BSc, 2010-06-09
N310T0011, valid for NEXACT® Drives and Positioning Systems

NEXACT® Technology

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NEXACT® PiezoWalk® drives break away from the limitations of conventional nanopositioning systems and combine large travel ranges with high resolution.

NEXACT® PiezoWalk® drives are piezo-based linear drives which are used in all applications where loads of up to 10 N must be precisely adjusted over longer distances (> 1 mm) and possibly dynamically readjusted over small distances in the micrometer range, as is the case with scanning applications, for example, or with tracking in microscopy or cell manipulation.

The NEXACT® PiezoWalk® drive consists of piezo-ceramic bender actuators which are cyclically controlled, and thus move a runner. Suitable selection of the piezo elements optimizes the step size, clamping force, velocity and stiffness to match each requirement.

Different modes of operation allow the characteristics of the NEXACT® drive to be used to optimum effect to suit the actual requirement. They allow constant, maximum velocity, fast steps and maximum holding force when switched off.

1. Characteristics of NEXACT® PiezoWalk® Drives

- Very high resolution, which is limited only by the sensor used. Resolutions below 1 nanometer are possible when used in open-loop mode.
- NEXACT® drives generate driving forces up to 10 N
- PiezoWalk® drives stably maintain the position with nanometer accuracy, even when powered down.

  The design of the drive ensures maximum clamping force at rest. Since a permanent electrical field can adversely affect the lifetime of piezo actuators, the durability of the drive benefits from the state when no electrical voltage is applied.
- The active components of the PiezoWalk® drives are manufactured from a vacuum-compatible ceramic.
- PiezoWalk® drives are distinguished by their suitability for use in clean rooms.
- PiezoWalk® drives neither produce magnetic fields nor are they affected by them. PiezoWalk® drives are therefore suitable for use in applications which are based on nuclear magnetic resonance, for example, or for experiments on superconductivity.
- The drives can also be used under hard ultraviolet radiation conditions.

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Patented Technology

The products described in this document are at least partially protected by the following patents:
German Patent No. P4408618.0
European Patent No. 0624912B1

2. Mechanical Properties

2.1 Design

A NEXACT® drive uses one or more NEXACT® piezo drive modules which are coupled to the same, moving runner.

The piezo drive modules are preloaded against the runner so that the runner maintains a stable position even without additional current being fed to the piezo module.

Fig. 1: NEXACT® piezo drive module

A NEXACT® piezo drive module consists of four NEXACT® piezo actuators. The individual actuators themselves each consist of two segments (Fig. 2) of piezo bender elements.

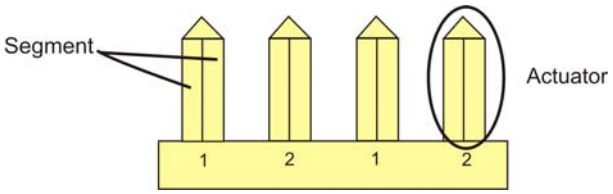

Fig. 2: Design of a NEXACT® piezo drive module. The four NEXACT® piezo actuators each consist of two segments. The numbers 1, 2 designate the actuator pairs which are controlled in an identical way

2.2 Control

The actuators of a piezo drive module are all cyclically controlled in pairs (= actuator pairs). When a drive contains several piezo drive modules, corresponding actuator pairs are controlled

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together. Every NEXACT® drive therefore has to be controlled by means of four different signals for the segments (U_1 to U_4). The voltage range for the bender elements is -10 to + 45 V.

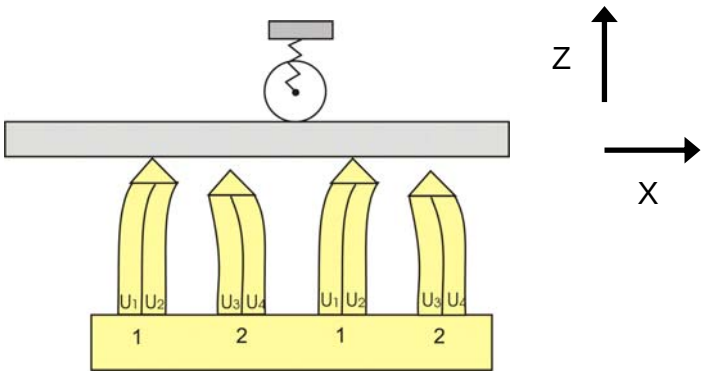

Fig. 3: The NEXACT® piezo drive module is preloaded against a runner. Coordinated control of the actuator pairs leads to a series of displacements in the X and Z-directions. The NEXACT® piezo actuators clamp the runner and thus move it forward in the X-direction. The actuator pairs lift off the runner alternately.

