

Nanometer Resolution Actuator with Multi-Millimeter Range and Power-Off Hold*

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ABSTRACT

Photonic assembly packaging, adaptive optics, large optical beam control, and semiconductor test and measurement are application areas that have needs for nanometer-level precision. Utility is increased with features such as greater than 10-millimeter travel, power-off hold, high acceleration and high stiffness. Alignment applications can benefit from a high mechanical power density. This translates into smaller package size for required force, speed, travel and resolution performance. In manufacturing of photonic packages, the space around the work piece often is limited and ergonomic design considerations for workspace are helped with a small profile. Smaller system size implies less total mass and power required for a given performance level, which is highly desirable for airborne or space applications. Smaller mechanical systems benefit from higher stiffness, lower Abbé error, and are less susceptible to environmental transients. A second-generation actuator system that provides about one nanometer open loop step size with 25 millimeters of travel will be characterized. The first-generation model provided more than 100 N force at 25 mm/s speed. The device is compatible to using proprietary thin film and MEMS technology for a high-friction clamping design that simulates an “infinite gear”.

Keywords: actuator, adaptive optics, alignment, nanometer, photonics, resolution, power density, voltage amplifier

1. INTRODUCTION

Controlled motion capabilities for system designers have been expanded with the new performance levels from the Inchworm[®] class actuator described in this paper. With a single actuator, a designer can utilize nanometer step size, tens of millimeters travel, 100 N force, 25 mm/s speed, 500 m/s² acceleration, power-off hold, in a significantly smaller package than currently available. Designers servicing applications as diverse as optics, microscopy, telecommunications, aerospace, bio-medical, life science, analytical instruments and research have a new set of design options.

Actuators, as all devices, have certain limitations, which in turn require design choices based on the application of interest to the designer and ultimately to the user. The actuator is the unseen infrastructure that is critical to the system performance desired by the end user. Whether observing the sky or assembling optical circuits, the controlled movement provided by the actuator is a prime determinant of system performance. For clarity, HMR refers to any motor designed under the development contract. The engineering models are sequential as EM1 described in a previous paper¹, and EM2 in this paper.

2. APPLICATION / DESIGN

2.1 Criteria

There are numerous criteria for describing movement needs. Some are quantified in standards; others have evolved into common usage. The following generically describes some widely used criteria.

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- Resolution (open-loop) – smallest discrete distance the actuator can be moved. This often is below the detection level of the system and commonly is called open-loop resolution. It is more an indication of intrinsic fineness of response than a practical control criterion.
- Step Size (closed-loop resolution) – smallest discrete distance over which the system can be controlled. The system requires a signal that can differentiate the level of movement and the control loop to reproduce that movement.
- Repeatability – the capability to return to a starting point with very little error, multiple times over time.
- Speed (velocity) – the distance moved per unit time
- Travel – the distance that movement occurs.
- Force – differentiated by how it occurs
 - Push Force – describes force being generated in a dynamic mode
 - Hold Force – describes force being resisted in a static mode
- Power – differentiated by type of energy used or produced
 - Mechanical power – generated by the actuator as it moves a mass some speed, continuous power. An artificial power number can be calculated by multiplying maximum force times maximum speed. However, since these maximums are not achieved at the same instant, this is an artificial metric.
 - Electrical power – the energy in the circuitry
 - Input power is line voltage times line current at the input power supply.
 - Output power is the voltage and current at the motor. This often varies hugely in a piezo-electric actuator because of the very high currents over very short times as the piezoelectric elements charge and discharge. The piezoelectric elements provide a large capacitance load and small resistance load.
- Stiffness – resistance to change from an external force.
- Acceleration – the rate of change of speed.

2.2 Applications

In aligning or positioning functions these criteria have different roles or degrees of importance. The designer must understand the relationships and choose accordingly. One approach is to separate the design or static factors from the in-use or dynamic factors. For example, at the nanometer level, most systems need stability and precisely controlled movement. Stability can arise from a very stiff system design, attention to thermal expansion effects, power-off hold and controlling environmental variations over time. Precise movement control uses position sensing, velocity, acceleration and force parameters to effect the desired result. Total system efficiency results from not only the power density of the actuator but also the system density by adding the controllers and power supplies. Although work is ongoing to provide similar levels of improvement in the electronics driving these actuators, we are presenting only the actuator contributions in this paper.

