ABSTRACT
Multi-motor configuration of multi-DOF (degree of freedom) optical system is a major source of redundant structure, putting a limitation on the simple and miniaturized design. Thus, a novel two-DOF ultrasonic motor (USM) is proposed to provide a feasible method of application in the lens autofocus of the optical system. The proposed USM operates by one longitudinal mode and two orthogonal bending modes, which is inspired by the bionic motion principle of the earthworms. The frequency degeneration among the three working modes is performed, and the working principle of the USM is verified via the FEM simulation. A prototype of the two-DOF USM is fabricated, and its mechanical output characteristics are tested. The experimental results indicate that the prototype achieves the maximum rotary and linear speeds of 3319.6 rpm and 57.6 mm/s, respectively. Furthermore, we demonstrate the result of a simple focusing experiment using the prototype and obtain a series of clear pictures, which verifies the feasibility of application in the optical focusing system.

KEYWORDS
Ultrasonic motor; bonded-type; two-DOF motions; optical focusing; bionic motion

CONTACT
Yingxiang Liu liuyingxiang868@hit.edu.cn State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, Heilongjiang Province, China

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Introduction

At present, optical focusing can significantly improve the imaging performance, and various motors have been utilized to design lens modules accordingly. For instance, as the magnetic field could vary with the position change of the lens module, Chien et al. proposed a voice coil motor (VCM) to apply in the optical lens module, which realized stable operation [1]. However, as an electromagnetic motor, the VCM is susceptible to external magnetic field. Besides, functional materials are widely used in the manufacturing of actuators due to their individual characteristics. For example, Jin and Ren developed a movable lens module driven by the dielectric elastomer actuator (DEA) [2]. However, the DEA has a slow response and needs high driving voltage, which is not suitable for most cameras. Moreover, thermally activated shape memory alloy (SMA) has attracted wide attention because of its shape memory effect and large output force. Hasan and Kim et al. proposed tunable lens devices based on the three SMA actuators, and a series of clear pictures could be obtained by controlling the length of springs connecting to the SMA actuator [3]. However, the SMA exhibits serious nonlinear hysteresis effects.

The emerging development of piezoelectric actuators (PEAs) increasingly promotes the rapid growth of the commercial motor market and has received substantial interest from both industry and academia [4–9]. The PEAs have excellent merits such as no electromagnetic interference, fast responsiveness, and self-lock when power-off and are widely used in manufacturing [10,11], adaptive optics instruments [12,13], medical auxiliary equipment [14], and robots [15–19]. Generally, PEAs can be classified as the resonant and non-resonant type from the viewpoint of their vibration states [20]. The non-resonant-type PEAs have been applied in the autofocus modules for improving their localization ability by researchers. Based on the smooth impact drive mechanism, Jonghyun et al. developed an autofocus module with a dual-slider and achieved linear speed of 5 mm/s [21]. However, the non-resonant-type PEAs with low speed cannot be applied in high-speed cameras that need to record most frames during a short operating time [22]. By contrast, the resonant type PEAs have the advantages of high speed and large travel range. Therefore, the resonant-type PEAs are one of the suitable candidates to solve the above problems.

