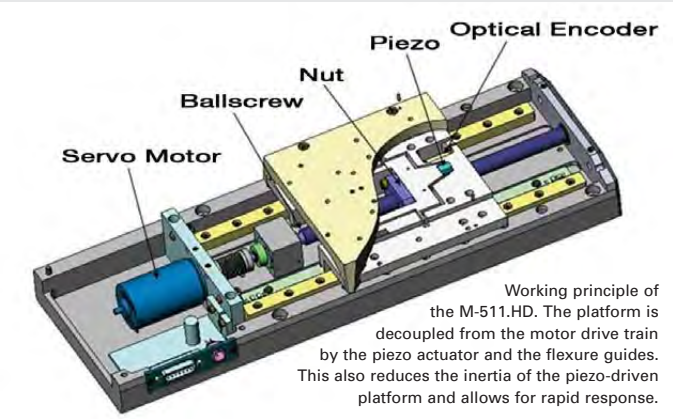
# Hybrid Nanopositioning Technology by PI

## Long Travel Linear Slides with Nanometer Precision




Working principle of the M-511.HD. The platform is decoupled from the motor drive train by the piezo actuator and the flexure guides. This also reduces the inertia of the piezo-driven platform and allows for rapid response.

- **Active Compensation of Stick/Slip During Startup and Settling**
- **Active Backlash Compensation**
- **Excellent Velocity Control**
- **Millisecond Settling to Nanometer Accuracy**
- **Reliable Execution of Minimal Increments**
- **High Drive and Holding Forces with Minimal Power**

The direct integration of piezo actuators in micropositioning stages allows combining travel ranges of hundreds of millimeters with resolutions in the nanometer range. Servo-control of the system employs a single high-resolution position feedback sensor (parallel metrology) which means that the high resolution can be used over the entire travel range. This makes hybrid systems ideal for applications where the position of an incident needs to be read and refound precisely, or where an externally specified target position needs to be hit within few a nanometers, such as in surface inspection or metrology. The challenge of implementing hybrid technology is not only the mechanical design of the positioning stage, but also the use of high-resolution sensors over large travel ranges, the processing of the resulting high-frequency signals and the design of special control algorithms to take full advantage of the hybrid design.

### Integrated Servo-Control Spans Both Drives

The basic idea of combining classical motorized micropositioners with high-resolution piezo actuators is not new. For example, PI offers a fiber-scanning and coupling system comprising a 6-DoF micropositioner (F-206) mounted beside a multi-axis piezo system (P-611 Nanocube®) with high position resolution.

The servo-control algorithms with stacked systems like these generally operate independently, with the piezo system only becoming activated after the motorized positioner has come to a complete stop. Because separate position sensors are used the absolute accuracy (not the resolution) is limited by the precision of the motorized long-range positioner.

The new PI hybrid systems use a single high-resolution encoder and a controller that can actuate both drives at the same time. Thus every move benefits from the specific advantages of both the motorized actuator and the piezo actuator from startup to settling.

On the mechanical side, this is accomplished by decoupling the motion platform of the hybrid positioning stage from the micropositioner's motor-ballscrew-drive by frictionless flexures and stiff, fast response piezo actuators.

The controller continuously compares the actual platform position (by reading the integrated linear encoder) with a calculated, smooth trajectory. The piezo actuators actively compensate out the irregularities in the motion of the platform caused by the motorized drive train.

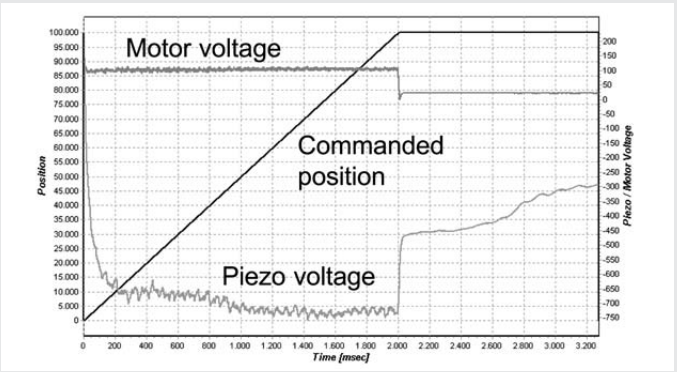
### Absolute Accuracy

The servo-control loops for both the motorized and the piezo drive use the same position sensor. The result is a motion system with hundreds of millimeters travel but with the precision of a piezo-based nanopositioner. The resolution and the positioning accuracy depend on the choice of the feedback sensor. PI hybrid systems currently use optical linear encoders with a resolution of 2 nm. Depending on the stage, a minimum incremental motion or a repeatability of 2 nm can be achieved over the entire travel range.

