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Piezoelectric Actuators for Micro Positioning Stages in Automated Machines: Experimental Characterization of Open Loop Implementations

This paper presents an experimental characterization of an industrial, entry level piezoelectric device with open loop control, whose working principle is based on friction. As a consequence, the length of the single step is dependent on the applied load. Test results confirm the strong dependence existing between the stroke length and the resistance force and are used to design some possible practical applications, both for automated machine common subsystems (positioning stages, gripping tools) and for an innovative differential mechanism which combines their output movement with the one generated with a traditional, larger DC motor, to obtain high torques and accurate positioning at competitive cost.

Keywords: *linear piezoelectric motor, miniaturized motor, hybrid actuator, positioning stage, gripping tool*

1. INTRODUCTION

Industrial applications of inverse piezoelectric effect have been around a long time, for instance to drive ultrasonic machining tools, injectors in internal combustion engines and printer heads. In the last decades, on the push of an increasing interest for miniaturizing positioning systems and for improving their accuracy, for instance in the fields of robotics [1] [2], machine tools [3] and vibration control [4][5], several different design solutions [6,7] have been developed to extend piezoelectric actuator use even in applications that require longer strokes and greater versatility. All these devices have in common excellent operating bandwidth and in most cases they can be used to obtain large forces with limited size and allow to get positional accuracy in the order of magnitude of nanometres [8]. In particular, linear stepper piezoelectric motors can be used to satisfy with great simplicity and high degree of miniaturization design requirements concerning the generation of linear movements with nanometric resolutions and relatively long strokes, typically up to 100 millimetres.

Despite these very interesting features, in practice their use with closed loop control systems poses complex problems for measuring the movement at the micro/nano scale, and this difficulty limits their role to small industrial niches. It is instead less explored their possible use with open loop control circuits which, albeit at the price of limited accuracy, allows to create extremely lightweight and compact devices for direct generating linear motion.

In particular, for low-cost applications it is particularly interesting the operation principle called Piezo LEGS®, developed by PiezoMotor® [9], which is based on a friction transmission mechanism of non-ultrasonic legs oscillations that allows to obtain stepped movements which produce virtually unlimited length strokes, depending only on the rod size, with very competitive cost.

The main limitation of this technology consists in the fact that the length of each step is highly dependent on the applied load and calculating the overall stroke from the step number could lead to significant errors, as shown in figure 1.

Therefore, to preserve the advantages given by the simplicity of open-loop control together with sufficient positioning accuracy is essential to experimentally characterize such dependence to properly calibrate the control system.

It should be noted that, as stated by the manufacturer [9], this phenomenon presents a great variability from one device to another, then the calibration procedure must then be repeated for each specific actuator.

Anyhow, the applicability of this study also extends to the closed-loop applications, in which the knowledge of the device characteristics allows to properly determine its state equations and to achieve optimal performances.

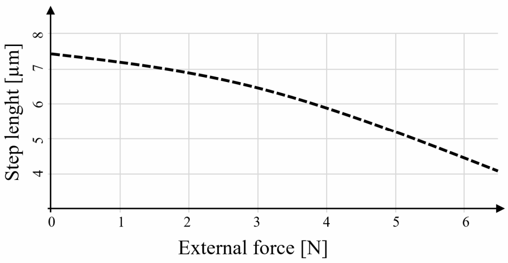

Figure 1. Motor step length on varying the exerted force

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2. ACTUATOR DESCRIPTION AND CHARACTERISTICS

The meaning of the tests carried out, their result interpretation and their usage in the industrial field are closely related to the particular operating principle on which the chosen device is based and that differentiate it from the more common families of piezoelectric linear actuators. In particular, the Piezo LEGS® approach may be regarded as a combination of a stepping working principles, like inchworm or inertial motors and the elliptic movement of a stator element, as in ultrasonic motors, obtained by bending legs similar to bimorph actuators.

a. Main piezoelectric motor architectures

Inchworm piezo motors are actuated through the quasi-static steps of the piezo stator which carries a second member that alternatively locks and unlocks the runner stem. With such a multi-phase approach, they can offer a good controllability at the price of a quite low maximum speed (<10mm/s). Moreover their complexity determines high manufacturing cost.

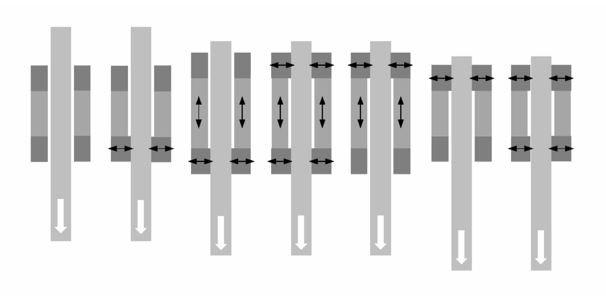

Figure 2. Schematic representation of the stepping process in inchworm piezoelectric motors.