The feed is achieved by coordinated control of the segments. The actuator pairs have different displacements. This causes the piezo drive module to execute a stepping motion on the runner (see Nanostepping mode).

2.3 Positioning

The step size of a NEXACT® drive depends on whether the drive must work against a force, such as the weight, for example.

The displacement of the NEXACT® piezo actuators used suffers from hysteresis and is therefore not linearly dependent on the voltage applied. The stepping motion of the PiezoWalk® drives is thus not comparable with the defined feed forward which conventional stepper motors perform.

It is recommended that a position sensor is used for tasks requiring repeatable and highly accurate positioning. PI uses high-resolution incremental sensors in stages with NEXACT® drives.

3. Modes of Operation

Unless stated otherwise, all information refers to drives operated with the E-861 digital controller.

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Note: The transition between the "nanostepping" and "analog mode" operating modes requires that the piezo voltages be changed so that the corresponding actuator pairs are in contact with the runner. A relax procedure is required as an intermediate step. (See Glossary)

3.1 Nanostepping Mode

Characteristics

- stepping motion over long distances
- high velocity over longer travel ranges, limited only by the length of the runner

Description

The feed forward is achieved by coordinated control of the segments of the NEXACT® drive module. This brings about a stepping motion of the module on the runner. The travel range for this is limited only by the length of the runner.

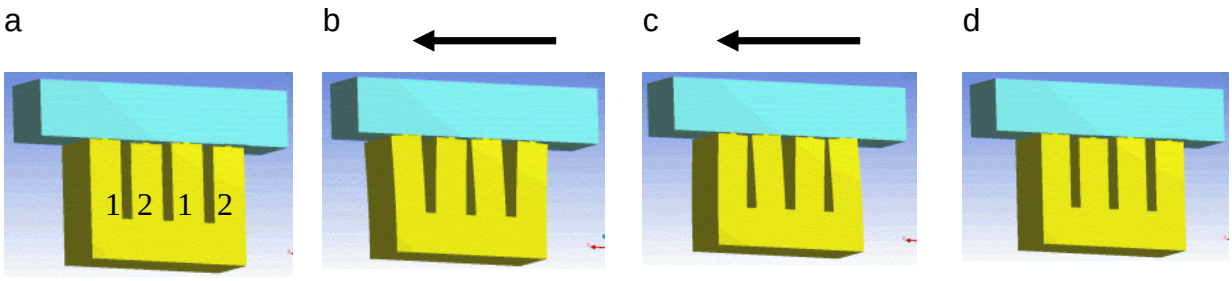

Fig. 4: A step cycle (= one step) in nanostepping mode. The arrow represents the direction of motion of the runner. a. One pair of actuators is in contact with the runner, the second pair of actuators is lifted off (motion state). b. Both actuator pairs have maximum displacement in opposite directions. Actuator pair 1 has moved the runner along during its displacement and now lifts off. Actuator pair 2 takes over the contact (the clamping). c. Actuator pair 2 has moved through the full displacement and thus moved the runner along accordingly. At the same time actuator pair 1 has moved in the opposite direction to actuator pair 2 and takes over the contact again. d. Initial state, as a

It is not necessary to complete a full step cycle in nanostepping mode: Commands can specify complete or parts of step cycles and both can be executed. After executing the command, the NEXACT® piezo actuators remain in the arbitrary final position they have reached.

Initial state for nanostepping motion: One pair of actuators is in contact with the runner, with maximum clamping, the second pair is lifted off as far as possible (motion state).