### One Controller for One Motion System

In PI hybrid systems, the motor-leadscrew and piezo actuator are fully integrated to form one motion system. The motor and piezo act together at all times. The result is far more than a coarse-adjust/fine-adjust system: effects like startup stick/slip and backlash can be completely compensated and a motion profile with high constancy of velocity can be followed. Because of the high piezo stiffness, setting to a few nanometers only takes a few milliseconds, significantly faster than with conventional, higher-inertia, linear-motor-driven stages. Furthermore minimal increments in the range of the sensor resolution can be reliably executed.

To allow high velocities beyond 100 mm/sec and nanometer-range incremental resolution, position information must be transmitted and processed very rapidly and a complex control algorithm is required. PI's C-702 is a controller providing PWM signal generators, piezo amplifiers and control algorithms specially tailored for hybrid systems.




PI hybrid servo-controller output during a positioning command. The controller reads the system position off a high-resolution encoder and actuates both the motor and piezoelectric actuator at the same time giving a system with the advantages of both drives.

# Product Overview

## Nanopositioning Systems with Hybrid Drive, Hybrid Controller


M-511.HD hybrid stage (left), M-714.00 (right front) and the C-702 controller (rear).

- **Long Travel Ranges with Nanometer Resolution**
- **Travel Range: to 100 mm Translation/7 mm Elevation**
- **Resolution to 2 nm**
- **Velocity to 125 mm/s**
- **Linear Encoder for Highest Precision**
- **Backlash-Free Precision Ballscrew under Frictionless Piezo Drive**

### C-702 Controller—Key to Hybrid Technology

The optimized interaction between the piezoelectric and motorized drive components to make them a single motion unit requires a high-speed sensor as well as powerful control algorithms. The digital, 2-channel, C-702 controller, based on modern CPU technology with a real time operating system, has been designed for this task. It is able to read the position signals with virtually no delay and process the data immediately. The integrated piezo amplifiers use a high-resolution 24-bit DAC to fully support the high position resolution of the piezo actuators. The new ultra-fast broadband SSI interface for the optical linear encoder supports stage velocities of 600 mm/s at a resolution of 1 nm. With custom firmware, one of the sensor interfaces can be reprogrammed for use as a high-speed command interface capable of processing commands at the servo rate.

### Application Examples

- Surface inspection
- Microscopy
- Laser technology
- Interferometry
- Metrology

### M-714 Heavy-Duty Nanopositioning System

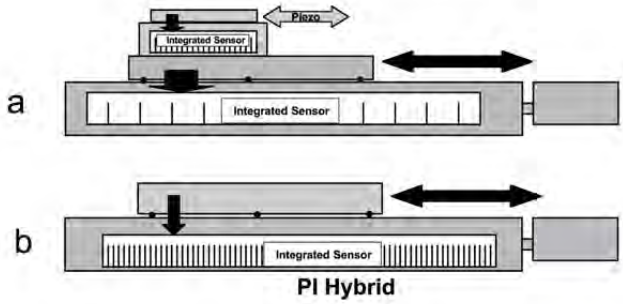
The M-714 was designed from the ground up to use the hybrid drive technology. A high gear reduction ratio enables the M-714 to position loads up to 10 kg with nanometer precision, even in the vertical direction. Compared to high-resolution magnetic linear drives, the hybrid principle allows high holding forces with minimum power consumption, without counterbalancing the load. The angular deviation is less than ±10 µrad over the entire travel range of 7 mm. The high-performance drive components, including ballscrew, bearings, motor and gearhead are chosen for minimum mechanical play and friction.

### M-511.HD Long-Travel, High-Speed Nanopositioning Systems

The M-511.HD is based on the proven design of the M-5x1 precision micropositioning stage series, with an integrated, flexure-guided, piezo actuator added. The M-511.HD allows velocities to 125 mm/s with an encoder resolution of 2 nm and load capacity of 50 kg for horizontal operation.

