A COMPACT LOW-COST CAMERA MODULE WITH MODIFIED MAGNETIC RESTORING FORCE

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ABSTRACT

In recent years, compact camera modules (CCMs) have been widely used in consumer electrical and electronic products. CCMs with low cost specially are necessary for portable devices. Therefore, the present group recently developed a miniaturized open-loop controlled camera module with low cost for cellphone applications, in which the Lorentz force is balanced by a magnetic restoring force. To enhance the performance of the camera module, this article reports a pattern structure to modify the linearity of the magnetic restoring force. We fabricated a CCM prototype with the dimensions of 8.5 mm × 8.5 mm × 5 mm and demonstrated the usefulness of the pattern structure with the CCM prototype. Its potential applications are foreseeable in portable devices, such as cellphones, web cameras, personal digital assistants and other commercial electronics.

Keywords: Camera, Compact camera module (CCM), Magnetic restoring force, Voice coil actuator (VCA), Autofocusing.

1. INTRODUCTION

In recent years for our modern daily life, consumer electrical and electronic products have been necessary and play an important role. In these devices, image capturing systems have become ubiquitous because people can communicate and share information via them. As a result, the compact camera modules (CCMs), one of the image capturing systems, on the portable consumer electrical and electronic products (such as cellphones, web cameras, laptop/notebook computer, personal digital assistants, and so on) are found in an ever-increasing number and have become the basic equipment due to their low power, competitive price, and compactness [1-3].

For the CCMs, in particular, autofocusing is an important mechanism to achieve better image quality. Hence, various kinds of CCMs with autofocusing mechanism have been developed and proposed in recent decades [4-6]. To the best of our knowledge, these CCMs with autofocusing mechanism can been classified into numerous types, for example, adaptive liquid lenses [4, 7], voice coil actuators (VCAs) [8-10], piezoelectric actuators [11, 12], conducting polymer actuators [13, 14], and so on. Amongst existing CCMs with autofocusing mechanism, VCA-type CCMs with autofocusing mechanism are specially competitive and attractive because of their robust characteristics, mass-productivity, easy manufacture, and cheap cost [6, 13]. However, as shown in Fig. 2 of [15], for the conventional VCA-type CCMs with autofocusing mechanism, highly flexible diaphragms are adopted as a suspension with complicated structure and thin thickness. It needs a high-precision manufacturing technology to produce these flexible diaphragms. As a result, these flexible diaphragms dominate the yield rate and cost of the conventional VCA-type CCMs with autofocusing mechanism [16]. Moreover, to fulfill the design requirements of

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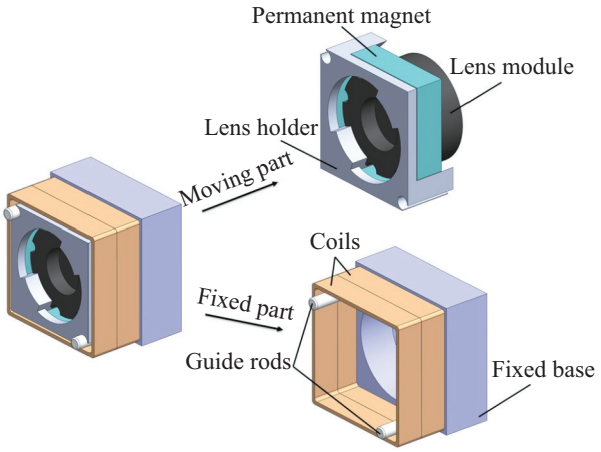


Fig. 1 Components and 3D model of original VCA-type CCM.

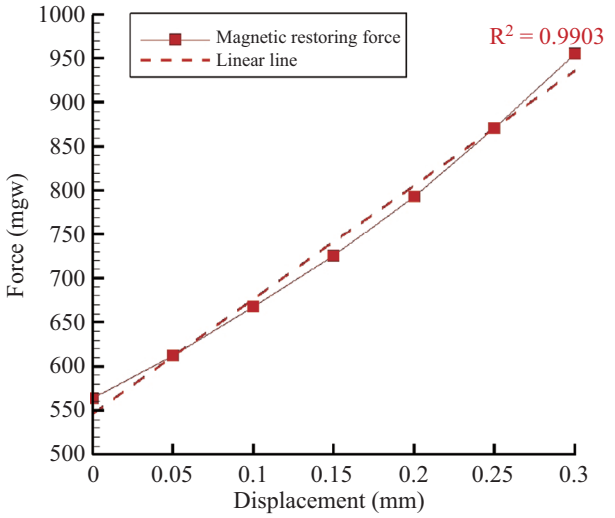


Fig. 2 Calculated results obtained for F_{mr} of original VCA-type CCM.

these devices with shock-resistance [17], a enough elastic constant for these flexible diaphragms is essential and then it is difficult to reduce the power consumption [6, 10].