The resonant-type PEAs are usually named as the ultrasonic motors (USMs) as their working frequency is beyond 20 kHz. Generally, USMs are mainly classified into three types according to the working principles: the traveling wave motor (TWM) [23,24], the standing wave motor (SWM) [25–27], and the hybrid modes motor (HMM) [28–31]. As the pioneer in the field of professional electronic photography, Canon, Inc., integrated the TWM in the single-lens reflex camera in the 1980s [32]. The torque and speed were 160 mN-m and 60 r/min, respectively; the response time was less than 1 ms. However, the complicated structure and signals are unsuitable for further miniaturization. By contrast, the SWM has the merits of simple configuration and control circuits. But the SWM is not suitable for applications that require bidirectional motions. In comparison with the TWM and SWM, the most remarkable characteristic of HMM is that the multi-DOF actuation can be achieved by adopting the desired vibration modes. To take advantage of HMMs, Canon, Co., Ltd., proposed a rod-shaped HMM and with dimensions of Φ10 mm×25 mm [33]. In this study, two orthogonal first-order bending vibration modes were excited by
the Langevin-type configuration. To adjust the position of lens module, the rotary motion of rotary HMMs needs to be converted into the linear motion. Thus, the autofocus module was processed with internal threads and moved back and forth accordingly. In 2005, New Scale Technologies, Co., Ltd., reported a tiny HMM with the screw transmission mechanism, which is named as the SQUIGGLE motor with the size of 1.8 mm × 8 mm × 0.6 mm. The SQUIGGLE motor transformed the rotary motion of the rod into the linear one, which was applied in the autofocus module successfully [34]. Compared with Langevin-type configuration, the bonded-type PEs are more suitable for miniaturization owing to their simple structures [35,36]. For instance, Mashimo et al. proposed a millimeter-scale two-DOF HMM, which successfully realized the focus of the image through the linear motion [37,38]. However, the application of rotary motion in the optical field has not been reported.

Generally speaking, focusing a large size of object is conducted by moving either the optical device or the object along the optical axis. In some cases, when a series of clear pictures of the partial object are captured, it may not be completed in the visual range of the objective lens due to the large size of the object. Thus, it is important to obtain clear and complete pictures of the object simultaneously. An effective strategy is to obtain clear pictures of large object via the linear motion, and the complete information of object is obtained through the rotary motion. Therefore, the position adjustment of the object and the expanded visual range of the objective lens can be realized by the linear motion and the rotary motion of the motor, respectively. The preliminary application aforementioned based on the multi-DOF USM has been rarely reported. The multi-DOF USM based on the Langevin-type configuration has the merits of large thrust force and high speed [39], but the compact and simple structure is achieved by the bonded-type one. Thus, it is meaningful to realize the integral design of the multi-DOF USM based on the bonded-type configuration.

The aim of this study is to provide a feasible method of application in the lens autofocus of the optical system. Additionally, imitating the biological organisms in actuation systems to design the piezoelectric actuator is important for the fabrication of biomimetic USM [15,16]. Thus, the two-DOF motions of USM are inspired by the bionic motion principles of the earthworms. This work is organized as follows. The configuration and operating principle of the BT (Bonded-type transducer) are determined and discussed in Section II. In Section III, the relevant FEM study is investigated mainly. The experimental results are presented in Section IV. Finally, the conclusions are stated in Section V.

2. Configuration and working principle of two-DOF bonded-type transducer

2.1. Structure design of two-DOF bonded-type transducer

Both earthworms (Lumbricus terrestris) and inchworms are multi-segmented creatures in nature, but the locomotion mechanism of earthworms is different from that of inchworms, and the retrograde peristaltic gaits are presented while the longitudinal and circular muscles serves as the actuating unit of the hydrostatic skeleton [40], as shown in Figure 1(a)). The somites of earthworms are contracted and expanded through the circular and longitudinal muscles. The soft setae are extended and serves as anchors fixed on the ground regularly, as shown in Figure 1(b)). Therefore, the thrust force is
provided by the fixed somite to push other parts moving forward. In fact, as shown in Figure 1(b) and Figure 1(c)), the peristaltic motion of earthworms is coupled by longitudinal and bending motions, which can be achieved via the longitudinal and circular muscles, respectively. Similarly, the BT can achieve the coupled motion bioinspired by the earthworms through the FEA simulation, which also includes the longitudinal and bending vibration components of the uniform beam, as shown in Figure 1(d)) and Figure 1(e)), respectively. Furthermore, the PZT plates could be regarded as the actuating unit. The coupled motion of BT is the elliptical trajectory or the oblique line formed on the end of the BT to push the mover or rotor, as shown in Figure 1(f)). Therefore, the linear or rotary motion can be generated through the BT since the bending motion is used to overcome the preload exerted by the mover, while the pushing motion is caused by the longitudinal motion through the friction effect.