### C-702 Highlights!

- Two channels
- 10 kHz Sampling Rate
- 24-Bit Piezo Motion Resolution (<1 picometer)
- High-Resolution Incremental Sensor with Serial Interface
- Real-Time Operating System
- Interfaces: VGA, Keyboard, Mouse, RS-232, TCP/IP Ethernet




Different types of combined motorized and piezo positioning systems:
a) Serially stacked drives with individual integrated position sensors
b) PI Hybrid drive with integrated, internal, high-resolution sensor, for use with highly specialized controller.


10 nm steps of an M-714 stage, as measured by an interferometer.

## Resolution does not equal to positioning accuracy

Resolution of a servo-system is the precision with which it can detect its motion. This is different from the precision with which a commanded motion can be executed. Closed-loop systems tend to be instable if they have high sensor resolution without being able to execute correspondingly small increments due to mechanical properties such as excessive play, friction, or elasticity. Because they are equipped with a highly stiff, frictionless piezo actuator, PI hybrid systems provide full move capability down to the sensor range. There is an excellent match between minimum incremental motion and sensor resolution.

# M-511.HD Linear Stage

## Hybrid Long-Travel, High-Load Translation Stage with Nanometer Precision

M-511.HD hybrid nanopostioner

- **Simultaneous Control of Piezo-Flexure Drives & DC-Servo/Ballscrew Drives**
- **100 mm Travel Range, 125 mm/sec Max. Velocity**
- **Reliable Execution of Nanometer Level Increments**
- **2 nm Linear Encoder Resolution**
- **Millisecond Settling Time to Nanometer Precision**
- **Frictionless Piezo Drive and Flexure-Decoupled Ballscrew**
- **Active Compensation of Backlash and Stick/Slip Effects**
- **Excellent Velocity Control**

The M-511.HD is an advancement on PI's proven M-5x1 precision micropositioning stage series. The new hybrid system overcomes the limitations of conventional precision positioning systems by combining the well-known advantages of piezo-flexure-drives (unlimited resolution and very rapid response) with the long travel ranges and high holding forces of a servo-motor/ballscrew arrangement. The M-511.HD allows velocities to 125 mm/s with an encoder resolution of 2 nm and load capacity of 50 kg for horizontal operation.

### Application Examples

- Surface Inspection
- Microscopy
- Laser technology
- Interferometry
- Metrology

### Long Travel Ranges with Nanometer Precision

The challenge of implementing hybrid technology is not only the positioning stage design, but also the use of high-resolution sensors over large travel ranges, the processing of the resulting high-frequency signals and the design of special control algorithms to take full advantage of the hybrid concept.

On the mechanical side, this is accomplished by decoupling the moving platform from the positioner's motor-ballscrew-drive by frictionless flexures and stiff, highly responsive piezo actuators.

Due to its high stiffness and instantaneous, sub-millisecond range response, the integrated piezo flexure drive provides active stick/slip compensation during startup and settling and is the key to achieving consistent and repeatable nanometer level positioning increments. It also cancels out motion irregularities caused by the ball screw and significantly improves velocity control.

Servo-control of the system employs a single high-resolution position feedback sensor (direct metrology) which means that the inherent piezo precision is available over the entire travel range of 100 mm, and longer travel ranges are basically feasible. The resolution and the positioning accuracy mainly depend on the choice of the feedback sensor.

### Hybrid Controller Technology is Key to Success

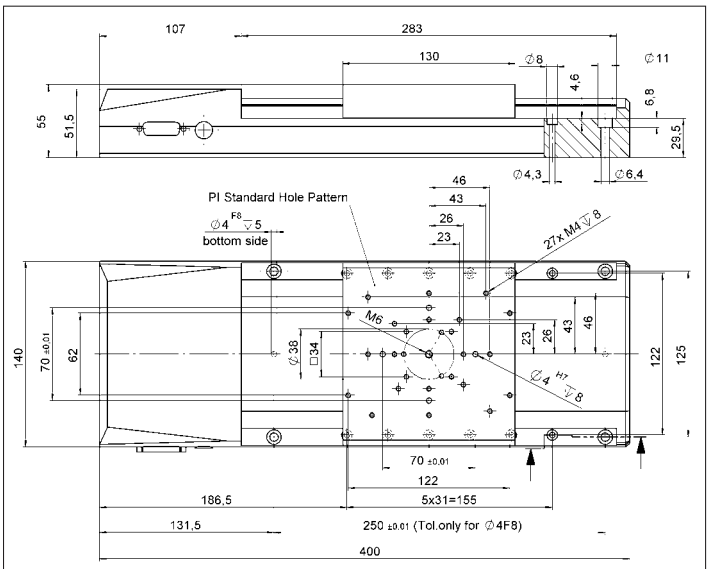
PI's highly specialized C-702 hybrid nanopositioning controller compares the actual platform position (by reading the integrated linear encoder) with a calculated, smooth trajectory in real time. Its complex control algorithms continuously actuate both the piezoelectric and servo motor drives in a way to provide the best possible overall performance.