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Control

In nanostepping mode the segments of both pairs of legs are controlled with a phase shift. Decisive for the feed of the runner are the resulting voltages below (Tab. 1):

Actuator pair 1 (U1, U2 in Fig. 2):	**Actuator pair 2 (U3, U4 in Fig. 2):**
Clamping voltage	
$U_{clamping} = \frac{U_1 + U_2}{2}$	$U_{clamping} = \frac{U_3 + U_4}{2}$
Feed voltage	
$U_{feed} = U_1 - U_2$	$U_{feed} = U_3 - U_4$

Tab. 1: Clamping and feed voltage.

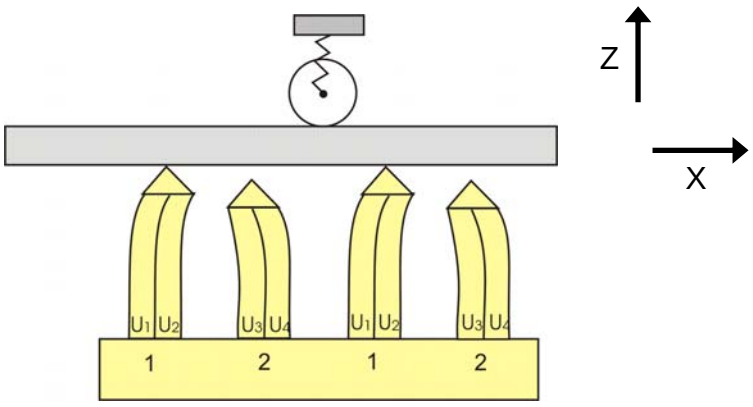

Fig. 5: The runner moves in the X-direction. The module is preloaded against the runner in the Z-direction.

The resulting voltages are shown in the diagram below (Fig. 6).

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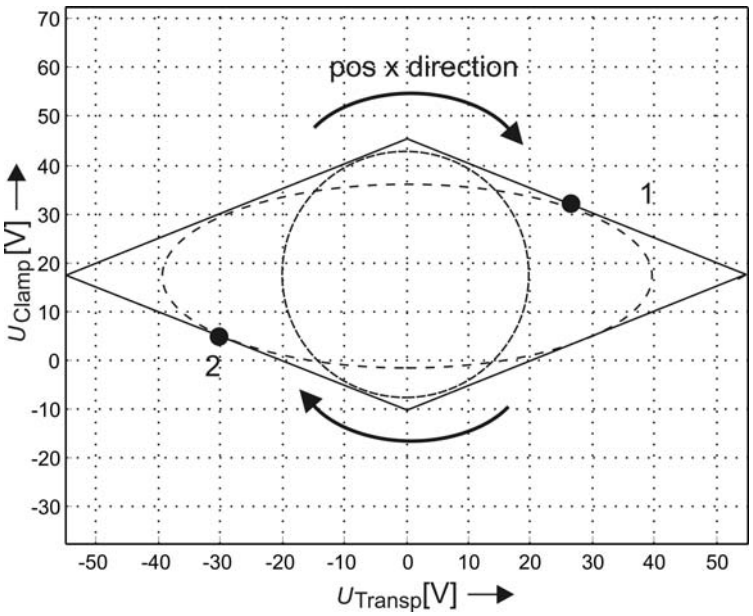

Fig. 6: The possible values for clamping and feed voltage are located within the rhombus marked. 1, 2 designate the actuator pairs

3.2 Analog Mode

Characteristics

- high-dynamics motion, limited by the actuator displacement in analog mode (a few µm)
- positioning accurate to one picometer (open-loop)

Description

Initial state for analog motion: All actuators are in contact with the runner (analog state).

Analog mode requires all NEXACT® piezo actuators to always be in contact with the runner. The actuators do not lift off the runner. The maximum feed corresponds to the deflection of the NEXACT® piezo actuators (see data sheets of the NEXACT® drives and positioning systems, “Travel range in analog operation”)

The dynamics correspond to the dynamics of direct-drive piezo stages.

Control:

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All actuators are controlled in phase. The clamping voltage in analog mode is 17.5 V, and hence the mean value of the possible piezo voltages of both segments. The maximum travel range is thus available for the deflection (see Figs. 6 and 7)

Decisive for the feed of the runner are the resulting voltages from Tab.1.

