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Automatic Adjustment for Optical Axes in Laser Systems Using Stochastic Binary Search Algorithm for Noisy Environments

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Summary. We have proposed an automatic adjustment method using genetic algorithms (GA) to adjust the optical axes in laser systems. However, there are still two tasks that need to be solved: (1) long adjustment time and (2) adjustment precision due to observation noise. In order to solve these tasks, we propose a robust and efficient automatic adjustment method for the optical axes of laser systems using stochastic binary search algorithm. Adjustment experiments for optical axes with 4-DOF demonstrate that the adjustment time could be reduced to half of conventional adjustment time with GA. Adjustment precision was enhanced by 60%.

Keywords: automatic adjustment, optical axes, genetic algorithm, binary search, noisy environments.

16.1 Introduction

Laser systems are currently essential in various industrial fields. For laser systems, the adjustment for the optical axes is crucial, because the performance of the laser system deteriorates when the optical axes deviate from their specification settings, due to disturbances such as vibrations. However, it is very difficult to adjust the optical axes, because adjustment requires high-precision positioning settings with micrometer resolutions and because it is necessary to adjust for multi-degree-of-freedom (DOF) that have an interdependent relationship. Thus, adjustment costs are a major problem due to the huge amount of time required for a skilled engineer to adjust the optical axes. In order to overcome this problem, we have proposed automatic adjustment methods for optical axes using genetic algorithms (GA) [1–3]. For example, our method has been successfully applied to the automatic adjustment of a femto-second laser

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that has 12-DOF [2]. However, there were two problems with the proposed methods that needed to be solved. First, it has been necessary to reduce the adjustment time to within 10 min. Because a laser system should ideally be readjusted every time it is used. For practical considerations, adjustment time must be as fast as possible. Second, because the adjustment of the optical axes is usually undertaken in very noisy environments, the precision of adjustment can vary widely.

In order to overcome these problems, we propose a novel adjustment method which has two characteristics (1) The method adopts a Binary Search Algorithm (BSA) [4]. The BSA gradually changes from the exploration phase to the exploitation phase. The exploration phase searches a region that has not previously been searched using a binary search tree. The exploitation phase searches a region around good points. (2) The fitness value adopts weighted average of sampled fitness values using a search history.

There are two advantages with the proposed method: (1)adjustment time can be reduced. The method does not search in regions that have previously been searched. In addition, it is not necessary to reevaluate the fitness function to mitigate the influence of noise. (2)It provides robust automatic adjustment. Instance of premature convergence or falling into local solutions do not occur because the adjustment is less influenced by noise. Accordingly, we can realize robust and efficient automatic adjustment systems for the optical axes within laser system by the proposed method. Conducted experiments involving 4-DOF adjustment with the proposed method demonstrate that (1)adjustment time can be reduced to half of conventional adjustment time, and (2)precision can be enhanced by 60%.

This chapter is organized as follows: In Sect. 16.2, we explain the adjustment system for the optical axes of laser systems and the conventional method of automatic adjustment. Section 16.3 describes our proposed method, and Sect. 16.4 outlines the automatic adjustment system used in the experiments. In Sect. 16.5, we present the experimental results obtained for the proposed method. Finally, a summary of this study and future investigations are provided in Sect. 16.6.

16.2 Adjustment Systems for Optical Axes and Automatic Adjustment Methods

16.2.1 Adjustment Systems for Optical Axes

For laser systems, the adjustment of the optical axes is crucial because the performance of laser systems deteriorates when the optical axes deviate from their specification settings. Let us explain adjustment systems taking a femto-second laser system as an example. A characteristic of femto-second lasers is that the high-peak power is inversely proportional to the short duration of the laser pulses, so they can generate high power levels, over 1 MW, during femtosecond (10^{-15} s) pulses. This system that consists of seven mirrors and two prisms has 12-DOF to be adjusted with micrometer resolutions. The optical axes are adjusted by moving stepping motors, so that the output power from the laser system is maximized.