This makes hybrid systems ideal for applications where extremely smooth motion is required, where the position of an incident needs to be read and refound precisely, or where an externally specified target position needs to be hit within few a nanometers, such as in surface inspection or metrology.

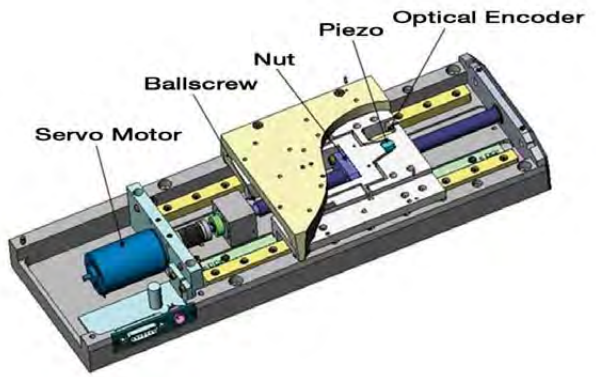
### Ordering Information

**M-511.HD**
Ultra-High-Precision Hybrid Translation Stage, 100 mm Travel, 2 nm Linear Encoder Resolution

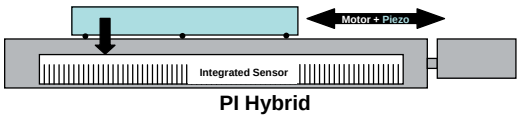
**Ask about custom designs!**



M-511.HD, dimensions in mm. Sub-D connector 26-pin, 3 m cable




Working principle of the M-511.HD. The platform is decoupled from the motor drive train by the piezo actuator and the flexure guides. This also reduces the inertia of the piezo-driven platform and allows for rapid response




**PI Hybrid**

PI Hybrid drive combines motorized and piezo positioning system with integrated, internal, high-resolution sensor in one control loop

| | **M-511.HD** |
|---|---|
| Active axes | X |
| **Motion and positioning** | |
| Travel range | 100 mm |
| Integrated sensor | Linear encoder |
| Sensor resolution | 0.002 µm |
| Design resolution | 0.002 µm |
| Min. incremental motion | 0.004 µm |
| Hysteresis at the platform | 0.01 µm |
| Unidirectional repeatability | 0.01 µm |
| Accuracy | <0.05 µm |
| Pitch | ±25 µrad |
| Yaw | ±25 µrad |
| Straightness | 1 µm |
| Flatness | 1 µm |
| Max. velocity | 125 mm/s |
| Origin repeatability | 1 µm |
| **Mechanical properties** | |
| Drive screw | Recirculating ballscrews |
| Guiding | Precision linear guiding rails, recirculating ball bearings |
| Screw pitch | 2 mm/rev. |
| Max. load | 500 N |
| Max. push/pull force | 80/80 N |
| Max. lateral force | 200 N |
| **Drive properties** | |
| Drive type | Hybrid drive: DC motor with low-inertia, flexure-decoupled and piezo actuated stage platform |
| Motor type | DC motor |
| Operating voltage (motor) | 24 V |
| Electrical power | 30 W |
| Piezo drive type | PICMA® Multilayer piezo with flexure |
| Piezo voltage | ±36 V |
| Limit and reference switches | Hall-effect |
| **Miscellaneous** | |
| Operating temperature range | -20 °C to +65 °C |
| Material | Al (black anodized) |
| Mass | 5.1 kg |
| Recommended controller/driver | C-702 hybrid motor controller |

