Design of Laser Cleaning System for Large-scale Plane Workpiece

Ma Qingzeng¹,a, Ren Yuan¹, Jin Shuo¹, Nan Leiguang¹, Ge Hailong¹, Cheng Wei¹*

¹Laser Institute, Qilu University of Technology (Shandong Academy of Sciences), Jinan China
²email: qingzeng.ma@sdlaser.cn
*corresponding author’s e-mail: chengw@sdas.org

Abstract. Surface cleaning is an essential procedure to improve quality and performance of workpiece in modern industrial manufacturing. Among surface cleaning technologies, laser cleaning has been regarded as the most promising green cleaning technology. Laser cleaning is a green cleaning technology that will not cause any environmental pollution. Laser cleaning has the ability of cleaning the area of the designated shape. A set of laser cleaning system that consists of two-dimensional galvanometer and 3-axis motion platform, was designed in this paper. The two-dimensional galvanometer was used to clean the area of the specified shape. The 3-axis motion platform expands the limited cleaning area of the two-dimensional galvanometer to a larger area. Laser displacement sensor is utilized to ameliorate the cleaning quality. To improve the cleaning accuracy of the system proposed in this article, a camera was adopted to recognize the origin of the workpiece and correct the pose of the workpiece. Experimental results demonstrate the performance of the proposed system for large-scale plane workpiece.

1. Introduction
Laser cleaning technology takes advantage of high-energy laser beams to irradiate the surface of workpiece to evaporate or peel off the dirt, rust spots or coating on the surface to achieve the purpose of surface cleaning [1-4]. It is known as the most promising green cleaning technology in the 21st century. Recent years, this kind of surface cleaning technique has attracted considerable attentions not only from academia but also from industry.

Compared with the conventional surface cleaning technologies, laser cleaning has the following advantages: (1) There is no damage to the substrate because it does not directly touch the substrate; (2) it will not cause environmental pollution because no chemicals or water is used during laser cleaning; (3) it is very convenient to integrate with other automation equipment; (4) it is a versatile technique with higher control accuracy. Therefore, High quality surface cleaning can be achieved by properly choosing laser power, pulse repetition rate and pulse width; (5) the process of laser cleaning can be controlled remotely, which reduces health implications to the workers and the cost of labor.

Laser cleaning has been applied to many industrial applications [5-9], such as microelectronic industry, aerospace industry, and rail traffic industry. Currently, portable hand-held laser cleaning is the mostly commonly used operation mode. The merits of the portable hand-held laser cleaning are flexibility and convenience. However, the disadvantages of hand-held laser cleaning are also apparent: (1) The cleaning speed of hand-held laser cleaning cannot be controlled precisely and stably; (2) it is not easy to position workpiece to the focus of laser; (3) the hand-held operation mode requires a
higher skills for the workers; (4) this operation mode cannot be applied to large-scale workpiece and large-scale demonstration applications.

Therefore, a class of laser cleaning system (LCS) for large-scale workpiece is urgently needed for surface cleaning. In this paper, we designed a set of LCS for large-scale plane workpiece. The LCS consists of a two-dimensional (2D) galvanometer, 3-axis motion platform, laser displacement sensor, camera, and laser cleaning devices. The 2D galvanometer is fixed at the end of the 3-axis motion platform, and is used to clean the specified areas, such as circle region and polygon region. The 3-axis motion platform expands the scope of cleaning of the 2D galvanometer. Laser displacement sensor measures the distance between the surface of workpiece and the laser cleaning head, and then controller adjusts the position of the laser cleaning head according to the distance to guarantee the optional cleaning quality. The camera captures the origin of the workpiece to correct the workpiece.

The rest of this paper is organized as follows. Section 2 describes the system architecture of the LCS. A kind of cleaning algorithm for area is presented in section 3. Section 4 introduces an automatic focusing method based on laser displacement sensor. Positioning of workpiece origin based on machine vision is presented in section 5. The experimental results are given to verify the effectiveness of the proposed system in section 6. Finally, section 7 concludes our work.

2. System configuration for the LCS

The LCS designed in this paper is used for the laser cleaning of large-scale plane workpiece. It consists of a two-dimensional galvanometer, 3-axis motion platform, laser displacement sensor, camera, and laser cleaning devices, as shown in Fig. 1.

![Schematic illustration of the LCS](image)

The 2D galvanometer is used to clean the specified regions, such as circle region and polygon region. But the working area of 2D galvanometer is usually limited to a smaller area, such as 100mm × 100mm. It fails to clean the area that exceeds the working range. To solve the problem, the 2D galvanometer is fixed at the end of the 3-axis motion platform. The 3-axis motion platform will move the 2D galvanometer to any position of the workpiece to expand the scope of cleaning of the 2D galvanometer. The laser cleaning of large-scale plane workpiece can be achieved by movement of the 3-axis motion platform.
Laser displacement sensor measures the distance between the surface of workpiece and the laser cleaning head, and feed the distance back to the main controller in real time. The main controller adjusts the position of the laser cleaning head in real time according to the distance, to guarantee the optional cleaning quality and effects.

