An Optimal Design Method for Actuators Layout of Space-based Telescope Control System

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***Abstract*-The layout of the shape actuators in the Primary Mirror segments for a space-based telescope is a crucial factor of the adaptive control system scheme, which determines the correction capability to eliminate the face-shape error caused by the environmental temperature fields and so on. The layout design of the actuators is converted to an optimization problem solved by a Genetic Algorithm. The design result of the Genetic Algorithm is identical with the global search method, which validate the optimization method.**

Keywords-space based telescope; optimal design; wavefront error correction; genetic algorithm

I. INTRODUCTION

Space-based telescopes allow higher resolution than those on the ground because of their freedom from atmospheric absorption, emission and scintillation. As a kind of prospective observatory for astrophysics, space-based telescopes need to overcome some special obstacles, such as the limited bulk of launch vehicles.[1] A deployable segmented primary, folded during the launch process, and deployed in orbit, is a feasible scheme. There have been many proposals for segmented telescopes in space such as HARD reflector, Forward Petal Deployment Concept, Rotating Stack Deployment Concept, Forward and Rear Petal Deployment Concept. In recent years there have been numerous studies of deployable telescopes with filled aperture ranging from 3- to 40-metters in diameter. [2]

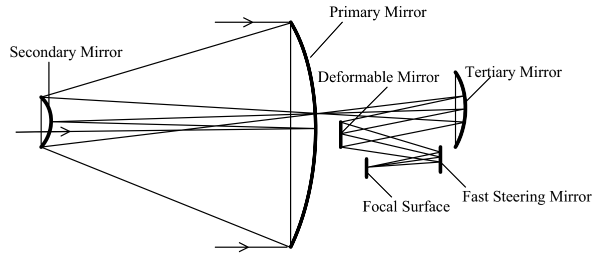

Figure 1. The optical system of a space-based telescope.

The optical system of the space-based telescope in our research is shown in Fig.1 which includes Primary Mirror (PM), Secondary Mirror(SM), Tertiary Mirror(TM), Deformable Mirror(DM) and Fast Steering Mirror(FSM). PM comprises a central segment and 8 outer fan-shaped segments (Fig. 2). Each outer segment is supported by many actuators behind the faceplate. These actuators can change the shape of the segment according the control command to eliminate the distortion error due to the segment distortion and machining error.

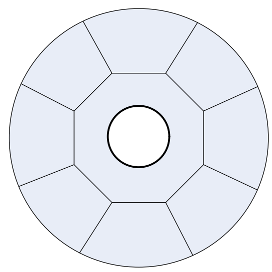

Figure 2. Primary Mirror sketch.

The layout of these shape actuators is one crucial part of the adaptive control system scheme for the space-based telescope, not only influencing the distortion of the PM segments induced by the environmental temperature fields, but only determining the correction capability of the segments to eliminate these shape errors. Any residual shape error will lead to the wavefront error decreasing the performance of the optics. Obviously it is value to find an optimal design of the actuators layout for better optical performance.

In our research, we focus the actuators layout optimization of ONE PM segment (Fig.4). First mathematical description of the actuators layout optimization problem is established; then a Genetic Algorithm (GA) is proposed to solve the optimization design problem; finally some examples and results are obtained using the method.

II. OPTIMIZATION PROBLEM

The adaptive shape control system of a PM segment is of close-loop (Fig.2) to eliminate the shape error induced by the environmental temperature field in orbit. The actuating elements are the PZT actuators which are arranged behind the mirror faceplate by some design rules; the error detector is the wave-front sensor, such as H-S sensor. The simulation procedure of the control system includes:

a) The model of the PM segment with the actuators is generated, and the initial shape distortion induced by some environmental temperature field is obtained by Finite Element Analysis (FEA). Ignoring the wavefront sensor, the above error is regard as the initial error ***E***;

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b) The influent function of each actuator is calculated out by FEA, which describes the changes of the shape of the segment face under the action of the actuator. The influence functions of all the actuators compose the influence matrix $\boldsymbol{H}$, i.e. the static linear model of the segment.

d) Using the pseudo inverse $\boldsymbol{G}_c$ of the influent function matrix $\boldsymbol{H}$ and the initial error $\boldsymbol{E}$, the controller outputs the commands of the actuators $\boldsymbol{U}$:

$$\boldsymbol{U} = \boldsymbol{G}_c\boldsymbol{E} \tag{1}$$

Where $\boldsymbol{E}$ is the error, $\boldsymbol{G}_c$ is the pseudo inverse of the matrix of influent function.

e) On the assumption of the linear system, the deformation of the PM segment under the action of all actuators is derived from the multiple of the influent function matrix and the command vector.

$$\boldsymbol{D} = \boldsymbol{H}^*\boldsymbol{U} \tag{2}$$

g) Finally, the residual distortion error of the segment is

$$\boldsymbol{E}_r = \boldsymbol{E} - \boldsymbol{D}. \tag{3}$$

where, $\boldsymbol{E}$ is the initial distortion error induced by the environmental temperature field. $\boldsymbol{D}$ is the deformation of the PM segment to eliminate $\boldsymbol{E}$.