# M-714 Linear Stage for Vertical Applications

## Heavy-Duty Nanopositioning System with Hybrid Drive

Hybrid Z-positioner M-714.HD

- **Simultaneous Control of Piezo-Flexure Drives & DC-Servo/Ballscrew Drives**
- **7 mm Vertical Travel Range, 10 kg Load Capacity**
- **High Holding Forces with Minimum Power Consumption**
- **Integrated Precision Linear Encoder Provides 2 nm Resolution**
- **Active Backlash Compensation and Stick/Slip Compensation**
- **Frictionless Piezo Drive and Flexure-Decoupled Ballscrew**
- **Millisecond Settling Time to Nanometer Precision**

The M-714 was designed from the ground up to use the hybrid drive technology. The hybrid design overcomes the limitations of conventional precision positioning systems by combining the well-known advantages of piezo-flexure-drives (unlimited resolution and very rapid response) with the long travel ranges and high holding forces of a servo-motor/ballscrew arrangement. The M-714 can position loads up to 10 kg with nanometer precision over 7 mm in vertical or horizontal direction. Compared to high-resolution magnetic linear drives, the hybrid principle allows high holding forces with minimum power consumption, without counterbalancing the load. The angular deviation is less than ±10 µrad over the entire travel range of 7 mm.

### Application Examples

- Surface Inspection
- Microscopy
- Laser technology
- Interferometry
- Metrology

### Long Travel Ranges with Nanometer Precision

The challenge of implementing hybrid technology is not only the positioning stage design, but also the use of high-resolution sensors over large travel ranges, the processing of the resulting high-frequency signals and the design of special control algorithms to take full advantage of the hybrid concept.

On the mechanical side, this is accomplished by decoupling the moving platform from the positioner's motor-ballscrew-drive by frictionless flexures and stiff, highly responsive piezo actuators.

Due to its high stiffness and instantaneous, sub-millisecond range response, the integrated piezo flexure drive provides active stick/slip compensation during startup and settling and is the key to achieving consistent and repeatable nanometer level positioning increments. It also cancels out motion irregularities caused by the ball screw and significantly improves velocity control.

Servo-control of the system employs a single high-resolution position feedback sensor (direct metrology) which means that the inherent piezo precision is available over the entire travel range of 7 mm, and longer travel ranges are basically feasible. The resolution and the positioning accuracy mainly depend on the choice of the feedback sensor.

### Hybrid Controller Technology is Key to Success

PI's highly specialized C-702 hybrid nanopositioning controller compares the actual platform position (by reading the integrated linear encoder) with a calculated, smooth trajectory in real time. Its complex control algorithms continuously actuate both the piezoelectric and servo motor drives in a way to provide the best possible overall performance.

This makes hybrid systems ideal for applications where extremely smooth motion is required, where the position of an incident needs to be read and refound precisely, or where an externally specified target position needs to be hit within few a nanometers, such as in surface inspection or metrology.

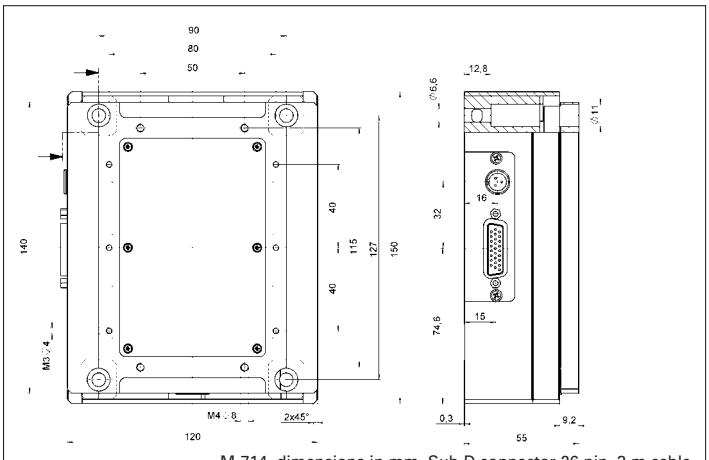
### Ordering Information

**M-714.2HD**
Ultra-High Precision Hybrid Nanopositioning Stage, 7 mm Travel, 2 nm Linear Encoder Resolution

**Ask about custom designs!**

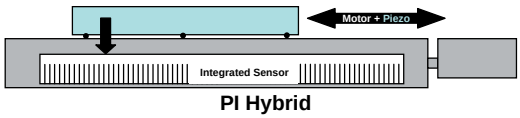
### Notes

The M-714.2HD positioning system is optimized for vertical operation. If horizontal operation is intended, please note with your order.



