Title:

Adaptive Assembly Adjustment Strategy for Optical Systems Based on Digital Twin

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Keywords:
Optical System Assembly, Digital Twin, Fuzzy Control

DOI: 10.14733/cadconfP.2024.276-282

Introduction:

Digital twin technology, important in intelligent manufacturing with industrialization and informatization[1], has progressed from conceptual to practical. However, the performance of the current assembly of coaxial optical systems, relying on manual operation, is limited by human experience and technique, causing uncertainty[2]. An adaptive posture adjustment strategy for optical systems based on the digital twin framework is proposed in this paper. First, the mathematical model of the optical system performance based on the assembly posture of the lenses is established. Second, the displacement and angle during the assembly are controlled by a fuzzy controller. A prototype system that can be adjusted and measured is constructed to validate this strategy, and the results are analyzed. The results show that this strategy can achieve posture control of coaxial optical systems and be compatible with the digital twin framework, facilitating its further application.

Assembly Digital Twin Framework for Optical System:

Assembly digital twin is a technology that integrates the physical, data, and virtual spaces of the whole assembly process to enhance its quality and efficiency[3][4]. Fig.1 shows the alignment process of the coaxial optical system constructed based on the assembly digital twin framework.

The alignment of the optical system is a complex task that involves many factors, such as the position, attitude, shape, bolt tightening force, temperature, humidity, etc. of the lenses, which affect the optical system performance. These factors are classified into macroscopic and microscopic factors. The macroscopic factors are the poses of each lens during the assembly process, while the microscopic factors are the effects of the bolt tightening force on the lens surface shape. This paper focuses on the macroscopic factors of the optical system alignment and applies the assembly digital twin framework to the optical system assembly process.

The physical space consists of the objects and environment in the assembly process, such as the five-axis serial slide, the optical system, the laser interferometer and their physical conditions. The five-axis

