Structure of distributed control system in Seimei telescope

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ABSTRACT

A segmented mirror control system is indispensable for operating an astronomical telescope with which distributed control systems can be used with multiple segmented primary mirrors. In this study, we focus on the distributed control system (DCS) proposed for Seimei telescope. An interesting hierarchical structure is found by analyzing its zero–nonzero structure in the DCS, and then, 54 gains are reasonably classified into 4 groups. Design examples for selecting gains of the DCS are presented so that the closed loop pole locations are similar to those of the centralized control system (CCS). The freedom in the selections of gains by taking account of the hierarchical structure is shown to be effective by numerically evaluating the stability region and by optimizing the maximum distance between the closed loop poles of DCS and CCS.

1. Introduction

Astronomical telescopes are increasing in size all over the world due to the demands for higher spatial resolution and higher light collection ability. One technique for increasing the size is the segmented mirror control system [1]. The segmented primary mirror is a method in which multiple segmented mirrors are arranged to function as a single primary mirror and the real-time control must be executed to maintain the ideal mirror surface shape during astronomical observation. More detailed descriptions on the roles and configurations of segmented mirror control system can be found in [1].

In Japan, Kyoto University has developed Seimei telescope which is the largest in East Asia [2, 3]. Keck telescopes and their copies are the unique segmented primary mirror telescopes which are equipped with the segmented mirror control system [4], and Seimei telescope is essentially the second one in the world. Keck telescope is the mosaic-type while Seimei telescope is the petal-type. Seimei telescope is therefore the first petal-type in the world. The development process and specifications of Seimei telescope and the comparisons with conventional segmented telescopes are summarized in [3].

The authors have proposed two types of segmented mirror control algorithms for Seimei telescope [5]. One algorithm is called the Centralized Control System (CCS) and the other is called the Distributed Control System (DCS), and they are expected to play complementary roles. The DCS has more design freedoms but its structure is still unclear. A preliminary version of this paper has been presented in our conference proceeding [6], where only the zero–nonzero structure of the DCS was discussed. In this paper, we further discuss a selection method of gains in the DCS. The gains are reasonably classified into several groups by taking account of the hierarchical structure. Design examples for selecting gains of the DCS are presented so that the closed loop pole locations are similar to those of the CCS. The regions of stabilizing/destabilizing gains are numerically evaluated, and then, the region for outer segments becomes large by taking account of the hierarchical structure. Optimizations for tuning gains are carried out to minimize the maximum distance between the closed loop poles of DCS and CCS, and then, the fluctuations of the closed loop poles are shown to be suppressed by taking account of the hierarchical structure. Hence, the freedom in the selections of gains is effective by taking account of the hierarchical structure.

This paper is organized as follows: Section 2 presents the preliminaries. The main results by the zero–nonzero structural analysis of the DCS are presented in Section 3. The conclusion is given in Section 4.

2. Preliminaries

The simplified plant model in the segmented mirror control system of the Seimei telescope is modelled by the MIMO integrator model in the SEIMEI telescope

\begin{align}
\dot{x}(t) &= u(t), \\
y(t) &= Cx(t),
\end{align}
where $t \in \mathbb{R}$ is the continuous time, $x \in \mathbb{R}^{54}$ is the state, $u \in \mathbb{R}^{54}$ is the input, $y \in \mathbb{R}^{72}$ is the output, and $C \in \mathbb{R}^{72 \times 54}$ is the constant matrix called the action matrix [5].

The state $x$ consists of the whole freedoms of motions of segmented mirrors as follows:

$$x = [\alpha_1 \beta_1 \ z_1 \ \alpha_2 \beta_2 \ \cdots \ \zeta_{18}]^T,$$  

where $\alpha_k$ and $\beta_k$ are the tilt angles and $z_k$ is the out-of-plane motion of $k$th segmented mirror for $k = 1, \ldots, 18$. Figures 1 and 2 in [5] show the definitions of $\alpha_k$, $\beta_k$, $z_k$, and the mirror numbers. The output $y$ consists of the whole sensor measurements. Figures 3 and 4 in [5] illustrate the design parameters $x_{S1}$, $y_{T2}$, and $y_{S3}$, which characterize sensor locations. Figures 5 and 6 in [5] illustrate the sensor measurements $S_{0,0a}$, $S_{1,1}$, $S_{2,2}$, and $S_{1,3}$, which measure the relative positions between segmented mirrors.