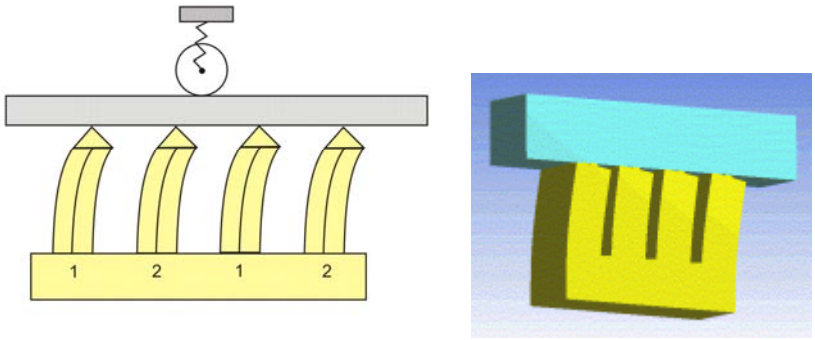

Fig. 7: Analog mode: All NEXACT® piezo actuators are in contact with the runner. The actuator pairs 1 and 2 are controlled in an identical way (segment voltages $U_1 = U_3$, $U_2 = U_4$)

3.3 Open-Loop Operation

Specific operating parameters: Step frequency (or cycle time). Recommended maximum value: 800 Hz.
The command • in nanostepping mode is the number of steps (any floating point number) • in analog mode is the voltage for the analog travel range
Note: The PiezoWalk Driving Mode parameter has no effect here. The mode of operation used is determined by the command. The switch between the modes of operation requires that the corresponding actuator pairs are in contact with the runner. A relax procedure must therefore be performed before the piezo voltages can be changed (see Glossary).

1. **Nanostepping mode:** Initial state: One pair of actuators is in contact with the runner, with maximum clamping, the second pair is lifted off as far as possible (motion state). Commands can specify complete or parts of step cycles and both can be executed.
2. **Analog mode:** Initial state: All actuators are in contact with the runner (analog state).

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3.4 Closed-Loop Operation

Specific operating parameters: PiezoWalk Driving Mode: Nanostepping mode, combined nanostepping and analog mode Velocity
The command specifies the target position or the change in position
Switching off the control and switching on the control in analog mode trigger a relax procedure (see Glossary).

1. **Nanostepping mode**

   Initial state: One pair of actuators is in contact with the runner, with maximum clamping, the second pair is lifted off as far as possible (motion state). Commands can specify complete or parts of step cycles and both can be executed. After the target position has been reached the actuators can have any bend. The control is via a PID-control with notch filter.

2. **Combined nanostepping and analog mode, with automatic change between the two modes of operation**

   Initial state and final state: All actuators are in contact with the runner (analog state). The target position is thus maintained with maximum stiffness (all piezo actuators are in contact with the runner). The basic algorithm works according to the follow principle (see Fig. 8):

   1. Analog mode in the closed control loop up to the maximum deflection.
   2. The control loop is opened, the piezo actuators switch to motion state.
   3. The control loop is closed, operation in nanostepping mode (over an arbitrarily long distance) until the target window (“On target tolerance”, see Glossary) is reached
   4. The control loop is opened, the piezo actuators then switch to analog state again
   5. Analog mode until the target position (commanded) is reached, a further cycle is performed where necessary.

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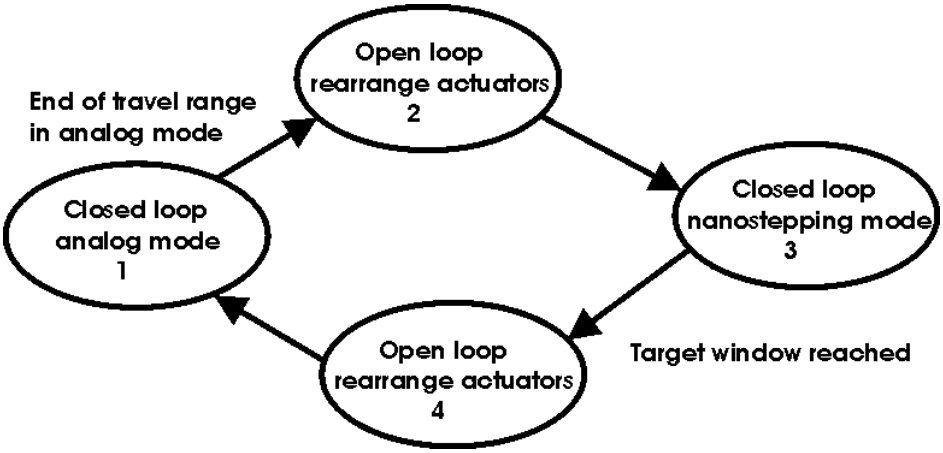

Fig. 8: Algorithm on reaching the target window ("On target tolerance")

3. **Analog mode**

   Analog mode cannot be selected specifically in closed-loop mode. In combined analog and nanostepping mode the analog mode is activated automatically near the target position.

