Distributed control optimization of space membrane reflectors based on machine learning

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EXTENDED ABSTRACT

1 Introduction

In space engineering, the shape accuracy of the large-scale space structures, such as antenna reflectors in orbit, is essential for high-resolution navigations and deep space detections. Electromagnetic performance of an antenna reflector mainly depends on its shape accuracy [1, 2]. In practice, the shape accuracy affected by external conditions such as thermal loads in orbit cannot meet the requirements. When a reflector moves in orbit around the earth, its temperature distributions at different orbital positions result in diverse displacement distributions, requiring the voltage re-adjustment of distributed actuation in general. Thus, it is more appropriate to consider the temperature changes of a complete orbital period into the actuation optimization. However, the on-line optimization for each case of orbital temperature distribution faces great challenges from the real-time computation and operation onboard. To solve those problems, offline optimization [3, 4] is a feasible method for the control and optimization of in-orbit spacecraft. This study focuses on the offline optimization method based on the machine learning algorithm of clustering to adapt a single control mode of distributed actuation to various temperature changes and to minimize the dynamic shape error of a reflector in orbit.

2 Analysis and optimization of a membrane reflector for a complete orbital period

The shape errors of the in-orbit membrane reflector depend on the thermal flux, which mainly come from thermal radiation and conduction in the vacuum environment of space with negligible thermal convection. Solving thermodynamic differential equation can give the temperature distribution of a spherical membrane reflector at different positions.

After that, the mechanics model of a membrane reflector with spherical surface is established to investigate its deformation under thermal loads and distributed actuation. The modeling approach proposed in [2] is utilized. The reflector is modeled as the spherical shell under the simply-supported boundary and internal inflation pressure. Piezoelectric actuators are used and bonded to the top surface of the reflector to control its deformation actively. According to the principle of the least action, the equilibrium equations of the system with respect to the generalized coordinate vector $\mathbf{X}$ can be obtained by minimizing the above total energy as follows

$$\mathbf{KX} = \mathbf{F}_T + \mathbf{F}_E \tag{2}$$

where $\mathbf{F}_T$ and $\mathbf{F}_E$ are the generalized force vectors that vary linearly with the temperature T and the electric fields E_{Ri} (or voltages x_i) of PVDF actuators, respectively. When T and E_{Ri} are known, the displacements of the reflector can be derived.

The PVDF actuators can provide the control forces to adjust the deformation of membrane reflector. However, the voltages applied to the actuators are limited in many aspects. First, the input voltages must be smaller than the breakdown voltages of the actuators. Second, the input channels of the applied voltages must be as few as possible to meet both requirements for the light weight of a spacecraft system and the high shape accuracy of a reflector. Finally, the temperature distribution of the reflector varies with the orbital position. Considering the difficulty of the hardware, it is more realistic to perform the off-line optimization that is able to obtain a single control mode of distributed actuation so as to adapt to the complete orbital period. For the above reasons, the method for deriving the unified group control of distributed actuation is proposed as follows.

In the first-run optimization, the objective is to minimize the RMS error of the reflector by optimizing the voltage within the allowable range for each actuator. The objective function constructed $f\left(\mathbf{x}\right)$ by the RMS error can be expressed as a convex quadratic programming problem and the path-following interior-point algorithm can be used to obtain the optimal solution.

Then, considering the difficulty of hardware under a large number of input channels, it is possible to impose a constraint condition that the number of input channels m is less than the number of the actuators n in the second optimization. And the vector of the optimal voltages $\mathbf{x}_{\mathrm{opt}}$ obtained in the first run will be used in this process. By subtracting the minimal value $f\left(\mathbf{x}_{\mathrm{opt}}\right)$, the optimization problem is reconstructed as

$$\begin{aligned} \min \quad & g\left(\mathbf{x}_{\mathrm{g}}\right) = \frac{1}{2}\left[\left(\mathbf{x}_{\mathrm{g}}^T + \mathbf{x}_{\mathrm{opt}}^T\right)\mathbf{H} + 2\mathbf{c}^T\right]\left(\mathbf{x}_{\mathrm{g}} - \mathbf{x}_{\mathrm{opt}}\right) \\ \text{s.t.} \quad & \mathbf{A}\mathbf{x}_{\mathrm{g}} \geq \mathbf{b} \end{aligned} \tag{3}$$