The nominal value of $C$ is determined from the design parameters of the Seime telescope. Applicability of open-loop system identification technique with integrators was discussed in [7] but a positive conclusion was not obtained because this technique is fragile for non-constant input offsets. Hence, the nominal value of $C$ is supposed in this paper. The procedure for deriving the nominal value of the action matrix $C$ is summarized in [8].

The objective of the segmented mirror control system is to keep the relative positions of segmented mirrors during observation. This objective is formulated as the stabilization problem of the plant model in Equations (1) and (2).

Two types of constant output feedback control algorithms have been presented and tested in simulations for the nominal value of $C$ by the authors [5]. Necessary information on control algorithms is described below and the details of control algorithms are summarized in [8].

One is called the centralized control system (CCS). From the sensor allocations, the action matrix $C$ is shown to be column full rank. The CCS is given by

$$u = -KC^Ty,$$  

where $K \in \mathbb{R}$ is the scalar gain in the centralized control and $C^T \in \mathbb{R}^{54 \times 72}$ is the Moore-Penrose inverse of $C$. The term $C^T y$ in the right hand side of Equation (4) recovers the state $x$ from the output $y$, and therefore, the centralized control in Equation (4) can be identified as the state feedback control $u = -Kx$. The closed loop system of Equations (1)–(4) becomes

$$\dot{x} = -Kx,$$  

which shows that the time constant of the CCS is specified to $1/K$.

The other is called the distributed control system (DCS). The idea of DCS is to estimate the state $x$ from local sensor information. For example, the DCS to the 1-st segmented mirror is given by

$$u_1 = -K_{a,1} \frac{-S_{0,0a} - S_{1,1}}{x_{S1}},$$  

$$u_2 = -K_{\beta,1} \frac{-S_{2,2} - S_{1,3}}{y_{T2} + y_{S3}},$$  

$$u_3 = -K_{z,1}S_{0,0a},$$

where $u_1$, $u_2$, and $u_3$ in the left hand sides are the 1-st to 3-rd elements of the input $u$, see Equation (10) in [5]. The terms $\frac{-S_{0,0a} - S_{1,1}}{x_{S1}}$, $\frac{-S_{2,2} - S_{1,3}}{y_{T2} + y_{S3}}$, and $S_{0,0a}$ in the right hand sides are estimates of $\alpha_1$, $\beta_1$, and $z_1$ from local sensor information $S_{0,0a}$, $S_{1,1}$, $S_{2,2}$, and $S_{1,3}$. The coefficients $K_{a,1}$, $K_{\beta,1}$, $K_{z,1}$ in the right hand sides are the gains of the DCS for the 1-st segmented mirror.

By aligning the elements of the input $u$, the DCS is written as

$$u = F_d y,$$  

where $F_d \in \mathbb{R}^{54 \times 72}$ is the constant output feedback gain.

The DCS can be identified as the quasi-state feedback control. In principle, the gains $K_{a,k}$, $K_{\beta,k}$, $K_{z,k}$ can be chosen for each mirror. But the common gains

$$K_{a,k} =: K_a, \quad K_{\beta,k} =: K_\beta, \quad K_{z,k} =: K_z,$$  

have been selected for $k = 1, \ldots, 18$ in [5] for simplicity. The authors have presented an example in which the DCS can stabilize the system as shown in Section 4.2 in [5] but the selection method of gains has not fully discussed yet.

The purpose of this study is to investigate the structure of the closed loop system, to discuss the appropriate freedom of gains, and to discuss the selection method of gains in the DCS.