Accordingly, to solve this issue, the present group proposed a novel VCA-type CCM in which the magnetic restoring force is used to replace the restoring force of these flexible diaphragms in the conventional VCA-type CCMs in a previous article [16]. However, with the continuing trend toward high-performance CCMs, it is necessary to improve the autofocusing accuracy of CCMs yet further. Consequently, in this article, the autofocusing performance of the VCA-type CCM presented in [16] is further improved by modifying the linearity of the magnetic restoring force in the original design with a pattern structure. The principle improving the linearity of the magnetic restoring force was first proposed and used in a novel force sensor in a previous article [18]. In this article, we use this principle to design a low-cost and enhanced-performance VCA-type CCM. The performance of the proposed VCA-type CCM is characterized numerically using MagNet electromagnetic field simulation software and is then verified experimentally using a laboratory-built prototype.

The remainder of this article is organized as follows. Section 2 reviews the design of the original VCA-type CCM presented in [16] based on a magnetic restoring force. Section 3 introduces the VCA-type CCM proposed in this article. Section 4 describes the numerical comparison between the original and proposed VCA-type CCMs. Section 5 discusses the experimental characterization and validity of the proposed VCA-type CCM prototype. Finally, Section 6 presents some brief concluding remarks.

2. DESIGN OF ORIGINAL VCA-TYPE CCM

The main principle and design of the original VCA-type CCM presented in [16] are reviewed in this section. The schematic components and 3D model of the original VCA-type CCM in [16] are illustrated in Fig. 1. Comparing this figure and Fig. 1 of [16], it is obvious that

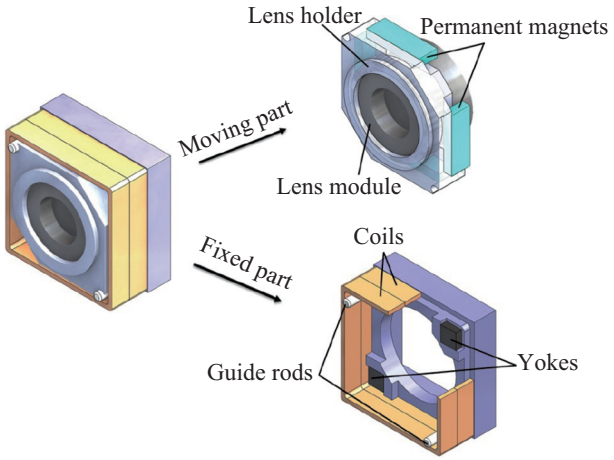


Fig. 3 Components and 3D model of proposed VCA-type CCM.

there are not flexible diaphragms in the structure of the original VCA-type CCM and two shaft-hole pairs between the guide rods and the lens holder guide its moving part. In the original design, the guide rods of the fixed part and the permanent magnet of the moving part give rise to a magnetic restoring force F_{mr} [16, 19]. When the autofocusing function of the original VCA-type CCM is turned on, F_{mr} will balance the Lorentz force F_{VCM} of the VCA and drive the lens module to different focusing position depended on the magnitude of the input current of the coils. As stated in [16, 19], this is just like the behavior of these flexible diaphragms in the conventional VCA-type CCMs. The linearity of the restoring force-displacement curve is a very important specification for commercial CCMs. Figure 2 illustrates the calculated magnetic restoring force F_{mr} with the displacement for the original VCA-type CCM. As shown, the linearity of the magnetic restoring force-displacement curve equals to 0.9903 and could be modified when compared to the linearity of the restoring force-displacement curve of the conventional flexible