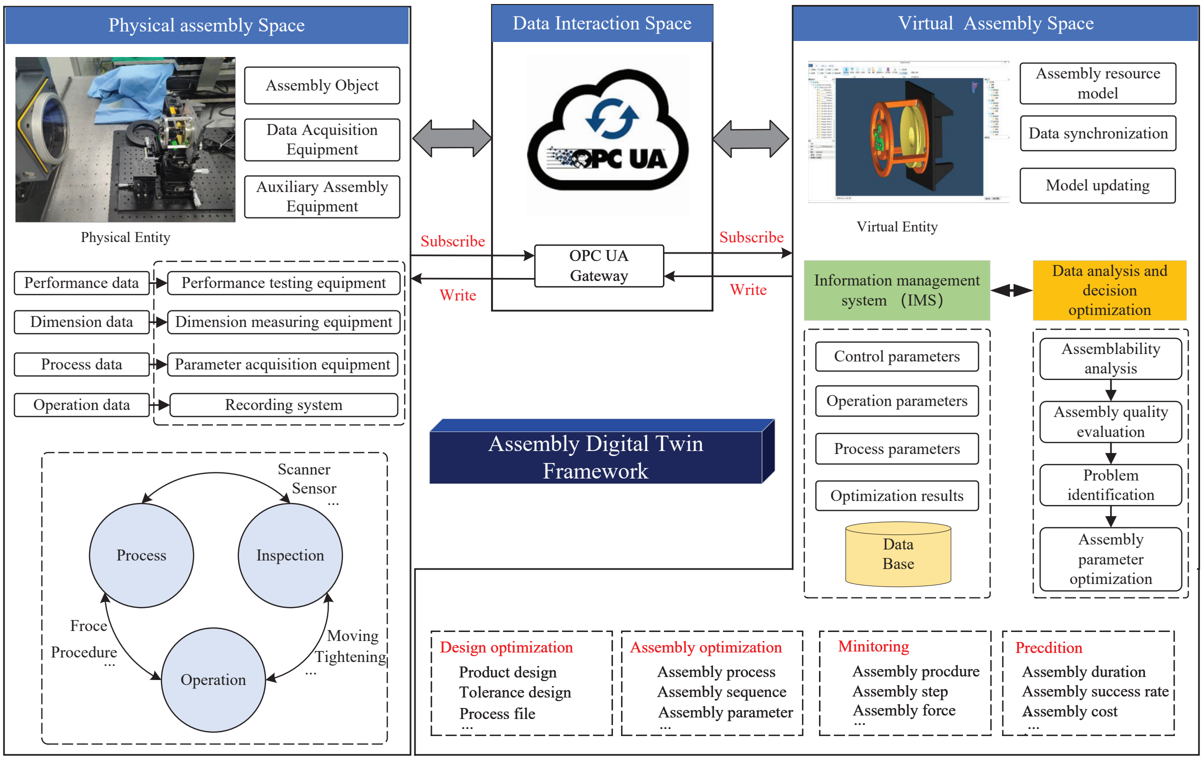


Fig. 1: Assembly digital twin framework.

tooling is a device that can control the translation and rotation of the optical system in the X, Y, Z axes directions, and adjust its position and attitude finely. The optical system is the object of alignment, and its performance depends on the poses of lenses. The laser interferometer is a tool that can measure the light wave wavefront, and evaluate the optical system performance under different poses, such as PV, RMS, etc.

The data interaction space is the data transmission and processing in the assembly process, and the Open Platform Communications Unified Architecture (OPC UA) is an open, cross-platform, secure, reliable and efficient communication protocol that can enable the information exchange and communication between the physical and virtual spaces. We use the OPC UA system to upload the pose and performance data of the optical system from the physical space to the virtual space, and send the control instructions from the virtual space to the physical space, achieving the function of the data interaction space.

The data analysis and assembly guidance are performed in the virtual space, which mainly collects data, calculates the assembly results and provides possible solutions. The effect of the lenses pose on its optical performance is analyzed, and the performance relationship of the optical system is obtained in this model. A fuzzy control algorithm based alignment strategy is designed, which handles uncertainty with fuzzy logic, achieves the closed-loop control of error with a controller, and realizes the adaptive attitude control of the optical system.

<u>Adaptive Assembly of Coaxial Optical System:</u>

Fuzzy system is a control method for complex and nonlinear models that can handle the uncertainty and fuzziness of the models. It is widely applied in multi-axis control applications such as robotics. In the assembly process of coaxial optical system, it is essential to ensure that each lens reaches a relatively ideal assembly pose, mainly to maintain the optical axis consistency of each lens. However, machining errors cause the alignment parameters of each lens to be inconsistent. Therefore, the relationship between the performance parameters of the optical system and the pose of the lens needs to be analyzed to quickly achieve the ideal assembly pose of the lens.

In this paper, the assembly performance of the coaxial optical system is measured by a laser interferometer, and expressed by the wavefront aberration. The wavefront aberration of the lens surface is represented by the Zernike polynomial coefficients, which are a set of orthogonal polynomials that are complete in the unit circle[5]. The wavefront aberration of any field point can be expanded as:

$$W(\rho,\phi)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n}C_n^m Z_n^m(\rho,\phi). \tag{3.1}$$

where $W(\rho,\phi)$ represents the aberration of the field point, ρ and ϕ are the radial and angular coordinates in pupil coordinate system, C_n^m are the Zernike polynomial coefficients, and $Z_n^m(\rho,\phi)$ are the Zernike polynomials, defined as:

$$Z_n^m(\rho,\phi)=\begin{cases} N_n^m R_n^{|m|}(\rho)\cos(m\phi), m\geq 0 \\ -N_n^m R_n^{|m|}(\rho)\cos(m\phi), m<0 \end{cases}. \tag{3.2}$$

where N_n^m is the normalization factor described in more detail below and $R_n^{|m|}(\rho)$ is given by:

$$R_n^{|m|}(\rho)=\sum_{s=0}^{(n-|m|)/2}\frac{(-1)^s(n-s)!}{s!\,[0.5(n+|m|)-s]!\,[0.5(n-|m|)-s]!}\times\rho^{n-2s}. \tag{3.3}$$