3. Main results

3.1. Zero–nonzero structure analysis

The closed loop system of the DCS is given by

$$\dot{x} = F_dCx,$$  

from Equations (1), (2), and (9). To study the structure of closed loop system, we introduce the new state variable $\tilde{x}$ as follows:

$$\tilde{x} = \begin{bmatrix} \tilde{x}_1^T & \tilde{x}_2^T & \tilde{x}_3^T & \tilde{x}_4^T \end{bmatrix}^T,$$

where the superscript T denotes the transpose of a vector or a matrix and the block elements of $\tilde{x}$ are given by

$$\tilde{x}_1 = [\alpha_1 \beta_1 \alpha_2 \beta_2 \cdots \alpha_6 \beta_6]^T,$$  

$$\tilde{x}_2 = [\alpha_7 \beta_7 \alpha_8 \beta_8 \cdots \alpha_{18} \beta_{18}]^T,$$  

$$\tilde{x}_3 = [z_1 \ z_2 \ \cdots \ \zeta_6]^T,$$
\[
\tilde{x}_4^T = [z_7 \ z_8 \ \cdots \ z_{18}]^T.
\] (16)

The block elements \(\tilde{x}_1\) and \(\tilde{x}_2\) are related to tilt angles and the block elements \(\tilde{x}_3\) and \(\tilde{x}_4\) are related to the out-of-plane motions. The block elements \(\tilde{x}_1\) and \(\tilde{x}_3\) are related to the inner segmented mirrors and the block elements \(\tilde{x}_2\) and \(\tilde{x}_4\) are related to the outer segmented mirrors.

The original state \(x\) and the new state \(\tilde{x}\) are related by
\[
\tilde{x} = \Sigma^T x,
\] (17)
where \(\Sigma \in \mathbb{R}^{54 \times 54}\) is the permutation matrix.

The closed loop system in Equation (11) is then written as
\[
\dot{\tilde{x}} = \tilde{A}\tilde{x},
\] (18)
where
\[
\tilde{A} = \Sigma^T F_d C\Sigma
\] (19)
is the coefficient matrix of the closed loop system in Equation (18).

The zero–nonzero structure of \(\Sigma^T F_d\) is displayed in Figure 1. The black dots represent nonzero elements, the green and white dots represent zero elements. The green dots are introduced to classify the zero–nonzero structure. By the definition of \(F_d\), two common values are included in the \(k\)th row \((k = 1, \ldots, 36)\) and only one value is included in the \(k\)th row \((k = 37, \ldots, 54)\).

The zero–nonzero structure of \(C\Sigma\) is displayed in Figure 2. The blue dots represent \(-1\), the red dots represent \(1\), and the black dots represent the other nonzero elements. The green dots classify the zero–nonzero structure. By the definition of \(C\), the same numbers of \(1\) and \(-1\) are included in the \(k\)th column \((k = 37, \ldots, 54)\).

By taking account of the structures of \(\Sigma^T F_d\) and \(C\Sigma\), the matrix \(\tilde{A}\) is decomposed as follows:
\[
\tilde{A} = \begin{bmatrix}
\tilde{A}_{11} & 0 & 0 & 0 \\
0 & \tilde{A}_{22} & 0 & 0 \\
0 & 0 & \tilde{A}_{33} & 0 \\
\tilde{A}_{41} & \tilde{A}_{42} & \tilde{A}_{43} & \tilde{A}_{44}
\end{bmatrix}
\] (20)

The zero–nonzero structure of \(\tilde{A}\) is displayed in Figure 3. The black dots represent the nonzero elements and the green dots classify the zero–nonzero structure. The block elements of \(\tilde{A}_{12}, \tilde{A}_{14}, \tilde{A}_{32},\) and \(\tilde{A}_{34}\) are zero because they are the sum of the multiplications of the zero and nonzero matrices as indicated in Figures 1 and 2. The block elements of \(\tilde{A}_{13}, \tilde{A}_{23},\) and \(\tilde{A}_{24}\) are zero because each of their elements is the difference of the same values as indicated in the blue and red dots in Figure 2.

