A Single Motor-Driven Focusing Mechanism with Flexure Hinges for Small Satellite Optical Systems

Jinwon Jung [1], Nguyen Van Sy [1], Dongkyu Lee [2,†], Seonggun Joe [3, 4], Jaihyuk Hwang [2], and Byungkyu Kim [2,*]

[1] Department of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang-si 10540, Gyeonggi-do, Korea; ultrajinwon@gmail.com (J.J.); nguyenvansy240@gmail.com (N.V.S.)
[2] School of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang-si 10540, Gyeonggi-do, Korea; eastar25@naver.com (D.L.); jhhwang@kau.ac.kr (J.H.); bkim@kau.ac.kr (B.K.)
[3] Center for the Micro-BioRobotics, Istituto Italiano di Tecnologia (IIT), 56025 Pontedera, Italy; Seonggun.Joe@iit.it (S.J.)
[4] The BioRobotics Institute, Scuola Superiore Sant'Anna, 56025 Pontedera, Italy
* Correspondence: bkim@kau.ac.kr
† Passed away in December 2019.

Text S1

Gravity compensation

The weight of a Single Motor-driven Focusing mechanism with Flexure Hinges (SMFH) can be neglected on the targeted orbit. However, since the developed experimental setups are performed on Earth, deflection of the Flexure hinges (FlexHe) could occur due to the gravity. Such undesired deformation may lead to an inaccurate evaluation of their performance. In other words, the variation of MTF relates to the De-space, De-center, and Tilt; therefore, any indistinct deflections that are caused by the gravity should be removed.

This section describes how the geometry of SMFH is manipulated by means of gravity compensation. First, by exploiting the cartesian coordinates, five spots (A, B, C, x, and y) were determined. For each spot, LVDT sensors were attached to obtain the displacement of the secondary mirror supporter, as shown in Figure S1a. Then, by vectorizing three spots (A, B, C) from origin O (0, 0, 0), the Tilt of SMFH was obtained (Figure S1b). Second, gravity affects all orientations of the SMFH and displaces along the x, y, or z-axis, as shown in Figure S1. Hence, according to various three-dimensional gravity directions, six cases should be determined, with respect to each axis e.g., (± x, 0, 0), (0, ±y, 0), and (0, 0, ±z)).

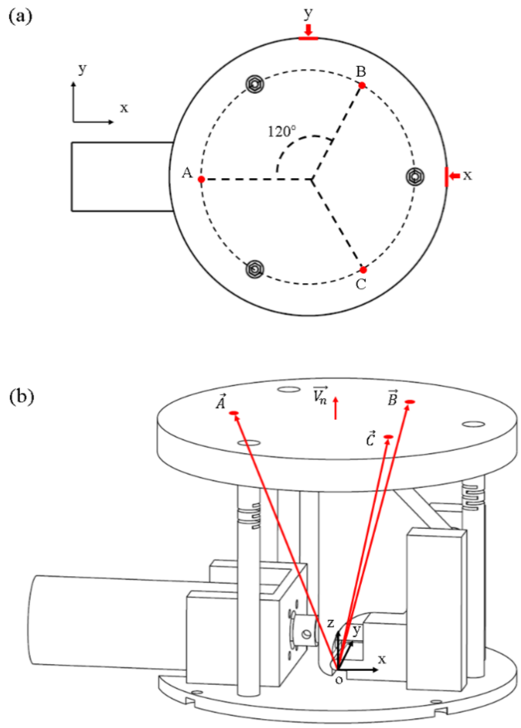

Figure S1. (a) Five spots for obtaining displacement data and (b) notation of coordinate and vector directions.

For instance, if SMFH is oriented as shown in Figure S2a, the gravity acts along the –z-direction, which is one of 6 cases. Table S1 summarizes all parameters and nomenclature used in gravity compensation.

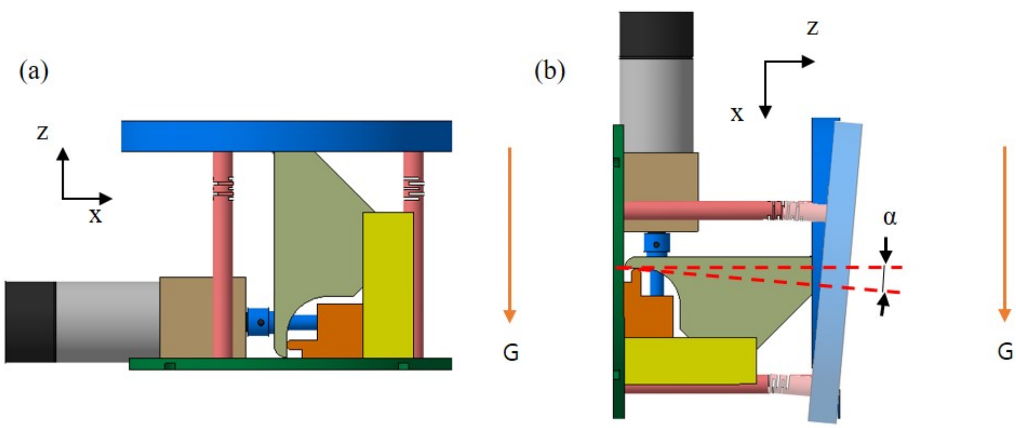

Figure S2. Examples of the SMFH orientation with the gravity that acts along (a) -z-direction and (b) -x-direction.