Bimorph actuators are made of thin bending piezoelectric elements which are built as a combination of two very thin piezoceramic beams bonded together to a thin metal plate. The poling orientation of the ceramics and the circuit configuration are combined so that, when powered, one of the beam will expand while the other contracts, causing the bending of the device.

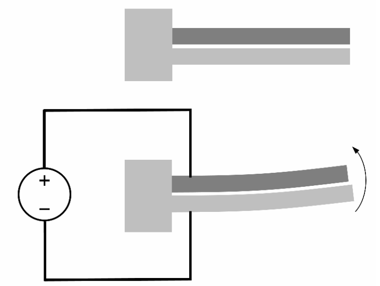

Figure 3. Schematic representation of bimorph motor concept.

Ultrasonic motors (USM) are based on an ultrasonic vibration generated as a combination of two vibrations which produce an elliptic motion on the stator surface. Usually they work at resonance frequency to amplify as much as possible the amplitude of the vibration itself and the generated wave put in motion the rotor by friction. They can reach high speed (> 100mm/s), offer and, because of the friction working principle, are sensitive to variations of loads and environment. The required electronic is complex and this impact on the manufacturing cost.

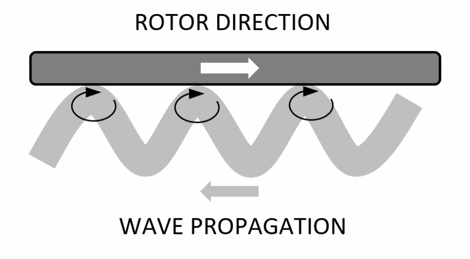

Figure 4. Schematic view of travelling wave motor concept.

Inertial Stepping Motors (ISM) are also called (Smooth) Impact Drive Mechanisms (IDM or SIDM) and are based on a stick and slip working principle: in the movement direction, the piezo material is actuated slowly, transmitting by friction the motion to the runner through an intermediate member. During the return phase, the same ceramic is actuated much faster, so that the contact surfaces could slip each other and the runner do not return back together with the contact element. This kind of motor can reach medium speeds (10-50mm/s) and needs only one piezo ceramic and one electronic channel to work, so its simplicity allows to obtain a very good level of miniaturization.

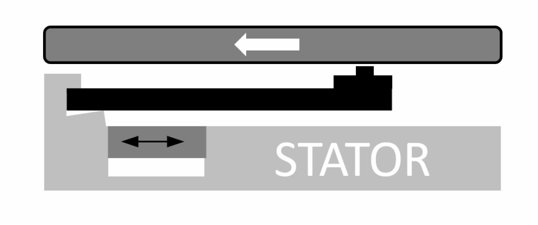

Figure 5. Schematic view of the inertial stepping motor concept.

b. The unit under test

Since this work is oriented to explore new application fields to substitute inexpensive devices, the tests were focused on the smallest motor of the Piezo LEGS® Linear motor series, whose dimensions are shown in Figure 6. It should be noted that the reduced size of the motor does not prevent to use the rod long approximately 100 mm that allows to reach the same maximum stroke of 80 mm obtainable with the other products of the same series (which can however exert higher forces).

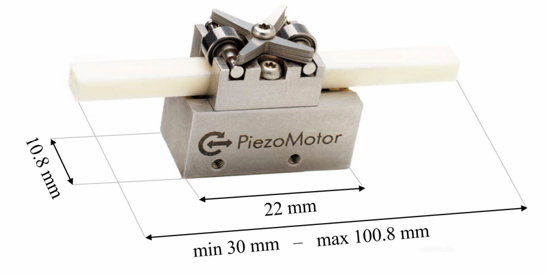

Figure 6. The device under test

The device running principle is of the non-resonant type, as a consequence, the position of the motor elements is always determined and it is possible to achieve a proper control of the system at any given speed. Similarly, to ultrasonic and inertial stepping motor described above, this is a friction based actuator, being the motion transferred through contact friction between the drive leg and the drive rod.

For each waveform cycle the motor will take one full step (≈7.5 μm at no load with the longer available waveform) which is composed by the four main phases shown in the schematic illustrations of figure 7: when legs are electrically activated they are elongated and bending. Alternate legs move as a pair: as the first pair of legs maintains contact with the rod and moves towards the right, the second pair retracts and their tips begin to move left, then the two couples change roles and the cycle of a single step is completed.