Because each element of the DCS is a multiplication of the scalar gain and local sensor measurements as illustrated in Equations (6)–(8), the matrix \(\tilde{A}\) can be further decomposed as follows:
\[
\tilde{A} = \tilde{K}\tilde{S},
\] (21)
where
\[
\tilde{K} = \begin{bmatrix}
\tilde{K}_{11} & 0 & 0 & 0 \\
0 & \tilde{K}_{22} & 0 & 0 \\
0 & 0 & \tilde{K}_{33} & 0 \\
0 & 0 & 0 & \tilde{K}_{44}
\end{bmatrix},
\] (22)
The matrix $\tilde{K}$ is diagonal as shown in Equation (22); specifically, $\tilde{K}_{11}$ contains $K_{\alpha,k}$ and $K_{\beta,k}$ for $k = 1, \ldots, 6$ in diagonal entries, $\tilde{K}_{22}$ contains $K_{\alpha,k}$ and $K_{\beta,k}$ for $k = 7, \ldots, 18$ in diagonal entries, $\tilde{K}_{33}$ contains $K_{\varepsilon,k}$ for $k = 1, \ldots, 6$ in diagonal entries, $\tilde{K}_{44}$ contains $K_{\varepsilon,k}$ for $k = 7, \ldots, 18$ in diagonal entries.

The matrix $\tilde{S}$ is upper triangular as shown in Equation (23) and only contains the design parameters such as $x_{31}$, $y_{T2}$, and $y_{S3}$ in its nonzero entries. Moreover, it can be shown that $\tilde{S}_{33} = -I \in \mathbb{R}^{6 \times 6}$ and $\tilde{S}_{44} = -I \in \mathbb{R}^{12 \times 12}$.

### 3.2. Appropriate freedom of gains

The hierarchical structure in Equations (21)–(23) indicates that the gains $K_{\alpha,k}$ and $K_{\beta,k}$ for out-of-plane motions can be independently selected.

The gains $K_{\alpha,k}$, $K_{\beta,k}$, $K_{\varepsilon,k}$ for the $k$th segmented mirror can be chosen for each mirror in principle but the common gains in Equation (10) were selected in [5] for simplicity. We note that the inner segmented mirrors and the outer segmented mirrors are point-symmetrically distributed as shown in Fig. 2 in [5], and therefore, we do not have a reasonable reason to assign different scalar gains $K_{\alpha,k}$, $K_{\beta,k}$, and $K_{\varepsilon,k}$ for inner segmented mirrors $k = 1, \ldots, 6$ or for outer segmented mirrors $k = 7, \ldots, 18$.

The result of zero–nonzero structural analysis in Equations (21)–(23) also indicates that it would be reasonable to choose the common gains

$$K_{\alpha,k} := K_{\varepsilon,i}, \quad K_{\beta,k} := K_{\beta,i}, \quad (24)$$

for the inner segmented mirrors ($k = 1, \ldots, 6$) and the common gains

$$K_{\alpha,k} := K_{\alpha,0}, \quad K_{\beta,k} := K_{\beta,0}, \quad (26)$$

for the outer segmented mirrors ($k = 7, \ldots, 18$). Hence, 54 gains are classified into 4 groups.

### 3.3. Gain selection without the hierarchical structure

Apart from the appropriate freedom of gains in the previous subsection, we firstly focus our attention to the common gains in Equation (10) along the previous work [5] and discuss the selection method of gains.

Figure 4 shows the eigenvalue locations of the matrix $F_dC$ in Equation (11) by substituting $K_{\alpha} = 1$, $K_{\beta} = 1$, $K_{\varepsilon} = 1$ into Equation (10), and it proves the closed loop stability under this gain selection. Here, we examine the correspondence to the classification of gains in Equations (24)–(27). Tilt motions of inner segments are displayed in a distributed manner in the red marks which correspond to gains $K_{\alpha,i}$ and $K_{\beta,i}$ in Equation (24) and the eigenvalue locations of $A_{11}$ in Equation (20). Tilt motions of outer segments are displayed in a distributed manner in the blue marks which correspond to gains $K_{\alpha,0}$ and $K_{\beta,0}$ in Equation (26) and the eigenvalue locations of $A_{22}$ in Equation (20). Out-of-plane motions of inner and outer segments are displayed concentrated at one point in the green mark which correspond to gains $K_{\varepsilon,i}$ and $K_{\varepsilon,0}$ in Equations (25) and (27) and the eigenvalue locations of $A_{33}$ and $A_{44}$ in Equation (20). Such correspondence of colour scheme will be common in the subsequent figures.