Different terms of the Zernike polynomials correspond to different types of wavefront aberrations. The 7th ($(3\rho^2-2)\rho\cos\phi$) and 8th ($(3\rho^2-2)\rho\sin\phi$) terms represent the X and Y directions of the third-order coma, respectively, while the 9th ($6\rho^4-6\rho^2+1$) term pertains to third-order spherical. The $X-coma$ is caused by misalignment due to displacement along the X axis and rotation around the Y axis, while the $Y-coma$ results from displacement along the Y axis and rotation around the X axis. Spherical aberration is triggered by misalignment in displacement along the Z axis. Therefore, calibrating the pose of lens using the five-axis adjustment fixture, corrections for the X axis and Y axis displacements and rotations are based on the respective comas, whereas Z axis displacement adjustments is informed by the spherical aberration. A fuzzy system is used in this paper to analyze the Zernike polynomial coefficients in real time, and generate control commands according to the coma and spherical values, adjust the lens pose, minimize the aberrations, and improve the optical system assembly quality and efficiency.

The control strategy aims to decrease the error and keep the alignment amount of the optical system within the desired range. The adjustment range of each axis was determined by previous experiments and experience, with the upper limit F_{dU} and the lower limit F_{dL}, to ensure that the lenses can form images during the alignment process. A fuzzy controller is designed based on the above analysis, which takes the 7th ($X-coma$), 8th ($Y-coma$) and 9th ($spherical$) terms of the Zernike polynomials as the input, and the adjustment amount of each axis of the five-axis adjustment fixture as the output. The fuzzy controller is shown in Fig.2 and its input and output variables are explained below.

Input variable: The wavefront aberration parameters $X-coma$, $Y-coma$ and *spherical* obtained by the laser interferometer are used as input variables. These parameters are quantized by using the universe of discourse, where the universe of discourse for $X-coma$ and $Y-coma$ are expressed as $I=[-0.25,0.25]$, corresponding to the values in the linguistic value set, $L=\{NB,NM,ZO,PM,PB\}$,

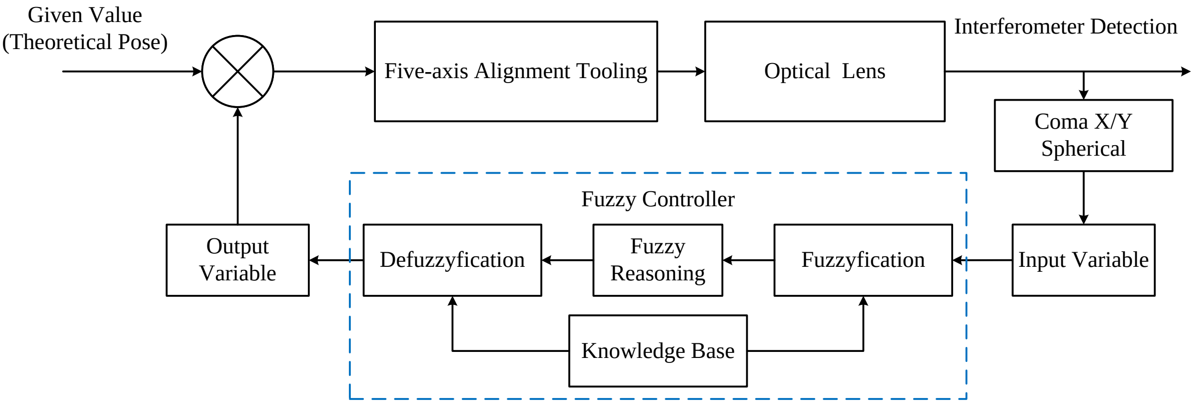
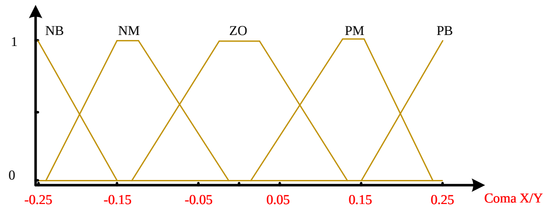
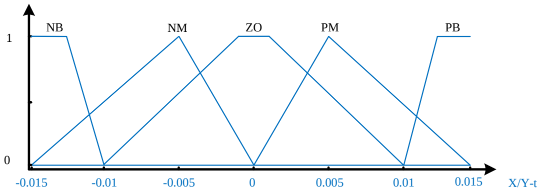