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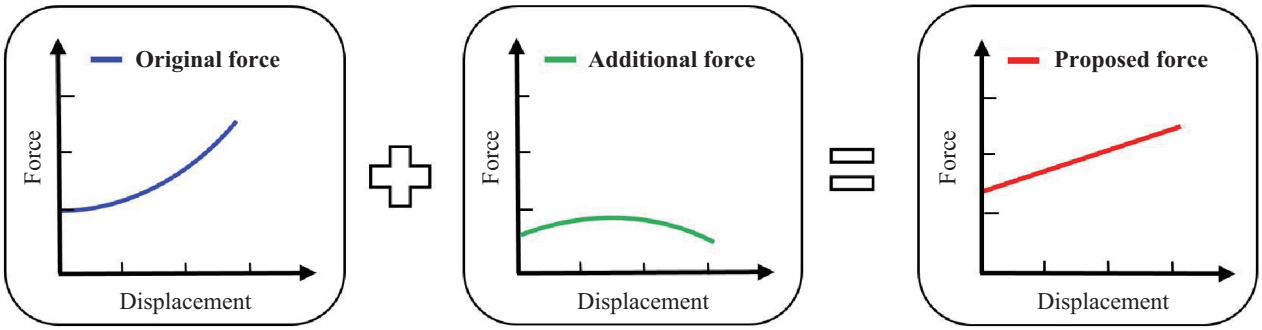


Fig. 4 Schematic illustration of original, additional, and resultant magnetic restoring forces of proposed VCA-type CCM, respectively.

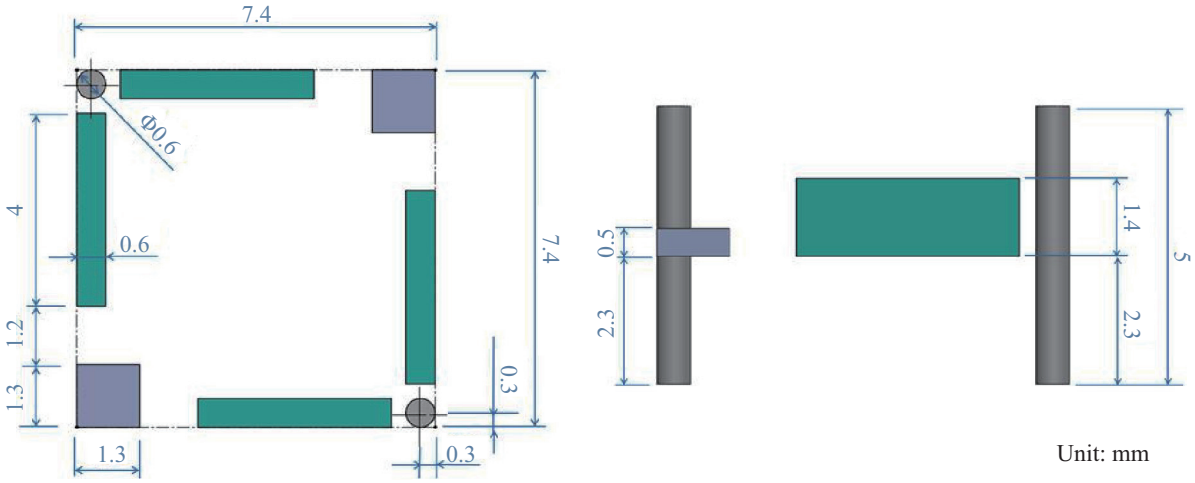


Fig. 5 Schematic illustration of key parameters of magnetic structure in proposed VCA-type CCM.

diaphragms (It is equal to 1 for ideal case.). As a result, in this article, a pattern structure is proposed to modify the linearity of the magnetic restoring force in the original VCA-type CCM presented in [16].

3. PROPOSED VCA-TYPE CCM WITH MODIFIED MAGNETIC RESTORING FORCE

In order to modify the linearity of the magnetic restoring force-displacement curve, this article reports a compact VCA-type CCM with a pattern structure. The schematic components and 3D model of the proposed VCA-type CCM in this article are illustrated in Fig. 3. From this figure, it is obvious that the proposed VCA-type CCM has not flexible diaphragms in its structure. From Figs. 1 and 3, it is seen that there are two yokes in the proposed VCA-type CCM. The proposed and original VCA-type CCMs have the similar structure except for these two yokes. As shown in Figs. 3 and 4, there are two magnetic restoring forces in the proposed VCA-type CCM. As the same as the original design [16], the guide rods of the fixed part and the permanent magnets of the moving part give rise to the first magnetic restoring force F_{mr1} (i.e. original magnetic restoring force). Especially, in the same time, the yokes of the fixed part and the permanent magnets of the moving part give rise to the second magnetic restoring force F_{mr2} (i.e. additional magnetic restoring force) in the proposed structure. The resultant magnetic restoring force F_{mr} (i.e. proposed magnetic restoring force) is given by