M-714, dimensions in mm. Sub-D connector 26-pin, 3 m cable


10 nm steps of an M-714 stage,
as measured by an interferometer




**PI Hybrid**

PI Hybrid drive combines motorized and piezo positioning system with integrated, internal, high-resolution sensor in one control loop

## Technical Data

| | M-714.2HD |
|---|---|
| **Motion and positioning** | |
| Travel range | 7 mm |
| Integrated sensor | Linear encoder |
| Sensor resolution | 0.002 µm |
| Design resolution | 0.002 µm |
| Min. incremental motion | 0.004 µm |
| Hysteresis at the platform | 0.01 µm |
| Unidirectional repeatability | 0.01 µm |
| Accuracy | <0.05 µm |
| Pitch | ±10 µrad |
| Yaw | ±10 µrad |
| Max. velocity | 0.2 mm/s |
| Origin repeatability | 1 µm |
| **Mechanical properties** | |
| Drive screw | Leadscrew |
| Guiding | Crossed-roller bearings |
| Screw pitch | 1 mm/rev. |
| Gear ratio | 80:1 |
| Belt drive transmission ratio | 3:1 |
| Max. push/pull force | 100/100 N |
| Self inhibition | 100 N |
| Max. lateral force | 200 N |
| **Drive properties** | |
| Drive type | Hybrid drive: DC-motor with low-inertia, flexure-decoupled and piezo actuated stage platform |
| Motor type | DC-motor, gearhead |
| Operating voltage (motor) | 24 V |
| Electrical power | 4.5 W |
| Piezo drive type | PICMA® Multilayer piezo with flexure |
| Piezo voltage | ±36 V |
| Limit and reference switches | Hall-effect |
| **Miscellaneous** | |
| Operating temperature range | -20 °C to +65 °C |
| Material | Al (black anodized) |
| Mass | 2.1 kg |
| Recommended controller/driver | C-702 hybrid motor controller |

# C-702 High-Performance 2-Axis Controller

## Controller for Hybrid Piezo Stages – Key to Hybrid Technology

C-702 Hybrid Controller

- **Motion Controller & Driver for Simultaneous Operation of Closed-Loop DC Servo Motors and Piezo Actuators**
- **2 Channels**
- **Sample Rate 10 kHz**
- **Piezo Resolution 24-bit**
- **Fast Serial Bus for Incremental High-Resolution Sensor**
- **Realtime Operating System**
- **Interfaces: TCP/IP Ethernet, RS-232, VGA, Keyboard**

The C-702 digital hybrid motion controller has been designed for precision control of the M-511.HD and M-714 nanopositioning stages. Both are based upon the PI hybrid drive technology integrating piezoelectric and motorized drive components to form one motion and servo-control system. The result is a nanopositioning system for high loads that can follow a motion profile with nanometer position accuracy and high constancy of velocity over several millimeters of travel.

### Application Examples

- Surface Inspection
- Microscopy
- Laser technology
- Interferometry
- Metrology

### Highly Effective Servo-Control for a Complex Drive Technology

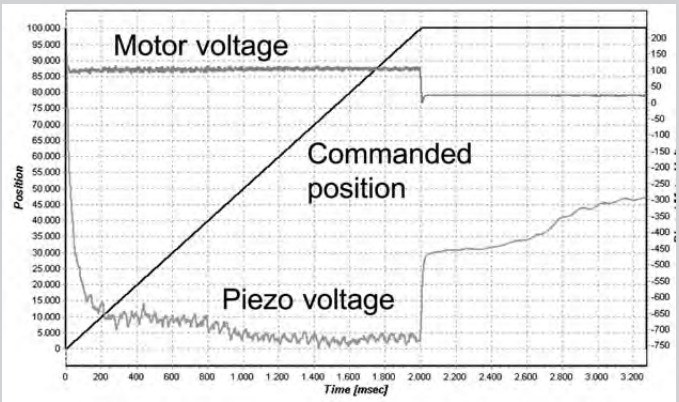
The optimized interaction between the piezoelectric and motorized drive components to make them a single motion unit requires a high-speed sensor as well as powerful control algorithms. The digital, 2-channel, C-702 controller, based on modern CPU technology with a real time operating system, has been designed for this task. It is able to read the position signals with virtually no delay and process the data immediately. The integrated piezo amplifiers use a high-resolution 24-bit DAC to fully support the high position resolution of the piezo actuators. The new ultra-fast broadband SSI interface for the optical linear encoder supports stage velocities of 300 mm/s at a resolution of 2 nm. With special cabling, external sensor signals, like those from an interferometer, can be used for servo-control via an SSI interface.