2.2.1 Adaptive Optics

Large-scale optics, such as telescopes, have evolved. They now benefit from discrete actuation that goes beyond moving a lens system along its axis. An adaptive-optic design systematically deforms the optics to compensate for changing conditions and thereby improves the “focus” or image quality. Some designs push-pull the reverse side of the mirror; others such as in Figure 1, push-pull the edge of a membrane optic to achieve focus. This localized focusing needs motion control in the nanometer range for optimum effectiveness.

Space-borne systems are compacted for lift-off and then must unfold to their working configurations. This deployment requires millimeters of travel and then micrometer to sub-micrometer resolution to effect final focus. See Figure 2 for an example of adjusting the secondary mirror through a deployable tower that requires precise actuation and hold.

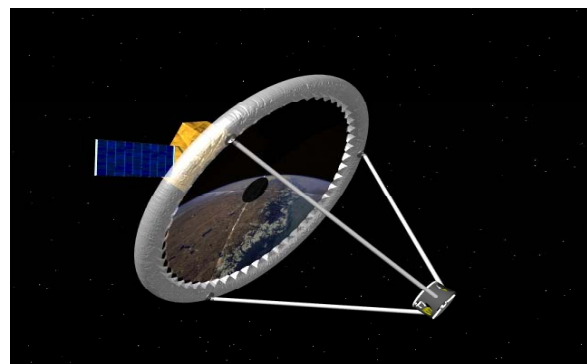


Figure 1: Deployable optical telescope

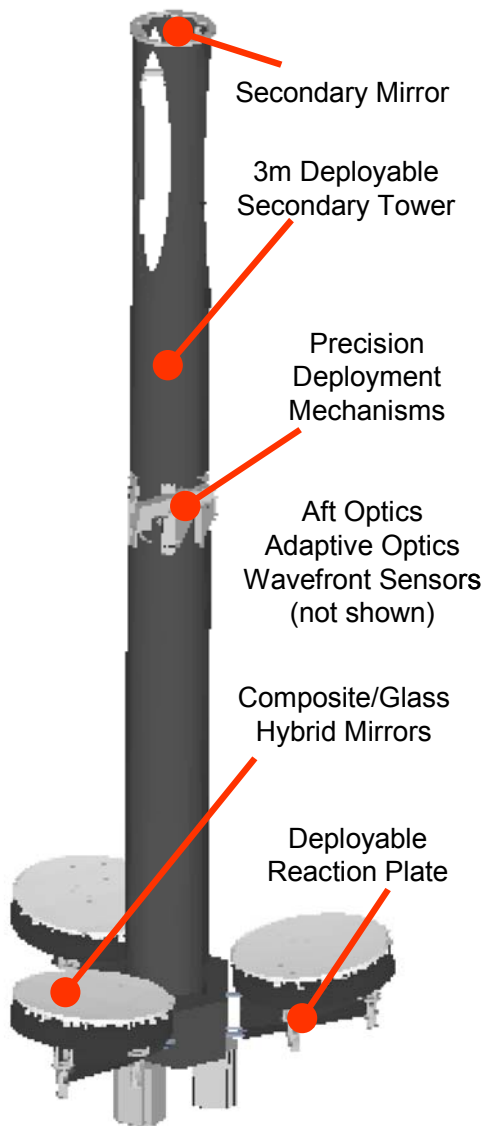


Figure 2: Deployable optical telescope

2.2.2 Alignment Automation

At the other end of the application range, optical device assemblers must align arrays of three-micrometer optical cores with minimal insertion loss in each channel. Slight misalignment can aggravate cross talk and attenuation problems (Figure 3). The planar lightguide circuit (PLC) array is on the left. It is misaligned by an angle and subsequently also by varying distance between the channels. The spectra displayed from the right hand output fiber array (FA) shows cross talk as two peaks from a single channel. Attenuation is shown as the peak power diminishes as a function of location (channel).