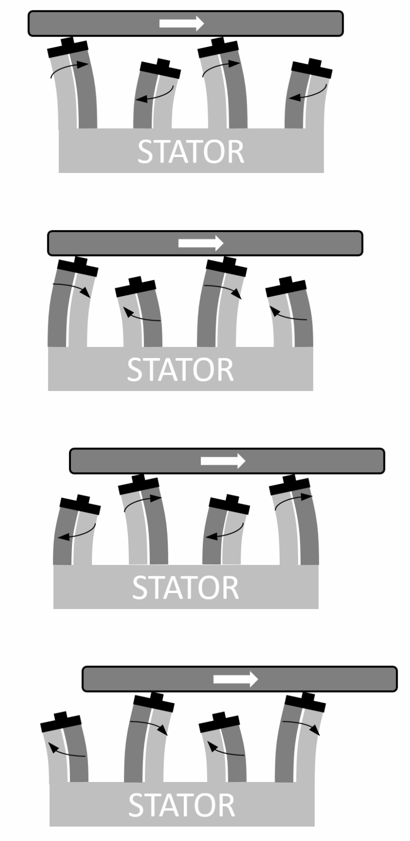

Figure 7. Piezo LEGS® working principle

The speed of the drive rod is given by the step length multiplied by the waveform frequency, that can reach the maximum value of 2 kHz, corresponding to a speed of 15 mm/s. Microstepping (and hence nanopositioning) is achieved by dividing the step into discrete points. The resolution will be a combination of the number of points in the waveform and the load [10] [11].

As explained in the introduction, the motor main drawback is related to the large variability of the step length, especially on varying the load under which the motor is operating, as shown in figure 8, where the dashed curve indicates the typical behaviour of the motor actuated with a longer waveform (called Rhomb), while the dotted one refers to a shorter waveform, suitable for smoother motion, called Delta.

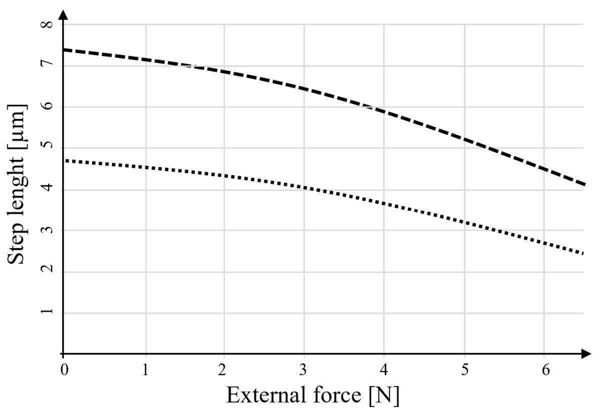

Figure 8. Exerted force for Rhomb waveform (dashed) and Delta waveform (dotted)

Moreover, this typical behaviour is indeed not very repeatable: as the following figure 9 shows, the minimum guaranteed performances are significantly far from the average ones. In practice, this means that the calibration operation described in the next paragraph cannot be considered representative of all the devices of the same type, but should be repeated for each single motor put into service.

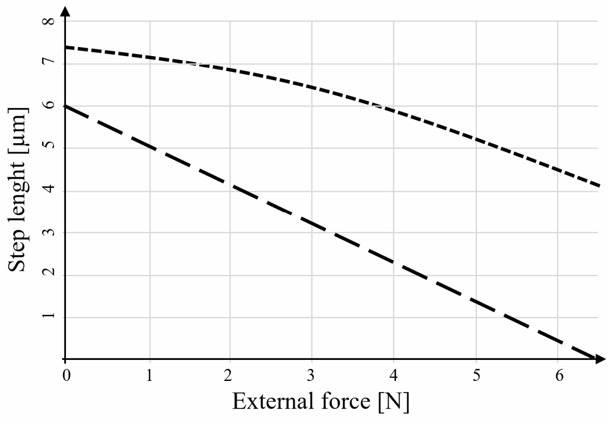

Figure 9. Exerted force for Rhomb waveform: typical (dashed) and guaranteed minimum (long dashed)

3. EXPERIMENTAL SETUP

The test bed used to characterize the motor has been built on the basis of the components described in [11], which were developed with the main purpose to obtain an ultra-precise positioning stage at competitive costs.

c. Mechanical structure

The mechanical structure has been designed as a flexure mechanism. The advantages of compliant elements in high precision measuring systems are well known [12] and can be summarized in the elimination of all nonlinearities, both those due to the presence of backlashes and those related to the presence of Coulomb friction.

Specifically, the single degree-of-freedom mechanism schematically represented in figure 10 has been used, which is capable to maintain 5nm of accuracy during operation.