The camera captures the origin of workpiece, and then calculates the actual position and orientation of the workpiece. The main controller will correct the pose of each area to be cleaned based on the difference between the ideal and actual pose of the workpiece. The process can reduce the cost of the fixture, and improve the accuracy of laser cleaning.

3. Cleaning algorithm for the LCS
In order to clean the surface of the specified shape (e.g. circle, polygon), the X- and Y-axis of the 2D galvanometer must rotate in the specified way. Firstly, the X-axis rotates to clean a straight line, then the Y-axis rotates a predefined angle. Then, the X-axis rotates again to clean another straight line. Repeating the above procedure until the whole area is cleaning, as shown in Fig. 2. The interval between adjacent straight lines is identical and adjustable.

3.1 Intersection calculation
From the description above, we can see that how to get the intersection between straight line and the polygon is a key issue. It can be drawn from Fig.2: (1) The single straight line will not be intersected with every edges of the polygon; (2) there is a step relationship between adjacent straight lines when the intersection relationship between straight line and edges keeps unchanged.

Assuming the intersection \((x_k, y_k)\) between current straight line and one edge of the polygon has been calculated. If next straight line is also intersected with the same edge of the polygon, then the coordinates of the new intersection can be calculated directly by step relationship, rather than recalculate the intersection between straight lines, as shown in Fig. 3.

Assuming the slope \(k\) of the edge of the polygon satisfies \(k \neq 0\). Then the new intersection is

\[
\begin{align*}
x_{k+1} &= x_k + \frac{\Delta y}{k} \\
y_{k+1} &= y_k + \Delta y
\end{align*}
\]

(1)
The special case is that the edge of the polygon is horizontal or vertical. In this case, no calculation is needed. Through this method, the calculating time is greatly reduced.

4. Automatic focusing based on laser displacement sensor

The laser beam has the strongest energy at the focal point, which can generate a high temperature of several thousand degrees or even tens of thousands of degrees, causing the dirt to evaporate, gasify or decompose instantly. The energy deviating from the focus will be weakened, affecting the efficiency and quality of laser cleaning. Therefore, in the laser cleaning process, it is necessary to effectively control the distance between the laser cleaning head and the workpiece, so that the focus of the laser beam is exactly on the surface of the workpiece, so as to obtain the optimal laser cleaning, as shown in Fig. 4.

![Fig. 4 Influences of focus changes](image)

In this paper, although the workpiece to be cleaned are flat workpiece, they may also have uneven surfaces in local area, or the base is not flat, which will affect the consistency of laser cleaning quality. In order to fix this problem, this article designed a Z-axis follow-up system based on laser displacement sensor. The laser displacement sensor can measure the actual distance between the laser cleaning head and the surface of the workpiece in real time, and feed it back to the control system. The control system compares the actual and set value, and then adjusts the height of the Z-axis in real time to get the purpose of positioning the focus.

The Z-axis follow-up control belongs to classic position negative feedback control. This paper adopts the commonly used PID control algorithm as the follow-up control algorithm. The flow chart of control structure is shown in Fig. 5. The difference between the setting value and the feedback value is used as the input of the PID algorithm. After PID calculation, the output value drives the motor to adjust the position of Z-axis to reduce the gap between the feedback value and the set value. When the difference between the setting value and the feedback value is zero, the system tends to a stable state.

![Fig.5 The flow chart of control structure](image)

The incremental PID algorithm is as follows

\[
\Delta u = K_p \left[ e(k) - e(k - 1) \right] + K_p \frac{T}{T_i} e(k) + K_p \frac{T}{T} \left[ e(k) - 2e(k - 1) + e(k - 2) \right]
\]  

(2)
where, $K_p$ represents the proportional gain; $T_I, T_D$ are the integration time and derivative time, respectively; $T$ is the sampling period; $e(k), e(k-1), e(k-2)$ demonstrate the error between the set value and the feedback value of $k, k-1, k-2$ steps; $\Delta u$ is the increment of control variable $u$.

5. Correction of the pose of workpiece based on machine vision

The laser cleaning requirement for a certain aerospace workpiece is to clean the designated graphics at the specified position, so there is higher requirement for the position and attitude of the workpiece. As shown in Fig. 6, if the origin of the workpiece changes or the attitude of the workpiece changes, the graphics to be cleaned change simultaneously. High-precision fixtures can improve the positioning accuracy of the workpiece, but at the same time will greatly increase the cost of the system. For this reason, this paper uses machine vision to correct the position and attitude of the workpiece, which can effectively reduce the cost of tooling and fixtures, and greatly improve the efficiency and quality of laser cleaning.

![Fig. 6 The effect of workpiece changes on cleaning](image)

In order to determine the zero point of the workpiece, the method adopted in this article is to manually paste a cross mark at the origin of workpiece, where the center of the cross mark represents the origin of workpiece, and the cross mark is parallel to the X-axis and Y-axis of the workpiece respectively. The center point and inclination angle of the cross mark can be identified by machine vision. So the purpose of positioning and correcting the origin of the workpiece is achieved. The cross mark are shown in Fig. 7.

