April 2011

PTE

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Features

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- Knowing Your Motor Options
- The Expanding Role of Advanced Ceramics in the Aerospace Industry

Technical Articles

- Tuning a PID Controller
- Upgraded DC Brush Gearmotor (UBGM) for Spacebus Platforms

Power Play

- When (Robotic) Animals Rule the Earth ...

Motors Motors Motors

you need them, we've got great prices on them!

IRONHORSE

General purpose AC motors

IRONHORSE motors are available in rolled steel *(1/3 to 2 hp)* and cast iron *(1 to 300 hp)* 1800 RPM models. Selected 1200 and 3600 RPM units for the most popular horsepower ratings start at just $70.

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- 56C frame rolled steel single-phase, 115/208-230V, from 0.33 to 1.5 hp, TEFC enclosure
- 56C frame rolled steel three-phase, 208-230/460V, from 0.33 to 2 hp, TEFC enclosure
- TC frame (C-face) cast iron three-phase, 208-230/460V, up to 100 hp, TEFC enclosure

MARATHON ELECTRIC

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PMDC, 56C, 2 hp, 180V	$368.00	$2,347.00	$1,261.00	$2,301.00

www.automationdirect.com/motors

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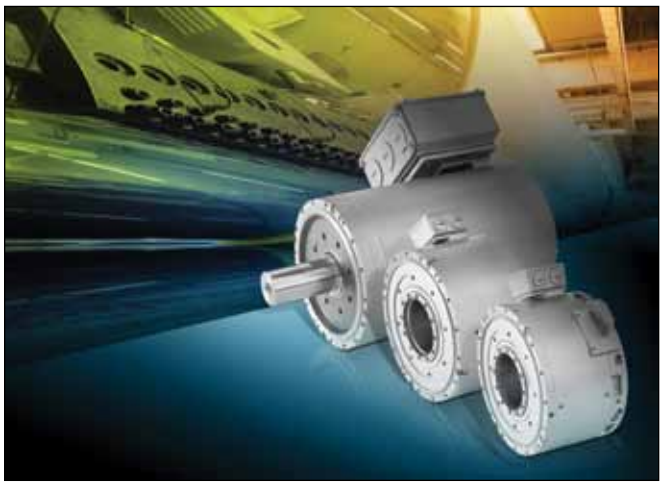

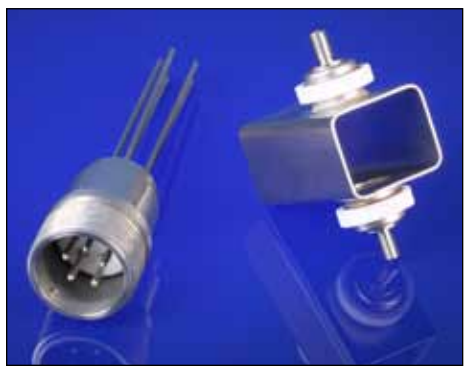

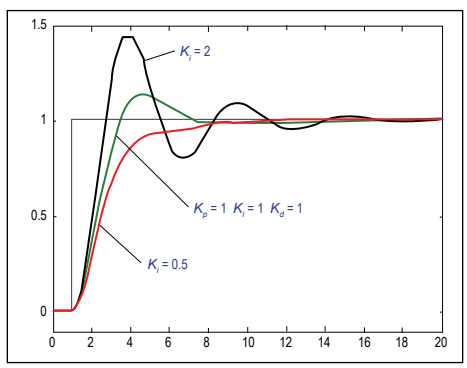

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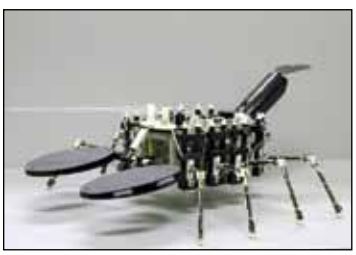

