New Horizons in **Motion-Automation Technology**

Recent advancements in drive technologies have significantly enabled a broad wave of applications, and there is no sign this trend of innovation will abate anytime soon.

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The pace of innovation in the motion-control industry has accelerated in the past decade, bringing to market fresh technologies ranging from new drive principles to new concepts in advanced controls. To the user, this has meant a steady progression of finer resolution, higher speeds, better price/performance and smaller sizes. It has also meant more maturity and ubiquity of precision automated motion solutions. Additive manufacturing, for example, has commoditized to the point that appliance-class implementations with micron-scale precisions are plentiful and cheap. Even custom integrations of complicated engineered systems have been facilitated, with new open, extensible controls architectures benefiting construction of arbitrarily complex applications.

But some advancements represent fundamental inflection-points, both for the motion industry and more importantly for the applications they animate. New drive technology is one example, while other innovations fall into the general category of newly intelligent positioning. In both cases, the motion system itself becomes the enabler of an application or its economic viability.

Drive technologies empower new applications

Familiar stepper-motor and DC servomotor mechanisms are still the foundation of the precision motion industry, but even these venerable drive principles have enjoyed significant advancements that have pushed applications forward. Dramatic cost reductions driven by chip-level implementations of electronic commutation (the sequencing of energizing windings as the motor rotates) has democratized brushless motor designs, improving lifetime in intensive usage by eliminating commutation brushes and their inevitable wear. The same technology has allowed linear motor stages, with their high speeds and dynamical benefits, to see increasing deployment and popularity.

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Where vendor-specific solutions were once the rule, now modular, open and standards-based control architectures, like EtherCAT, allow integrators to build tightly synchronized and safe systems that can mix different motion technolo-

Figure 1a (left): Miniaturized Integrated XY Stage, driven by closed-loop ultrasonic ceramic linear motors, provides high-speed motion with 20nm resolution over a travel range of 22 x 22mm. (Image courtesy PI) Figure 1b (right): Vacuum compatible nanopositioning motor, based on an piezo inertia ratchet mechanism. (Image courtesy PI).

gies, with each element implemented in optimized fashion without compromise. In this way, specialized subsystems can perform targeted tasks in focused fashion in coordination with broader and often parallel actions and metrology elsewhere in the system.

Clever new drive technologies have also emerged to address tough applications challenges. Piezo-ceramic technology, for example, is still essential for its exquisite nanoscale positioning capability, leveraging the subatomic-scale potential resolution and supersonic responsiveness of this fascinating class of solid-state material. These actuators remain the vital technology underlying semiconductor microlithography, with its relentlessly tightening design rules and advancing nodes.

But new configurations of piezo-ceramic materials and mechanisms have surfaced in recent years, in addition to the layered stacks familiar from nanopositioning. Ultrasonic piezomotors are an example: tiny slabs of piezo-ceramic that are driven in resonance at ultrasonic frequencies, causing a pusher tip to oscillate in a micron-scale elliptical path to convey tangential force to a driven linear or rotary element. By replacing the bulky spindle assembly, these innovative drives allow especially compact stage configurations with no over-hanging motor assemblies. Speeds to 500 mm/sec are routinely seen in stages built with these new motors – even in form factors barely 30 mm square – and elimination of a conventional spindle assembly also means any slow, nanoscale drift caused by gradual lubricant displacement in the drivetrain is eliminated. This has enabled a wave of groundbreaking applications such as advanced microscopies in the life sciences and optical trapping in single-molecule biophysics, where the combination of speed, responsiveness and proven nanoscale in-position stability have opened new possibilities. As a bonus, stages based on these new motors can offer footprints reduced 30 percent or more versus legacy spindle-driven designs.

Other varieties of novel piezo-based mechanisms abound. In one example, clever stick-slip drive designs combined with compact new linear encoder technologies allow closed-loop stages the size of a lozenge to be offered, with travels of many millimeters and resolutions down to the nanoscale. Other commercial examples include a piezomotor that drives a rotary screw, for automated actuation of formerly micrometer-actuated mechanisms such as mirror mounts, and long-travel walking piezo-ceramic actuators that can provide previous unattainable combinations of travel, resolution and force. Novel piezo-ceramic "shims" are even available now, allowing fine adjustability of leveling and spacing of sensitive assemblies with permanent stability with power removed.

