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New "HAPA", "FTA" and "HD-FTA" Piezoelectric Actuators

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Abstract: "HAPA" stands for High-Authority Piezoelectric Actuator, which describes high-performance piezoelectric actuators of large stroke and blocking force. "HAPAs" are made possible by high-bending-stiffness connectors which connect multiple units of piezoceramic stacks into a 2-level actuation structure. Present HAPA actuators are fitted with commercial piezoceramic stacks. For instance, a "HAPA-(2+2)" comprises 4 PZT stacks, 2 in the upper level with displacement projecting upward and 2 in the lower level with displacement projecting downward. They not only double the axial displacement of individual stacks with only fractional increase in device length but also of 1.5× to 3× larger blocking force depending on the actual design. "FTA" stands for Flex-tensional Actuator, in which the horizontal extensional displacement of PZT stacks is amplified to yield much larger contractional vertical displacement via a diamond-shaped elastic frame structure. A range of new FTAs have been developed by us using single or multiple units of PZT stacks, of which the performances are described in this work. "HD-FTA" stands for HAPA-Driven Flextensional Actuator, in which HAPA piezoelectric actuators are used as the motor section to drive diamond-shaped elastic members of various designs for further displacement amplification. Several HD-FTAs, driven by a HAPA-(2+2) actuator, have been developed. Compared with standard FTAs of comparable stroke, HD-FTAs display higher working load but of smaller overall length. "HAPA", "FTA", and "HD-FTA" piezoelectric actuators find applications when a smaller actuator length is advantageous in addition to the required moderate-to-large displacement and working load.

Keywords: stacks; displacement amplification; large blocking force; high working load

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1. Introduction

Piezoelectric stack actuators, made by bonding tens to hundreds of thin thickness-poled piezoceramic plates into a bar-like construction, are extensively used today in micro- / nano-positioning and motion control in precision instrument and machinery. They are of large blocking force but limited axial displacement, of > 500N and a few to tens of μm respectively [1]. To increase the axial displacement of piezoelectric stacks, various amplification mechanisms had been devised, such as the lever-arm, flextensional and telescopic approaches [2-7]. In doing so, however, the blocking force of the resultant device is reduced significantly.

In this work, three new types of piezoelectric actuator are described which not only have amplified axial displacement but also maintain moderate-to-large blocking force including twice to thrice that of individual stack actuator.

2. High-Authority Piezoeletric Actuator (HAPA)

High-authority Piezoelectric Actuator (HAPA) is made possible by a patented high-bending-stiffness connector (HBSC) [8], which connects multiple units of piezoelectric stack into a 2-level actuation configuration. This can be visualized from the illustration shown in Figure 1. Depending on the type of HBSC used, HAPA actuators may be further divided into HAPA-(1+2), HAPA-(2+2) and HPAP-(3+3), where the numerals "i" and 'j" in the symbol (i+j) denote the number of upward projecting stacks and that of the downward projecting stacks, respectively. For the HAPA actuators described in this work, the HBSC is made of an aluminum alloy (AA6061) and the piezoceramic stacks used are NEC-Tokin stack actuator (model no. AE0505D44H40DF), of 5×5 mm^2 in foot-print and 40 mm in length. Various designs of the end caps are available including solid designs and those with a through or threaded central hole for preloading and/or mounting purposes.