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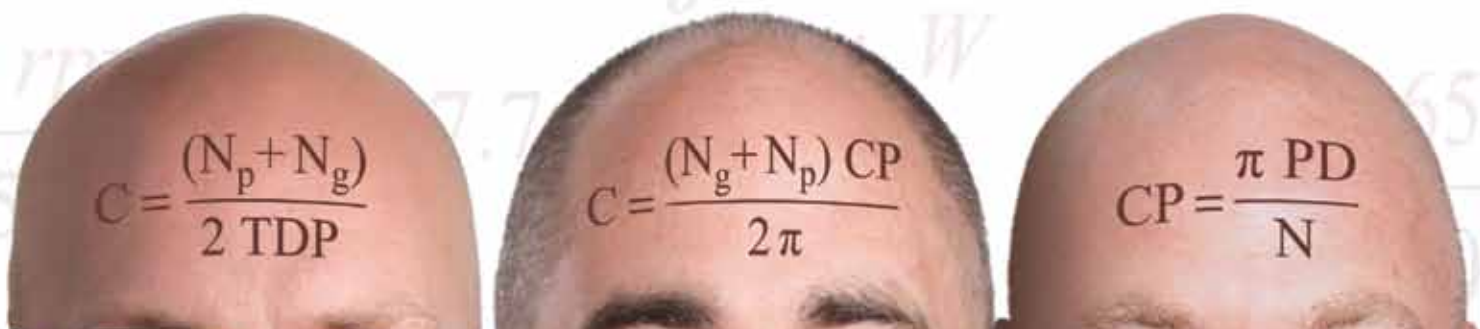

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Active Contact Flange

OFFERS TOUCH-SENSITIVE PROCESSING

KEBA Corp., an Austrian based industrial automation products manufacturer, recently announced the launch of the KEBA Active Contact Flange, a device combining highly sensitive sensor, positioning and control technologies. This product enables automatic, touch-sensitive surface processing independent of the robot or end of arm tooling device through a combination of fast and targeted force regulation.

"The combination of active pneumatics and sensing devices along with KEBA's closed loop control platform will streamline implementation processes of robotic positioning based on force, dramatically cutting implementation times, while increasing quality and productivity," said Helmut Schreiberhuber, vice president, KEBA Corp. "The reaction time of this product eliminates typical delayed response times when compared to existing technologies, which allows for unparalleled touch-sensitive positioning of the tooling. We are proud and excited to offer this unique touch-sensitive device to the automation market."

The Active Contact Flange can be used to simplify and improve a multitude of processes, including surface treatment procedures, force sensitive and complex assembly applications. The touch-sensitive handling of the workpiece is vital in automating sanding, polishing, buffing, stripping, cleaning and deburring procedures, to name a few, because the device automatically compensates for position and force control. This is equally key in force-sensitive applications including gluing, bonding, testing and delicate positioning.

Quality and productivity gains have been proven by customers, including Volkswagen Bratislava, MC, Neubacher, Wifi–Linz and Austrian-based systems integrator SPS Technik. The KEBA Active Contact Flange allows for robotic path programming to be greatly simplified since the flange independently and automatically compensates for positioning to maintain a constant force on the work surface regardless of its contour (within the 100 mm stroke envelope of the flange.) This allows for a straight line (linear move) to be employed in the robot program while buffing a curved object. All that is required is to set the force required and the system takes care of the rest.

The KEBA Active Contact Flange is available as a stand-alone product solution or can be a part of a total KEBA solution for the turnkey control of the complete application from robot kinematics to I/O interfaces to system wide control. As a stand-alone product, the KEBA flange package can be employed immediately in a variety of applications. The program logic can be quickly and simply extended in the IEC program language. Common communication interfaces through Ethernet, field bus or digital I/O provide quick and straightforward integration into existing control systems. Data concerning the actual force, position and contact situation is tracked on a permanent basis, providing a comprehensive accessible parameter log, eliminating the need for separate process and quality controls.

As part of a total KEBA control solution, the flange acts as an integral device on the KEBA master control platform. Scalable software provides system control including motion, I/O, process, supervisory and HMI visualization packages. Hardware such as motors, drives, I/O, process controls and fixed and mobile HMI devices round out the KEBA product offering for the ultimate turnkey coordinated automation solution.

The special mechanical design of the KEBA Active Contact Flange minimizes the risk of workpiece damage due to tool collisions in a highly effective manner. Even in the case of sudden interference, the system reacts at great speed and gives way. The combination of touch-sensitive features and collision protection are very economical when compared to the high investment solutions offered to date.

For more information:

KEBA Corp. U.S.
100 West Big Beaver Road
Troy, MI 48084
Phone: (248) 526-0561
www.keba.com

Kollmorgen

RELEASES AKM 8 MOTOR SERIES

Kollmorgen introduces AKM 8 servomotors, the latest addition to the company's global AKM motor series. AKM 8 motors deliver higher torque density to cover the broadest torque/speed range in a housing that is 30 percent shorter than any standard motor in its class available today. As a result machine builders can reduce the size of their machines without sacrificing performance, or they can select a longer stack length to achieve higher performance without having to specify a larger, more expensive motor that would typically require mechanical changes to the machine.

