

Article

Precision Calibration of Robot Magnetorheological Finishing System Based on Laser Tracker

Yujing Wei ¹, Runmu Cheng ^{2,3,*}, Longxiang Li ^{2,3,*}, Qiang Cheng ^{2,3}, Yue Pan ¹, Chaoyue Zhu ^{2,3}, Jinbo Zhang ^{2,3}, Jun Zheng ^{2,3} and Bo Ai ²

¹ Measurement and Control Technology and Instruments, School of Optoelectronic Engineering, Changchun University of Science and Technology, Changchun 130022, China; wyj201908@outlook.com (Y.W.); panyue@cust.edu.cn (Y.P.)

² Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China; chengq@ciomp.ac.cn (Q.C.); zhuchaoyue23@mails.ucas.ac.cn (C.Z.); zhangjinbo23@mails.ucas.ac.cn (J.Z.); zhengjun23@mails.ucas.ac.cn (J.Z.); 15943002795@163.com (B.A.)

³ University of Chinese Academy of Sciences, Beijing 100049, China

* Correspondence: chengrunmu@ciomp.ac.cn (R.C.); lilx@ciomp.ac.cn (L.L.)

Abstract: Six-degree-of-freedom industrial robots, known for their low cost and high flexibility, have been extensively applied in optical processing. Precise pose control in robot-based optical processing systems depends on the accurate calibration of the tool coordinate system. However, in robot magnetorheological finishing (Robot-MRF) systems, the spherical shape of the polishing wheel poses significant challenges in precisely identifying the working point on the tool's surface. Traditional calibration methods, such as the four-point or six-point techniques, fail to accurately calibrate the tool coordinate system for MRF tools. To overcome this limitation, a laser tracker-based calibration method is proposed for parameter calibration of the Robot-MRF system. Experimental results show that this method achieves a maximum repeatability error of just 0.0505 mm, significantly improving the stability and reliability of the calibration results and meeting the high-precision processing requirements of MRF technology.

Keywords: robot; laser tracker; magnetorheological finishing; tool center point



Received: 4 December 2024

Revised: 30 December 2024

Accepted: 3 January 2025

Published: 10 January 2025

Citation: Wei, Y.; Cheng, R.; Li, L.; Cheng, Q.; Pan, Y.; Zhu, C.; Zhang, J.; Zheng, J.; Ai, B. Precision Calibration of Robot Magnetorheological Finishing System Based on Laser Tracker. *Photonics* **2025**, *12*, 57. <https://doi.org/10.3390/photonics12010057>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In recent years, with the increasing demands for optical systems in fields such as space remote sensing, astronomical observation, and medical imaging, optical components, as core elements of these systems, directly determine the imaging quality. As a result, the manufacturing quality of optics is facing higher requirements. Large-aperture optical systems, such as the Giant Magellan Telescope [1], the European Extremely Large Telescope [2,3], the Thirty Meter Telescope [4], and the 4 m SiC Aspheric Mirror [5], urgently need high-precision, low-cost, efficient, and scalable optical manufacturing technologies. However, traditional large-scale precision CNC machine tools are expensive, have low degrees of freedom, require large floor space, and have low space utilization, making them unable to meet current processing requirements. The six-degree-of-freedom industrial robot, with its low cost, high degree of freedom, flexible motion, and quick deployment for mass production, has been combined with various optical manufacturing technologies to achieve high-precision processing. Examples include robot-computer-controlled optical surfacing [6,7], robot-wheeled polishing [8], and robot bonnet polishing [9,10]. Robots are currently primarily applied in processing fields where the precision requirement is a root

mean square > 30 nm. To expand the application of robots in higher-precision fields and achieve nanometer-level processing precision, integrating robots with highly deterministic magnetorheological finishing (MRF) [11,12] has become a hot topic in current research and development.