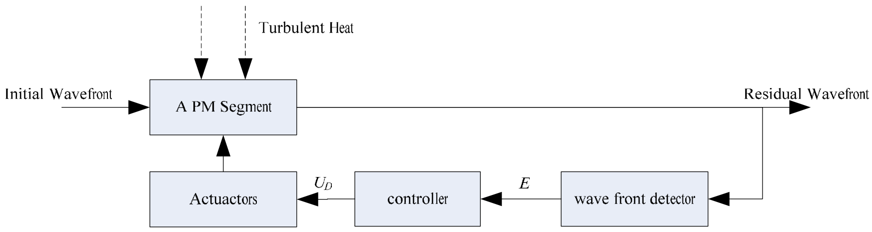

Figure 3. Control architecture of a single primary mirror correction.

The layout design of the actuators in the PM segment can be described by an optimal problem (Eq.4).

$$\min \mathrm{RMS}(\boldsymbol{E}_r((x_1,y_1), (x_2,y_2),\ldots(x_n,y_n))) \tag{4}$$

$$\text{s. t. } (x_i,y_i)\in \mathbf{A} \quad i = 1,2,\ldots,n$$

where $\boldsymbol{E}_r$ is the residual distortion error after correction. (x_i,y_i) is the coordinate of the ith actuator. $\mathbf{A}$ is the area of the the PM segment.

The above optimization problem is difficult to solve, especially with the increase of the number of the actuators, if the positions of the actuators can appear anywhere. In another word, the feasible solution space is infinite.

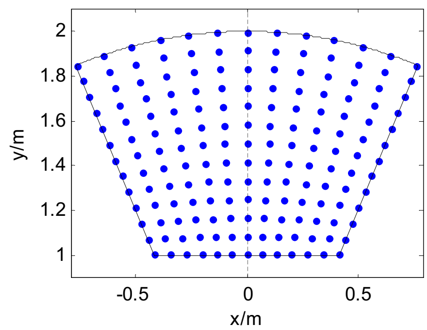

Figure 4. The schematic diagram of the candidate positions of the actuators.

To simplify the problem, $\boldsymbol{A}$ is discretized as Fig 4. All actuators are limited at the points in the PM segment. Meanwhile all actuators must be exactly symmetrical with respect to the central line.

III. GENETIC ALGORITHM

Genetic algorithms are categorized as global search heuristics. Genetic algorithms make use of techniques inspired by evolutionary biology such as selection, inheritance, mutation, crossover to reach the optimal solution.

A. Genetic representation

A typical genetic algorithm requirements a genetic representation of the solution domain . Traditionally, solutions are represented in binary as strings of 0s and 1s, but other encodings are also possible. The genetic representation of the actuator layouts is as a bit string. Each bit stands for a candidate location of an actuator in the left half part of the PM segment (including that on the symmetry axis, except the central location). A “1” value of any bit indicates an actuator on the corresponding location. A “0” indicates none. As a rule, there is always an actuator at the segment center.

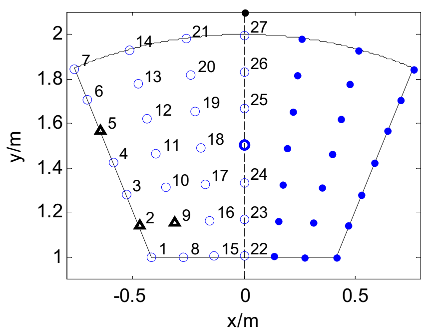

Figure 5. An example scheme of the actuators layout.

An example scheme of the actuators layout is Fig.5, which are encoded in Fig. 6. There are 49 candidate locations in the figure, 27 ones in the left part of which are encoded. Three actuators are placed at 2, 5, 9. Because of symmetry, another three actuators are in the right part of the segment, not marked in Fig.5. At the candidate position between 24 and 25, the central actuator exists.

Candidate location	1	2	3	4	5	6	7	8	9	10	…	27
Code string	0	1	0	0	1	0	0	0	1	0	…	0

Figure 6. Code string of the layouts scheme.