**Figure 1.** The locomotion mechanism of the earthworm and bonded-type transducer (BT). (a) The longitudinal and circular muscles of earthworm. (b) and (d) The longitudinal motion of the earthworm and BT, respectively. (c) and (e) The bending motion of the earthworm and BT, respectively. (f) The longitudinal and bending PZT plates of BT.
The inferior mechanical performance caused by inconsistent vibration characteristics of multi-feet configuration and the extra usage cost caused by multi-feet BT. Aimed at the current deficiencies in design of multi-feet BT, the single-foot driving system is designed for the developed of two-DOF BT in this study. Furthermore, the driving foot is arranged at the intermediate wave crest of bending mode for efficient actuation. Generally speaking, it is difficult to tune the resonant frequency of the first bending and longitudinal vibration modes to be close since the speed of sound for longitudinal vibration is larger than that for bending one [41]. Therefore, several studies were performed to investigate the design philosophy of BT [42–44]. Traditionally, the odd-order bending modes and even-order longitudinal modes are adopted simultaneously due to their adjacent wave nodes and closed resonant frequencies, or vice versa. In this study, the odd-order bending modes are considered as the tentative working modes according to the distribution of the wave crest of the uniform beam. The driving foot can be arranged at the intermediate wave crest of the uniform beam reasonably under free-free condition. The second-order longitudinal vibration mode (named as \( L_{2X} \) mode) of BT is selected due to its large amplitude compared to high-order ones. Namely, the longitudinal–bending (L-B) modes of BT are adopted to generate the linear motion along the length of BT. The adoption of the L-B modes can achieve miniaturization of the USM compared with the longitudinal–longitudinal (L-L) modes [30]. Furthermore, the rotary motion can be achieved via the two orthogonal bending (B-B) vibration modes, and frequency degeneration can be taken away due to the symmetrical section of BT. Therefore, the \( L_{2X} \) mode and two orthogonal bending vibration modes are selected as the tentative working modes in this study. The order of bending vibration is determined through the FEM method, and then the results are obtained subsequently.

The design flow chart of proposed two-DOF USM are shown in Figure 2. First, the cone-shaped horn is utilized to amplify the vibration amplitudes of BT effectively, as shown in Figure 3(a)). For the beam-type BT, the length of the beam is determined first; the resonant frequencies of USMs range from 20 kHz to 60 kHz in most studies [28–30]. Subsequently, the relationships between the resonant frequencies of the tentative working modes and the length of the metal substrate \( L \) are as shown in Figure 3(b)). The \( L_{2X} \) mode and the odd-order bending modes of the substrate are plotted in Figure 3(c)), Figure 3(d)), Figure 3(e)) and Figure 3(f)). Furthermore, it can be seen that the resonant frequencies of \( B_{3Y} \) and \( B_{5Z} \) modes are within the range of human hearing when the \( L \) exceeds 140 mm. Therefore, the \( L \) determined ranges from 100 to 140 mm in this study. Additionally, the seventh-order bending modes (named as \( B_{2Y}/B_{2Z} \) mode) are not considered due to their inferior vibration characteristics such as the low-amplitude. However, the resonant frequency of the \( L_{2X} \) mode is close to the one of the fifth-order bending modes (named as \( B_{5Y}/B_{5Z} \) mode) by comparison with the other vibration modes. Especially, when the \( L \) is 108.8 mm, the resonant frequencies of \( L_{2X} \), \( B_{5Y} \), and \( B_{5Z} \) mode are 56.031, 56.462, and 56.481 kHz, respectively, namely, the \( L_{2X} \) and the \( B_{5} \) modes can be excited simultaneously through the same exciting frequency. Therefore, the \( L_{2X} \) mode and \( B_{5Y}/B_{5Z} \) modes are chosen as the desired working modes when the three modes have approximated resonant frequencies in this study.

The three-dimensional model of the BT is shown in Figure 4. In order to improve the mechanical performance of the USM, 16 PZT plates are placed in the wave loop of \( B_{5Y}/B_{5Z} \) mode. Furthermore, these PZT plates are divided into two groups (the \( B_{5Z} \) and \( B_{5Y}/L_{2X} \) mode).
groups) equally and bonded on the substrate via the conductive epoxy resin. Therefore, the $L_{2X}$ mode, $B_{5Y}$ mode, and $B_{5Z}$ mode are excited individually by the $L_{2X}/B_{5Y}$ and the $B_{5Z}$ group of PZT plates, respectively.