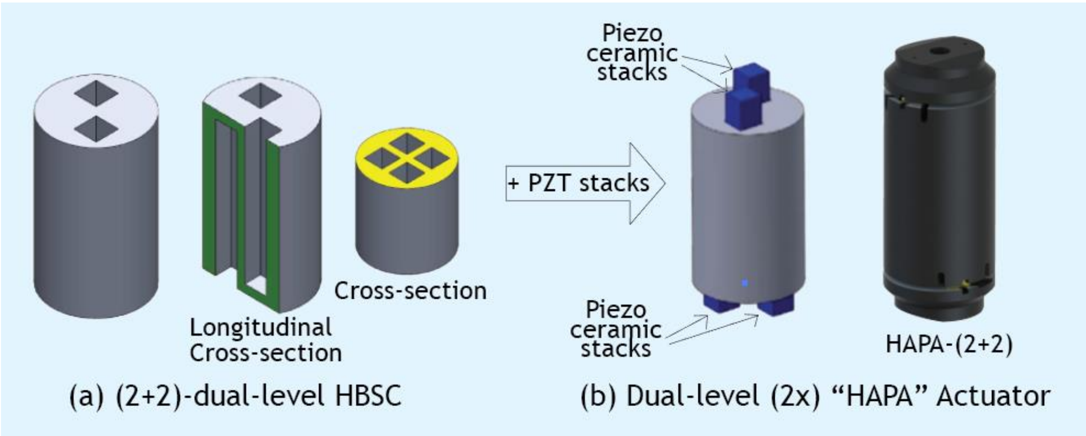

Figure 1. (a) Perspective and sectional views of a HBSC showing the configurations of deep recesses for housing piezoelectric stacks and (b) a HAPA-(2+2) actuator made from it by bonding 4 stacks at the base of respective recesses in a 2-up-and-2-down configuration and topped up with end caps at both ends. The wirings are not shown for clarity's sake.

Figure 2 shows the performance characteristics of HAPA actuators fabricated (see Ref. [9] for a detailed description on the performance evaluation of HAPA actuators). As shown, it has nearly twice the axial displacement of individual stacks which make up the HAPA and 1.5× to 3× the blocking force depending on its actual construction. Unlike most displacement amplified mechanisms via which the blocking force of the resultant device is decreased accordingly, HAPA piezoelectric actuators thus not only double the axial displacement but also multiply the device blocking force. Furthermore, its overall length is only a fraction longer than the length of individual stacks despite having a larger foot-print. For instance, a HAPA-(2+2) actuator measures about 25 mm in diameter and 60 mm in length including specially designed end-caps. It has a stroke of about 85 μm and 1700 N in blocking force @150V. More about different types of HAPA actuator and end cap designs can be found in Ref. [10].

Table 1 compares the performance of HAPA-(2+2) with conventional amplified piezoelectric actuators of comparable stroke including lever-arm, flextensional and telescopic. It is evident that, compared with individual stacks, while the blocking force is decreased significantly with conventional ampliflied approaches, this is not so for HAPA. In fact, as multiple stacks are used in HAPA, its blocking force is 1.5× to 3× that of individual stacks. Thus, in addition to being stand-alone actuators, HAPAs can be used as the motor section of other amplified designs, leading to further enhancement in stroke of the resultant device. As will be shown below, HAPA driven flextensional actuators (HD-FTA) of various designs have also been successful developed in the present work.