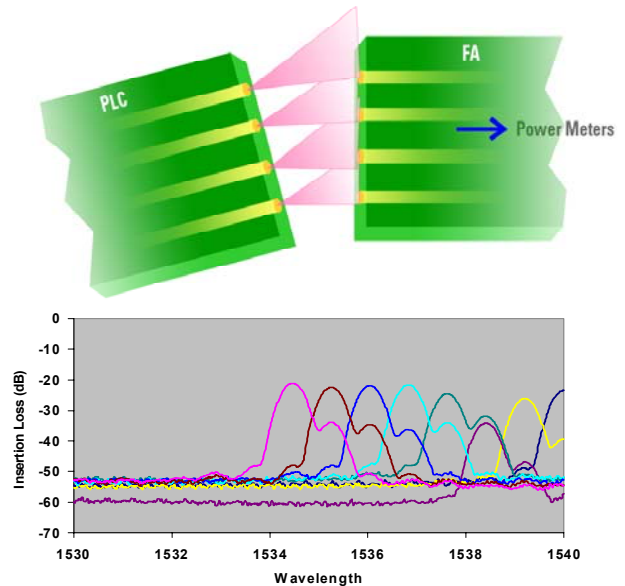


Figure 3: Misalignment effects in fiber arrays

The fabrication process often includes some combination of alignment, optical measurement to ensure performance, separation for secondary processing, and realignment for final fixing. Figure 4 illustrates a secondary process, bonding, where a lightguide array has adhesive applied prior to final positioning and curing. The input PLC and output FA have been optimally aligned and then separated to allow adhesive application. Figures 5 and 6 show deposition of a drop of adhesive and separation. After retracting the applicator, the two optical components will be rejoined and the adhesive cured to complete this process step.

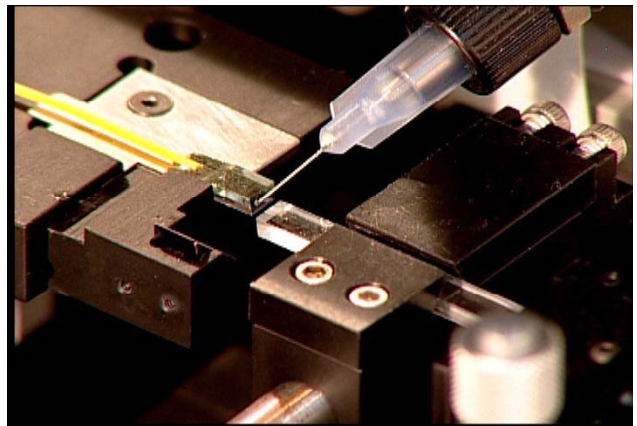


Figure 4: Adhesive application

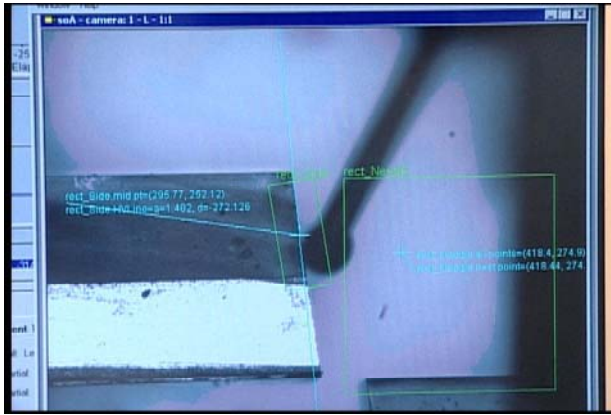


Figure 5: Drop deposition



Figure 6: Drop separation



Figure 7: Developmental Comparative Active Telescope Testbed with Inchworm actuators - NASA

Nanometer precision is needed to effect minimal insertion loss but centimeter motion is needed for the adhesive processing. The robot's alignment and realignment performance depends on its resolution, repeatability, and range capabilities. These are greatly affected by the actuator's stiffness, step size, range, position sensing and control system algorithms. This is a variant of the needs of the semiconductor industry for wafer inspection, processing, and qualifying.

Processing space for very small parts is limited. This puts a premium on high power density actuators that can minimize workstation volume.

2.2.3 Robotics

Figure 7 shows a Stewart Platform, more commonly called a hexapod, using commercially available Inchworm motors. It is a version of parallel link manipulators that provide six degrees of freedom: x, y, z, pitch, roll, and yaw. Substituting the new EM2 motor's performance capabilities for the standard Inchworm motor's shown, one could expect a 10-fold increase in load carrying, a 15-fold increase in response or velocity, with a 40% reduction in mass from the motors. A version of this configuration could be used for beam control of a large laser system or a very high resolution machining head.