### One Controller for One Motion System

In PI hybrid systems, the motor-leadscrew and piezo actuator are fully integrated to form one motion system. The motor and piezo act together at all times. The result is far more than a coarse-adjust/fine-adjust system: effects like startup stick/slip and backlash can be completely compensated and a motion profile with high constancy of velocity can be followed. Because of the high-piezo stiffness, setting to a few nanometers only takes a few milliseconds, significantly faster than with conventional, higher-inertia, linear-motor-driven stages. Furthermore minimal increments in the range of the sensor resolution can be reliably executed. To allow high velocities beyond 100 mm/sec and nanometer-range incremental resolution, position information must be transmitted and processed very rapidly and a complex control algorithm is required.

### Ordering Information

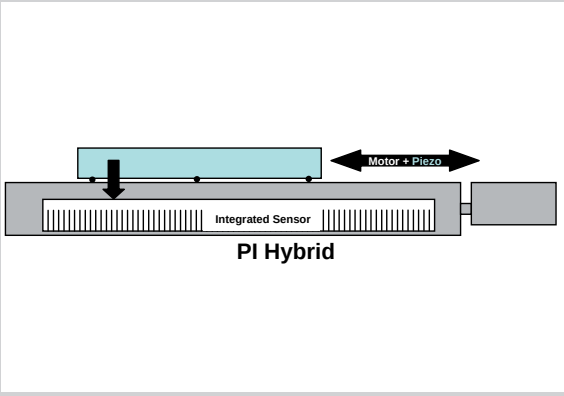
**C-702.00**
Ultra-High-Precision
Hybrid Controller, 2 Channels



PI hybrid servo-controller output during a positioning command. The controller reads the system position off a high-resolution encoder and actuates both the motor and piezoelectric actuator at the same time giving a system with the advantages of both drives

10 nm steps of an M-714 stage, as measured by an interferometer

M-511.HD hybrid stage (left),
M-714.00 (right front) and the C-702 controller (rear)




PI Hybrid drive combines DC motor and piezo actuator with integrated, internal, high-resolution sensor in one servo loop

## Technical Data

| | C-702.00 |
|---|---|
| Function | Motion Controller for Hybrid Nanopositioning Systems |
| Drive type | DC motor (PWM)/piezo |
| Channels | 2 |
| **Motion and control** | |
| Servo characteristics | PID V-ff filter, notch filter, hysteresis setting (motor); proportional-integral (P-I) algorithm with notch filter (piezo) |
| Sampling rate | 10 kHz |
| Trajectory profile modes | Trapezoidal, S-curve |
| Processor | 32-bit Intel Celeron |
| Position range | 32 bit |
| Limit switches | 2 lines per axis |
| Reference switch | 1 line per axis |
| Motor brake | Software programmable |
| **Electrical properties** | |
| Operating voltage | 24 VDC (via M-500.PS wide range power supply*) |
| Output power/channel | PWM: 19.5 kHz, 10-bit resolution |
| Piezo voltage | ±36 V (24-bit resolution) |
| Power consumption | < 25 W |
| **Interfaces and operation** | |
| Communication interfaces | TCP/IP, RS-232, VGA, Keyboard |
| Motor connector | Sub-D connector, 26-pin** |
| Encoder input | Serial SSI interface for incremental encoder |
| Controller network | via TCP/IP |
| I/O ports | 8 TTL inputs, 8 TTL outputs |
| Command set | ASCII, PI General Command Set (GCS) |
| User software | PIMikroMove® |
| Software drivers | GCS (PI General Command Set)-DLL, LabVIEW™ drivers |
| Supported functionality | Autostart macro, user-programmable macro |
| **Miscellaneous** | |
| Operating temperature range | +10 to +50 °C |
| Mass | 1.35 kg |
| Dimensions | 130 x 205 x 76 mm |

* M-500.PS: wide range power supply, 100 to 250 VAC, 50 to 60 Hz
** Sub-D 26 contains connection for motor, piezo, reference and limit switches, sensor Internal heat sink with very silent fan