Adaptive laser focusing head design for the 3D free surface in parallel kinematic machining

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Abstract. An adaptive laser head was designed for microscale patterning and welding applications. An optical design for laser head was performed by using ray tracing technique with commercial software. Setting the focal length of the lens at 100mm the calculated focus beam diameter was offset to be 10 μm for the CFRP welding applications. To perform an auto-focusing calibration an LRF (Laser Range Finder) distance sensor was used to measure the distance to the target surface. Using a DC Motor with PID control loop, the distance was kept at constant between the laser head and the target material. In this paper, we propose an algorithm for auto-focusing calibration function and detail schematics of laser head design.

1. Introduction
Recently, many researches have been carried out new ways of machining using laser processing. In modern machine tool market it is required to shorten the time of the machining processes and improve productivity and quality of the product. Many efforts have been made in manufacturing process to combine a cutting process and a non-cutting process such as a laser [1-3]. The conventional machining processing requires tools which have friction between the tool and the material, and it takes up unnecessary load on the tool and material. In results, machining process is not energy efficient and sacrifices the precision of machining. However, when a non-contact tool is introduced, it is possible to process materials such as alloys and ceramics which are difficult to process by cutting regardless of hardness and rigidity [4].

In this paper, using a specially designed laser head we present a non-contact processing method, and propose a method for more precise processing using a laser head with an auto-focus correction. All the processes are designed to perform in a single machine without any additional equipment.
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![Image](216x606 to 380x719)

**Figure 1.** PKM (Parallel Kinematic Machines)

2. Laser head device development

2.1. Laser head design
In general, 5-axis machining is evaluated to be more efficient and flexible than 3-axis machining. It can be applied to various products such as aviation parts, blades, molds, etc., which cannot be machined in conventional 3-axis machining [5]. The laser head is optimally designed to be applied to a 5-axis processing machine in PKM (Parallel Kinematics Machine) Fig. 1.

Fig. 2 is an example of beam delivery system that can separate the visible light spectrum from the mixed spectrum of lights. In addition, focal length was set at 100mm and the optical design was optimized to flexibly work near 100mm. To minimize the chromatic aberration, achromatic lenses were used for various wavelengths. As a distance control hardware with DC Motor, the system was designed to perform an auto-focusing calibration and a pulley system was used to transmit the power from the motor to focusing unit. We modified several design alternatives and confirmed the possibility of prototyping using 3D printing. The final version was completed and the prototype was completed.

![Image](84x206 to 300x377)

![Image](317x214 to 497x369)

(a) 3D modelling of driving system  
(b) Beam delivery system

**Figure 2.** Laser Head Design and Beam Delivery System Diagram

In Fig. 3, a schematic diagram of distance measurement system was described and it uses an LRF based on the triangulation method. After measuring the distance from the optics to the target object by using the LRF, the predefined position of the laser head to the motor was controlled by using the analog data from LRF.
To calculate the position of the laser focusing head, it is necessary to define the size of the focus of the laser in the designed optical system. The spot size of the laser focused on the target material is approximately \(13\mu \text{m}\) according to Equation 1, assuming that the Beam quality factor \(M^2 = 1\), the laser wavelength \(\lambda = 1064\text{nm}\), the focal length of the lens \(f = 100\text{mm}\) and the entrance pupil \(D = 10\text{mm}\) (Fig. 4).

\[
\text{Spot size} = \frac{4M^2\lambda f}{\pi D}
\]  

(1)

2.2. Position control algorithms

The laser head introduced in this paper should be compatible with the machine tool regardless of the noisy environment. Therefore, it is necessary to use minimum apparatus for the reduction of control time. Using the analog control data from the LRF, the PWM signal was generated for the Motor control which compensates the distance between the laser head and the target (Fig. 5). Based on the developed control method, it was proved that the system always keeps the distance at a certain distance neighboring the focal length. As shown in Fig. 6, the distance is always maintained at the predefined constant location and the current position data is transported along the direction of the laser head.
The feedback control algorithm measures the current location and compares it to the measured tolerance in LRF to reach the target value of “0” in real time. This control logic is applied to the embedded system, ARDUINO in Fig. 7. The ARDUINO is an open-source project controller that creates microcontroller-based kits for building digital devices and interactive objects with very compact control system design.