"The AKM high performance motor series offers a wide range of mounting, connectivity, feedback and other options and, with the addition of the AKM 8, is now available in eight frame sizes, 28 frame/stack combinations and 112 'standard' windings. The result is unprecedented choice and flexibility to satisfy the exact needs of even more global applications, with the favorable delivery times and lower cost of a standard product. This is particularly significant for today's machine builders who need to get a better, globally-deployable machine to market, faster," says Gene Matthews, product manager.

The AKM 8 is available in two standard flange/shaft combinations designed to seamlessly integrate with 80–90 percent of machine builder needs around the globe, with no modifications to the customer flange needed. As standard, AKM 8 windings are designed to operate at 230, 400, 480 VAC, eliminating the need for voltage transformation for machines that will be deployed in various geographic regions. AKM 8 motors feature Class F insulation for a temperature rating of 155 degrees C, and provide stall torque from 75 to 180 Nm, operating speeds up to 2,500 rpm, and power up to 19.8 kW, with bearing lifetime rated to 20,000 h. These motors are RoHS- and REACH-compliant, UL listed and carry the CE mark.

"A low-cog design provides smooth performance to maximize power efficiency and improve the quality of final product, making it a particularly attractive motor solution in metal forming and processing, printing, converting, molding and alternative energy applications, among others," explains Matthews.

All AKM series motors feature a robust one-piece housing with potted windings for maximum wire isolation and excellent heat dissipation, resulting in robust performance and long life in even the most demanding application environments. Market-standard high resolution feedback options for high-performance/precision or rugged environments are available, including Endat, BISS, Hiperface, and resolver option, among others. AKM motors are available for low or high speed (to 8,000 rpm) applications, with windings that can be applied to all standard global voltages including 75 VDC, 120, 240, 400 and 480 VAC. A number of options are available to satisfy wide ranging application needs including a reinforced bearing to handle higher radial force, a sealing option to achieve IP67 protection at the flange, as well as varied connectivity and mounting options.

For truly unique applications where the more than 200,000 standard AKM offerings don't meet the requirements of a given application, the Kollmorgen engineering support team can work alongside OEMs to customize a solution to satisfy their needs. AKM motors can also be combined with Kollmorgen's AKD servo drives. The AKD series ensures plug-and-play commissioning for instant, seamless access to everything in the machine. No matter what the application demands, AKD offers industry-leading servo performance, communication options and power levels, all in a smaller footprint than competitive options.

For more information:

Kollmorgen
201 Rock Road
Radford, VA 24141
Phone: (540) 633-3545
www.kollmorgen.com

Mayr Brake

INCREASES SAFETY OF VERTICAL AXES

If there is a danger of falling loads on vertical axes in areas where personnel have to work, additional measures must be taken to minimize the risk of accidents. The brake specialist Mayr Power Transmission has developed brake systems capable of providing safety in any critical situation occurring during vertical axis operation. Vertically-moved masses, particularly when they are heavy parts such as motors or gearboxes, become a serious safety hazard if, on power failure, their movement is inadvertently accelerated or if they drop uncontrollably.

Mayr Power Transmission offers the ROBA-topstop, a modular construction brake type series with individual brakes and redundant dual-circuit brake modules for the prevention of any critical danger situations which can occur during vertical axis operation and which are defined in the DIN EN 954-1, Categories 1-3. The aspect of safety was not the only target criterion during development of the ROBA-topstop. The constructional conditions for drive elements in vertical axes were also considered carefully. Due to their adapted flange dimensions, ROBA-topstop brakes can be integrated problem-free into pre-existing constructions between the servomotor and the counter flange.

The modular assembly is flexible enough to allow many different designs, for example with a shaft; with a hollow shaft; with a flexible coupling; with an additional safety clutch for torque limiting or with two individual brakes. Using a ROBA-topstop brake system with a hollow shaft and an integrated, insertable shaft coupling means that the separate compensation coupling and the coupling housing usually necessary are no longer needed. A driveline with this brake system is only minimally longer than the usual axis with servomotor and shaft coupling for connection to a spindle or to a gearbox shaft. ROBA-topstop designs with shafts are principally conceived for installation between the servomotor and the hollow shaft gearbox.

For more information:

Mayr Corporation
4 North Street
Waldwick, NJ 07463
Phone: (201) 445-7210
www.mayrcorp.com

Balluff

ADDS I/O TO IO-LINK

As part of its expanding package of control connectivity solutions, Balluff has introduced a full line of I/O Hubs to their IO-Link device offering. Balluff understands that one size does not fit all, and different applications require different housing materials. For this reason, Balluff offers a large range of IO-Link I/O hubs, ranging from M8 to M12 with plastic or metal housing. When adding IO-Link I/O Hubs in an application, the hub usually replaces a standalone module that is connected directly to the bus network. Most of these standalone modules have a certain level of diagnostics that assist in fast troubleshooting and aid in reducing downtime. Balluff's line of IO-Link I/O Hubs are offered with or without

diagnostics, thus giving your application the same level of short circuit and overload diagnostics as the network connected standalone modules. The M8 Hubs range from four to eight ports, with three or four pole varieties. The M12 Hubs are all eight port with single or dual input versions, as well as a configurable model with output capabilities.