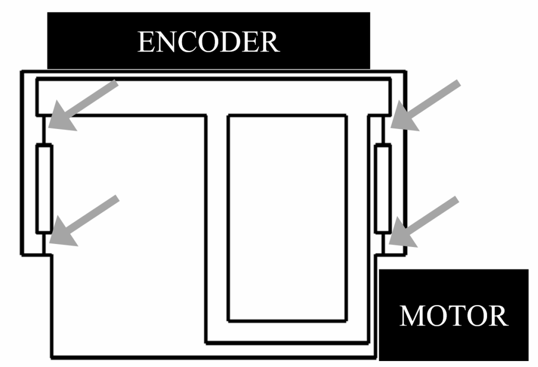

Figure 10. Schematic draw of the flexure, equivalent to a four bar linkage mechanisms, with hinges pointed by arrows

This existing support was coupled with the linear motor by a flange composed of L-shaped plates, which can be securely screwed in some M3 threaded holes already provided on the motor housing.

d. Control and measurement system

The measuring system is based on a rapid controller prototyping platform consisting of a Compact-PCI system running under the Linux RTAI real-time extension. The system exploits the results of the RTAI project (www.rtai.org), which offer real time extensions of the Linux OS and interfaces with various CACSD tools (Matlab/Simulink or Scilab/Scicos). The real-time application can send data to a remote PC, where the data is stored, displayed and analysed. [11]

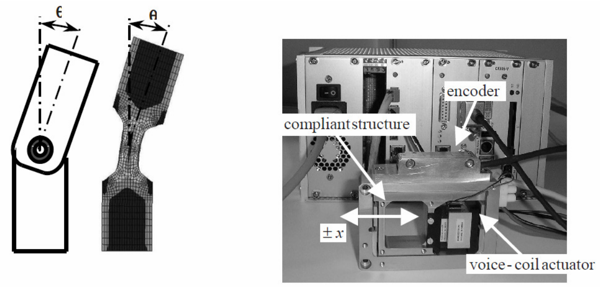

Figure 11. The mechatronics system used as support and measuring station [9]

The figure 11 shows the detail of the flexure mechanism hinges and the complete system which includes the compliant structure, a voice-coil actuator, an encoder and control and acquisition system. The figure 12 that follows highlights the main data links and, in particular, how the sin/cos signal coming from a sinusoidal encoder signal interpolation board is used to generate the position measures which are then stored in the remote PC which acts as human machine interface.

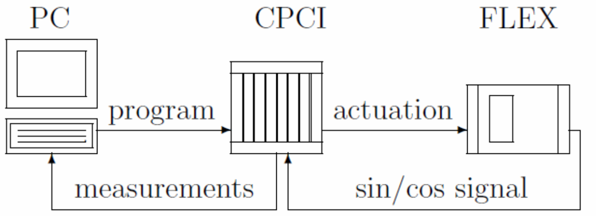

Figure 12. Compliant joint and mechatronics device used as slide and measuring system [9]

The encoder interpolation board is able to sample the inputs at a frequency of 500 kHz and to resolve 13 bits within a signal period.

To test the effect of the load on the motor positioning, the system controller performs a complete forward stroke and return in the presence of a constant unidirectional load.

Therefore, the load exerts its thrust in the same direction of the velocity during the forward stroke and contrasts the motion during the return one. The two movements are of course composed of the same number of steps, equal to 200 in case of the lowest resolution and proportionally increased for smaller ones. At the end of the sequence is measured the distance of the reached position reached from that of departure.

Tests were repeated for different values of load (0.2, 0.4, 0.6, 0.8, 1, 1.5, 2, 3, 4 and 5 N), and for different values of resolution, corresponding to an indicative length of micro steps equal to 4, 2, 1 and 0.5 nm with Delta waveform and 6, 3, 1.5 and 0.75 nm with Rhomb waveform.

A further test carried out, only in case of load applied equal to 0.8 N, consisted of measuring the influence of the step trigger frequency, which was adjusted in the range between 10 and 100 Hz.

4. TEST RESULTS

The obtained results confirm the significant length variation of the distance travelled by the motor rod on varying the applied load. Their interpretation must take account of the specific test conditions and namely the fact that the represented variation is not calculated with respect to a nominal stroke, but of as the relative change obtained by reversing the movement direction and maintaining constant the load one.

The graphs were drawn with logarithmic scales that allow to better observe the found relationship between load and length. Figures 13 to 15 show the behaviour of the system on varying the resolution adopted for the step using the waveform Rhomb that allows to have longer steps (and therefore higher speed).

To assess these results it should be noted that, although the used motors allow to apply a load of up to 6.5 N, the recommended operating range reaches only 3 N.

Below are reported the results obtained in similar test conditions using the Delta waveform, which ensures a smoother movement at the price of a reduced step length.

