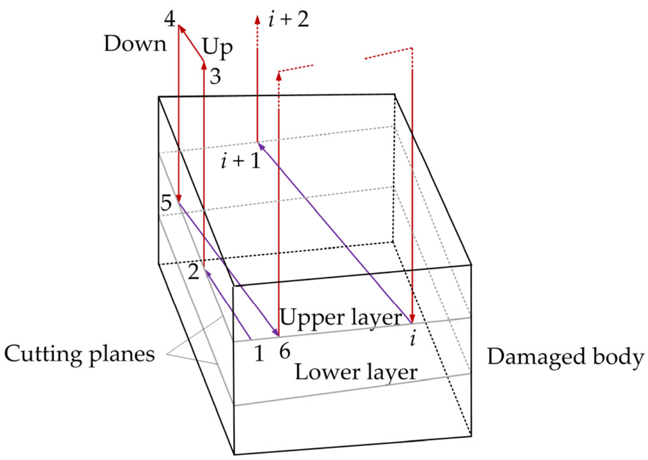


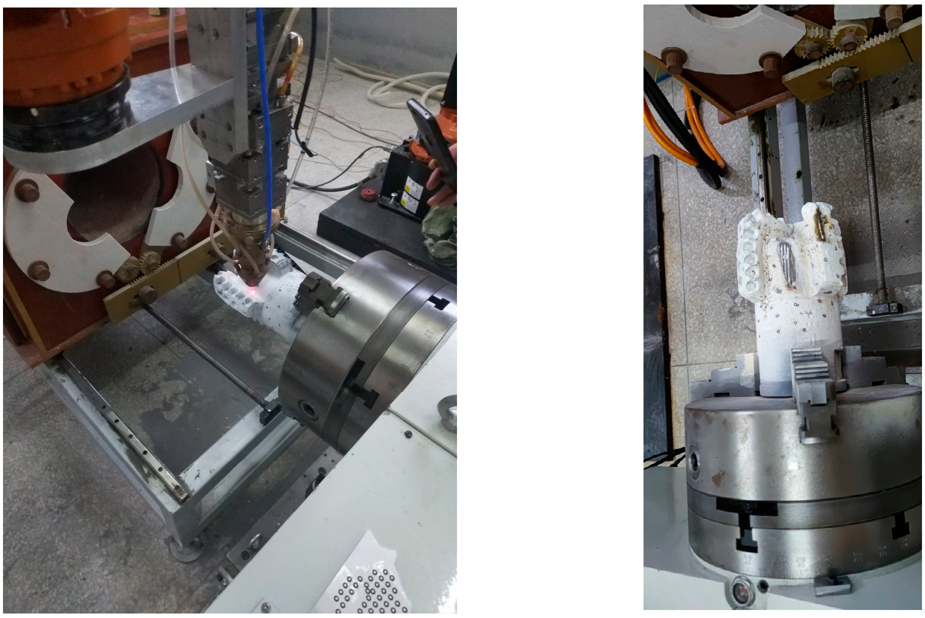
Figure 11. Path planning for repairing the damaged region of PDC bit.

As seen in Figure 11, parallel line segments can be used to fill up the whole area of the layer, such as the segments from intersection point 1 to 2, from 5 to 6, and so on, and the cladding header must lift up at the end of each line segment and move over to the top of the start point of the next line segment and then fall down, such as the path from intersection point 2 to 3, from 3 to 4, and from 4 to 5. When the cladding header moves in the direction of the line segments along the arrow within the layer, such as the segment from point 1 to point 2, the powder flows out, and the alloy is melting. While moving along the line segments out of the layer, such as from point 2 to point 3, the powder is terminated. The distance between the two adjacent parallel line segments within the layer is just the width of the cladding alloy, so that the layer of the damaged region can be filled up by the cladding alloy. After a layer is filled up, the next layer can be repaired in the same way.

Program module is operated in table "Path" in Figure 5. In order to travel the planned path, the robot need waits for an inflection point of the planned path from the upper computer program and then drives the cladding head to such a point in a straight line via command "ptp" of KUKA robot (abbreviation for "point to point"), and the next inflection point is accepted till the cladding header has just completed moving at the former point. The key for the robots receiving the planned path successfully is that the program of the robot follows the Ethernet and TCP protocol.

4. Repair Test of the Damaged Bit

After setting the process parameters for all equipment and sending the planned path to the KUKA-KR60 robot, the laser-cladding device starts to work, as shown in Figure 12a and Video S1 in the Supplementary Materials. Finally, the repaired bit can be seen in Figure 12b.



(**a**) (**b**)

Figure 12. Experiment of laser-cladding repair for a damaged PDC bit: (**a**) Laser cladding in process; (**b**) The PDC bit after repair.

5. Conclusions

According to the theoretical analysis and repairing experiment of the damaged PDC bit above, the proposed scheme of the integrated automatic system of laser-cladding repair is feasibility and the implementation that derived from such guidance via using the KUKA dual-robot system can meet the actual demand of PDC bit repairing, which means the inspecting process and cladding process can be driven by a program rather than by humans operating robots. The effectiveness of the implementation has been enhanced.

There are still two main aspects to be achieved in the future work: the 3D scanner in such a project is a commercial product, so the coordinate data of the spatial points of the measured object can only be processed by using the supplied specific software rather than the proposed integrated system, and comparing the process of 3D point cloud in the desktop computer is also achieved by commercial software, i.e., Geometric Studio, which means there are three kinds of software working in the desktop computer. Therefore, the3D scanner, as well as point cloud data processing software, needs to be developed in the next stage.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/electronics12040900/s1.

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