2.2.4 Smart Structure approach

A prototype two-axes stage was constructed using an earlier motor configuration, EM1 (Figure 8). The stage frame also is the motor structure. The position sensor system is embedded in the stage structure. The overall effect is a two-axes stage assembly, in slightly smaller volume than the commercial single-axis stage. It has 15× higher speed, and 10× higher force capabilities with comparable resolution.

2.3 Benefit / Features

Designers must translate users' needs such as alignment, focusing, beam steering, contour generation and position stability into a set of design criteria. Boundary conditions such as repeatability, resolution, speed, acceleration and load levels are applied to further refine the design criteria. Ultimately, components must be chosen and integrated into the system.

The following is a form of benefit analysis linking desired system performance to an actuator system capability that must be specified.

- Step size, closed loop control limits for positioning

- Resolution establishes uncertainty about target point
- Feedback signal, encoder resolution
- Stability over time for measurements and processing
 - Motor stiffness, power-off hold, thermal noise susceptibility
- Volume constrained, space available is very costly
 - Power density – given amount of energy delivered from a smaller motor package
- Weight constrained, mass transport is very costly
 - System Power density – given amount of energy delivered from total system mass (motor, electronics and electrical power supply)
 - Multiplex power-off hold motors with single control electronics
 - Single actuator instead of serial set with various resolution and travel ranges
- Response range for repositioning
 - Speed, acceleration, force, stiffness, repeatability
- Power available constraints
 - High efficiency amplifiers, power-off hold to “set-and-hold”

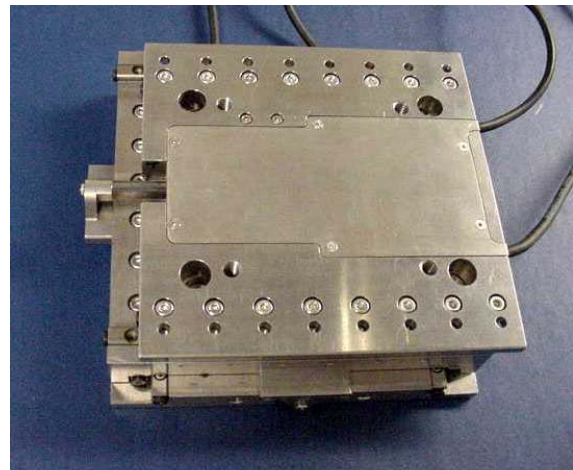


Figure 8: Prototype stage

3. MOTOR DESIGN

The motor design is similar to the commercially available Inchworm motor in that it uses piezoelectric elements to transform electrical energy to mechanical energy and micrometer displacements to millimeter travel and nanometer step size. The motor also utilizes a variation of the Inchworm motor’s clamp and extend actuation motion. As in the earlier EM1 version, the extension piezoelectric element is integral to the shaft configuration. The major change for this motor is in the clamp design. This design yields a significantly more compact motor, provides power-off hold capability and can be part of the actuated structure itself. Figure 9 shows a motor configuration size smaller than a white board marker.

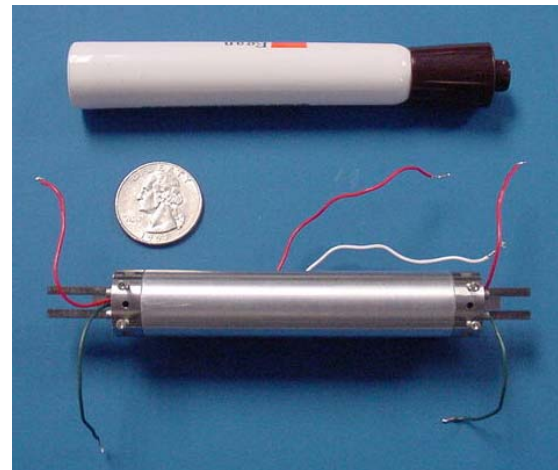


Figure 9: New HMR Inchworm Motor - Model EM2

3.1 What is truly new and how does it impact system designs?

Power-off hold (new feature) and the piezoelectric motor combine to offer an electrically and thermally efficient design option. Energy and heat generation occur only when the motor is in motion. This also has reliability implications because only actual “use time” is accumulated against failure rate. For applications with “set and hold” requirements, the hold feature transfers stability to the mounting structure and away from the dynamic elements in a motor. Power-off hold allows a single driving circuit to serially drive several motors by multiplexing, thereby increasing system efficiency. System control becomes easier because only changes to the system need be addressed; there is not constant monitoring and adjustment of each motorized element. Finally, compared with power-on hold mechanisms, power-off hold mechanisms usually provide extra safety protection against an unexpected power failure.