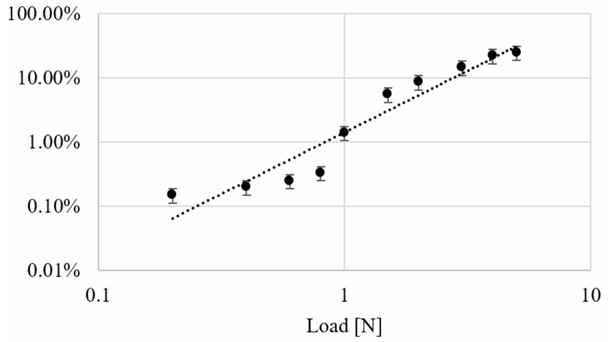

Figure 13. Change in the stroke length on varying load @ 32p resolution, 50 Hz, Rhomb waveform

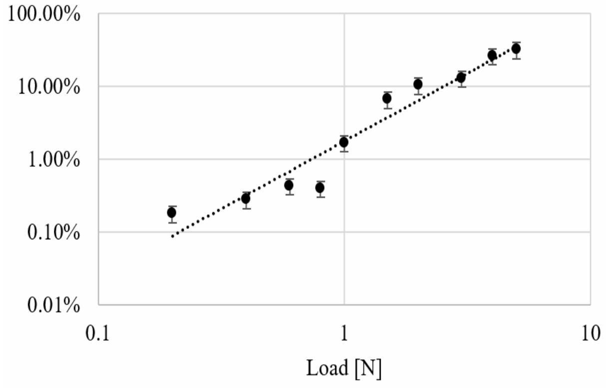

Figure 14. Change in the stroke length on varying load @ 64p resolution, 50 Hz, Rhomb waveform

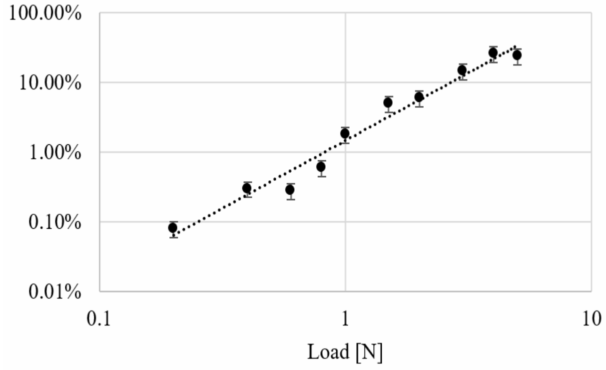

Figure 15. Change in the stroke length on varying load @ 128p resolution, 50 Hz, Rhomb waveform

The diagram below shows the effect of the generation frequency of the steps.

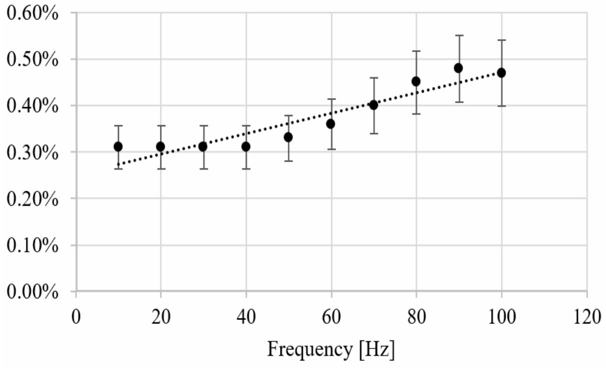

Figure 16. Change in the stroke length on varying frequency @ 32p resolution, 0.8 N load, Rhomb waveform

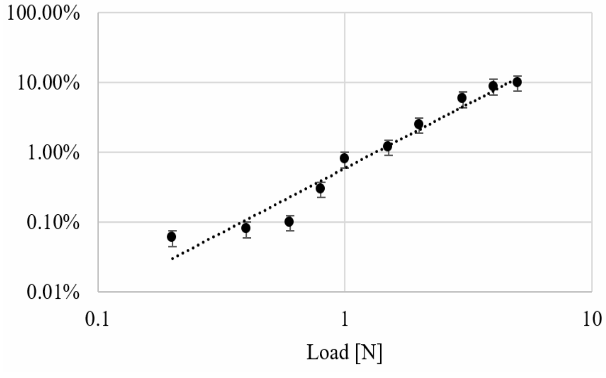

Figure 17. Change in the stroke length on varying load @ 32p resolution, 50 Hz, Delta waveform