$$F_{mr} = F_{mr1} + F_{mr2}. \quad (1)$$

As shown, it can be observed that for the first magnetic restoring force F_{mr1}, the original magnetic restoring force-displacement curve is concave, and the trend of the magnetic restoring force-displacement curve is a result of the dimensions and relative positions of the magnetic structure. It is characterized numerically using MagNet electromagnetic field simulation software. If the additional magnetic restoring force-displacement curve could be designed to be convex for the second magnetic restoring force F_{mr2}, the linearity of the resultant restoring force-displacement curve of the proposed VCA-type CCM can be modified. As a result, in this article, the autofocusing performance of the VCA-type CCM presented in [16] is further improved by modifying the linearity of the magnetic restoring force in the original de-

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sign with two additional yokes which are optimized to provide a convex magnetic restoring force-displacement curve. The key parameters of the magnetic structure in the proposed VCA-type CCM are shown in Fig. 5.

4. NUMERICAL SIMULATION

MagNet electromagnetic field simulation software was utilized to calculate the Lorentz force F_{VCM} and resultant magnetic restoring force F_{mr}, and select the design parameters of the proposed VCA-type CCM. In this design procedure, we must consider the linearity of the resultant restoring force-displacement curve, module sizes (for 8.5 mm × 8.5 mm), power efficiency, lens dimension (for M6), full stroke (for 0.3 mm), and so on. This design procedure includes the analysis of static and dynamic mechanics. From the design principle of [16], the resultant magnetic restoring force F_{mr}, the weight of the moving part F_w, and the Lorentz force F_{VCM} must satisfy the following equations:

$$F_{mr} \geq F_w, \tag{2}$$

$$F_{VCM} \geq F_{mr} + F_w. \tag{3}$$

Table 1 shows the main structural and electromagnetic design parameters of the proposed VCA-type CCM.

Table 1 Structural and electromagnetic design parameters in proposed VCA-type CCM.

Variable		Corresponding value
Sizes (mm)		8.5× 8.5 × 5.0
Stroke (mm)		0.3
Weight of moving part (mgw)		300
Guide rods	Material	420 grade stainless steel
	Diameter (mm)	0.6
	Length (mm)	5
Permanent magnet	$(BH)_{max}$ (MGOe)	43~46
	Material	Nd-Fe-B N46H
	Height (mm)	1.4
	Length (mm)	4
	Thickness (mm)	0.6
Yoke	Material	SAE1008
	Height (mm)	1.3
	Length (mm)	1.3
	Thickness (mm)	0.5
Coils	Height (mm)	1.4
	Length (mm)	8.4
	Thickness (mm)	0.3
	Core diameter (mm)	0.04
	Winding turns (turns)	125
	Electrical resistance (Ω)	64
Air gap width between permanent magnet and coil (mm)		0.2

Figure 6 shows the numerical model and simulation results for the magnetic flux density in the proposed VCA-type CCM. From the numerical model and simulation results, the resultant magnetic restoring force F_{mr},

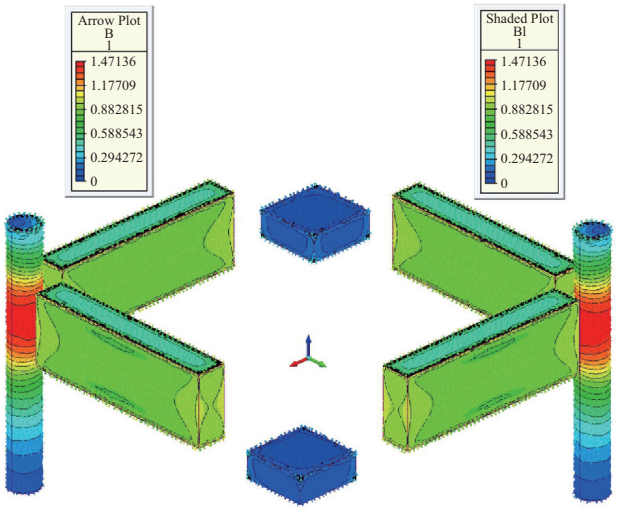


Fig. 6 Numerical model and results for magnetic flux density in proposed VCA-type CCM.