### 2.2 Working principle of two-DOF USM

The electrical connections and polarization configurations of the PZT plates are presented in **Figure 5**. The PZT plates are polarized along their thickness directions, which are indicated by red arrows. See **Figure 5(a)**, the three voltage signals with the phase difference of $\pi/2$ are named as Signal I, Signal II, and Signal III, respectively. The BT can produce continuous self-reciprocating vibration when the PZT plates are excited with
these voltage signals. As shown in Figure 5(b)), the \( B_{5Y} \) mode can be excited when the PZT plates are excited with Signal I and Signal III with the phase difference of \( \pi \), and reciprocating vibration of BT could be achieved, which is consistent with the \( B_{SY} \) mode plotted in Figure 3(e)). Similarly, the \( B_{5Z} \) mode can be excited while the \( B_{5Z} \) group PZT plates are excited with the Signal II. Under the uniform electric field, the 4 PZT plates are elongated in thickness direction and the remaining ones are shortened regularly. Theoretically speaking, the \( B_{5Z} \) group PZT plates can be utilized to produce the \( L_{2X} \) mode, but the vibration is undesirable in this study. The \( L_{2X} \) mode can be utilized to produce the axial vibration components when the Signal I is applied to the \( L_{2X} \) group PZT plates, as shown in Figure 5(d)). Therefore, the \( B_{SY} \) and \( B_{SZ} \) modes are employed to generate the rotary motion around the X-axis when two orthogonal bending vibration modes are excited, and the linear motion along the X-axis can be obtained when the \( B_{SZ} \) and \( L_{2X} \) mode are excited simultaneously.
The working principle of two-DOF USM is similar to our previous study [39]. Furthermore, several slim poles are utilized to serve as the mover, and the rotary speed can be protruded. When the electrodes are applied with the desired signals, the three desired working modes aforementioned are excited and the rotary and linear motions of the mover can be obtained individually, as shown in Figure 6(a)) and Figure 6(b)). Thus, the continuous rotary and linear motions are performed by the stator. Finally, the counter-direction motions of two-DOF BT can be achieved by adjusting the exciting signals flexibly.
3. FEM simulation of two-DOF bonded-type transducer

The decisive dimensions of the metal substrate are determined; thus, the resonant frequency of the $L_{2X}$ mode is close to that of the bending one. To minimize the difference among the resonant frequencies of the working modes, the frequency degeneration among the three working modes is carried out by FEM simulation with ANSYS software. The decisive dimensions of the metal substrate have been determined in Section 2.1. First, the material of the PZT plate is PZT-4 (Model: Hong sheng Co., Ltd, Baoding, China), and its density is 7500 kg/m$^3$, and the total size of PZT-4 is $18 \text{ mm} \times 12 \text{ mm} \times 0.5 \text{ mm}$. The aluminum alloy (2A12) is selected as the material for the metal substrate (mass density: 2700 kg/m$^3$, Young's modulus: $7.2 \times 10^{10}$ Pa, Poisson’s ratio: 0.3). It is worth noting that the conductive epoxy resin is depicted in Figure 4, but it is not considered in the model settling since it is really thin and can be ignored. Moreover, the SOLID 226 and SOLID 186 elements are selected for the PZT plates and metal substrate, respectively. The desired working modes of the BT under free-free boundary conditions and their resonant frequencies are obtained by adjusting the structural parameters. The structural parameters of the stepped holes are the most sensitive parameters to the resonant frequency, namely the length and the diameter of the stepped holes hold the greatest influence on the resonant frequency, while the length of BT has been determined in Section 2. The three working modes are obtained by adjusting the parameters of stepped holes. The variation trend of the length of the stepped hole with the resonant frequencies of three working modes are plotted in Figure 7(b)) to Figure 7(d)), respectively. Furthermore, in order to study the change trend of stepped holes intuitively, the relationships between the diameter and resonant frequency are plotted in Figure 7(c)), and the decisive values are marked with blue stars on the coordinate axes. Finally, the tentative dimensions of the BT are confirmed and plotted in Figure 7(a)), and the resonant frequencies of the $B_{SZ}$ mode, $B_{SY}$ mode, and the
L\text{2X} mode are 54.798 kHz, 54.803 kHz, and 54.826 kHz, respectively, as shown in Figure 8 (a)). The maximum difference among the resonant frequencies is 28 Hz and satisfies the design of multi-mode USM. The vibration characteristic of the local particle on the driving surface is obtained via transient analysis. In the simulation part, the damping ratio is set to 0.003. The voltage and excitation frequency applied in the simulation are 100 V\text{p-p} and 54.80 kHz, respectively, and the related results as shown in Figure 8(b)). The vibration amplitudes in the OZ and OY direction are more significant than that in the OX direction; the maximum amplitude of the former is 9.01 μm, while the latter is 1.98 μm. The PZT plates are arranged at the position more biased toward the wave loop of bending modes to degenerate the frequencies of desired working modes, which may be the reason that the lower amplitude is achieved by the longitudinal mode. Moreover, compared to the d_{31} operating mode, the large amplitudes of longitudinal mode are achieved by the d_{33} operating mode [39]. The trajectory in blue and pink color represents the results of the L-B and B-B modes in the steady-state, respectively, as shown in Figure 8(b)). The longitudinal mode and bending one are two different vibrations with diverse properties for a uniform beam. The two elliptical trajectories are not the same due to the different phase lag of the longitudinal displacement response and the bending mode one. Therefore, the two-DOF motions can be achieved, which are illustrated in the next section.
4. Experimental characterization