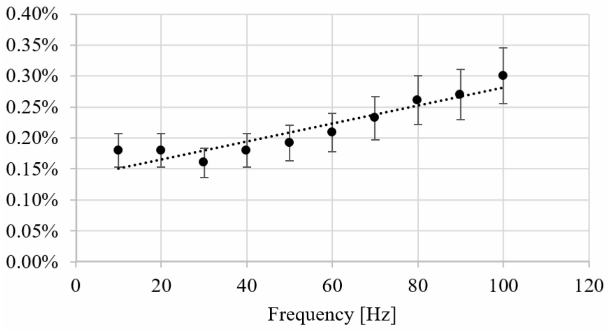

Figure 18. Change in the stroke length on varying frequency @ 32p resolution, 0.8 N load, Delta waveform

5. APPLICATIONS

The presented analysis is completed with some examples of possible applications. They take into account not only their mechanical performance, but also some unique characteristics that distinguish piezo linear motors from traditional electric or pneumatic actuators. Among these should be cited: the extremely limited overall dimensions and weight, the very extended operating range of temperatures, the insensitivity to magnetic fields and the ability to be sterilized by autoclaving.

Moreover, it is important to highlight how the friction transmission principle allows the motors to withstand a possible overload without damage and to maintain the reached position even when they are not powered. This allows the use of these motors to drive gripping devices, in which can be used both to provide a form locking, controlling the position, or a force locking.

e. XY stages

The traditional way to drive translational stages lays into the adoption of brushed DC, brushless DC or stepper motors coupled with screw-nut or recirculating spheres to provide translational motion. This leading to relatively low costs but also to the need of having lubrication systems and short maintenance intervals are necessary to maintain the performances. Accuracy in positioning is also limited by screw-nut mechanisms theirselves [13].

Figure 19. Stepper motor coupled with a screw-nut mechanism driving a translational stage

More precise and accurate solutions exist in the field of linear motion, which is now the leading technology in the market for precise translational stages positioning. The accuracy, for precision applications, lays into nanometre order of magnitude and there is no need for lubrication.

Studies of [14] demonstrate the implementation of piezo-electric actuators in the field of translational stages nano-scale positioning. In Figure 20 and 21 are reported the schematic illustrations of the developed translational stage.

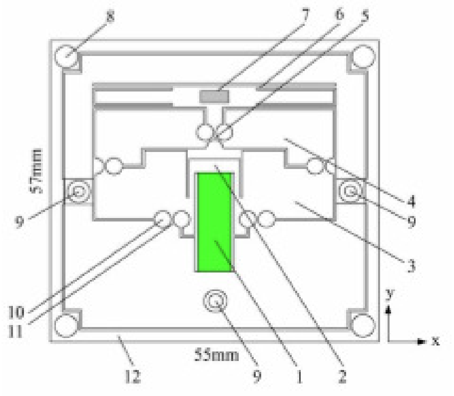

Figure 20. Schematic diagram of linear micro positioner. (1) Piezoelectric actuator, (2) lever guide device, (3) lever mechanism, (4) toggle amplification mechanism, (5) flexible pivot, (6) parallel guide spring, (7) friction tip, (8) fixed screw holes, (9) preload. [12]

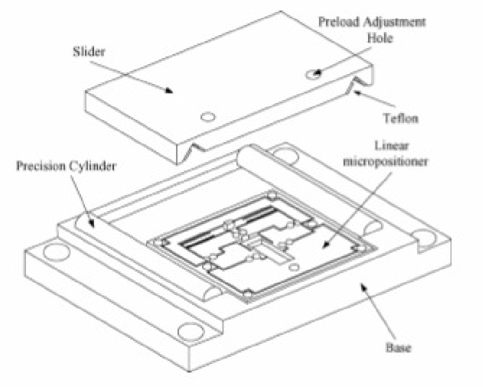

Figure 21. Schematic illustration of complete positioning stage system. [12]

In this case some high-precision rails were used to guide the translational motion, and a lever mechanism, made by flexible joints, was used to amplify the actuator motion range. As a result, the translational stage is able to reach 70mm of motion range with 50 nm of accuracy, without the need of lubrication in the whole system. The same concept has been proposed by [14] to develop translational stages for a small-size (25 × 25 × 10 mm^3) Coordinate Measuring Machine (CMM), achieving performances of 1 nm in accuracy and 15 nm in repeatability.

In both cases the characteristics of the inchworm piezo-electric actuator (very precise motion and no need for lubrication) have been enhanced. On the other hand, flexible levers and mechanisms have been implemented to amplify the speed (from the typical 0.25mm/s up to 4mm/s) and the range of motion enabled by these actuators.

In Table 1 is reported a comparison among different commercially available technologies for translational stages systems including more traditional solutions such as the combination of stepper motors and belt/screw mechanisms and more advanced ones such as linear motors and piezo-electric actuators [16] [17].