where $g(\mathbf{x}_g)=f(\mathbf{x}_g)-f(\mathbf{x}_{opt})$; the voltages in $\mathbf{x}_g$ are divided into m groups with $C=\{C_1,C_2,\cdots,C_m\}$, and the actuators in the set C_i have the same voltage value. $f(\mathbf{x}_g)$ must be equal to or greater than $f(\mathbf{x}_{opt})$. Consequently, the problem is transformed to searching voltages $\mathbf{x}_g$ to make the value of $g(\mathbf{x}_g)$ closest to zero. Thus, second optimization problem can be simplified as finding $\mathbf{x}_g$ the distance of which is closest to $\mathbf{x}_{opt}$ and can be solved by clustering such as k-means.

In the third-run optimization, the task is to obtain the characteristic positions $\mathbf{k}$ which can reflect the entire progress of the orbital temperature changes and to minimize the maximum of the dynamic RMS errors in a complete orbital period. Figure 1 shows the flowchart for the computation of the vector of characteristic positions $\mathbf{k}$. After obtaining the vector of characteristic positions $\mathbf{k}$, the grouping mode C_{opt} can be directly calculated by clustering the corresponding optimal-voltage matrix $\mathbf{X}_{opt}$.

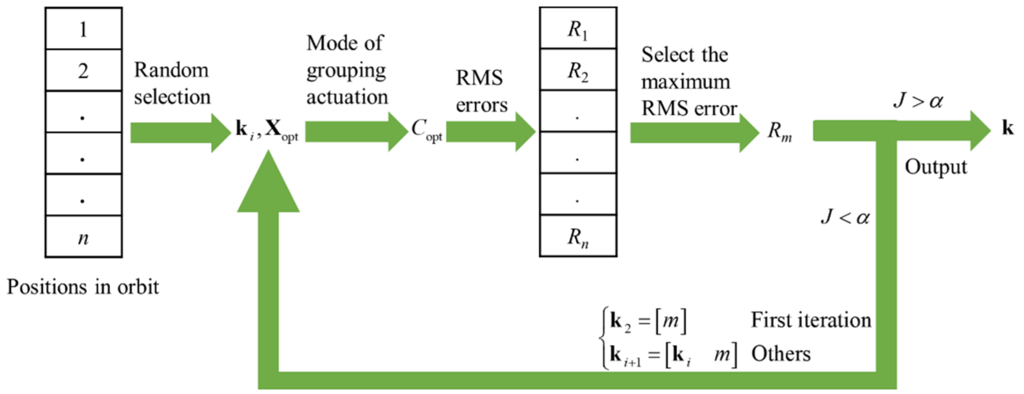

Figure 1: The computational flowchart to determine the characteristic positions.

3 Numerical results

Under in-orbit thermal loads, the temperature distribution of a reflector varies periodically as the orbital position changes which results in the change of the RMS shape error. The range of the RMS error of the reflector with different positions and inclinations of a GEO varies from 2.64 mm to 8.49 mm. The optimization method proposed in Section 2 enables one to derive the unified grouping-control mode of distributed actuation when displacement distribution is known. The shape control ability of the on-line optimization outperforms that of the off-line optimization. However, the large-scale computation and real-time adjustment required by the on-line optimal control are usually unavailable. Alternatively, the off-line optimization is suitable for the shape control with acceptable precision in many cases. Compared with the results without control, the maximum RMS error of the reflector decreases by 74.91% (from 8.49 mm to 2.13 mm) under five input channel control.

4 Conclusion

The paper presents an off-line optimization method for the unified grouping-control mode of distributed actuation to reduce the RMS errors of a membrane reflector of future satellite antenna in a complete orbital period. The study shows how to compute the temperature distributions under the in-orbital thermal flux. Then, it gives the mechanics model of the membrane reflector to analyze the displacement distributions under the influence of thermal loads and actuator control. Afterwards, the study demonstrates how to compute the unified grouping-control mode of distributed actuation by solving the clustering problem iteratively. The method can solve the off-line optimization problem efficiently, especially when the number of actuators is large. The numerical result demonstrates that the grouping control with small number of input channels can effectively reduce the maximum RMS error.

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