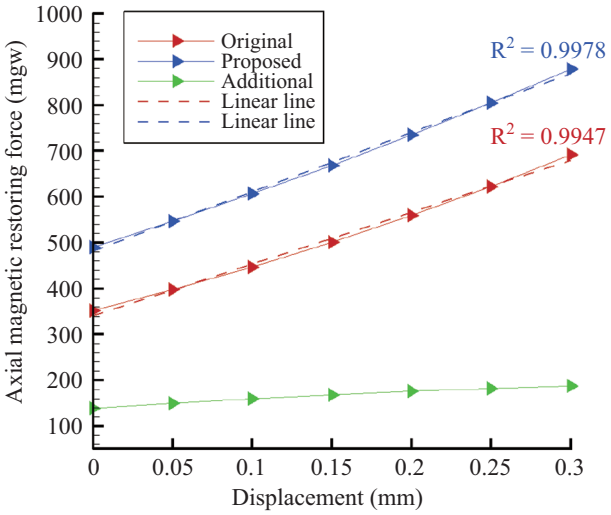


Fig. 7 Calculated results for original, additional, and resultant magnetic restoring forces of proposed VCA-type CCM, respectively.

the original magnetic restoring force F_{mr1}, and the additional resultant magnetic restoring force F_{mr2} with the displacement, respectively, and the Lorentz force F_{VCM} can be obtained for the proposed VCA-type CCM. Figure 7 illustrates the calculated original, additional, and resultant magnetic restoring forces with the displacement, respectively, for the proposed VCA-type CCM. As shown, it can be observed that the original magnetic restoring force-displacement curve is concave and its linearity equals to 0.9947; the additional magnetic restoring force-displacement curve is convex; and the linearity of the resultant restoring force-displacement curve of the proposed VCA-type CCM is modified as 0.9978. As a result, it verifies that the linearity of the magnetic restoring force in the original design could be further modified with two additional yokes, which agrees with the principle stated in Section 3. Figure 8 illustrates the calculated F_{VCM} and $F_{mr} + F_w$ with the dis-

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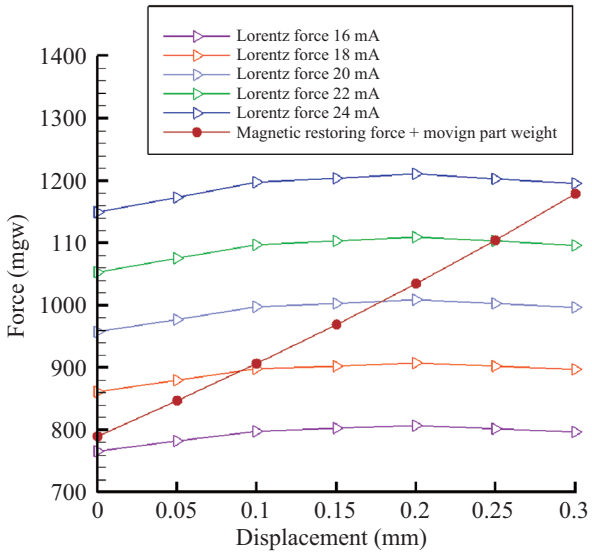


Fig. 8 Calculated results for F_{VCM} and F_{mr} + F_w of proposed VCA-type CCM, respectively.

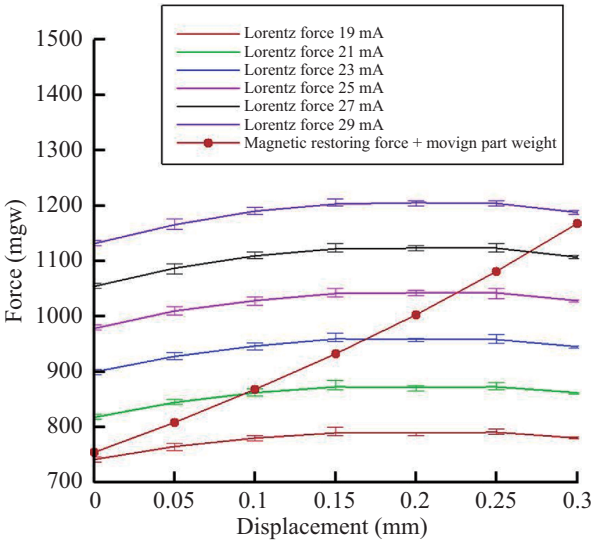


Fig. 10 Experimental results for F_{VCM} and F_{mr} + F_w of proposed VCA-type CCM, respectively.