Power density (new range) for a nanometer-level actuator offers a capability to move significantly larger platforms or devices faster with a smaller motor configuration and still keep nanometer step size. The new motor has travel ranges

exceeding 20 millimeters; therefore the total system size is less than using serial approaches combining transportation motors and high-resolution flexure devices with their respective dual controllers to achieve the same range of motion.

Actuator design (new feature) is such that it can be incorporated into structures as well as in a discrete motor housing. This offers opportunities for weight and volume design efficiencies.

4. PERFORMANCE

4.1 Performance data

The motors have been evaluated on a continuous power basis. This is consistent with actual in-use demands. Typical specification values for designers also have been measured. The motor push force is measured by a load cell; the displacement is measured by a Linear Variable Differential Transformer (LVDT). The speed is obtained by the time derivative of the displacement. The continuous power thus can be derived directly from the force and speed. Since many other types of motors use peak power as a specification, we will also include it in this paper.

Figure 10 is a plot of the continuous mechanical output power vs. push force. The classic Inchworm motor and the Inchworm HMR-EM1 motor power vs. force curves are shown as a reference. The EM1 and EM2 models were evaluated under similar conditions; they can be compared on a relative bases. The new EM2 model's huge improvement over the EM1 is due to the new compact and stiffer design.

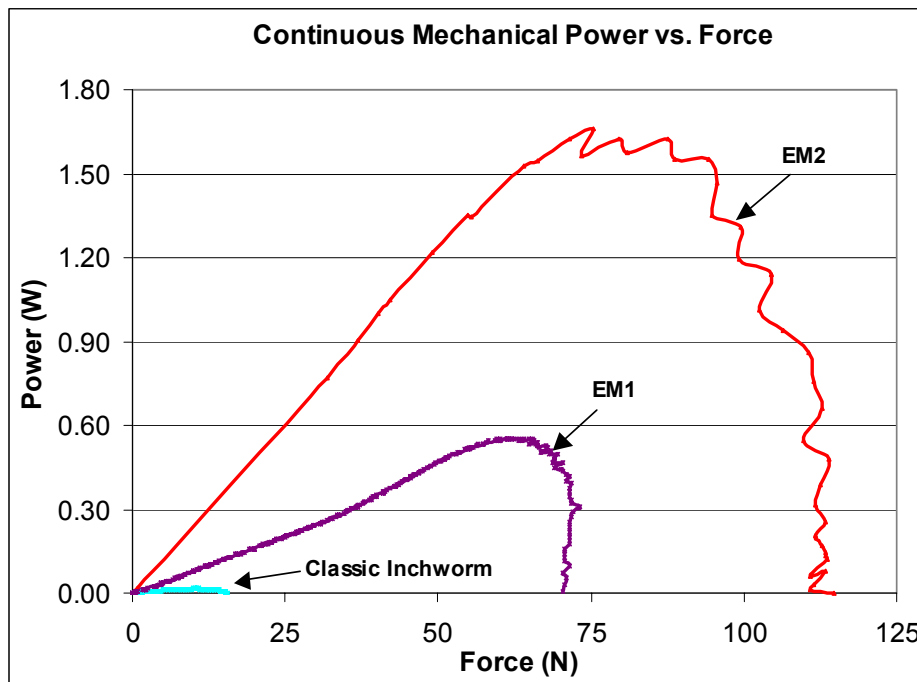


Figure 10: Continuous mechanical output power vs. push force for classic Inchworm, EM1, and EM2.

As part of the power density optimization work, several size configurations were developed which changed the piezoelectric element size and resultant clamping or normal force in the motor. Table 1 summarizes various performance data for these three versions of the newest motor, EM2. Figure 11 shows the power vs. push force curves for these three motors. The major difference among these motors lies in the clamp actuator size and thus the clamp assembly size. The motor mass increases with the clamp size and the power density also increases. It seems to saturate at between the 6 mm and 8 mm thick piezoelectric stacks. This is expected as the other design elements were not

optimized but only resized to accept different piezoelectric elements. This design could be modified to deliver higher power, smaller size, or optimized power density without sacrificing nanometer resolution.