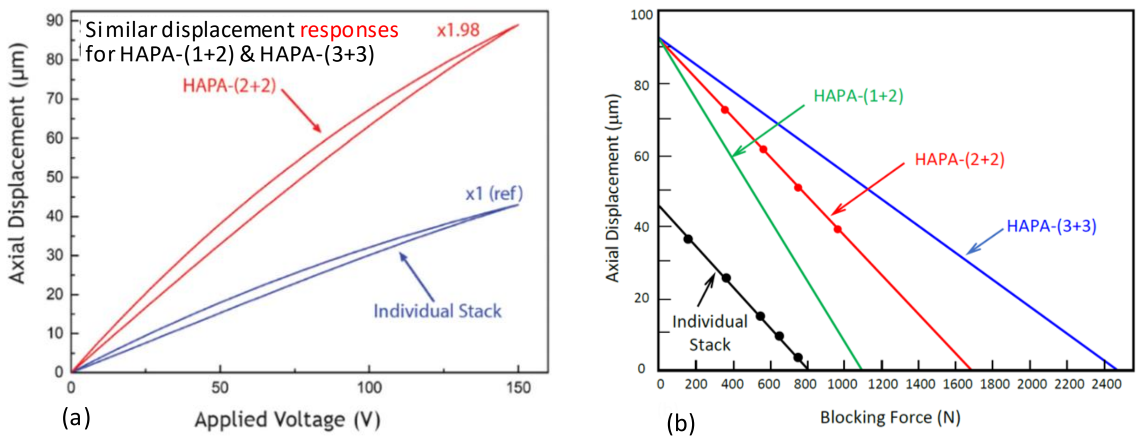

Figure 2. (a) Displacement-versus-voltage curves and (b) displacement versus axial compressive load plots of HAPA actuators. The intercepts at the abscissa of the various curves in (b) give the blocking forces of respective HAPAs.

Table 1. Performance comparison of HAPA, lever-arm, flextensional and telescopic actuators

Product / Model	Size (mm)	Stroke (μm)	Blocking Force (N)
HAPA-(2+2) [this work]	ϕ24×47(H)*	88	1700
P.I.-P-601.10 [11] (Lever-arm)	46.5(L)×12(D)×25.2(H)*	100	30
Cedrat-APA100 [12] (Flextensional)	55.2(L)×10.5(D)×25.2(H)*	126	235
Telescopic [13] (3-cylinder design)	ϕ26.5×80(H)*	22-28	257-270

* H indicates height of device which is also the excitation direction.

3. Flextensional Actuator

Flextensional Actuators (FTA) has been widely used in the industry, notably when large displacement is required with low to medium payload (payload or maximum working load is used here because flextensional actuators contract in the active direction instead when a positive polarity voltage is appled to the stack actuator, hence making the definitaion of blocking force invalid). In such a design, a diamond-shaped elastic frame structure is employed to amplify the horizontal extensional displacement of PZT stacks into much larger contractional displacement in the vertical direction. This allows for a compromise, effectively converting the high blocking force and low displacement of a piezoceramic stack into a device of moderate blocking force and moderate-to-large displacement. In conventional FTAs, the motor section is made of one piezoceramic stack, typically of a square cross-section.

A range of new FTAs have been developed by us using one, two or four units of identical PZT stack as the motor section, which offers flexibility in design and device performance. For instance in one design, as shown in Figure 3(a), two stacks of 5×5 mm^2 cross-section are placed vertically with respect to one another. This results in a “slim FTA” of only 5 mm in depth but of improved height displacement and maximum working load allowed. When four 5×5 mm^2 cross-sectioned stacks are used, they are arranged in a 2×2 square matrix manner, producing a performance equivalent to that driven by a single 10×10 mm^2 cross-sectioned stack.

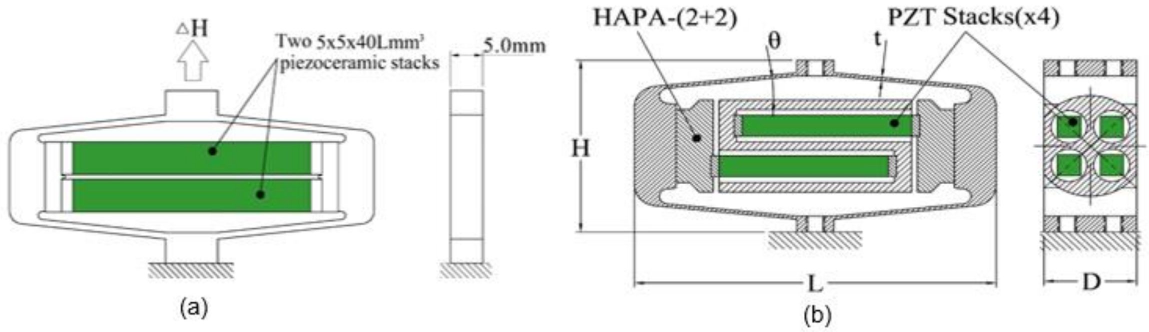

Figure 3. Schmatics showing the constructions of (a) "Slim FTA" and (b) HAPA-Driven FTAs.