Table 1. comparison among different translational stage drives methods

	Accuracy	Motion range	Max load capacity	Speed
Stepper motor + screw-nut mechanism	1 µm	25 mm	60 N	0.4 mm/s
Linear motors	20 nm	20 mm	100 N	250 mm/s
Piezo-electric actuators	1 nm	25 - 100 mm	6-40 N	0.5 – 15 mm/s

The advancements, enabled by piezo-electric actuators, in translational stages accuracy have paved the way for the implementation of such concepts in the field of additive manufacturing, with the particular focus on the realization of millimetre scale freeform objects with a high degree of accuracy, shown in figure 22.

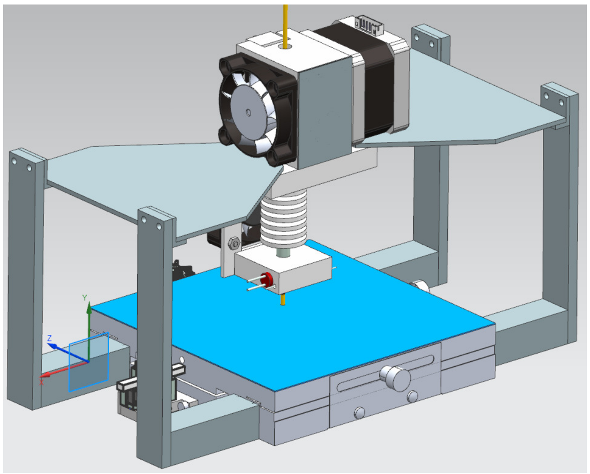

Figure 22. An example of high precision translational stages implemented for additive manufacturing

Being the inchworm actuators not capable of working under radial loads, in this solution there are no constraints between the actuator rod and the translational stage, this also leading to the need of springs, embedded inside the stage itself, to invert the motion direction. Figure 23 illustrate the detail of the XY stage coupling with the motor.

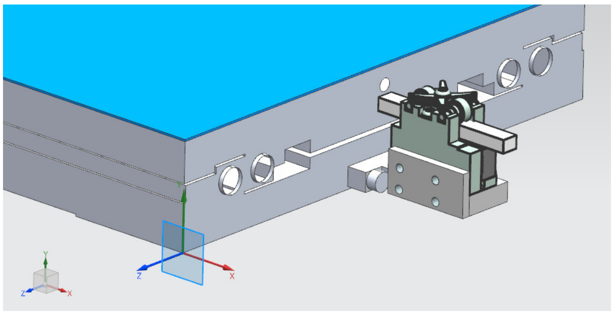

Figure 23. Detail of the XY stage

This solution enables the building of a relatively low cost 3D printer capable of cutting-edge performances in terms of accuracy, and with no need for lubricants and belts.

f. Gripping tool

Inchworm piezo motors allow to build lightweight, compact and precise grippers thanks to the intrinsic characteristics of this type of drive. This enables several advantages for picking small, lightweight and soft products which are usually picked by small robots. The contained weight allows also to increase the speed of the robot, which, in turn, allows to speed up the whole process. Figure 24 shows a possible design for the gripper whose operation, exploiting the position control of the motor could be based on form locking grip.

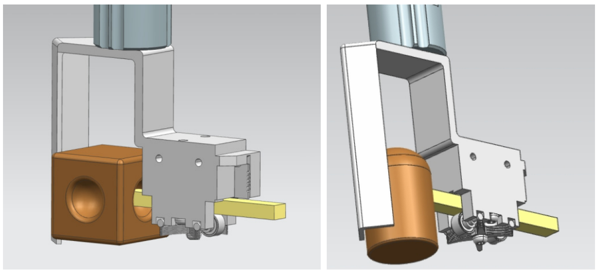

Figure 24. Examples of shape locking and force locking grip

The same motor can also be used, to obtain a force locking grip in a very straightforward manner: the motor is actuated up to the blocking of the rod (that is harmless) and then it maintains the reached position even if it is not powered for an undetermined amount of time.

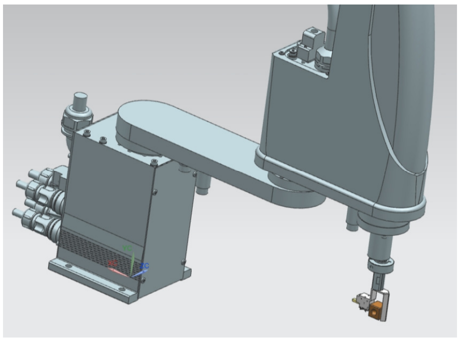

Figure 25. Linear motor based double translational stage

In addition, a big advantage is given by the possibility to develop a linear motion driven gripper with no additional mechanisms and then without needing to add more weight to the gripper [13].