Table S1. Parameters for gravity compensation

Nomenclatures	Description
h	Length of the flexure hinge
x_i, y_i	x and y measured displacement based on gravity direction of i
z_i	Average of A, B, and C measured displacement based on gravity direction of i
$(\Delta x, \Delta y, \Delta z)_i$	Displacement error caused by gravity direction of i
α_i	Deflected angle of the SMFH caused by gravity direction of i
$\vec{A}, \vec{B}, \vec{C}$	Vector of A, B, and C considering compensated z-axis displacement
$\overrightarrow{V_v}$	Norm vector on z-axis, $[0 \quad 0 \quad 1]$

Where, i=±x, ±y, ±z.

To simplify the analysis, we assumed that the gravity causing x and y displacement is negligible when gravity acts along the -z-axis. With this assumption, the average displacements with respect to x and y-axis are determined as reference displacements of x and y.

$$\frac{x_{+z} + x_{-z}}{2}, \frac{y_{+z} + y_{-z}}{2} \tag{1}$$

The displacements along the x and y-axes include the errors that could be induced by the deflections. Such undesired deformations are caused by the structure's own weight, while the gravity is acting on x and y-axis. Thus, the displacement error of x and y can be written as:

$$\begin{aligned} \Delta x_{+x} &= x_{+x} - \frac{x_{+z} + x_{-z}}{2} \\ \Delta x_{-x} &= x_{-x} - \frac{x_{+z} + x_{-z}}{2} \end{aligned} \tag{2}$$

$$\Delta y_{+y} = y_{+y} - \frac{y_{+z} + y_{-z}}{2}$$

$$\Delta y_{-y} = y_{-y} - \frac{y_{+z} + y_{-z}}{2}$$

Therefore, the deflected angle (α) of the SMFH can be written by the following inverse triangular function, with respect to the length of the FlexHe (h):

$$\begin{aligned} \alpha_{+x} &= \sin^{-1}\frac{\Delta x_{+x}}{h} \\ \alpha_{-x} &= \sin^{-1}\frac{\Delta x_{-x}}{h} \\ \alpha_{+y} &= \sin^{-1}\frac{\Delta y_{+y}}{h} \\ \alpha_{-y} &= \sin^{-1}\frac{\Delta y_{-y}}{h} \end{aligned} \tag{3}$$

Then, the displacement error along the z-axis can be written as a function of the deflected angle, as:

$$\begin{aligned} \Delta z_{+x} &= h(\cos\alpha_{+x} - 1) \\ \Delta z_{-x} &= h(\cos\alpha_{-x} - 1) \\ \Delta z_{+y} &= h(\cos\alpha_{+y} - 1) \\ \Delta z_{-y} &= h(\cos\alpha_{-y} - 1) \end{aligned} \tag{4}$$

Similarly, if gravity acts along with other directions, a function of the deflected angle can be obtained. By exploiting Eq (4) with respect to all three-dimensional directions, the deflections of SMFH are then eliminated. The De-space can be written as:

$$\sum\nolimits_{i=\pm x,\pm y,\pm z} \frac{z_i - \Delta z_i}{6} \tag{5}$$

Since the closed vectors are equal to a triangular scheme, the De-center can also be written as:

$$\sqrt{\left(\sum\nolimits_{i=\pm x,\pm y,\pm z} \frac{x_i - \Delta x_i}{6}\right)^2 + \left(\sum\nolimits_{i=\pm x,\pm y,\pm z} \frac{y_i - \Delta y_i}{6}\right)^2} \tag{6}$$

The Tilt corresponds to the norm vector of the secondary mirror supporter; therefore, it can be obtained through a calculation of the vectors, as shown in Figure S2b. As a result, the Tilt is derived from Eq (5) to Eq (9), by using linear algebra.

$$\overrightarrow{V_1} = \vec{A} - \vec{B} \tag{7}$$

$$\overrightarrow{V_2} = \vec{B} - \vec{C} \tag{8}$$

$$\vec{V} = \overrightarrow{V_1} \times \overrightarrow{V_2} \tag{9}$$

$$\overrightarrow{V_n} = \frac{\vec{V}}{\|\vec{V}\|} \tag{10}$$

$$\overrightarrow{V_n} \cdot \overrightarrow{V_v} = \cos\theta_{tilt} \tag{11}$$

Accordingly, the Tilt (θ_{tilt}) can be written as:

$$\theta_{tilt} = \cos^{-1}\left(\overrightarrow{V_n} \cdot \overrightarrow{V_v}\right) \tag{12}$$