4. HAPA-Driven Flextensional Actuator (HD-FTA)

In addition to conventional FTA, new high-performance FTAs, of which the motor section is made of a HAPA-(2+2) actuator containing 4 identical stacks in a 2-up-and-2-down configuration as described in Section 2 above, have also been developed. A schematic of the construction of a HD-FTA is provided in Figure 3(b). This is to take advantage of the much higher axial displacement and blocking force displayed by the HAPA-(2+2) while its overall length being only fractionally longer than an individual stack.

With the driving element pre-selected, the design optimization involves choosing a flextensional (FT) frame of the correct length (L), depth (or thickness, D) and height (H), and the inclined angle (θ) and the thickness (t) of its 4 flexural arms (see Figure 3b), such that both the height displacement (ΔH) and the maximum working load allowed of the resultant device meet the specified requirements. In the present work, the FT frame is made of martensite stainless steel (SS440C).

In addition to optimising the various parameters of the FT frame to meet the displacement and working load requirements, another key design consideration is that the FT frame must have the correct elastic stiffness and the initial pre-load level between the PZT stack or HAPA and the FT frame must be just right. This is because too high initial preload level and frame stiffness would exert exceedingly large compressive stress on to the stacks, which increases further when the stacks extend under the applied voltage. This, in turn, will reduce the attainable displacement of the stacks and degrade the overall performance of the resultant actuator (i.e., a smaller ΔH will result) and hence is uncalled for. On the other hand, when the initial preload is insufficient and/or the FT frame is not stiff enough, the FT frame may expand too much in its length direction when its height direction is subject to sufficiently high payload. This in turn would place the piezoceramic in the stacks and the various joints in the device in tension, which is highly undesirable. In the worst scenario, the joints may break off and the stacks would become loose in the device.

All these can be carefully modelled and avoided in the design stage while one attempts to maximize either the height displacement (ΔH) and/or the working load of the FTA and HD-FTA when the other parameters are pre-set. An ATILA computer simulation software was used in this work in the modeling.

Another performance indicator of an FTA is its resonance frequencies, both in free-free and blocked-free end conditions. Both resonance frequencies can be obtained from the computer simulation by assigning appropriate boundary conditions to the device and by running the simulation in dynamic analysis mode.

Based on the simulation results, a range of FTAs of conventional design and 4 different types of HD-FTAs have been fabricated and evaluted. The performance of selected FTAs and HD-FTAs are provided in Table 2. In the table, each actuator is denoted with two numbers, e.g., FTA-700-100 and

HD-FTA-450-200, etc., where the first numeral denotes the height displacement (ΔH) in μm and the second numeral the maximum working load allowed in N. The overall dimensions of the resultant devices vary from 56(L)×5(D)×25.4(H) mm for Slim-FTAs to 78(L)×20(D)×43(H) mm for HD-FTAs, where H is the height of the device which is also the excitation direction.

Prototypes of selected designs of FTA and HD-FTA were fabricated. Both the stack or HAPA and the FT frame were assembled with care by first compressing the frame in its height (H) direction with a sufficiently high pre-load to expand its length dimension sufficiently such that the stack or HAPA-(2+2) actuator can be inserted inside the frame interior with relative ease. After releasing the pre-load to allow the frame to clamp onto the stack or HAPA via the pre-set interference fit, the assembly was tested to ensure that the stack or HAPA remained firmly in place when a working load higher than the designed maximum load was applied onto the frame. Then, the frame was similarly expanded again and the stack or HAPA was taken out to enable epoxy adhesive to be applied onto its both ends before again inserting it back and carefully positioning it inside the FT frame. Finally, the load applied onto the FT frame was released to make the resultant device. Pictures of a slim FTA and one of the HD-FTAs fabricated are provided in Figure 4.