Motor	Power-off Hold Force	Power-on Hold Force	Maximum Push Force	Maximum Speed	Maximum Peak Power	Motor Mass	Maximum Peak Power Density
	(N)	(N)	(N)	(mm/s)	(W)	(g)	(W/Kg)
4mm Clamp	120	110	80	24	1.92	63	30.5
6mm Clamp	>140	>120	100	27	2.70	70	38.6
8mm Clamp	>280	>240	120	26	3.12	80	39.0

Table 1: Mechanical performance of EM2 power-off hold motors with different clamping actuator sizes.

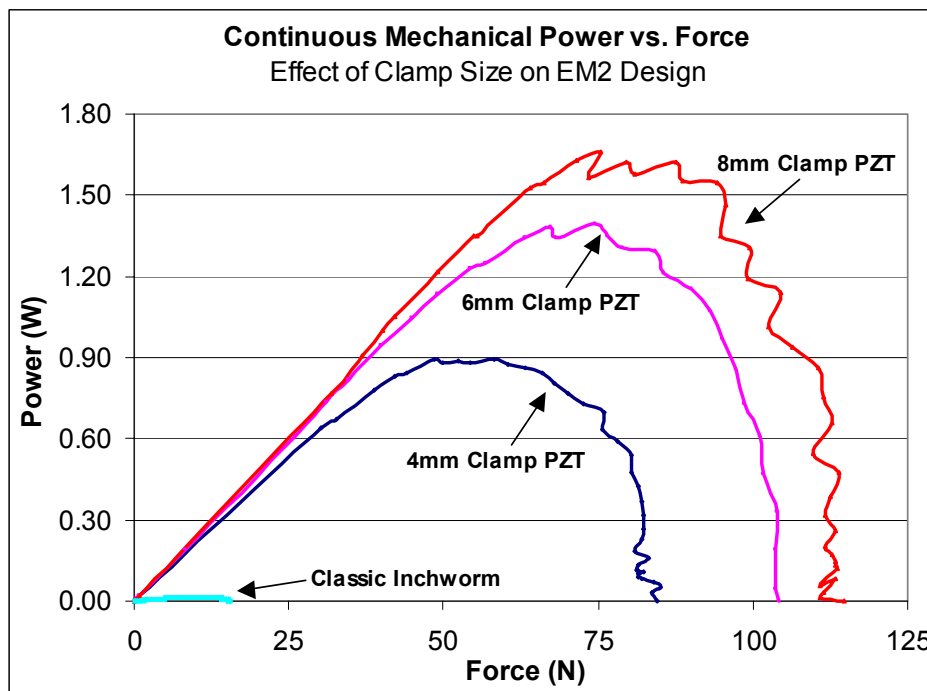


Figure 11: Continuous mechanical output power vs. push force for EM2 motors of 4, 6 and 8 mm clamping PZT.

These motors provide true power-off hold with hold force >120 N or even much higher, depending on the size of the clamp actuator (see Table 1). For all three motors, the power-off hold capability is evidenced by the fact that the motor power-off hold force is even higher than the power-on hold force or the push force, confirming its effectiveness.

The speeds are essentially the same (about 25 mm/sec) as in EM1. This is expected since all motors use a similar extension assembly design and clamp change frequency as employed in EM1.¹ Motor stiffness of the EM2 motor of the 6 mm clamping piezoelectric element also was characterized. The stiffness in the motor’s long axis is about 25 N/ μ m. This high stiffness combined with high push force ensures fast response and high acceleration during operation. Table 2

summarizes the performance data and other specifications of the EM2 model along with previous models. This can serve as basic guidance to a designer who needs to specify motors in a positioning system. Notice that two push force values for EM1 models are due to different frictional interfaces, while three push force values for EM2 models are due to different clamp actuator sizes (thus different clamping normal forces).