High-precision processing using Robot-MRF [13,14] relies on accurate motion control within the robot's workspace, which requires precise calibration of the positional relationship, known as the tool center point (TCP), between the working point of the MRF polishing module and the center of the robot's end flange. Common TCP calibration methods include four-point and six-point methods [15], sphere-fitting calibration [16], and vision-based measurement techniques [17]. For example, Fakherddine Fares and colleagues [18] used a KUKA KR3 r540 robot to compare the four-point and sphere-fitting methods, finding that sphere-fitting provided higher accuracy, with calibration errors below 1 mm. Similarly, Zhiyu Yang and colleagues [17] achieved a TCP calibration error of 0.181 mm using a vision-assisted approach. However, both the four-point and sphere-fitting methods depend somewhat on operator experience. In MRF, the working point is defined as the intersection between the polishing wheel's surface and the normal direction at a given point on the optics' surface, generally considered the lowest point of the wheel. This makes it challenging to accurately locate the working point on the polishing wheel for contact with a "needle tip" or "sphere" surface. Additionally, vision-based calibration methods struggle to fully capture the MRF tool, making it difficult to pinpoint the exact working point of the MRF tool.

In recent years, laser tracker-based calibration techniques have become a widely used method for robot system parameter calibration. These systems take advantage of the unique benefits of laser trackers, such as non-contact measurement, high accuracy, a wide measurement range, and broad applicability, to achieve effective TCP calibration. For instance, Guangyun Li [19] successfully used a laser tracker for TCP calibration, achieving an RMS calibration error of less than 1 mm. However, precisely positioning the laser tracker's target sphere at the working point of the polishing wheel remains a challenge, making it impossible to directly use the laser tracker to determine the exact pose transformation between the robot's end flange and the working point coordinate system of the polishing wheel.

To address the challenge of accurately calibrating the TCP (tool center point) in the Robot-MRF system, this paper introduces a laser tracker-based parameter calibration method for the Robot-MRF tool. By leveraging the geometric features of the robot's end flange and the polishing wheel, a TCP transformation model is established, followed by calibration experiments to validate its effectiveness. This method not only enables TCP calibration for the Robot-MRF but also applies to the precise calibration of other optical processing tools with well-defined geometric shapes.

2. The MRF TCP Calibration Method Based on Laser Tracker

Aiming at the problem of precise calibration of the coordinate system of MRF tools, a non-contact TCP calibration method is proposed. The overall calibration process is as follows:

Firstly, the measuring coordinate system $\{M\}$ of the laser tracker is established, and the measurement coordinate system $\{M\}$ is consistent with the flange coordinate system $\{F\}$, as shown in Figure 1.

Secondly, the attitude parameters of the MRF tool coordinate system $\{T\}$ are calibrated. The target ball is adsorbed on the outer surface of the polishing wheel through the magnetic field; it then slowly rotates the polishing wheel and measures the coordinates of the target ball in at least four different positions. The normal line of the surface on which the

measuring point is located can be obtained by using the least square fitting, which can be expressed by the following equation:

$$\frac{x - x_0}{A_0} = \frac{y - y_0}{B_0} = \frac{z - z_0}{C_0} \quad (1)$$

where (A_0, B_0, C_0) represents the direction vector of the normal line, and (x_0, y_0, z_0) is a point on the normal L_0 .

$$\begin{cases} \alpha = \arccos \frac{A_0}{\sqrt{A_0^2 + B_0^2 + C_0^2}} \\ \beta = \arccos \frac{B_0}{\sqrt{A_0^2 + B_0^2 + C_0^2}} \\ \gamma = \arccos \frac{C_0}{\sqrt{A_0^2 + B_0^2 + C_0^2}} \end{cases} \quad (2)$$

The attitude of the MRF polishing tool is actually calibrated as follows:

$$\begin{cases} \alpha' = 2\alpha_0 - \alpha \\ \beta' = 2\beta_0 - \beta \\ \gamma' = 2\gamma_0 - \gamma \end{cases} \quad (3)$$

where α_0, β_0 , and γ_0 are the theoretical setpoints of the angles between the normal line and the X, Y, and Z axes of the measuring coordinate system $\{M\}$, respectively.