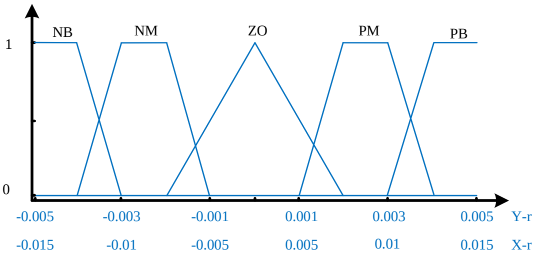
Fig. 2: Five-axis fuzzy controller.



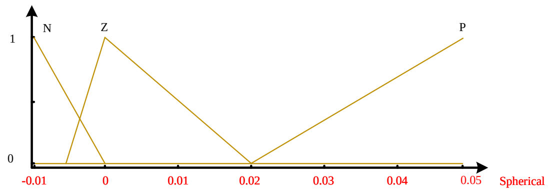
(a) Membership function of $X/Y - coma$



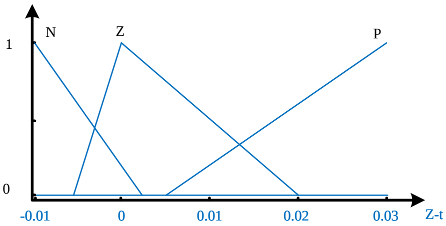
(b) Membership function of $X/Y - t$



(c) Membership function of $X/Y - r$.



(d) Membership function of *spherical*



(e) Membership function of $Z - t$.

Fig. 3: Membership functions of input and output parameters.

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Tab. 1: Rule matrix for fuzzy controller.

Input			Output				
$X - coma$	$Y - coma$	*spherical*	X-T	Y-R	Y-T	X-R	Z-T
NB/PB	NB/PB		PB/NB	PB/NB	PB/NB	NB/PB	
NB/PB	NM/PM		PB/NB	PB/NB	PM/NM	NM/PM	
NB/PB	ZO		PB/NB	PB/NB	ZO	ZO	
NM/PM	NB/PB		PM/NM	PM/NM	PB/NB	NB/PB	
NM/PM	NM/PM	N/Z/P	PM/NM	PM/NM	PM/NM	NM/PM	N/Z/P
NM/PM	ZO		PM/NM	PM/NM	ZO	ZO	
ZO	NB/PB		ZO	ZO	PB/NB	NB/PB	
ZO	NM/PM		ZO	ZO	PM/NM	NM/PM	
ZO	ZO		ZO	ZO	ZO	ZO	

denoting the values of $X - coma$ and $Y - coma$ as NB (negative big), NM (negative middle), ZO (zero), PM (positive middle), and PB (positive big). The universe of discourse for *spherical* is denoted as $I = [-0.01, 0.05]$, and corresponding linguistic value set is $L = \{N, Z, P\}$.

Output variable: The output variables are the adjustment amount of each axis in the five-axis adjustment fixture, where the universe of discourse for the translation along the X and Y axes are both $I = [-0.015, 0.015]$, the universe of discourse the rotation around the X and Y axes are $I = [-0.015, 0.015]$ and $I = [-0.005, 0.015]$ respectively, corresponding linguistic variables are also L. The universe of discourse for the translation along the Z axis is $I = [-0.01, 0.03]$, its corresponding linguistic value set is same as *spherical*.

In the fuzzification process, the input and output data sets are converted into fuzzy data sets through the fuzzy membership functions. Fig.3 shows the membership function of each input and output parameters. Then, a rule matrix base with several control rules is established based on the experience and logic of the human operators to reduce the error value to a reasonable range quickly. A large adjustment amplitude is used when the error value is large; a small adjustment amplitude is used when the error value is small, to avoid overshooting. The stability of the control system is also considered, to ensure the effect and safety of the attitude adjustment. A rule matrix of the five-axis adjustment fixture parameters is used to represent these rules, as shown in Tab.1.