To verify the design and working principle of BT, a prototype was fabricated according to the design results listed in Figure 7(a). The two-DOF BT was fabricated and assembled in simple and scalable steps as shown in Figure 9. The metal substrate and PZT plates are cleaned with acetone first to clean up. Subsequently, the conductive epoxy resin (Model: Hysol E-120HP, LOCTITE, USA) and rubber band are utilized to bond and fasten the PZT plates to the metal substrate, respectively. Afterward, the assembled BT solidified at room for 48 hours; thus, the PZT plates are fixed in the metal substrate completely. The BT is soldered at 250°C, which is lower than the Curie temperature of the PZT plates. Finally, the total weight of the prototype is 117.6 g. The dynamic characteristics of the BT are tested through the experimental method, and then a series of experiments of mechanical performances are obtained in sequence.

4.1. Vibration characteristics tests of the BT

Vibration characteristic tests were carried out using a Doppler laser vibrometer (Model: PSV-400-M2, Polytec, Germany). In the experiment, three spatial planes perpendicular to the vibration direction are selected as frequency sweep areas, which are named as Area I, Area II, and Area III, respectively. The sweep range and voltage of the chirp signal are set to 20 kHz to 80 kHz and 10 Vp-p, respectively, as shown in Figure 10(a)). The characteristics of normalized magnitude verse frequency are extracted and plotted in Figure 10(b)) to Figure 10(d)), respectively. It can be seen that the resonant frequencies of $L_{2X}$, $B_{5Z}$, and $B_{5Y}$ modes are 52.54 kHz, 52.31 kHz, and 52.40 kHz, respectively. Furthermore, the slight difference is caused by the discrepancies in materials and assembly errors, which is acceptable within a reasonable range for operating.
4.2. Output characteristic experiments