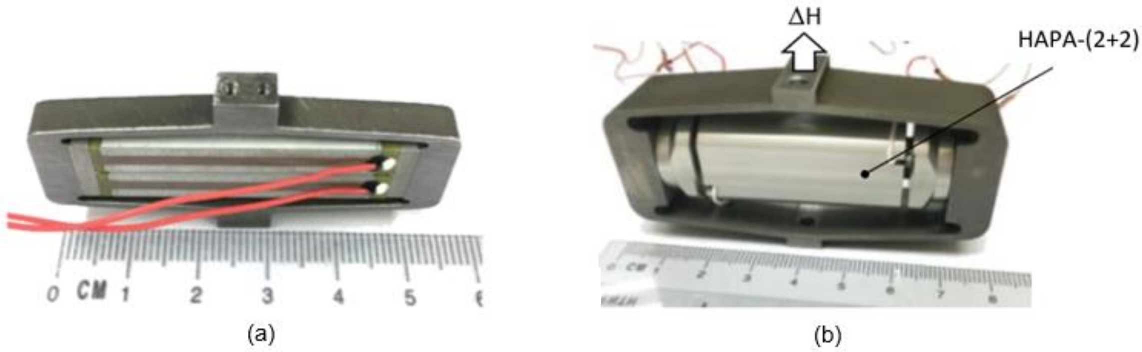

Figure 4. Pictures of (a) a Slim FTA and (b) a HD-FTA fabricated.

The various FTAs and HD-FTAs were evaluated by measuring their height displacement (ΔH) as a function of the applied voltage initially under load-free condition and subsequently under increasing working loads up to the maximum load allowed. The details of the test set-up used can be found in Ref. [9] including the working load placement arrangement. Selected results are shown in Figures 5(a) to (d). The obtained ΔH at the maximum applied voltage of 150V under no load condition and under the maximum working load allowed agree reasonably well with our computer simulation results. These results are compiled in Table 2 for easy reference.

Compared with conventional FTA designs, HD-FTAs developed in the present work display comparatively large height displacement, comparable or higher working loads and smaller overall length. However, they have smaller resonance frequencies notably under blocked-free end conditions, due to the extra mass of the aluminum alloy HBSC in the HAPA actuator.

5. Conclusions

Three new types of piezoelectric actuators are described in this work: High-authority piezoelectric actuator, or HAPA, made possible by means of the high-bending stiffness connector (HBSC) which connects multiple units of piezoceramic stacks in a 2-level actuation configuration, displays about twice the displacement of individual stacks and 1.5× to 3× the blocking force depending on the actual construction. MMT flextensional actuators (FTA) are driven by one to four identical PZT stacks, offering a wide range of performance characteristics. FTAs driven by a HAPA-(2+2) actuator (HD-FTA) have also been successfully developed, which provide large height displace-