The quaternion converted to the robot demonstrator is [20]:

$$\begin{cases} q_0 = \frac{1}{2} \sqrt{1 + r_{11} + r_{22} + r_{33}} \\ q_1 = \frac{1}{4q_0} (r_{32} - r_{23}) \\ q_2 = \frac{1}{4q_0} (r_{13} - r_{31}) \\ q_3 = \frac{1}{4q_0} (r_{21} - r_{12}) \end{cases} \quad (4)$$

where

$$\begin{aligned} & \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \\ &= R_z(\gamma') \cdot R_y(\beta') \cdot R_x(\alpha') \\ &= \begin{bmatrix} \cos \gamma' & -\sin \gamma' & 0 \\ \sin \gamma' & \cos \gamma' & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos \beta' & 0 & \sin \beta' \\ 0 & 1 & 0 \\ -\sin \beta' & 0 & \cos \beta' \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha' & -\sin \alpha' \\ 0 & \sin \alpha' & \cos \alpha' \end{bmatrix} \\ &= \begin{bmatrix} \cos \beta' \cos \gamma' & \sin \alpha' \sin \beta' \cos \gamma' - \cos \alpha' \sin \gamma' & \cos \alpha' \sin \beta' \cos \gamma' + \sin \alpha' \sin \gamma' \\ \cos \beta' \sin \gamma' & \sin \alpha' \sin \beta' \sin \gamma' + \cos \alpha' \cos \gamma' & \cos \alpha' \sin \beta' \sin \gamma' - \sin \gamma' \cos \gamma' \\ -\sin \beta' & \sin \alpha' \cos \beta' & \cos \alpha' \cos \beta' \end{bmatrix} \end{aligned}$$

The modified quaternion is introduced into the robot teaching device to complete the attitude calibration of the MRF polishing tool.

Finally, the position parameters of the MRF polishing tool coordinate system $\{T\}$ are calibrated. Adjust the end attitude to the actual zero attitude, place the target ball on the side cylinder of the flange, and fix it. Rotate the sixth axis at the end of the robot, measure the coordinates of different positions of the target ball in the measurement coordinate system $\{M\}$, and measure no less than four points. Use the ball-fitting function of the laser tracker to determine the coordinates of the center point of the ball where the target ball is located (x_0', y_0', z_0') . Place the target ball near the center of the flange end face and measure

the position coordinates (x_0'', y_0'', z_0'') at this time; then, the center point coordinates of the flange are as follows:

$$\begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = \begin{bmatrix} x_0' \\ y_0' \\ z_0'' - R_1 \end{bmatrix} \quad (5)$$

where R_1 indicates the radius of the target ball.

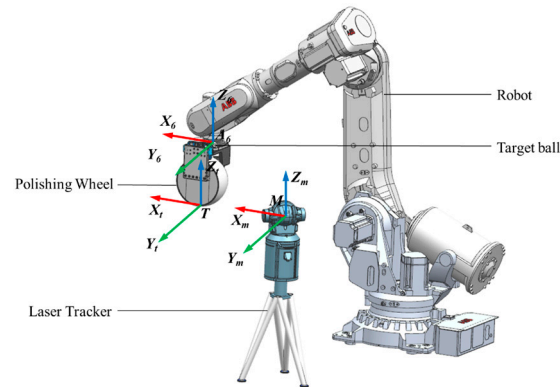


Figure 1. The establishment of a measuring coordinate system.

The target ball is placed in at least four different positions on the outer surface of the polishing wheel, and the target ball coordinates at different positions are measured by the laser tracker. The measured data can be calculated through the fitting ball function of the laser tracker, and the center point of the polishing wheel (x_2, y_2, z_2) and the actual radius R_2 of the polishing wheel can be obtained. Therefore, the coordinates of the lowest point of the polishing wheel can be expressed by the following formula:

$$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} x_2 \\ y_2 \\ z_2' - R_2 \end{bmatrix} \quad (6)$$

Then, the offset of the lowest point of the polishing wheel relative to the center point of the flange is determined as follows:

$$\begin{bmatrix} \Delta X_2 \\ \Delta Y_2 \\ \Delta Z_2 \end{bmatrix} = \begin{bmatrix} x_2 - x_0 \\ y_2 - y_0 \\ z_2' - z_0 - R_2 \end{bmatrix} = \begin{bmatrix} x_2 - x_0' \\ y_2 - y_0' \\ z_2' - z_0'' + R_1 - R_2 \end{bmatrix} \quad (7)$$

The calculated offset is input into the instructor to complete the calibration of the position parameters of the tool coordinate system $\{T\}$. This method does not require the intervention of auxiliary equipment and can realize the double calibration of the attitude and position of the coordinate system of the MRF polishing tool only by using the laser tracker.