The two-DOF motions are realized by tuning the frequency and excitation voltage of the three AC signals. To experimentally investigate the mechanical performance of the two-DOF USM, the mechanical experimental system is established to verify the optimal frequencies of linear and rotary speeds, as shown in Figure 11(a). In order to demonstrate the experimental setups of two-DOF motions intuitively, the blue and the purple line are used to represent the flow direction of current and signal among the equipment, respectively. A power supply (Model: QD-8D, China) utilized to produce the three voltage signals are plotted in Figure 5(a)). The linear and rotary speeds of the mover were tested by the laser displacement sensor (Model: LKH020, KEYENCE, Japan) and the tachometer (Model: UT371, UNI-T, China). The slim poles are selected as the mover, and an ultrathin wafer is bonded to the end of the mover to increase the testing area. The relationships of output speeds and excitation frequency are plotted in Figure 11(b)). Under the voltage of 100 V_{p-p} and on-load conditions, the maximum linear and rotary speeds are 33.21 mm/s and 2184.95 rpm at 52.40 kHz and 52.35 kHz, respectively. In this study, there are small discrepancies in resonant frequencies of three working modes due to the assembling and manufacture error. The optimal frequencies of linear and rotary motions are 52.40 kHz and the 52.35 kHz, respectively, which are consistent with the vibration test results. Therefore, there are two excitation frequencies for rotary and linear motion, respectively.
Two frequencies are chosen as the optimal excitation frequency for a series of experiments subsequently. Furthermore, the optimal frequencies of linear and rotary motions are consistent with the testing results in Figure 10. Therefore, both L-B modes and B-B modes are successfully excited and verified.
The slim poles made of stainless steel (SUS304) are applied to the speed and carrying load tests, respectively. First, the output speeds of the mover under no-load conditions are tested, and the results are plotted in Figure 12. It can be observed that the starting voltages for rotary and linear motions are 60 $V_{p-p}$ and 82 $V_{p-p}$, respectively. In Figure 8, the amplitudes of longitudinal and bending modes are 1.98 $\mu$m and 9.01 $\mu$m, respectively. The simulation result indicates that the longitudinal mode achieves lower amplitude under the same excitations. Thus, the slim pole cannot overcome the friction between the driving face, and the slim pole until sufficient voltage is applied. Moreover, there is a clearance fit between the driving face and the slim poles. In the experimental part, the rotary and linear motions of prototype are observed when the 60 $V_{p-p}$ and 82 $V_{p-p}$ are applied to the PZT plates, respectively. Furthermore, it can be seen from the curve that the speeds increase with the increment of voltage amplitude. The maximum output speeds for rotary and linear motions are 3319.6 rpm and 57.6 mm/s under the voltage of 150 $V_{p-p}$, respectively.

In order to investigate the load capacity of the two-DOF USM, the external load tests were carried out by varying the weight. The experimental setup for the load capacity tests is shown in Figure 13(a)). The slim pole with diameters of 1.98 mm is applied to increase the friction between the driving surface and the mover, and the black adhesive tape is pasted on the wafer asymmetrically. Furthermore, a string-pulley system was established for linear actuation tests. As shown in Figure 13(b)), the mover could rotate when the excitation frequency varies from 52.08 kHz to 52.72 kHz, which are close to the optimal frequency of rotary motion. Thus, the three frequencies are selected as the exciting frequencies in the experiment, and the output speeds decreases with the increase of the external load. Compared to the fifth-order bending modes, the vibration amplitude of the $L_{2x}$ mode is smaller in this work. Therefore, the mover could drive along the

![Figure 12. Relationships between the rotary and linear speeds and the voltage under no-load conditions.](image-url)
X direction with the external load at its optimal frequency. The testing results show that the maximum load and torque are 6 g and 0.14 mN·m, and the speeds are 14.875 mm/s and 155.6 rpm under the voltage of 100 V_{p-p} in linear and rotary motions, respectively. These results show that the proposed USM can withstand light loads, and the related demonstration will be discussed in the next section.

In order to investigate the influence of preload on the transient characteristics, the transient responses of the linear speed under no-load conditions were carried out, as shown in Figure 14. The green (from starting to 0.027s) and pink areas (from 0.027s to 0.463s) represent the states of power-on and power-off of the USM, respectively. The rising curve exhibits the delay characteristic since the time constant is mainly determined by the friction force between the slim pole and the driving face. Compared with the electromagnetic motor, the USM has an obvious drooping characteristic. During the
braking interval, the power was turned off at 0.463 s and the speed began to decrease rapidly, which shows the negative acceleration due to the friction force. Due to the limited measuring range of the laser sensor, the acceleration interval of the mover existed for a short time. The phenomenon shows that the USM has not reached a stable working interval of operation.