In such an adjustment system, there are two sources of observational noise influencing output evaluation. The first is the noise in the detectors that evaluates the output from the laser system.The second source is the precision of the positioning motors. While the positioning motors are moved according to constant displacements, actual axial displacements are not constant. Therefore, the optical axes can deviate from the desired state, even if motors are moved according to the displacement settings in seeking to adjust the target state. Thus, the adjustment of optical axes must be carried out by considering these sources of noise. In the system, for example, manual adjustment takes about a week.

16.2.2 Automatic Adjustment Methods

We have already demonstrated how it is difficult for a hill climbing method to automatically adjust optical axes [2]. There are two reasons for this. The first reason is that the adjustment becomes trapped by local solutions, because the adjustment points of the laser system have an interdependent relationship. The second reason is that adjustment must be executed in noisy environments. In order to overcome these problems, we have proposed an adjustment method using GA [1–3]. In the proposed method, a chromosome is a set of genes, which represent motor displacements, and fitness is the output from the laser system. We have demonstrated the effectiveness of automatic adjustment using GA for the laser system.However, there were two problems that needed to be solved: (1) Adjustment took a long time, because the method also performed exploration during the final phase. The time for motor movements, which accounts for nearly all of the adjustment time, increases in proportion to the degree of motor displacement. (2) Robust adjustment is difficult, because search is influenced by the two sources of noise explained in sect. 16.2.1. Consequently, instances of premature convergence occurred or adjustment became trapped to local solutions, so adjustment precision varied widely.

16.3 Proposed Method

We propose a robust and efficient automatic adjustment for the optical axes of laser system using a binary search algorithm (BSA) [4] for noisy environments. The flowchart of the proposed method is shown in Fig. 16.1. This method utilizes weighted averaged fitness [5] in the BSA as explained in Fig. 16.1. We refer to the proposed method as BSW. The algorithm is explained in more detail later.

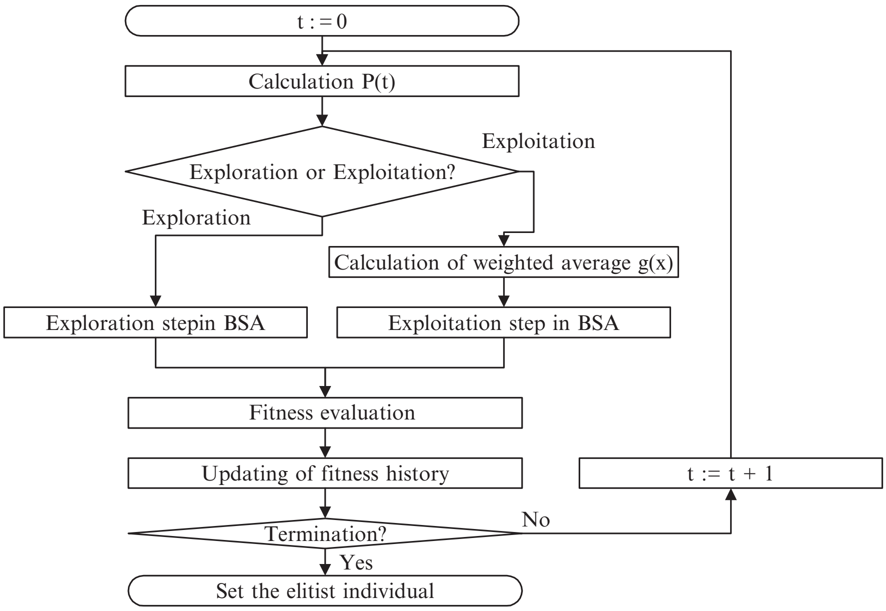

Fig. 16.1. Flowchart for the proposed method

16.3.1 Binary Search Algorithm

The strategy of BSA is to use a binary search tree [4] to divide the search space into empty regions, allowing for the largest empty regions to be approximated. The search tree is constructed by generating a point x_t at random within the chosen hypercube, then by dividing the hypercube along the dimension that yields the most "cube-like" subspaces. The basic algorithm for constructing the binary search tree works by repeatedly choosing an exploration or exploitation step:

1. Exploration: Next point x_{t+1} is generated within the largest empty region.
2. Exploitation: Next point x_{t+1} is generated within the largest empty region that is within a small distance from a "good point."