3. The MRF TCP Calibration Experiment

3.1. The Construction of Measurement System

A parameter measurement system for the MRF module based on a laser tracker was constructed, as shown in Figure 2. The system comprises a robot, MRF module, laser tracker, and associated software and hardware. The robot used is an ABB IRB 6700, featuring a repeatability positioning error of ± 0.05 mm, a payload capacity of 150 kg, and a working range exceeding 2 m. Meanwhile, the MRF module is equipped with a spherical polishing wheel that has a diameter of 160 mm and a smooth surface without distinct features. The

employed laser tracker is the FARO Vantage, which provides a measurement accuracy of $16 \mu\text{m} + 0.8 \mu\text{m}/\text{m}$. The environmental temperature is controlled at $22 \text{ }^{\circ}\text{C} \pm 0.5 \text{ }^{\circ}\text{C}$, and the impact of this temperature on the measurement results can be neglected. Based on the theoretical working pose requirements, the quaternion of the tool coordinate system $\{T\}$ of the Robot-MRF setup is defined as $[0, 1, 0, 0]$. The measurement coordinate system $\{M\}$ of the laser tracker is aligned along the X, Y, and Z axes to ensure parallelism with the tool coordinate system $\{T\}$. Considering the robot's minimal pose error and the high manufacturing and assembly precision of the MRF module, the theoretical pose is regarded as equivalent to the actual pose. Therefore, the TCP calibration experiment primarily focuses on the calibration of position parameters.

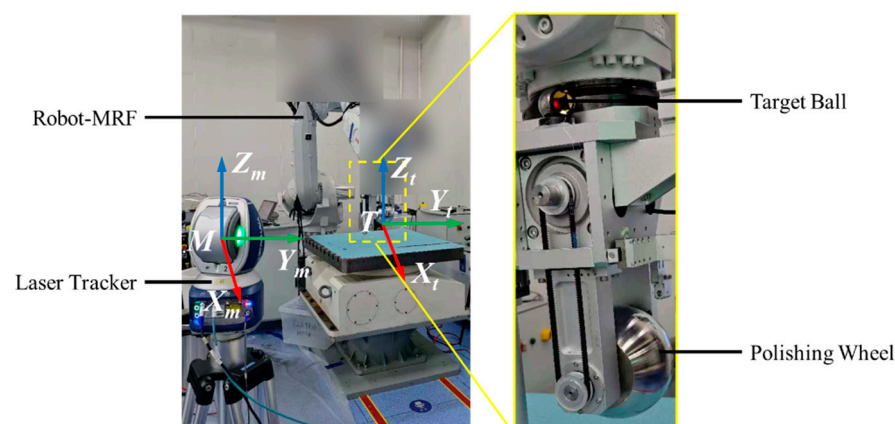


Figure 2. The structure of the Robot-MRF.

3.2. The TCP Calibration Results

The commonly employed six-point calibration method was utilized to perform TCP calibration, as shown in Figure 3, with a total of 10 calibration trials conducted. The calibration results, along with the associated errors, are summarized in Tables 1 and 2. By averaging the data from the 10 trials, the final TCP parameters were determined to be (2.0127, 1.9557, and 401.0524). Analysis of the data in Tables 1 and 2 reveals that the maximum repeatability calibration error in the X-axis is 4.8677 mm, in the Y-axis is 3.7153 mm, and in the Z-axis is 5.3324 mm. The corresponding results are shown in Figure 4. These error magnitudes represent significant systematic deviations, which are critical for MRF systems that demand high processing precision. Consequently, the six-point calibration method introduces substantial TCP calibration errors and demonstrates limited reliability in achieving accurate calibration results.