![Fig. 7 Cross mark](image)

The coordinates of the vision system are shown in Fig. 8. The frame $O_eX_eY_eZ_e$ represents the coordinate system of the 2D galvanometer. The distance between the origin $O_e$ and the center point of the 2D galvanometer is equal to the focal length $f$ of the laser. The frame $O_cX_cY_cZ_c$ demonstrates the camera coordinate system. The frame $O_wX_wY_wZ_w$ is the workpiece coordinate system. The coordinate axes of the three coordinate frames are parallel, respectively, and the Z-axis is vertical to the surface of the workpiece.

The flow chart of image processing is shown in Fig. 9. After capturing the image of cross mark from the camera, the center point and the inclination angle of the cross mark is computed by extracting
the skeleton of the cross mark. The position and orientation of the workpiece to be cleaned is confirmed. Then the main controller will correct the cleaning data based on the actual pose of the workpiece.

6. Experimental results
To evaluate the rationality and effectiveness of the proposed laser cleaning system, a series of experiments were carried out. The laser cleaning system is shown in Fig. 10. Several experimental results are briefly described as follows.

During the Z-axis follow-up experiments, the set value of distance between the laser displacement sensor and the surface of the workpiece is 50mm. The surface of the workpiece is inverted-V shape, as shown in Fig. 11. The tracking curve is shown in Fig. 12. The biggest tracking error is 1.4mm, which occurs on the turning point of the surface and can satisfy the laser cleaning process requirements. The tracking error is bigger on the turning point, because the motor will change the movement direction, slow down, and accelerate again.
The result of visual recognition is shown in Fig. 13. After extracting the skeleton of the cross mark at the origin of workpiece, the center point and inclination angle of the cross mark are obtained.

The effect of laser cleaning is shown in Fig. 14. From the Fig. 14, we can see that the system can implement the cleaning of designated shape (e.g. circle shape, polygon shape), and meet the accuracy requirements.

Fig. 10 Laser cleaning system

Fig. 11 The surface of workpiece

Fig. 12 The tracking curve of Z-axis

Fig. 13 The result of visual recognition (a-skeleton extraction; b-origin recognition)
7. Conclusions
In this paper, a laser cleaning system is presented to perform laser cleaning operation for large-scale plane workpiece. Experimental results show the rationality and effectiveness of the proposed system which can greatly improves the efficiency of the laser cleaning and further promotes the application of laser cleaning in industry.

Acknowledgments
This work is supported by Key R&D Program of Shandong Province (Public Welfare Science and Technology) under Grant 2019GGX104082, Youth Science Funds of Shandong Academy of Sciences under Grant 2019QN0031, International Science and Technology Cooperation Program of Shandong Academy of Sciences under Grant 2019GHP21, and Major Scientific and Technological Innovation Project of Shandong Province under Grant 2019JZZY010452.

References
[1] Vorobyev, A. Y. and Guo, C., 2017. Residual thermal effects in laser ablation of metals. In: Journal of Physics: Conference Series of Eighth International Conference on Laser Ablation. 59(2017):418–423.
[2] Zhang, F. D., Liub, H., Suebkab, C., Liu, Y. X., et al. (2018) Corrosion behaviour of lasercleaned AA7024 aluminium alloy. Applied Surface Science, 435: 452–461.
[3] Li, X., Zhang, Q., Zhou, X., Zhu, D., Liu, Q. (2018) The influence of nanosecond laser pulse energy density for paint removal. Optik, 156: 841–846.
[4] Kumar, A., Bhatt, R., Behere, P., Afzal, M., et al. (2014) Laser-assisted surface cleaning of metallic components. Pramana - Journal of Physics, 82: 237–242.
[5] Mohammad, K. A. A. R., Mohammad An’amt, N., Mohamad, S. J., Nor, A. H., et al. (2018) A review of incorporating Nd:YAG laser cleaning principal in automotive industry. Journal of Radiation Research and Applied Sciences, 11: 393-402.
[6] Lopez, A. J., Lamas, J., Pozo-Antonio, J. S., Rivas, T., Remil, A. (2020) Development of processing strategies for 3D controlled laser ablation: Application to the cleaning of stonework surfaces. Optics and Lasers in Engineering, 126: 1-9.
[7] Siano, S., Agresti, J., Cacciari, I., Ciofini, D., et al. (2012) Laser cleaning in conservation of stone, metal, and painted surfaces: State of the art and new Insights on the use of the Nd:YAG laser. Applied Physics A, 106: 419-446.
[8] Guan, Y. C., Ng, G. K. L., Zheng, H. Y., Hong, M. H., at al. (2013) Laser surface cleaning of carbonaceous deposits on diesel engine piston. Applied Surface Science, 270: 526-530.
[9] Rauh, B., Kreling, S., Kolb, M., Geistbeck, M., at al. (2018) UV-Laser cleaning and surface characterization of an aerospace carbon fibre reinforced polymer. International Journal of Adhesion and Adhesives, 82: 50-59.