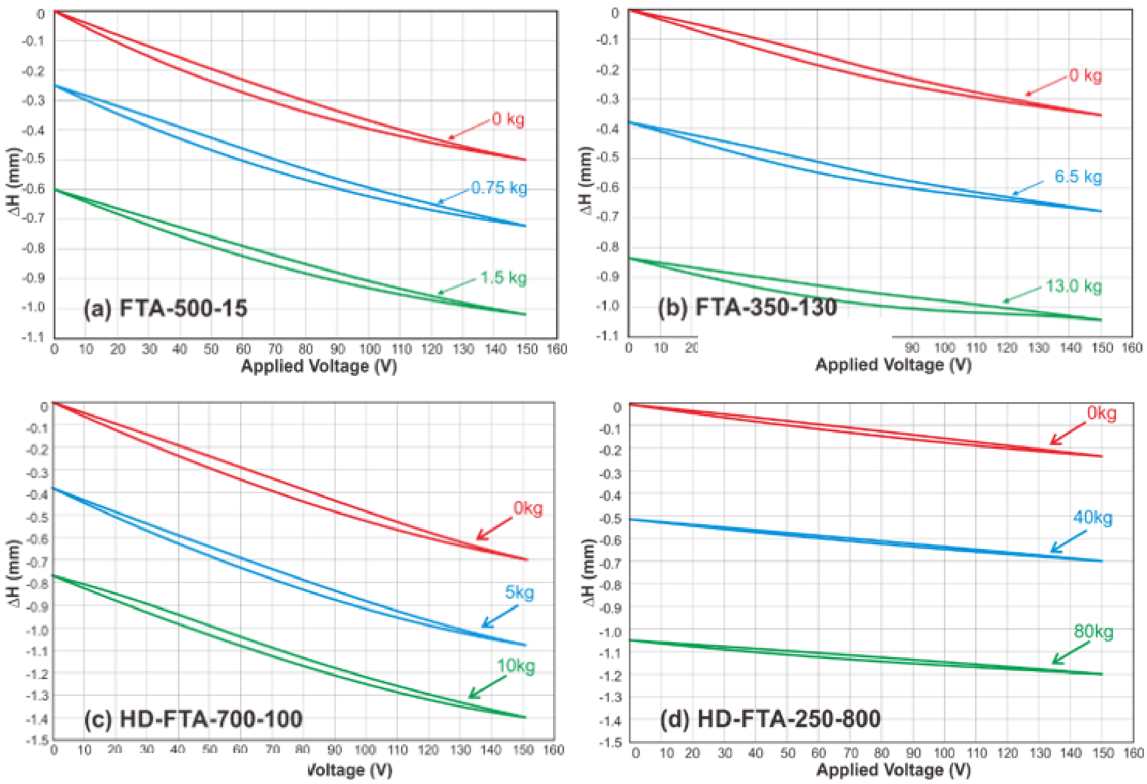

Figure 5. Height displacement (ΔH) versus voltage responses under different loads for (a) FTA-500-15, (b) FTA-350-130, (c) HD-FTA-700-100 and (d) HD-FTA-250-800.

Table 2. Measured performance of FTAs and HD-FTAs developed in the present work

Feature	FTA-500-15*	FTA-200-140*	FTA-350-130*	HD-FTA-700-100*	HD-FTA-250-800*
Dimensions (L×D×H; mm)**	56×5×25.4(H)	56×5×25.4(H)	56×11.5×25.4(H)	78×20×40(H)	78×20×43(H)
ΔH (μm) @ 150V	500	200	350	700	250
Max. working load (N)	15	140	130	98	785
Approx. stiffness (N/μm)	0.03	0.7	0.38	0.15	3.20
Resonance Freq. (free-free; Hz)	2050	3270	1734	1000	2300
Resonance Freq. (free-blocked; Hz)	570	970	450	200	574
Weight (g)	27.2	30.5	61.0	167	189

*The first number gives vertical displacement in μm and the second number maximum working load allowed in Newton. **H indicates height of device which is also the excitation direction.

ments for moderate to high payloads but of smaller overall length. Table 3 compiles the performance of these new types of piezoelectric actuators for easy reference. Also included in this table are Hi-Fi Stake single crystal piezoelectric actuators [14,15] of which the displacement responses are linear with negligible strain hysteresis when used under specified conditions.

Max. Load / Stroke	15-40 N	40-100 N	120-240 N	250-500 N	500-2500 N
5-30 µm	HFS-CE(*)	HFS-HL(*)	"Hi-Fi Stake" actuators of various constructions - Linear, hysteresis-free		
30-100 µm	HFS-LS(*)				**HAPA-(1+2)**-85µm-1250N **HAPA-(2+2)**-85µm-1700N **HAPA-(3+3)**-85µm-2500N
100-250 µm		**FTA-175-70** 175µm-70N	**FTA-200-140** 200µm-140N	**FTA-200-250** 210µm-260N	**HD-FTA-250-800**(*) 250µm-785N
250-400 µm	**FTA-300-40** 310µm-40N	**FTA-350-50** 350µm-50N	**FTA-350-130** 350µm-130N	**HD-FTA-350-400**(*) 350µm-400N	
400-700 µm	**FTA-500-15** 500µm-15N		**HD-FTA-450-200**(*) 450µm-220N		
	FTA-500-30 500µm-30N	**HD-FTA-700-100**(*) 700µm-96N			