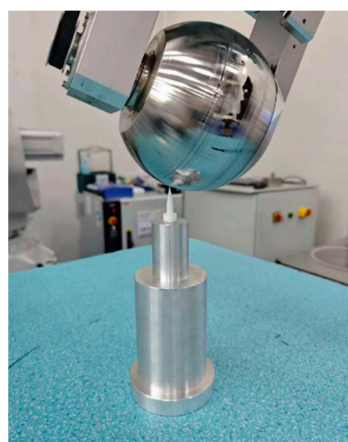


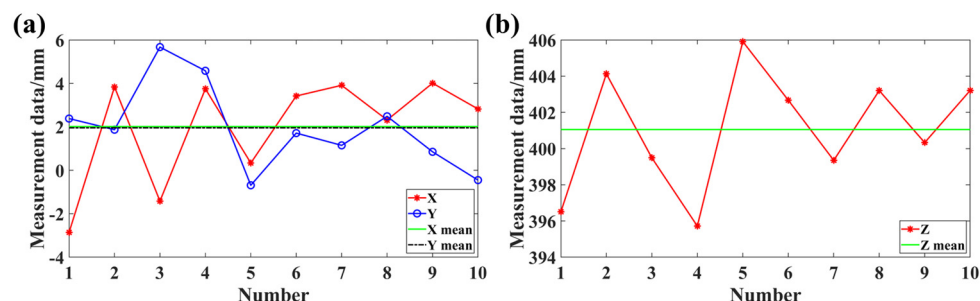
Figure 3. The six-point calibration method field.

Table 1. The six-point method TCP calibration results.

Number	X/mm	Y/mm	Z/mm
1	−2.855	2.381	396.510
2	3.837	1.869	404.127
3	−1.419	5.671	399.490
4	3.749	4.580	395.720
5	0.335	−0.689	405.911
6	3.420	1.712	402.673
7	3.912	1.148	399.350
8	2.315	2.485	403.203
9	4.011	0.851	400.330
10	2.822	−0.451	403.210
Mean	2.0127	1.9557	401.0524

Table 2. The six-point method TCP repeatability calibration error.

Number	$\Delta X/\text{mm}$	$\Delta Y/\text{mm}$	$\Delta Z/\text{mm}$
1	−4.8677	0.4253	−4.5424
2	1.8243	−0.0867	3.0746
3	−3.4317	3.7153	−1.5624
4	1.7363	2.6243	−5.3324
5	−1.6777	−2.6447	4.8586
6	1.4073	−0.2437	1.6206
7	1.8993	−0.8077	−1.7024
8	0.3023	0.5293	2.1506
9	1.9983	−1.1047	−0.7224
10	0.8093	−0.451	2.1576

**Figure 4.** The six-point method TCP calibration results curve: (a) X-axis and Y-axis calibration results, and (b) Z-axis calibration results.

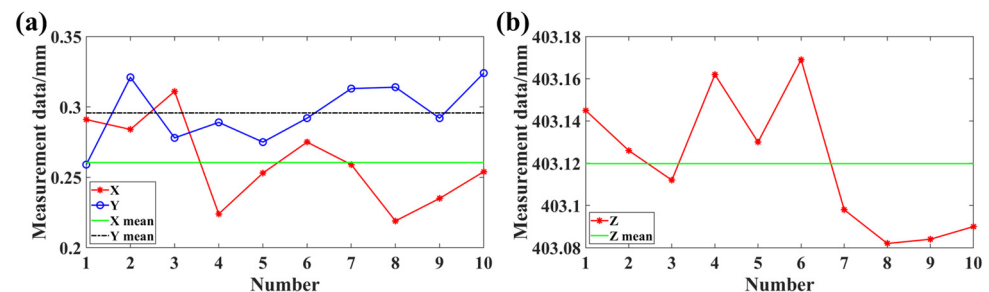
Using the proposed method, parameter calibration of the MRF module was performed. The established measurement system facilitated sequential TCP calibration, with each parameter measured 10 times and the average taken as the final calibration result. The measurement data are detailed in Tables 3 and 4. The results demonstrate that the proposed method yielded TCP parameters of (0.2605 mm, 0.2957 mm, and 403.1198 mm), with maximum repeatability errors in the X, Y, and Z axes of 0.0505 mm, 0.0367 mm, and 0.0492 mm, respectively. The corresponding results are shown in Figure 5. These findings indicate that the repeatability accuracy of this calibration method is ten times higher than that of the six-point method, significantly enhancing the stability and reliability of the calibration results while satisfying the stringent precision requirements of MRF processing.