Figure 5 also shows the eigenvalue locations of the matrix $F_dC$ by substituting $K_{\alpha} = 1$, $K_{\beta} = 10$, $K_{\varepsilon} = 1$ into Equation (10), and it proves the closed loop instability under this gain selection.
For comprehensive numerical search, we have evaluated the stability/instability of the closed loop system for $K_\alpha = 1, 2, 3, \ldots, 100$, $K_\beta = 1, 2, 3, \ldots, 100$, and $K_z = 1, 2, 3, \ldots, 100$. Figure 6 shows the result of comprehensive numerical search for $K_\alpha = 1, 2, 3, \ldots, 100$, $K_\beta = 1, 2, 3, \ldots, 100$, and $K_z = 1$, where the blue dots indicate the closed loop stability and the red dots indicate the closed loop instability. The same figures are obtained for $K_1 = 2, 3, \ldots, 100$, and these results indicate that the zero–nonzero structural analysis in Equations (21)–(23) are correct.

The pointwise results in Figure 6 indicate that the regions of stabilizing/destabilizing gains are isolated by the straight line, and the numerical evaluation indicates that the separation straight line is approximately $K_\beta = 4.5973 K_\alpha$. Therefore, this result shows that excessively increasing the feedback gain in the circumferential direction causes instability.

Let us consider the selection of gains that realizes a pole assignment similar to the CCS. The closed loop poles are overlapped to $-1$ for selecting gain $K = 1$ in the CCS. The eigenvalues of $\tilde{A}_{33}$ and $\tilde{A}_{44}$ are overlapped to $-1$ by selecting $K_z = 1$ so that there is no need to tune $K_z$. Our problem is to tune $K_\alpha$ and $K_\beta$ so that the eigenvalues of $\tilde{A}_{11}$ and $\tilde{A}_{22}$ are closed to $-1$. Numerical optimization is carried out by minimizing the cost function $J$ with respect to $K_\alpha$ and $K_\beta$. The cost function $J$ is defined by the maximum distance between the closed loop poles of DCS and $-1$

$$J = \max_k |\lambda_k + 1|, \quad (28)$$

where $\lambda_k$ is the $k$th eigenvalue of $\tilde{A}_{11}$ and $\tilde{A}_{22}$ for $k = 1, \ldots, 36$.

The CMAES (Covariance Matrix Adaptation Evolution Strategies) [9], which does not require the differentiation of the cost function, is adopted to solve this optimization problem. As the result of optimization, the optimal cost function is $J = 0.86590054$ for $K_\alpha = 1.4464553$, $K_\beta = 0.52579602$. Figure 7 shows the optimized closed loop eigenvalue location. Compared with Figure 4, fluctuation of pole locations in Figure 7 are suppressed as a result of optimization.

### 3.4. Gain selection with the hierarchical structure

We focus our attention to the classified gains in Equations (24)–(27) in this work and discuss the selection method of gains.

For comprehensive numerical search, we have evaluated the region of stability/instability of $\tilde{A}_{11}$ with respect to $K_{\alpha,i}$ and $K_{\beta,i}$. We have also evaluated the stability/instability of $\tilde{A}_{22}$ with respect to $K_{\alpha,o}$ and $K_{\beta,o}$. Figures 8 and 9 show the result of comprehensive numerical search, where the blue dots indicate the closed loop stability and the red dots indicate the closed loop instability.