The coordinates of the point x_t and the evaluated value f_t at x_t are stored in a search history $F(t)$ represented in (16.1).

$$F(T) = \{(x_1, f_1), (x_2, f_2), \ldots, (x_i, f_i), \ldots, (x_T, f_T)\} \tag{16.1}$$

The decision of whether to perform exploration or exploitation is made based on a probability distribution $P(t)$ that varies with the number of fitness evaluations. $P(t)$ calculated using (16.2) is illustrated graphically in Fig. 16.2.

$$P(t) = (C-1)\frac{\tanh(\frac{t/N-K}{\sigma}) - \tanh(\frac{-K}{\sigma})}{\tanh(\frac{1-K}{\sigma}) - \tanh(\frac{-K}{\sigma})} + 1 \tag{16.2}$$

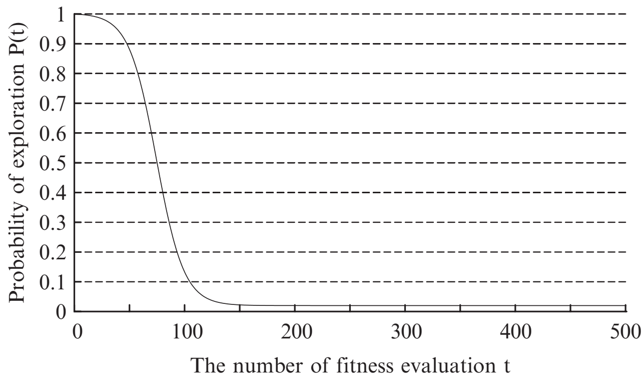

Fig. 16.2. Probability of exploration for C=0.02, K=0.1, σ=0.05, and N=500

C is the minimum probability of performing the exploration step, σ is the rate at which the probability of exploration decays, K is the mid point of the decay, and N is the maximum number of trials that are to be performed.

The automatic adjustment method using BSA can efficiently adjust optical axes, because the search phase in BSA gradually shifts from exploration to exploitation according to $P(t)$ based on the number t of fitness evaluation, as shown in Fig. 16.2.

16.3.2 Weighted Averaged Fitness

The conventional method of coping with noisy fitness functions is to evaluate the fitness values several times for each individual and to adopt the average of the sampled values [6, 7]. However, adjustment for laser systems by the conventional method is not practical, because adjustment time increases. For example, if moving the motors and detecting to obtain a fitness value are performed N times, then the adjustment time increases N-fold.

In order to solve this problem, a weighted average value, which is calculated from the search history, is used for the fitness value. For the laser system, we assume the detected value f_t at x_t increases or decreases in proportion to a distance d_t from a certain point x to the point x_t and that noise varies according to a normal distribution. The maximum likelihood estimation of $f(x)$ can be obtained as follows:

$$g(x) = \frac{f(x) + \sum_{t=2}^{T} \frac{1}{1+k\times d_t^2} f_t}{1 + \sum_{t=2}^{T} \frac{1}{1+k\times d_t^2}}, \tag{16.3}$$

$$d_t = \|x - x_t\|, \tag{16.4}$$

where $f(x)$ is evaluated value with the detector, $f_1 = f(x)$, $x_1 = x, k$ is the proportional value, and d_t is the distance from sampled points. The "good point" in exploitation step of the BSA is decided using this weighted averaged fitness $g(x)$.

There are two advantages of this method. The first is that this method can prevent premature convergence during the exploitation phase due to observational noise. The second advantage is that the number of evaluation is just one time for each individual. Thus, this method is capable of adjusting the optical axes robustly and efficiently in noisy environments.