Table 3. The laser tracker method TCP calibration results.

Number	X/mm	Y/mm	Z/mm
1	0.291	0.259	403.145
2	0.284	0.321	403.126
3	0.311	0.278	403.112
4	0.224	0.289	403.162
5	0.253	0.275	403.130
6	0.275	0.292	403.169
7	0.259	0.313	403.098
8	0.219	0.314	403.082
9	0.235	0.292	403.084
10	0.254	0.324	403.090
Mean	0.2605	0.2957	403.1198

Table 4. The laser tracker method TCP repeatability calibration error.

Number	$\Delta X/\text{mm}$	$\Delta Y/\text{mm}$	$\Delta Z/\text{mm}$
1	0.0305	−0.0367	0.0252
2	0.0235	0.0253	0.0062
3	0.0505	−0.0177	−0.0078
4	−0.0365	−0.0067	0.0422
5	−0.0075	−0.0207	0.0102
6	0.0145	−0.0037	0.0492
7	−0.0015	0.0173	−0.0218
8	−0.0415	0.0183	−0.0378
9	−0.0255	−0.0037	−0.0358
10	−0.0065	0.0283	−0.0298

**Figure 5.** The laser tracker method TCP calibration results curve: (a) X-axis and Y-axis calibration results and (b) Z-axis calibration results.

4. Discussion

The results from the two experiments show that the traditional six-point calibration method has a maximum TCP calibration error of 5.3324 mm in the Z-axis, whereas the proposed method achieves a maximum error of only 0.0505 mm in the X-axis. In terms of calibration accuracy, the proposed method is 10 times more precise than the six-point method, as shown in Figure 6. Further analysis of the standard deviation (STD) of the calibration results, as shown in Table 5, indicates that both methods exhibit the highest STD values in the Z-axis direction, with 3.3316 mm for the six-point method and 0.0318 mm for the proposed method. In terms of calibration stability, the proposed method also outperforms the six-point method by a factor of 10. This improvement is due to the lack of distinct surface features on the MRF polishing wheel, which makes the accuracy of the six-point method heavily dependent on factors such as the alignment precision between the probe and the working point, as well as the operator's experience, resulting in calibration errors

at the millimeter scale. In contrast, the proposed method's error is primarily influenced by the measurement accuracy of the laser tracker and slight movements of the handheld target sphere, resulting in calibration errors of only tens of micrometers. Consequently, the proposed method ensures significantly higher stability, reliability, and confidence in the calibration results. Furthermore, using the 3σ rule for further analysis of the measurement results, the calibration data error ranges for the X, Y, and Z axes using the six-point method are $2.0127 \text{ mm} \pm 7.4133 \text{ mm}$, $1.9557 \text{ mm} \pm 5.9898 \text{ mm}$, and $401.0524 \text{ mm} \pm 9.9948 \text{ mm}$, respectively. The method proposed in this paper yields error ranges of $0.2605 \text{ mm} \pm 0.0897 \text{ mm}$, $0.2957 \text{ mm} \pm 0.0651 \text{ mm}$, and $403.1198 \text{ mm} \pm 0.0954 \text{ mm}$ for the X, Y, and Z axes, respectively. By comparing these results with the data presented in Tables 1 and 3, it can be seen that the measurement data obtained by both methods do not contain gross errors, thereby strongly supporting the correctness of the aforementioned data analysis. Therefore, the TCP parameters obtained using the laser tracker-based method are adopted as the final TCP parameters for the MRF system: $[x, y, z, q1, q2, q3, q4] = [0.2605, 0.2957, 403.1198, 1, 0, 0, 0]$.