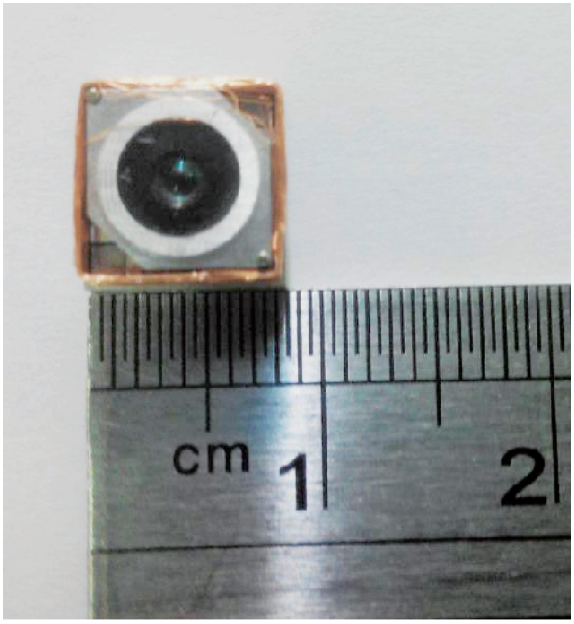


Fig. 9 Picture of fabricated camera module prototype.

placement, respectively, for the proposed VCA-type CCM. From this figure, it can be observed that the proposed VCA-type CCM can reach the maximal displacement of 0.3 mm with an input current of 24 mA, which has lower power consumption when compared to conventional VCA-type CCMs with autofocusing mechanism [20].

5. EXPERIMENTAL CHARACTERIZATION AND VALIDITY OF PROTOTYPE

In this article, we fabricated a laboratory-built VCA-type CCM prototype to evaluate the characteristics and performance of the proposed VCA-type CCM. Figure 9 shows the picture of the fabricated CCM prototype with dimensions of 8.5 mm × 8.5 mm × 5 mm. We used a Transducer Techniques load cell (type: GSO-25) to measure the Lorentz force F_{VCM} and the resultant magnetic restoring force F_{mr}, and a Keyence laser displacement sensor (type: LK-G80) to measure the displacement of the proposed VCA-type CCM, respectively, in the experiments. Figure 10 illustrates the experimental results for F_{VCM} and F_{mr} + F_w with the displacement, respectively, for the proposed VCA-type CCM. It is noted that the measured data were repeated ten times and recorded at each measuring displacement. As shown, it can be observed that the linearity of the resultant restoring force-displacement curve of the proposed VCA-type CCM is measured as 0.9935 and it is in good agreement with the simulation value of 0.9978 given in Section 4. From this figure, it can be observed that the proposed VCA-type CCM can reach the maximal displacement of 0.3 mm with an input current of 29 mA, which is a little greater than the simulation value of 24 mA. This discrepancy is reasonable between the physics model and fabricated prototype [16].

Moreover, as shown in Fig. 11, we used 45 degree, horizontal, and overturned experimental postures to measure the displacement-current motion characteristics of the proposed VCA-type CCM, respectively. The experimental results are presented in Fig. 12. As shown, the repeatability is not well due to the friction force between guild rods and lens holder. However, the friction can result in indeterminate factor that is hard to overcome in open-loop control for high precision. Therefore, in a future study, the proposed VCA-type CCM will be combined with a proper compliant translation joint in order to overcome the issue [16, 21, 22]. Figure 12 also shows the proposed VCA-type CCM has the lowest power consumption at overturned posture. This is because the direction of the weight of the moving part is the same with the direction of its movement. In addition, we used a Suruga Seiki optical autocollimator (type:

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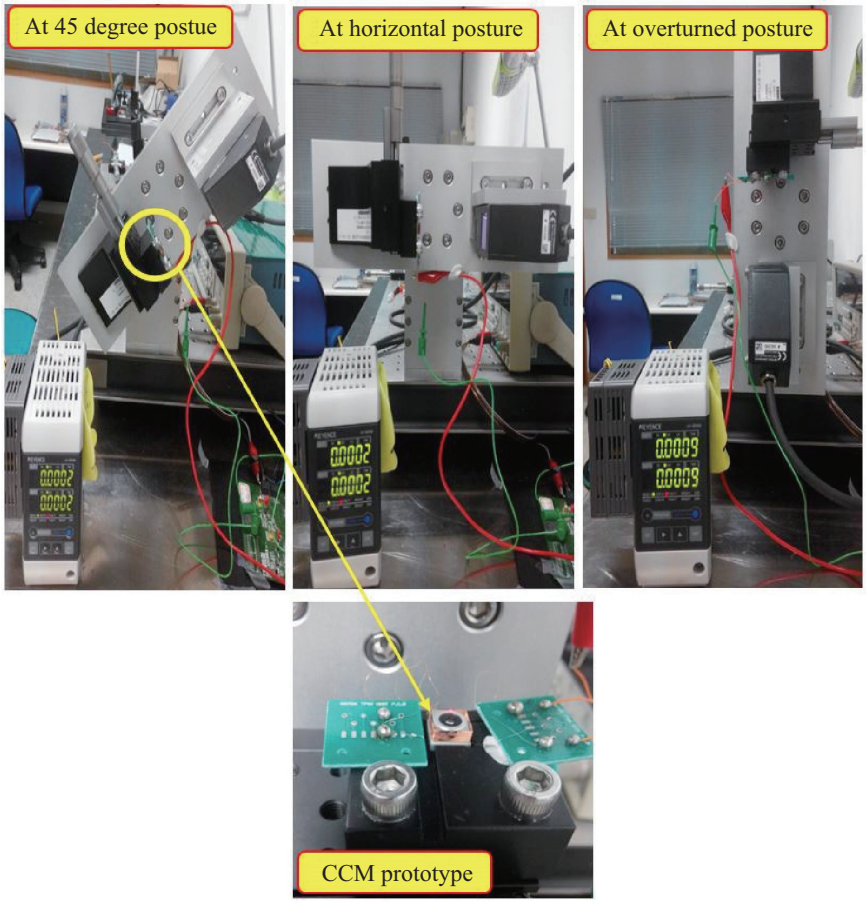


Fig. 11 Picture of three experimental postures.

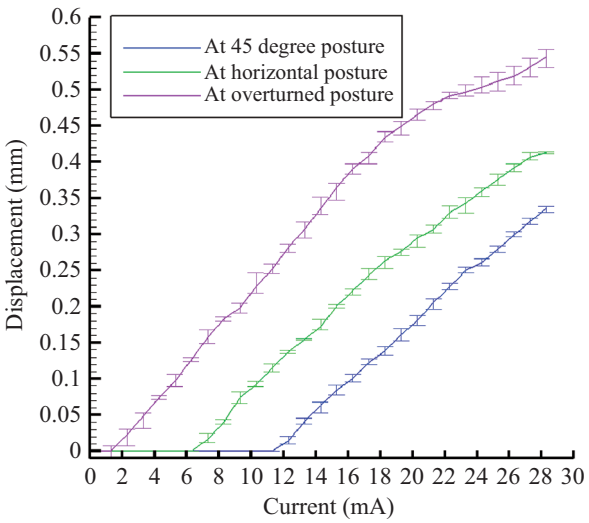


Fig. 12 Experimental displacement-current motion characteristics of the proposed VCA-type CCM.

HIP-550/025A, as shown in Fig. 13) to measure the dynamic tilt angle of the proposed VCA-type CCM. Figure 14 shows the experimental results for measuring dynamic tilt angle. It can be observed that the proposed VCA-type CCM has a dynamic tilt angle of 0.141 degree (equal to 8.46 arc-min) and is less than the standard of 10 arc-min.



Fig. 13 Picture of experimental setup for measuring dynamic tilt angle.