Figure 8. Region of stabilizing/destabilizing gains for $\tilde{A}_{11}$ with the hierarchical structure, where the blue dots indicate stabilizing gains and the red dots indicate destabilizing gains.
The pointwise results in Figures 8 and 9 indicate that the regions of stabilizing/destabilizing gains are isolated by the straight lines, and the numerical evaluation indicates that the separation straight lines are approximately $K_{\beta,i} = 10.2000K_{\alpha,i}$ and $K_{\beta,o} = 4.5973K_{\alpha,o}$. Compared with Figure 6, the regions of stabilizing gains in Figure 8 are common for the inner segments but the regions of stabilizing gains in Figure 9 are enlarged for the outer segments.

Let us consider the selection of gains that realizes a pole assignment similar to the CCS. The eigenvalues of $\tilde{A}_{33}$ and $\tilde{A}_{44}$ are overlapped to $-1$ by selecting $K_{\alpha,i} = 1$ and $K_{\alpha,o} = 1$ so that there is no need to tune $K_{\alpha,i}$ and $K_{\alpha,o}$. Our problem is to tune $K_{\alpha,i}$, $K_{\beta,i}$, $K_{\alpha,o}$, and $K_{\beta,o}$ so that the eigenvalues of $\tilde{A}_{11}$ and $\tilde{A}_{22}$ are closed to $-1$. Numerical optimizations are carried to minimize the cost function $J$ in Equation (28) with respect to $K_{\alpha,i}$, $K_{\beta,i}$, $K_{\alpha,o}$, and $K_{\beta,o}$.

The CMAES is adopted to solve this optimization problem. As the result of optimization, the optimal cost function is $J = 0.83350134$ for $K_{\alpha,i} = 1.9353902$, $K_{\beta,i} = 0.49680558$, $K_{\alpha,o} = 2.2397460$, $K_{\beta,o} = 0.67260333$. Figure 10 shows the optimized closed loop eigenvalue locations. Compared with Figure 7, fluctuation of pole locations in Figure 10 are suppressed as a result of optimization.

Let us further consider the selection of gains by taking account of the hierarchal structure. Our problem can be reformulated twofold: One is to tune $K_{\alpha,i}$ and $K_{\beta,i}$ so that the eigenvalues of $\tilde{A}_{11}$ is closed to $-1$ and the other is to tune $K_{\alpha,o}$ and $K_{\beta,o}$ so that the eigenvalues of $\tilde{A}_{22}$ are closed to $-1$. Numerical optimizations are then carried out in parallel: One is to minimize the cost function $J$ in the form of Equation (28) with respect to $K_{\alpha,i}$ and $K_{\beta,i}$ and the other is to minimize the cost function $J$ in the form of Equation (28) with respect to $K_{\alpha,o}$ and $K_{\beta,o}$.

The CMAES is adopted to solve these optimization problems. As the result of optimization, the optimal cost function is $J = 0.55554390$ for $K_{\alpha,i} = 2.0232901$, $K_{\beta,i} = 0.45633165$. The optimal cost function is $J = 0.83350134$ for $K_{\alpha,o} = 2.2397460$, $K_{\beta,o} = 0.67260333$. Figures 11 and 12 show the optimized
eigenvalue locations of $\tilde{A}_{11}$ and $\tilde{A}_{22}$. The overlap of those figures is shown in Figure 13. By comparing Figures 10 and 13, the fluctuations of the eigenvalue locations of inner segments in Figure 13 are narrower than those in Figure 10; in contrast, the eigenvalue locations of outer segments are completely the same located outside those of inner segments, and therefore, the optimized cost functions are the same. These comparisons indicate the freedom in the selections of gains is effective by taking account of the hierarchical structure in the DCS.

4. Conclusion
The zero–nonzero structure of the DCS proposed for the Seimei telescope has been investigated in detail. The hierarchical structure in the closed loop system indicates that the tilt motion does not affect the out-of-plane motion, the inner tilt motion does not affect the outer tilt motion, and the inner out-of-plane motion does not affect the outer out-of-plane motion. Based on this observation, the appropriate freedom of selecting gains would be classified by those four types of motions. The design examples for selecting gains of the DCS are presented so that the closed loop pole locations are similar to those of the CCS, and then, the freedom in the selections of gains is effective by taking account of the hierarchical structure. Future research topics include further development of gain selection methods as well as experimental verification.

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