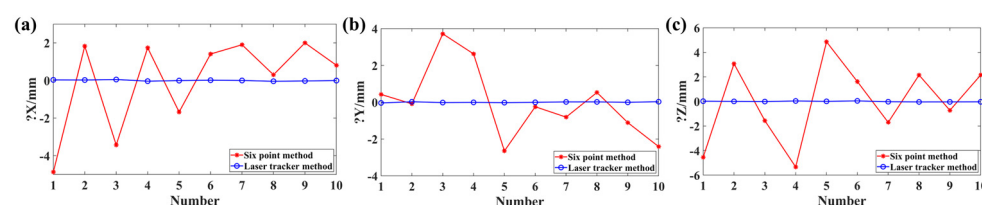


Figure 6. Calibration error comparison curve between the six-point method and laser tracker calibration method: (a) X-axis calibration error, (b) Y-axis calibration error, and (c) Z-axis calibration error.

Table 5. The STD of the calibration results for two methods.

Method	Std(X)/mm	Std(Y)/mm	Std(Z)/mm
Six-Point Method	2.4711	1.9966	3.3316
Laser Tracker-Based Method	0.0299	0.0217	0.0318

When integrating other optical manufacturing technologies with robotics, accurately calibrating the TCP remains a significant challenge. For example, in computer-controlled optical surfacing, the tools are disk-shaped, and in bonnet-polishing technology, the tool surfaces are spherical, making it difficult to precisely determine the working point locations on their surfaces. The laser tracker calibration method fully leverages the geometric features of the processing tools and the robot flange. By utilizing spatial transformation relationships, TCP calibration can be performed with high precision. Therefore, the method proposed in this paper is also applicable to TCP calibration of other robot-based optical manufacturing equipment.

5. Conclusions

This paper addresses the challenge of precise tool coordinate system calibration in Robot-MRF systems by introducing a laser tracker-based method for TCP calibration of the MRF tool. The experimental results demonstrate that the widely adopted six-point calibration method yielded a repeatability calibration error of 5.3324 mm, substantially undermining the accuracy of processing poses and making high-precision processing infeasible. In contrast, the proposed laser tracker-based TCP calibration method achieved a repeatability calibration error of only 0.0505 mm, representing an order-of-magnitude improvement in calibration accuracy over the six-point method. This enhanced precision satisfies the stringent requirements of MRF technology, meeting the high-precision processing requirements of MRF technology.