Finally, we constructed a laboratory-built digital image capturing and recording device to capture photo-

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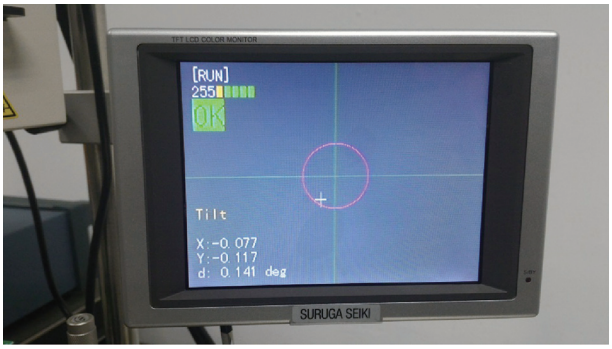


Fig. 14 Experimental results for measuring dynamic tilt angle.

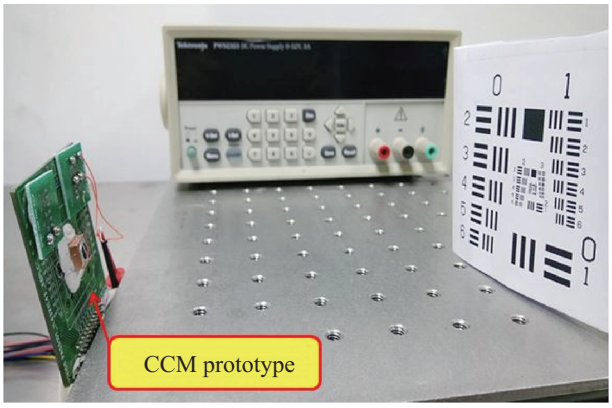


Fig. 15 Picture of experimental setup for capturing photograph.

graphs. As shown in Fig. 15, the proposed VCA-type CCM prototype was fixed on a custom-made image sensor demo board (PixArt Imaging Inc., Taiwan), in which the function of the proposed VCA-type CCM prototype is to moving the lens module to focusing position and capture a sharp photograph. Figure 16 shows two captured photographs when the autofocusing mechanism is activated and not activated, respectively. It can be observed that the quality of the captured photograph is better with the autofocusing mechanism. Consequently, the experimental results have verified the performance of the proposed VCA-type CCM. Its potential applications are foreseeable in portable devices, such as cellphones, web cameras, personal digital assistants and other commercial electronics.

6. CONCLUSIONS

This article has reported a low-cost and enhanced-performance VCA-type CCM, in which the linearity of the magnetic restoring force is further modified with two additional yokes. Its performance has been characterized using numerical simulation and then verified using a laboratory-built prototype. The experimental results have shown that the proposed VCA-type CCM has a compact dimensions of 8.5 mm × 8.5 mm × 5 mm, a

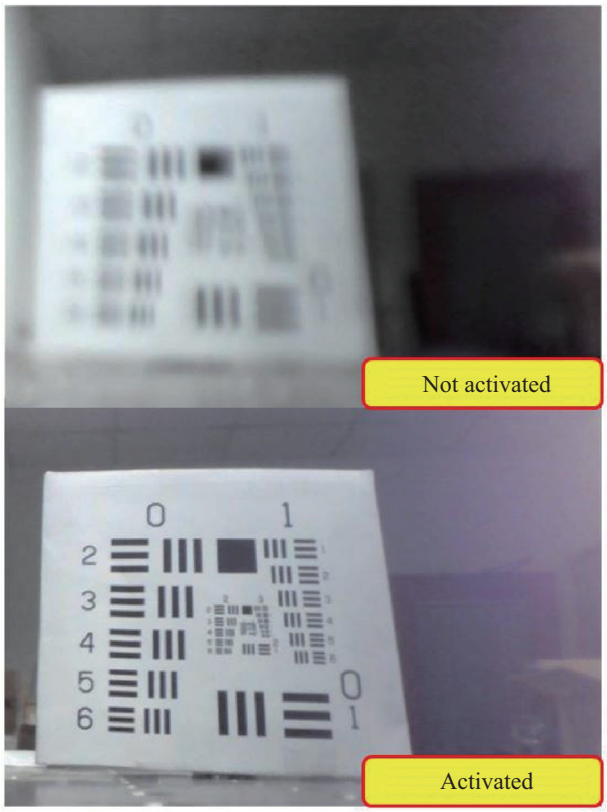


Fig. 16 Experimental results for capturing photograph.

high power efficiency (with a maximal input current of 29 mA for the displacement of 0.3 mm), a high linearity of the magnetic restoring force with 0.9935, and an excellent dynamic tilt angle of 8.46 arc-min. Therefore they have proven that the proposed VCA-type CCM has many foreseeable applications in portable devices.

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