16.4 An Automatic Adjustment System for Optical Axes

In this chapter, we demonstrate the effectiveness of the proposed method using the most basic adjustment system [3, 5]. This adjustment system consists of two mirrors with two stepping motors, an evaluation detector to detect the positioning of the optical axis, a motor controller to control the stepping motor for the mirror, and PC to execute the flow explained in Fig. 16.1. The mirrors in the system can be adjusted according to 2-DOF to adjust the positioning of the optical axis.

A photograph of the experimental system is shown in Fig. 16.3. The motor controller consists of the stepping motor driver and the mirror holder system with a resolution of 0.075 μm/step. With this controller, the time to move the motors in evaluating each individual is at maximum of about 4 s. The detector with a resolution of 1.39 μm, can detect X–Y coordinates of the optical axes on the detector front. The pumping source is a *He–Ne* gas laser and the beam diameter is 2 mm.

The optical axes are adjusted automatically based on the flow shown in Fig. 16.1. A chromosome in the BSW represents displacement for the four stepping motors, which moves the two mirrors. The displacement of each

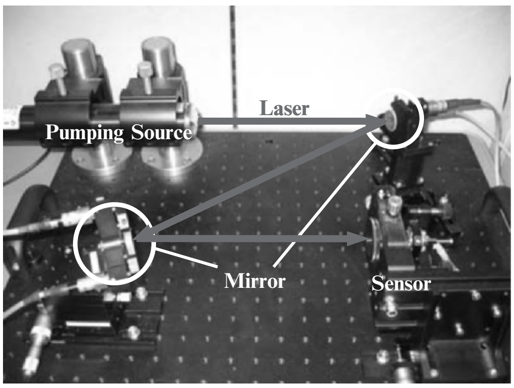

Fig. 16.3. The automatic adjustment system for optical axes with 4-DOF

stepping motor is represented by 8 bits. The evaluation value $f(x)$ uses a positioning error, which is the Euclidean distance between the positioning of the optical axes and the target position, calculated from the detected X–Y coordinates.

16.5 Adjustment Experiments

16.5.1 The Details of Experiments

Three experiments were conducted to examine the effectiveness of the proposed method. These were an automatic adjustment experiment using a GA, automatic adjustment experiment using BSA, and the automatic adjustment experiment using BSW.

The adjustment goal in each case was set to the laser system to its ideal state (i.e., the error in terms of the target positioning of the optical axes is 0). The initial conditions were random state where the positioning was altered within a range of ±5 mm. Adjustment started from the initial states. Adjustment terminated when the number of fitness evaluations was 500, and were conducted over 10 trials. After adjustment, the optical axes were set to the best state based on the identified elitist individual. The parameters in these experiments were as following:

- GA: The population size was 20 and the probabilities for crossover and mutation were 0.7 and 0.05, respectively.
- BSA: Parameters of $P(t)$ were $C = 0.02$, $K = 0.15$, $\sigma = 0.05$, and $N = 500$.
- BSW: Parameters of $P(t)$ were the same as BSA, and $k = 100$.

16.5.2 Experimental Results

Table 16.1 presents the average results for 10 trials for each adjustment. Each trial result is shown in Table 16.2. In these table, "fit" refers to fitness and "reset" is the evaluation value, i.e., positioning error, when the optical axis is reset to the best state based on the adjusted results. In these tables, the fitness values for the GA and BSA are actual detected values, while the fitness value of BSW is a calculated weighted average value, which is indicated by $*$ in Tables 16.1 and 16.2.