Results for the fuzzy controller: A specific instance of optical system assembly has validated the effectiveness of the designed fuzzy controller. As illustrated in Fig.4, a prototype system for the alignment and adjustment of an optical system is presented. The initial aberrations of the optical system are detected, and its third-order aberrations are used as the input for the fuzzy controller. The adjustment amounts for each axis of the five-axis alignment fixture are taken as the output. Subsequent aberration detection indicates that the fuzzy controller has effectively adjusted the lens?s pose and significantly reduced the aberration terms, as shown in Tab.2. This case demonstrates the rationality and feasibility of our fuzzy controller. In future research, we will explore the integration of the fuzzy control module into the digital twin assembly framework to achieve more efficient and intelligent alignment.

Conclusions:

This paper proposes a solution based on fuzzy control algorithm to address the low efficiency and low automation problems in the alignment process of coaxial optical systems. By using the interference images of the optical systems, we analyze the relationship between the aberration coefficients and the adjustment amounts, and design a fuzzy control system accordingly. The system can automatically calculate the appropriate adjustment amounts based on the different aberration coefficients, and output

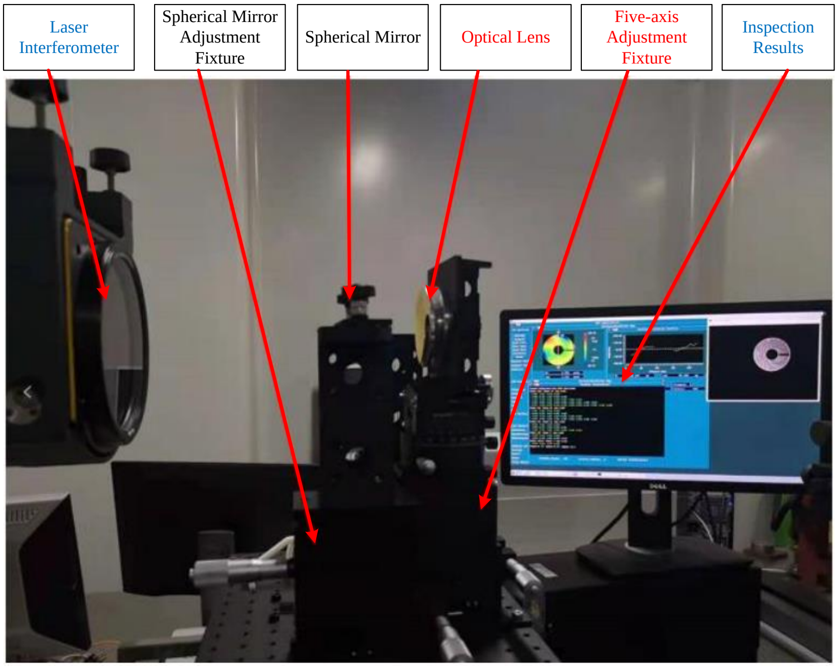

Fig. 4: Optical lens assembly prototype system.

Tab. 2: Simulation results of fuzzy controller.

Original wavefront aberrations	7th-coma X 0.108		8th-coma Y 0.134		9th-spherical 0.01
Five-axis alignment fixture adjustment parameters	X-T -0.005	Y-R -0.001	Y-T -0.006	X-R 0.006	Z-T 0.005
Original wavefront aberrations	7th-coma X -0.023		8th-coma Y -0.039		9th-spherical -0.003

them to the five-axis fixture, achieving the precise alignment of the lens. Moreover, we integrate the system as a reusable computational module into the digital twin assembly framework. In this way, when we need to align different types of optical systems, we only need to adjust the relevant parameters of the fuzzy control system, and we can deploy and run it quickly.

Acknowledgement:
This research was supported by the Chinese National Natural Science Foundation through grants 62102011, 62102012.

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