Recent studies of multi-DOF USMs are compared and summarized in Table 1. The similar configuration proposed by Liu et al. achieves a high linear speed of 573 mm/s and 543 mm/s and a thrust force of 24 N and 22 N in two directions [39]. However, its total volume was larger due to the Langevin-type configuration adopted. Similarly, 16 PZT plates were utilized in the three-DOF USM developed to improve the rotary speed, but its rotary speed is at the middle level [45]. A tiny USM was proposed by Mashimo et al. [37], but the rotary speed in this work is more prominent. In this work, we achieved significant rotary speed through 16 PZT plates and slim pole, and the bonded-type feature is conductive to realize further miniaturization of USM.

The high displacement resolution of USM could be obtained when the sinusoidal burst mode is applied [15,39]. In this study, the linear step displacement of mover is studied when the pulse signal is employed. The pulse repetition frequency is set as 50 Hz, while the duty factor varies from 5% to 50%, which could be utilized to control the step displacement. The starting points of the curves are set to the end point of measurement range to be observed and contrasted intuitively. As shown in Figure 14, the linear step displacement achieved by prototype varies to the duty factor while the starting voltage is applied. The minimum step displacement of 1.2 μm is obtained when the duty factor turned to 5%. Namely, the step displacement could be controlled by adjusting the duty factor successfully. The burst mode cannot only control the displacement of USM but also bring a high resolution of displacement conveniently.

5. Demonstration of two-DOF motions

To verify the effectiveness of the two-DOF motions, a simple focusing operation and posture adjustment system were established to obtain the detail information from the clear pictures. Figure 15(a)) shows the experimental system and the pictures captured by an industrial camera (MER-031-860U3M, Daheng Imaging) with a frame rate of 860 FPS (frames per second). Moreover, the special design is adopted and regarded as a marker, which is bonded to the end of the tiny rod. First, the distance between the marker and the industrial camera are adjusted through the linear motion, until the picture of marker is clear, as shown by (1)–(5) in Figure 16(b)) and the posture of the marker aligned by the rotary motion, as shown by (I)–(V) in Figure 16(b)). Finally, the clear picture of marker was
obtained, and its posture could be aligned through rotary motion. Here, the rotary motion of the two-DOF USM can be utilized to obtain more detailed information and expand the visual range of objective lens in a rough optical focusing device.

**Figure 15.** Relationships between the step displacements and the duty factor.

**Figure 16.** Demonstration of two-DOF motions. (a) Experimental setup for two-DOF motion tests. (b) The demonstration of two-DOF motions.
6. Conclusion

In this work, a two-DOF USM based on the bonded-type transducer combining the longitudinal-bending (L-B) and orthogonal bending (B-B) modes was proposed and designed. The proposed two-DOF USM was composed of 16 PZT plates and one metal substrate. The working principle of the USM was analyzed and verified by the FEM simulation. A prototype of USM was fabricated, and related mechanical characteristics were tested. The resonant frequencies of $L_{2X}$, $B_{5Z}$, and $B_{5Y}$ modes were 52.54 kHz, 52.31 kHz, and 52.40 kHz, respectively. The experimental results showed that the maximum linear and rotary speeds of mover were 57.6 mm/s and 3319.6 rpm under the voltage of 150 V_p-p, respectively. The mechanical load were 0.06 N and 0.14 mN·m when the linear and rotary speeds were 52.72 mm/s and 155.6 rpm, respectively. Moreover, the linear step displacement was 1.2 µm, while the duty factor and the pulse repetition frequency were set to 5% and 50 Hz, respectively. Therefore, the working principle and feasibility of the design were verified by means of the FEM simulation and experimental results. Moreover, a simple focusing operation and posture adjustment system were established to demonstrate the preliminary application of optical focusing. The linear motion was utilized to adjust the position of the object, while the rotary one was adopted to expand the visual range of the objective lens in optical focusing system. In future work, the study related to the two-DOF USM will be focused on the integration of the focal length adjustment and aperture control functions.

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Disclosure statement

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ORCID

Yingxiang Liu  http://orcid.org/0000-0001-5684-9159

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