Characteristics of the combined nanostepping and analog mode

- The target position is maintained with maximum stiffness because all piezo actuators are in contact with the runner.
- Two sets of PID-control parameters are effective (one set each for nanostepping and analog mode).
- Time required for the positioning: Depending on the load and the direction of motion it may be necessary to change between the operating modes several times. Since the control loop is opened and closed each time, the step-and-settle can take longer than in simple nanostepping mode.
- Precondition: The sensor resolution must be better than 20 nm.

4. Important Parameters

4.1 Step Frequency

The recommended maximum step frequency for NEXACT® drives is 800 Hz. This applies to continuous operation. For short periods it is also possible to work with higher frequencies (see

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considerations regarding velocity, Glossary). The duration of a step cycle is set in the controller as the corresponding parameter (cycle time).

4.2 PiezoWalk Driving Mode

The parameter is only effective in closed-loop operation. The setting of the parameter defines how the feed is performed:

- Pure nanostepping mode
- Combined nanostepping and analog mode, with automatic change between the two operating modes (internal specifications, see 3.4). The criteria for the change are fixed in the firmware of the E-861 controller.

5. Glossary

5.1 Piezo Drive Module

See Chapter 2. Mechanical properties, 2.1 Design

5.2 Step Cycle

A step cycle (= one step) has been fully completed when a PiezoWalk® piezo drive module has gone through all phases during one stepping motion. The piezo voltages at the beginning and the end of a step cycle are identical.

In nanostepping mode it is possible to complete parts of step cycles.

5.3 Duty Cycle

The maximum permissible velocity of a PiezoWalk® drive depends greatly on the type of application. The duty cycle is relevant for a higher velocity in order to prevent the drive heating up, which could shorten the lifetimetime of the NEXACT® piezo actuators.

5.4 Specifications for the Mechanical Properties: Vmax

The step size of a NEXACT® drive depends on whether the drive must work against a force, such as the weight, for example.

For a fixed step frequency the velocity of the NEXACT® drive is proportional to the step size.

The open-loop velocity in the positive and negative directions can be different.

The maximum velocity in nanostepping mode is designed for the best possible constancy so that the velocity does not fluctuate when executing the steps.

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The maximum velocity depends greatly on the NEXACT® drive application. The drive can provide a high velocity for a short period if sufficient time is available for cooling down. Continuous operation with high step frequencies causes the NEXACT® piezo actuators to heat up, and can lead to damage and even to failure of the NEXACT® piezo actuators in the long term. The values in the datasheet are guide values which allow the drives to be operated safely.

5.5 States of the NEXACT® Piezo Drive Module

Analog state: All actuators are in contact with the runner. The clamping voltage in analog mode is 17.5 V, and thus corresponds to the mean value of the possible piezo voltages of both segments. The maximum range is thus available for the feed.

Motion state: One pair of actuators is in contact with the runner, with maximum clamping, the second pair is lifted off as far as possible (motion state).

Relax state: All NEXACT® piezo actuators of a piezo drive module are in contact with the runner. All piezo voltages are zero. This maintains the position stably without requiring the further supply of power. The holding force is maximum.

The lifetime of the piezo actuators is thus improved because long-term loading with constant high voltage is avoided. (A permanent electric field can adversely affect the life of piezo actuators.)

5.6 Relax Procedure

A relax procedure puts the drive into the relax state. This sets all actuator voltages applied to zero. The relax procedure is started by

- the RNP command
- Switching from closed-loop to open-loop operation “Servo off”)
- Switching to closed-loop operation in analog mode

Depending on the application conditions and parameter settings this causes a positional error of a few tens of nanometers up to one micrometer.