	Inchworm HMR EM2	Inchworm HMR EM1	Classic Inchworm Motor
Dimension	~ 4" × ϕ 0.7"	~ 4" × 2" × 0.5"	~ 5" × ϕ 1"
Open loop resolution	< 1 nm	< 1 nm	0.1 nm
Travel	25 mm	12 mm	6.2, 25 and 50 mm
Speed	25 mm/s	25 mm/s	1.5 mm/s
Push Force	80 N, 100 N and 120 N	70 N, 115 N	10 N – 15 N
Acceleration	500 m/s ²	500 m/s ²	250 m/s ²
Stiffness	25 N/ μ m	8.5 N/ μ m	18 N/ μ m
Power-off Hold and Force	Yes (> 120 N)	No	No
Continuous Output Power	0.9 to 1.6 W	~ 1 W	0.015 W
Mass	60 – 80 g	170 g	100 g
Continuous Power Density	~ 20 W/kg	~ 5.4 W/kg	0.15 W/kg
Peak Power Density	~ 40 W/kg	~ 16 W/kg	0.23 W/kg

Table 2: Inchworm motor performance summary

Push force can be increased either by using an interface with higher frictional coefficient, or by applying higher clamping forces. For example, we have seen that for EM2, the push force is larger for bigger clamping actuators. In addition, although the frictional interface was not optimized, the push force for EM1 was indeed increased 1.7 times by using a new patent-pending technology from UCLA. This technology combines MEMS generated structures and thin film to produce an “infinite gear” for high friction coefficient at the clamp interface. We have not tested the EM2 motor using this high friction interface yet. However, we estimate that the push force can reach 400 N, as long as the coefficient of friction can reach 1.2, which experimentally has proven to be feasible. The motor output power and power density will increase accordingly.

The reliability of flexures and brittle piezoelectric elements used in Inchworm-style motors is an issue to be addressed. Little rigorous data is available as a baseline. Unpublished² estimates of MTTF (mean time to failure) are about 4000 meters for the commercial Inchworm motor. A linear stage with the embedded HMR style motor is still running, at publication, with more than 4000 meters accumulated travel. We have found no obvious performance degradation in flexures and piezoelectric elements at over 100,000,000 clamping cycles.

4.2 Comparison with other alternative technologies

Several linear actuator systems capable of 25 mm travel were selected and qualitatively compared to the Inchworm-HMR system in terms of stiffness, resolution, push force, acceleration and (continuous) power density. The reported values for the Burleigh Inchworm HMR are based on the latest performance data for the EM2 models. The comparison results are displayed in Figures 12(a)-(e), respectively. The performance values for each are only illustrative; the actual values may vary depending on different brand or model.

Alternative motor technologies used in positioning systems include servomotors, stepper motors, ultrasonic piezoelectric motors and DC linear motors. For comparison, alternative technologies with similar size were assumed. Two types of servo motors were investigated: 1) 12 mm diameter (macro) and 2) 3 to 8 mm diameter (micro). The stepper motor was limited to approximately 1.5" diameter. The ultrasonic motor assumed a Nanomotion SP series motor. The Linear motor was a LinMot^{®3} motor approximately 1" diameter.

Like the Inchworm motors, each technology has to be coupled to the system in order to operate as a positioning device. In many instances, it is this coupling to the final product which ultimately limits the performance of the overall system.