■ Figure 2a (above): NanoCube 6-Axis Nanopositioning and scanning stage based on piezo flexure drives. Piezo flexure stages are available with up to 6 degrees of freedom, allowing fast and highly precise scanning, positioning and alignment with virtually unlimited lifetime due to the non-wear and zero-friction design. (Image courtesy PI). ■ Figure 2b (right): Application of compact XYZ piezo flexure scanning stage in the TERA-print® E series, mask-free, high resolution desk-top nanofabrication tool, a 2020 Prism Award winner. (Image courtesy TERA-print).

Add to these some cunning new implementations of voice coil actuation. This straightforward type of linear motor is known for its dynamical capabilities and has recently been deployed in new ways and with new controls principles to build on this foundation to provide longer useful travels and new operating modalities. Examples include a force-controlled actuator for high-throughput industrial testing of touch-driven devices, and a six-degree-of-freedom hexapod offering extraordinary dynamics for simulation and testing in camera, drone and satellite development.

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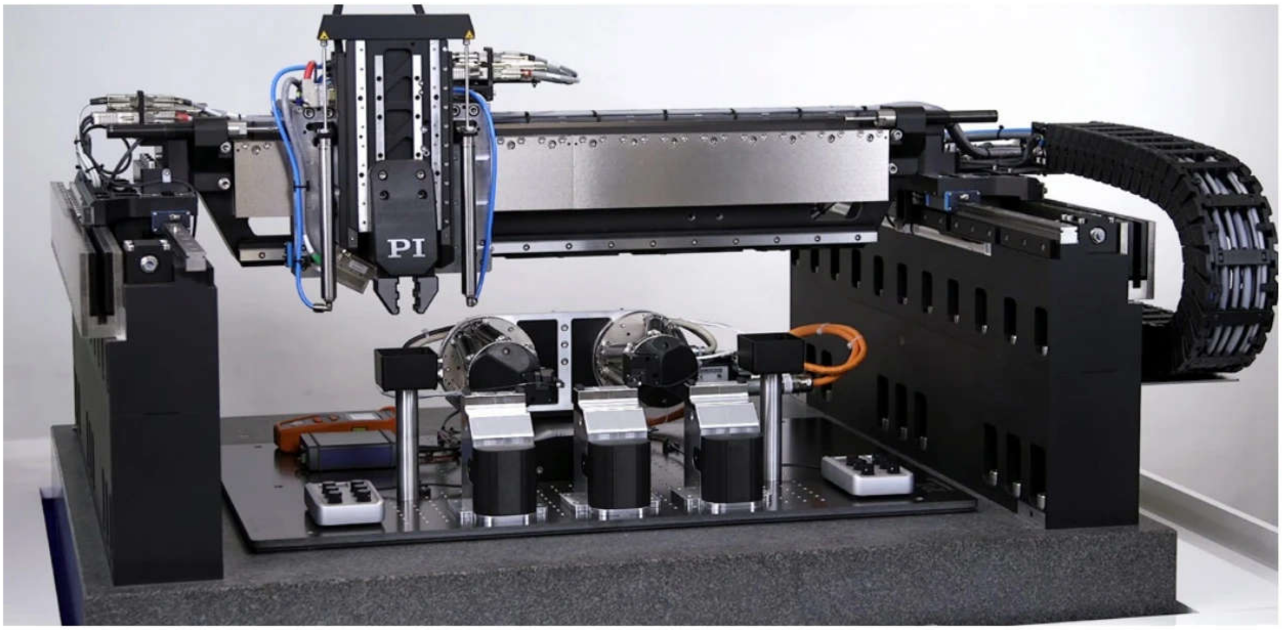
Controls gain intelligence and a new applications focus

Traditional motion controllers are general-purpose devices that simply perform positioning in response to commands. The most advanced examples also implement data recorders, waveform generation, utility interfaces and macro functionalities, but the fundamental position-per-command functionality is consistent across the whole industry. Motion systems vary in architectural approach but are often differentiated by speed, resolution and similar attributes. These can be regarded as metrics of obedience: a