3. Prototype productions and testing
The prototype laser head designed as shown in Fig. 8 was completed. To maintain the focus of the optical system precisely, the backlash in all drive parts is designed to be close to zero. Based on precision machining with minimum backlash, the system response was proved to be fairly high which is suitable in this project. Even though there is some backlash, the gravity always helps to mesh the gap in the downward direction.
For the optimum motor driving system design, we tested the stepping motor and a DC motor as the basic test motors. First, a stepping motor that moves 1.8 degrees per step was used for the motion. The designed laser head has a driving ratio of 1:2, and the lead of the head part screw is 3mm. In this case, as shown in Equation 2, the vertical travel distance of the head per pulse is about 7.5μm. The change in diameter of the beam per pulse was calculated to be about 0.76μm.

\[
\text{Distance} = \frac{\text{deg/step}}{360°} \times \text{lead}
\]  

Second, we tested a DC motor for faster response than the stepping motor in real time. As shown in Fig. 9, the response time between the output of the PWM to the DC motor and the analog data coming from the LRF in the embedded system was measured. As a result, the response time was measured to be about 10ms. It is a time that can be ignored when machine tool is transported with constant feed rate in real environment. Since typical traveling speed of PKM is 1,000mm/min, the system can move only 0.16mm in 10ms which may be negligible.

When the analog data of the LRF reaches the desired target distance value of “0”, the DC motor was slightly unstable or vibrating. By optimizing the PID controller parameters, it was possible to reduce the vibration of the DC motor near the target value. Tuning the PID gain value, the motor’s fast response speed can be obtained while reducing the error value.
4. Applied tests on machine tools
After completing the basic tests, we conducted test on the machine tool, which is a real environment. The experimental setup was constructed as shown in Fig. 10.

![Test equipment setting](image1)

**Figure 10.** Test equipment setting

The diode laser used in the experiment has wavelength of 980nm and the maximum output power of 30W. In order to perform the auto-focusing function, an artificially bent specimen was prepared on the table of CNC system as shown in Fig. 11.

![Curved specimens](image2)

**Figure 11.** Curved specimens

The test performed with a range of laser output power of 5 to 10W on a CFRP work piece. The range of laser power selected so that the CFRP material is not bunt by the laser power. As a scanning
speed, the feed rates of the machine tool were set as 1000, 2000 and 3000mm/min. From the visual inspection of the laser head motion, the auto-focusing function was normally functioning at the feed rate of 1000 and 2000mm/min. However, if the feed rate is increased at 3000mm/min, the speed of the DC motor tends to be unstable which cannot compensate the distance difference.

![Image](image.png)

**Figure 12.** Auto focusing function test and sample results

Experiments using laser head with auto focusing function is depicted in Fig. 12. If the focal length of the laser does not match with the predefined value, defocusing occurs. Therefore, some unfocused parts will not burn which proves the unfocusing. However, the auto focusing function normally works, all the curved surfaces are burned.

5. **Conclusion**

The laser head was developed in this paper and a prototype of laser head was used for the experiment. However, instead of directly applying to the 5-axis machining centre, the test was first demonstrated with 3-axis machining centre. The proposed system will be applied to the 5-axis machine in near future. From this research, we found that it is possible to apply auto focusing correction to the conventional 5-axis machining tool.

The developed system is expected to provide the machine tool be more stable, flexible and precise with the non-contact advantages. By applying a laser heat source to a machining process of a general machine tool in a hybrid form, the time of the machining process can be shortened and the quality can be expected to be improved. In addition, the laser has advantages not only in processing but also in processes such as marking, texturing, welding, cutting, and heat treatment. If the system is equipped with auto focusing function, much more precise machining will be possible.

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