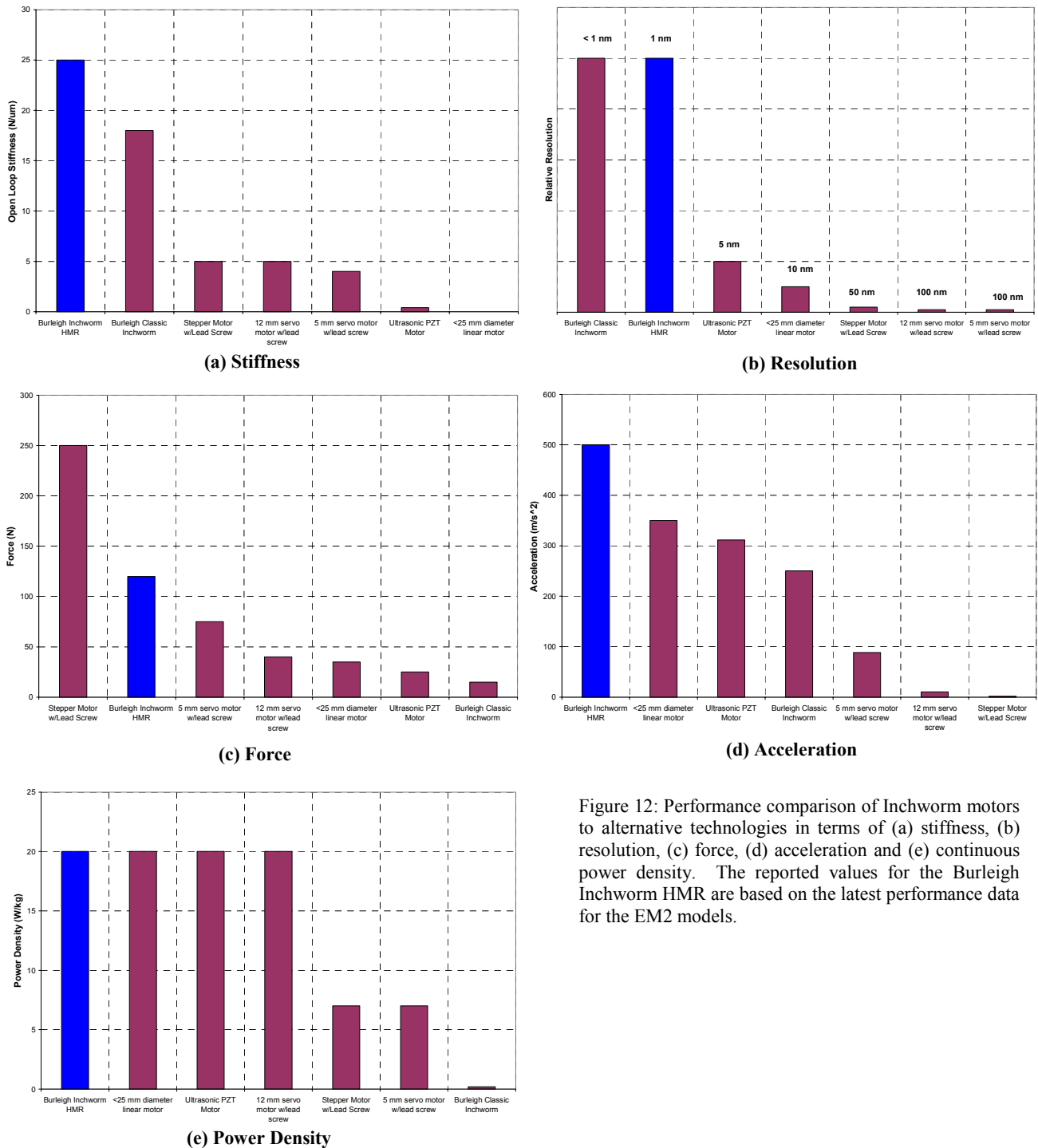


Figure 12: Performance comparison of Inchworm motors to alternative technologies in terms of (a) stiffness, (b) resolution, (c) force, (d) acceleration and (e) continuous power density. The reported values for the Burleigh Inchworm HMR are based on the latest performance data for the EM2 models.

To use servo and stepper motors in a linear positioning system requires the use of a lead screw or ball screw. In order to achieve high resolution, the lead screw must have a high screw pitch. This introduces friction, which reduces the efficiency of the motor. For comparison with Inchworm motors, high resolution and stiffness were required and

therefore an 80-pitch screw with 25% efficiency and no gear reduction was assumed. The ultrasonic motor and linear motor were assumed to be operating in open-loop mode, as were the Inchworm motors.

The new motor design ranks among the top one or two performers for all five categories. The new motor system provides a very high stiffness value, which allows the designer to accommodate vibration in the environment and provide a very stable system over time. The outstanding open-loop resolution enables a designer to couple a variety of feedback devices for closed loop nano-alignment with full confidence. These feedback devices typically have 10 times or larger step sizes than the Inchworm motor's open-loop resolution, and therefore the motor open loop resolution will not be the limiting factor for the closed-loop resolution of the system. The large increase in force can now accommodate substantial fixture loads. The high acceleration value assures rapid response to movement commands. Ultimately, the high continuous power density allows the flexibility to trade various design parameters to match the needs of different applications.

5. CONCLUSIONS

A greatly expanded set of motor performance parameters is available to system designers for use in their applications by this new member of the Inchworm class of actuators.

The new motors demonstrate more than 100 times increase in power and power density over commercial versions, while maintaining the range (6 to 50 mm) and resolution (1 nm) of the class. The typical achievable push force and speed now exceed 100 N and 25 mm/s with the mass of the motor reduced to approximately 70 grams.

The new actuator has power-off hold that opens design options for multiplexing multiple actuators from single electronics, optimizing system responses in align and hold applications, conserving energy, and surviving power failures.

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