Table 16.1. The results for three adjustments

	Time	Fit-ave	Fit-σ	Reset-ave	Reset-σ	Positioning error-ave (μm)
GA	26.1	17.7	11.2	31.3	16.8	43.5
BSA	10.6	10.7	16.0	28.9	19.8	40.2
BSW	13.1	22.7$*$	12.1$*$	13.5	10.4	18.8

Table 16.2. The results for each trial of the averaged results for the three adjustments

	GA		BSA		BSW	
	Fitness	reset	Fitness	reset	Fitness	reset
1st trial	14.0	7.6	1.4	10.6	14.0∗	4.5
2nd trial	20.0	19.8	7.0	19.0	16.5∗	13.0
3rd trial	9.4	40.3	53.6	54.9	13.5∗	16.3
4th trial	28.3	51.6	8.5	63.0	11.2∗	4.1
5th trial	17.2	22.1	1.0	17.1	46.7∗	38.3
6th trial	28.0	24.7	11.4	9.1	23.1∗	7.3
7th trial	38.1	49.9	18.0	30.5	21.5∗	13.9
8th trial	9.2	56.2	4.1	43.0	26.6∗	7.3
9th trial	3.2	23.0	1.0	7.1	40.7∗	22.5
10th trial	9.0	17.7	1.4	35.2	13.8∗	8.1
Average	17.7	31.3	10.7	28.9	22.7∗	13.5
Standard deviation(σ)	11.2	16.8	16.0	19.8	12.1∗	10.4

First, looking at the results for the GA and BSA, clearly both could adjust the optical axes, because the fit-average values were 17.7 ($17.7 \times 1.39 = 24.6\,\mu m$) and 10.7 ($10.7 \times 1.39 = 14.9\,\mu m$) for the GA and BSA, respectively. Moreover, efficient adjustment was achieved by BSA, because, in terms of adjustment times, the BSA required 10.6 min while the GA took 26.1 min. The reason for this difference is that BSA does not carry out the exploration step in the final phase. However, the levels of precision with GA and BSA deteriorated after resetting of the optical axes: the precision for the GA dropped to 31.3 ($31.3 \times 1.39 = 43.5\,\mu m$) from 17.7 ($24.6\,\mu m$), while the precision for the BSA dropped to 28.9 ($28.9 \times 1.39 = 40.2\,\mu m$) from 10.7 ($14.9\,\mu m$). The reason for this is that both the GA and BSA are influenced by observation noise. The large reset-σ values are consistent with this explanation, as shown in Table 16.1. Therefore, both BSA and GA failed to provide robust adjustment.

Second, turning to compare the results for the BSA and BSW, in terms of the average value after the optical axes were reset, the precision with the BSW improves quite remarkably in contrast with that for the BSA, because BSA was 28.9 ($40.2\,\mu m$) while BSW was 13.5 ($13.5 \times 1.39 = 18.8\,\mu m$), as shown in Table 16.1. This results indicates that the precision was enhanced by 60% compared to the results for the GA. Moreover, the BSW was able to achieve a robust adjustment, because reset-σ value for the BSW was 10.4 while reset-σ value for the BSA was 19.8. The BSW was less influenced by noise than the BSA, because it adopted a weighted average value for the fitness value. In terms of adjustment times, the BSW could adjust the optical axes within half the time required for the GA, because the BSW required only 13.1 min while GA took 26.1 min. However, adjustment using BSW took a little more time compared to the BSA, because of the time involved in calculating the weighted average values, although this can be improved by limiting the extent of search history used.

16.6 Conclusions

In this chapter, we have proposed a method for the robust and efficient automatic adjustment of optical axes using BSW. From the results of adjustments experiments using the proposed method, we have demonstrated that adjustment could be performed with half the time and with enhanced precision compared to the conventional method by 60%. Our proposed method achieved robust and efficient automatic adjustment of the optical axes.

There are three aspects of this method that require future investigation. The first aspect is the application of the proposed method to optical systems involving multiple components with several D.O.F to verify its effectiveness for more difficult adjustment tasks. The second aspect is the extension of the proposed method in order to adjust the optical axes of laser systems with multiobjective [3], because the adjustment of optical axes needs essentially multiobjective adjustment. The third aspect is to reduce the levels of calculation in the weighted average values, because most of the overhead cost in our method is the additional time to calculate the weighted average values. We are aiming to demonstrate the effectiveness of the proposed method in high-end laser systems, such as femto-second lasers.

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