Author Contributions: Conceptualization, R.C., L.L. and Y.P.; methodology, Y.W. and R.C.; software, Y.W. and Q.C.; validation, C.Z. and B.A.; formal analysis, Y.W.; investigation, C.Z.; resources, L.L. and Q.C.; data curation, R.C.; writing—original draft preparation, J.Z. (Jinbo Zhang); writing—review and editing, J.Z. (Jun Zheng) All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Martin, H.M.; Allen, R.; Gasho, V.; Jannuzi, B.; Kim, D.W.; Kingsley, J.; Law, K.; Loeff, A.; Lutz, R.; McMahon, T. Manufacture of primary mirror segments for the Giant Magellan Telescope. In Proceedings of the Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III, Austin, TX, USA, 10 June 2018. [\[CrossRef\]](#)
2. Vernin, J.; Muñoz-Tuñón, C.; Sarazin, M.; Ramió, H.V.; Varela, A.M.; Trinquet, H.; Delgado, J.M.; Fuensalida, J.J.; Reyes, M.; Benhida, A.; et al. European extremely large telescope site characterization I: Overview. *Publ. Astron. Soc. Pac.* **2011**, *123*, 1334. [\[CrossRef\]](#)
3. Ramió, H.V.; Vernin, J.; Muñoz-Tuñón, C.; Sarazin, M.; Varela, A.M.; Trinquet, H.; Delgado, J.M.; Fuensalida, J.J.; Reyes, M.; Benhida, A.; et al. European extremely large telescope site characterization. II. High angular resolution parameters. *Publ. Astron. Soc. Pac.* **2012**, *124*, 868. [\[CrossRef\]](#)
4. Kamikawa, K.; Nagai, A.; Ashida, T.; Tani, K.; Nariyama, T.; Ishida, T.; Takaki, J.; Kawaguchi, N.; Endo, M.; Ezaki, Y. High precision processing in TMT (Thirty Meter Telescope) structure manufacturing. In Proceedings of the Ground-Based and Airborne Telescopes VIII, Online, 14 December 2020. [\[CrossRef\]](#)
5. Liu, Z.; Li, L.; Qi, E.; Hu, H.; Luo, X. Fabrication of a 4 m SiC Aspheric Mirror Using an Optimized Strategy of Dividing an Error Map. *Photonics* **2024**, *11*, 125. [\[CrossRef\]](#)
6. Derst, G.; Giggel, V. Fabrication technologies for large optical components at Carl Zeiss Jena GmbH. In Proceedings of the Modern Technologies in Space and Ground-Based Telescopes and Instrumentation, San Diego, CA, USA, 19 July 2010. [\[CrossRef\]](#)
7. Walker, D.; Dunn, C.; Yu, G.; Bibby, M.; Zheng, X.; Wu, H.Y.; Li, H.; Lu, C. The role of robotics in computer controlled polishing of large and small optics. In Proceedings of the SPIE Optical Engineering + Applications, San Diego, CA, USA, 27 August 2015. [\[CrossRef\]](#)
8. Liu, Z.; Xie, B.; Wang, A. The research of the precise aspheric wheeled polishing technology. In Proceedings of the Sixth International Conference on Optical and Photonic Engineering, Shanghai, China, 8 May 2018. [\[CrossRef\]](#)
9. Wang, C.; Han, Y.; Zhang, H.; Liu, C.; Jiang, L.; Qian, L. Suppression of mid-spatial-frequency waviness by a universal random tree-shaped path in robotic bonnet polishing. *Opt. Express* **2022**, *30*, 29216–29233. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Huang, X.; Wang, Z.; Li, L. Study on the Impact of Positioning Errors on the Process Performance of Robotic Bonnet Polishing. *Int. J. Precis. Eng. Manuf.* **2023**, *24*, 1587–1598. [\[CrossRef\]](#)
11. Wang, B.; Tie, G.; Shi, F.; Song, C.; Guo, S. Research on the influence of the non-stationary effect of the magnetorheological finishing removal function on mid-frequency errors of optical component surfaces. *Opt. Express* **2023**, *31*, 35016–35031. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Chen, C.; Dai, Y.; Hu, H.; Uan, C. Study on the influence of a magnetorheological finishing path on the mid-frequency errors of optical element surfaces. *Opt. Express* **2024**, *32*, 523072. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Li, L.; Zhang, J.; Song, C.; Zhang, X.; Yin, X.; Xue, D. Robotic magnetorheological finishing technology based on constant polishing force control. *Appl. Sci.* **2022**, *12*, 3737. [\[CrossRef\]](#)
14. Cheng, R.; Li, L.; Li, X.; Yang, B.; Luo, X.; Xue, D.; Zhang, X. High-precision magnetorheological finishing based on robot by measuring and compensating trajectory error. *Opt. Express* **2022**, *30*, 44741–44768. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Cakir, M.; Deniz, C. High precise and zero-cost solution for fully automatic industrial robot TCP calibration. *Ind. Robot* **2019**, *46*, 650–659. [\[CrossRef\]](#)
16. Wang, X.; Ren, W.; Wang, K.; Liu, J.; Lin, J.; Feng, J.; Zheng, J.; Li, F. A Self-Calibration Method for Robot End-Effector Using Spherical Constraints. *Appl. Sci.* **2024**, *14*, 9824. [\[CrossRef\]](#)
17. Yang, Z.; Gong, L.; Liu, C. Efficient TCP calibration method for vision guided robots based on inherent constraints of target object. *IEEE Access* **2021**, *9*, 8902–8911. [\[CrossRef\]](#)

18. Fares, F.; Souifi, H.; Bouslimani, Y.; Ghribi, M. Tool center point calibration method for an industrial robots based on spheres fitting method. In Proceedings of the 2021 IEEE International Symposium on Robotic and Sensors Environments (ROSE), Virtual, 28 October 2021. [[CrossRef](#)]
19. Li, G.; Luo, H.; Wang, L. Fast calibration method of robot tool coordinate. *Opt. Precis. Eng.* **2021**, *29*, 1375–1386. [[CrossRef](#)]
20. Landis, M. Unit quaternion from rotation matrix. *J. Guid. Control Dyn.* **2008**, *31*, 440–442.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.