(*) HFS-CE=Cost Effective Hi-Fi Stake; HFS-LS=Large Strain Hi-Fi Stake; HFS-HL=High Load Hi-Fi Stake; HD-FTA=HAPA Driven FTA.

Table 3. Stroke and blocking force (or max.working load) of MMT piezoelectric actuators of various designs

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:
MMT: Microfine Materials Technologies Pte Ltd
HBSC: High Bending Stiffness Connector
FTA: Flextensional Actuator
HAPA: High Authority Piezoelectric Actuator
HD-FTA: HAPA-Driven Flextensional Actuator

References

1. Niezercki, C.; Beri, D.; Balashrishnan, S.; and Moskalik, A. Piezoelectric actuator: State of the art. *Shock and Vibration Digest*, **2001**, *33*, 269-280.
2. Toulis, E.J. Flexural-extensional electromechanical transducer. U.S. Patent No. US 3,277,433, 4 October, 1966.
3. Royster, L.H. The flextensional concept: A new approach to the design of underwater acoustic transducers. *Applied Acoustics*, **1970**, *3*, 117-126.
4. Uchikawa, T. Mechanical amplification mechanism combined with piezoelectric elements. U.S. Patent No. US 4,570,095, 11 February, 1986.
5. Asano, H. Piezoelectric actuator. U.S. Patent No. US 4,783,610A, 8 November, 1988.

6. Wu, C.C.M.; Lewis, D.; Kahn, M.; and M. Chase. High authority telescopic actuators. *Proc. SPIE*, **1999**, *3674*, 212-219.
7. Brei, D.E.; and Hallovan, J. Solid state high authority telescoping actuators. Available online: http://www.dtic.mil/dtic/tr//fulltext/u2/a400693.pdf.
8. Lim, L.C.; Huang, Y.; Xia, Y.X.; and Lin, D.H. Displacement connectors of high bending stiffness and piezoelectric actuators made of such. WIPO/PCT Patent No. WO / 2017 17629 A1, 12 October, 2017.
9. Huang, Y.; Xia, Y.X.; Lin, D.H.; and Lim, L.C. High-bending-stiffness-connector (HBSC) and high-authority piezoelectric actuator (HAPA) made of such. *Actuators* **2018**, *7*, 61; doi: 10.3390 / act7030061.
10. http://www.microfine-piezo.com/files/HAPA-4page.pdf
11. P.I. P-601 PiezoMove Linear Actuator with Guides. Available oneline: http://www.physikinstrumente.com/en/products/piezoceramic-acutators/liner-actuators/p-601-piezomove-flexture-guided-linear-actuator-202600/
12. Cedrat Technologies, Amplified Piezoelectric Actuators. Available online: http://www.cedrat-technologies.com/en/products/actuators/apa.html
13. Alexander, P.W.; and Brei, D. Piezoceramic telescopic actuator: quasi-state experimental characterization. *J. Intell. Mater. Syst. Struct*., **2003,** *14*, 643-655.
14. Huang, Y.; Zhang, S.; Wang, P.; Xia, Y.X.; Lin, D.H.; Yao, K.; and Lim, L.C. Hi-Fi Stake piezo single crystal actuator. *Actuators* **2018**, *7*, 60; doi: 10.3390 / act7030060.
15. Lim, F.C.; Lin, D.H.; Xia, Y.X.; Koh, J.H.; and Lim, L.C. Hi-Fi Stake piezoelectric actuators and new developments. (This issue).