Table 2. comparison among different linear actuators for drive the same gripping tool

	Piezo	Pneumatic	Stepper	DC
stroke	80 mm	80 mm	60 mm	25 mm
weight	23 g	66 g	120 g	100 g
length	80 mm	166 mm	11 mm	120 mm
height	19 mm	20 mm	28 mm	18 mm
wideness	11 mm	20 mm	28 mm	18 mm

g. Hybrid actuator

A hybrid actuator is a configuration that combines the motions of two characteristically different electric motors by means of a mechanism to produce inexpensive programmable output. Where one of the motion coming from a constant speed motor provides the main power, a small servo motor introduces programmability to the resultant actuator [18] [19].

To combine the piezoelectric motor accuracy with the torque obtainable by a DC motor, it is proposed to realize the differential mechanism drawn in figure 26.

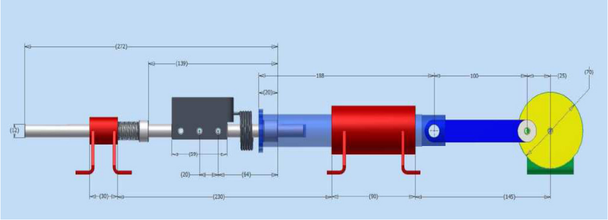

Figure 26. Hybrid actuator obtained through a differential mechanism

Its kinematic chain consists of crankshaft which moves a rod with linear reciprocating motion. The rod is formed by a sleeve within which is inserted a shaft that can rotate around its axis. The piezo motor acts on a flap coupled with the rotating shaft and allows to correct the rotation of the shaft itself, with a maximum range of approximately 30°. This rotation, thanks to the cylindrical cam mounted on end of the shaft, allows to correct the end effector final position, while the piezo motor cannot be charged by the axial forces transmitted by the mechanism.

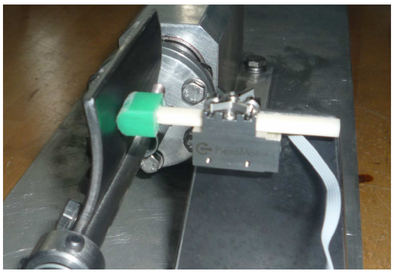

Figure 27. Linear motor mounted on the hybrid actuator

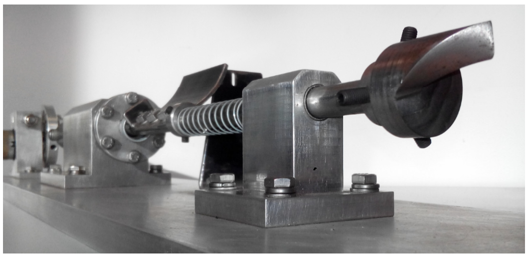

Figure 28. Cylindrical cam on the end of the shaft

6. CONCLUSION

A series of experimental tests has been performed to verify the behaviour of a particular type of piezoelectric linear motor, which can be used with a very simple and inexpensive open loop control but obtaining strokes whose length is very sensitive to the applied load.

In order to calibrate this motor, it has been adapted and used a sophisticated mechatronics platform, constituted by a flexure mechanism with zero backlash and by a control and measurement system based on Linux RTAI. Obtained results show with good repeatability the needed calibration curves in the different operating conditions.

After that the feasibility of the open-loop control approach has been demonstrated, the practical implementation of this concept has been developed through a prototype of a hybrid actuator system and through the design of other industrial applications.

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НУМЕРИЧКА АНАЛИЗА И ЕКСПЕРИМЕНТАЛНО ИСПИТИВАЊЕ ПЛЕТЕНИХ КОМПОЗИТНИХ СТРУКТУРА ПОД НАПОНОМ УВИЈАЊА КОРИШЋЕЊЕМ ДИГИТАЛНЕ ФОТОГРАФИЈЕ

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Рад је фокусиран на развоју модела за предвиђање крутости и чврстине плетених композита. Нумерички модел је заснован на моделу у мулти скали, узимајући у обзир својствене карактеристике материјала на различитим структурним нивоима. Плетена структура је реализована као детаљ предива по нивоима, узимајући у обзир таласање предива и интеракцију између слојева предива. Применом модела отказ, оштећење у предиву и интеракцију између слојева предива је израчунато. За валидацију нумеричког модела, извршено је тестирање на увијање биаксијалних плетива по једном слоју цеви, користећи дигиталну корелацију фотографије (DIC) за пуно мерење деформације на површини узорка. Упоређујући експерименталне податке и нумеричку симулацију, добра сагласност налази се и како за реакције при глобалом оптерећењу тако и при нестабилном понашању и локалном расподелу деформација