5.7 On Target Tolerance

In closed-loop operation, the distance to the target position given in the command at which nanostepping mode is switched to analog mode. The value is less than the maximum displacement of the bender actuators in the direction of travel (see Datasheet: “Travel range in analog mode”) and is implemented as a fixed parameter in the firmware of the E-861 controller.

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5.8 Step Size

The step size of a NEXACT® drive depends on whether the drive must work against a force, such as the weight, for example.

Step size in nanostepping mode: Typical values are given in the data sheets of the NEXACT® drives and positioning systems.

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6. Product Examples

N-310 NEXACT® OEM Miniature Linear Motor/Actuator

Compact, High-Speed PiezoWalk® Drive

- 20 mm Standard Travel Range, Flexible Choice of the Runner Length
- Compact and Cost-Effective Design
- 0.03 nm Resolution**
- To 10 N Push/Pull Force
- Low Operating Voltage
- Self Locking at Rest, No Head Dissipation, Nanometer Stability
- Non-Magnetic and Vacuum-Compatible Working Principle

N-380, N-381 NEXACT® Linear Actuator, Manipulator, Piezo Stepper

High-Resolution PiezoWalk® Linear Actuator with Optional Position Sensor

- Travel Range 30 mm
- Novel, Zero-Wear Piezo Stepping Drive, Ideal for Micro- and Nano-Manipulation
- Integrated Linear Encoder Option for Highest Accuracy with 20 nm Resolution
- Very High Acceleration, e.g. for Cell Penetration
- Two Operating Modes: Continuous Stepping Mode and Continuously Variable, High-Dynamics Analog Mode for 30 pm Resolution**
- Up to 10 N Force Generation
- Self Locking at Rest, no Heat Generation
- Smooth Motion, no Closed-Loop Jitter
- Vacuum-Compatible and Non-Magnetic Versions

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N-725 PIFOC® High-load Objective Scanner

1 mm Travel, fast Response and Nanometer Precision

- High Force & High-Dynamics for Positioning and Scanning of Large Objectives up to 28 mm Ø
- 1 mm Travel for Applications with Large Penetration Depth
- Ideal for e. g. Two Photon Microscopy
- Very Fast Response: 20 ms Step and Settle Time
- Self Locking at Rest, no Heat Generation, no Servojitter
- Drive Resolution < 1 nm, 20 nm Encoder Resolution
- Two Motion Modes: Continuous Nanostepping and High-Dynamics Analog Mode
- Compact Design: Ø 48 mm, 40.5 mm Height
- Frictionless, High-Precision Flexure Guiding System for Better Focus Stability
- QuickLock Thread Adapter for Simple Installation

N-661 Miniature Linear Stage with NEXACT® Drive

PiezoWalk® Drive Provides Nanometer Precision and Smooth Motion

- Travel Range 20 mm
- Self Locking at Rest, no Heat Generation, no Servo Dither
- Compact Design: 70 x 50 x 20 mm
- Zero-Wear Piezo Stepping Drive, Ideal for Micro- and Nano-Manipulation
- Integrated Linear Encoder Option for Highest Accuracy with 20 nm Resolution
- Two Operating Modes: Continuous Stepping Mode and Continuously Variable, High-Dynamics Analog Mode for 30 pm Resolution**
- Up to 10 N Force Generation

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E-861 PiezoWalk® NEXACT® Controller/Driver

Networkable Controller for NEXACT® Linear Drives and Positioners

- For NEXACT® Drives and Positioning Systems
- Complete System with Controller, Integrated Power Amplifiers and Software
- Open-Loop Operation, or Closed-Loop with Linear Encoder
- High Performance at Low Cost
- Daisy-Chain Networking for Multi-Axis Operation
- Non-Volatile Macro Storage for Stand-Alone Functionality with Autostart Macro
- I/O for Automation, Joystick for Manual Operation
- Parameter Changes On-the-Fly

E-862 NEXACT® Drive Electronics

Low-Cost Drive Electronics for NEXACT® Piezo Stepping Drives

- For NEXACT® PiezoWalk® Drives & Stages
- Combined Step Generator and Power Amplifier
- Cost-Effective Design
- Interface for Automation, Joystick for Manual Operation

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