B. *Solving process*

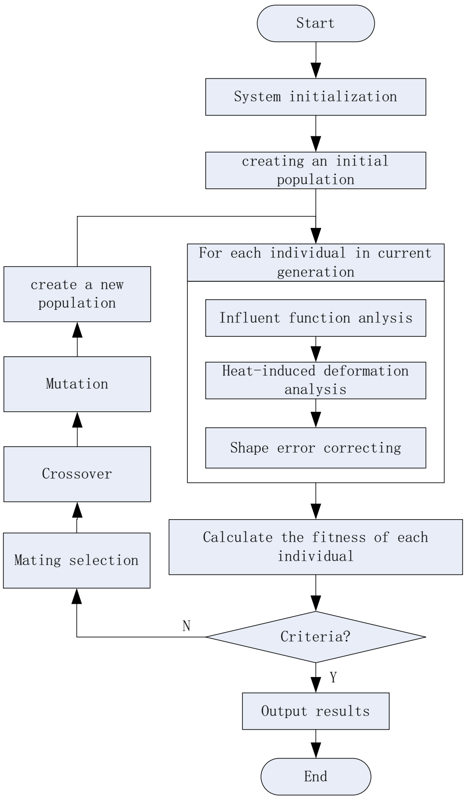

Figure 7. Solving process of the Genetic algorithm.

Genetic algorithms are implemented as a computer simulation in which a population of abstract representations of candidate solutions to an optimization problem evolves toward better solutions. For the layout optimization, the solving process includes the following steps (Fig. 7):

a) The solving process starts from a population of randomly generated individuals which are presented according to the method in the above subsection.

b) In each generation, the fitness of every individual in the population is evaluated. The fitness function is $\boldsymbol{E}_r$ in Eq.2.

c) Then, if a satisfactory fitness level has been reached for the population or a maximum number of generations has been produced, the algorithm terminates and the results are outputs.

d) Otherwise, multiple individuals are stochastically selected from the current population (based on their fitness), and modified (mutation and crossover.) to form a new population. The new population is then used in the next iteration of the algorithm.

Something must be paid a special attention to. During the operation of crossover, the total actuator number should keep identical with initial setting. The method is that additional crossovers are done when the number differs. For mutation, if the actuator number is changed, another mutation is done to balance it. If an actuator appears or disappears at the candidate location in the symmetry line in new population, another random-selected actuator in the symmetry line must added or deleted in order to balance the actuators in the whole PM segment.

IV. Examples and Results

To validate the genetic algorithm, a simple example is solved by means of the Genetic Algorithm and the global search. The candidate locations of actuators are distributed in the PM segment as Fig.5. Only 3 face shape actuators need to be placed at these candidates to minimize the RMS of the residual distortion error after correcting the distortion caused by the environmental temperature field (The temperature difference from the bottom surface of the mirror to the top surface is 5^{o}C). These two methods reach the same result (Fig.8).

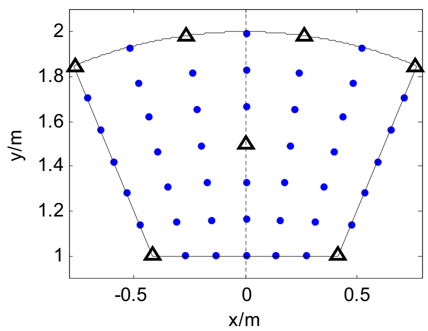

Figure 8. The same result of two methods for a simple example.

With the increase of actuators and candidate locations, the feasible solution space will expand dramatically to lead the global search impossible. Fortunately the GA method still works. A more complex design require to arrange 19 actuators at the candidate locations in Fig.1 to correcting the distortion caused by the environmental temperature field. The optimal solution reached by the GA method is reveal in Fig.9.

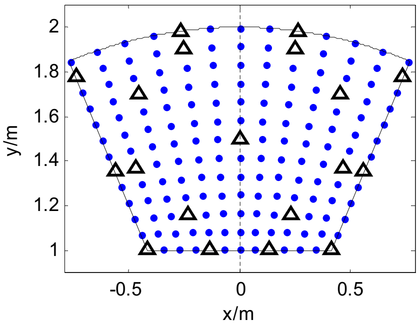

Figure 9. The result of an complex example.

V. CONCLUSIONS

The layout of the shape actuators in a Primary Mirror segment for a space-based telescope is a crucial part of the adaptive control system scheme, that determines the correction performance to eliminate the face-shape error caused by the environmental temperature fields and so on. The layout design of the actuators is converted to an optimization problem solved by a Genetic Algorithm. The design result of the Genetic Algorithm is identical with the global search method, which validate the optimization method. However, only very simple environmental temperature field is considered in the research. If the temperature field changes, the optimal solution will also changes. The layout of the shape actuators of the PM segments must synthesize the various conditions.

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