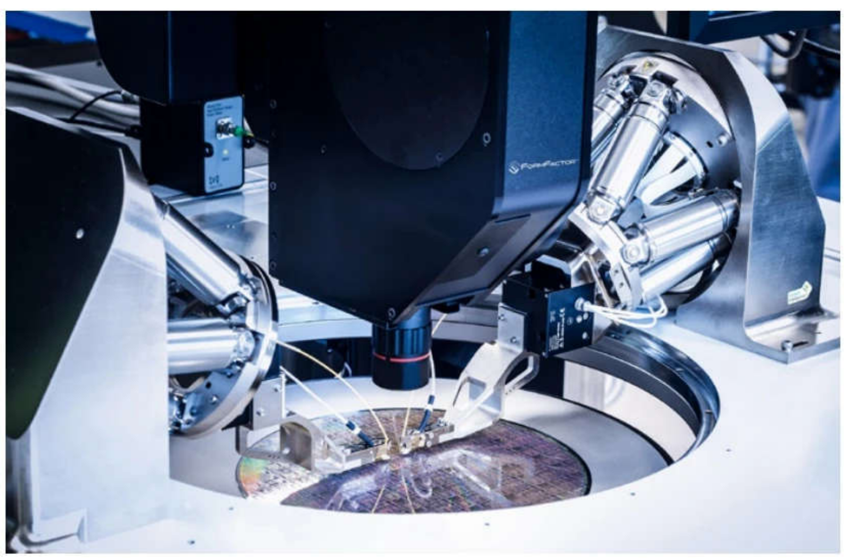
■ **Figure 3: Automated system for optical device testing based on EtherCAT® control architecture, gantry XYZ Cartesian robot, hexapod 6-axis motion platforms and high-speed piezo nano-precision mechanisms. (Image courtesy PI).**

motion system capable of positioning with nanometer resolution is basically that much more obedient than a motion system with micron-scale positionability.

Recently, however, advances in compute-power have enabled a new class of task-focused, internalized controller algorithms that speed and facilitate specific application needs.

A globally significant example is seen in the revolutionary technology that addresses the need for rapid alignment of elements in testing and packaging of photonic networking products. Immense investments in data centers and networking infrastructure are ongoing worldwide, driven by the world's appetite for data, which in turn is driven by phenomena ranging from personalized medicine to Industry 4.0, to genomics, social networks, streaming media, 5G and even selfies. Between capacity and throughput requirements, as well as scalability and energy consumption, photonic solutions are essential for meeting these demands. Similarly, trends in video frame-rates and pixel density as well as new computer bus architectures has birthed a new industry of high-throughput optical HDMI, USB and Thunderbolt cables for consumer and business applications.

Multiple studies have shown that the costs of manufacturing photonic devices are dominated by the repeated alignments needed to optimize photonic couplings for testing and packaging. Since the dawn of fiber optics in the 1980s, these alignments have been performed by slow approaches includ-



■ **Figure 4: Advances in Silicon Photonics: An 18-Axis double alignment system integrates unique parallel, multi-DOF alignment functionality to provide fast multichannel alignment of SiP array devices in wafer probers. FormFactor's pioneering CM300xi photonics-enabled engineering wafer probe station integrates PI's Fast Multichannel Photonics Alignment systems for high throughput, wafer-safe, nano-precision optical probing of on-wafer silicon photonics devices. (Image courtesy Cascade Microtech, a FormFactor company).**

ing meandering hill-climbs, raster scans and pointwise gradient searches. With photonic devices exponentiating in complexity and production volume, these approaches posed an intractable, escalating economic roadblock to the industry. To meet this challenge, a new class of alignment automation functionalities was developed in 2016 and implemented as built-in firmware commands in powerful industrial nanopositioning and hexapod controllers. These new commands included non-stop, vibration-eliminating sinusoidal and spiral area scans that were much faster than legacy raster and serpentine scans, and a new category of parallel gradient search that could simultaneously align multiple elements, channels, and inputs/outputs in multiple degrees of freedom, in one fast step. The reduction in overall alignment time is not small – improvements of two orders of magnitude are common. This can have a profound impact on production economics. Pioneering implementations include FormFactor's photonic wafer probers and Tegema's new Integrated Photonics Assembly tools.

The many possible combinations of new motion drive technologies and new controls featuring autonomous, application-focused functionalities present opportunities for game-changing approaches to mission-critical applications.

Moreover, the alignment technique is now seen to be broadly applicable, offering benefits to many other application fields well outside of photonics. After all, many manufacturing challenges boil down to adjusting or controlling positions of elements in multiple degrees of freedom to peak-up a signal or figure-of-merit. And so the technology that has revolutionized the economics of photonic-device test and packaging can now do the same for applications as diverse as laser manufacturing and imaging-lens assembly.

The trends add up to opportunity

The many possible combinations of new motion drive technologies and new controls featuring autonomous, application-focused functionalities present opportunities for game-changing approaches to mission-critical applications. From the tantalizing possibilities of a matchbox-sized positioner with 500mm/sec speeds, 18mm travel and 100nm resolution, to the potential hundredfold reduction of alignment costs in photonic, optical and laser/electro-optic manufacturing, the new wave of motion innovations enable rapid and profitable progress in many fields.