For more information:

Balluff Inc.
8125 Holton Drive
Florence, KY 41042
Phone: (859) 727-2200
www.balluff.com

AutomationDirect

EXTENDS INDUSTRIAL SENSORS SERIES

AutomationDirect has extended its offering of industrial sensors to include the PEW series of stainless steel DC proximity sensors. The shielded eight mm sensors are flush-mountable and feature a two mm sensing range. Available with either M8 or M12 quick disconnects, they are equipped with LED status indicators visible at wide angles, and have PNP outputs. PEW series inductive proximity sensors are priced at $45. Also added are the LF40 series rectangular inductive DC proximity sensors. Two shielded and two unshielded models are available with 20 mm or 35 mm sensing ranges. The rectangular plastic PNP sensors provide either normally-open or normally-open/normally-closed complementary outputs. LF40 series sensor prices start at $39.

For more information:

AutomationDirect
3505 Hutchison Road
Cumming, GA 30040
Phone: (770) 889-2858
www.automationdirect.com

Mico

INTRODUCES HYDRAULIC-OVER-AIR RELAY VALVES

Mico, Incorporated recently introduced its hydraulic-over-air relay valves. The valves are designed to convert hydraulic modulated input pressure to a proportional output air pressure. The new relay valves are suitable for various on- and off-highway applications, such as controlling an air-braked trailer with a hydraulically braked towing vehicle that has an air power source. The system originates with a hydraulic vehicle component, such as a master cylinder or hydraulic control valve, which delivers a given hydraulic input pressure. This input pressure sends a pilot signal to the relay valve in order to modulate air brake pressure on the other end. Mico offers three different hydraulic-over-air relay valve designs: single, dual and tandem. The single input design provides one hydraulic pilot port to control modulated air braking pressure. The dual input features two independent ports, either of which can accept pilot pressure; when pressure is applied to both ports simultaneously, the controlled air braking pressure ratio increases proportionally. The dual input ports can be set up for different pressure ratios, making the dual design a good fit for certain steering assist applications. Functionally similar to the single design, the tandem input provides redundancy by utilizing two independent pilot pressure ports. This enables hydraulic pilot pressure to be applied to either port while allowing the pressure ratio to remain the same. The new relay valves can accommodate a maximum air pressure of 150 PSI and maximum hydraulic pressure of 2,000 PSI. The valves can be adjusted to operate at anywhere from a 3:1 to 21:1 hydraulic-to-air-pressure ratio. Maximum operating temperature for the valves is 250 degrees Fahrenheit.

For more information:

Mico Incorporated
1911 Lee Boulevard
North Mankato, MN 56003
Phone: (507) 625-6426
www.mico.com

Marsh Bellofram

LAUNCHES SPM SERIES

The ATC Diversified Electronics division of Marsh Bellofram Corporation has recently launched the SPM series, a dual function alarm and relay, designed to monitor shaft seal and stator temperature of a submersible pump motor, providing early warning of machinery failure to reduce downtime and maintenance costs. The SPM series is designed to operate from a 120 VAC supply voltage, with reliable operation over 10 million continuous duty cycles. The series detects leaks by either resistive float switch or a pair of conductive probes installed in the seal cavity, while over-temperature is detected by a normally-closed low-temperature switch that is mounted on the stator, with LEDs that indicate green for "normal" and red for "leak" and "over temperature" condition values. The SPM series also incorporates the use of a bi-stable relay which can retain its position during power failures or energy surges. The relay automatically resets following leakage detection. Sensor voltage is 12 VDC at 50 to 60 Hz. Units are UL listed and include a 10-year comprehensive product warranty.

For more information:

Marsh Bellofram
8019 Ohio River Blvd.
Newell, WV 26050
Phone: (304) 387-1200
www.marshbellofram.com

Haydon Kerk Magnetic Encoder Technology

Haydon Kerk Motion Solutions Inc., a manufacturer of precision linear motion products, offers an integrated magnetic encoder available on the 1" 25000 Series linear actuators. The extremely compact and fully enclosed incremental encoder utilizes solid state technology and includes both analog detection circuitry and full signal processing from a single chip. When combined with the Haydon can stack linear actuator, suitable position feedback can be obtained for use in critical applications including medical equipment, analysis devices and robotics. The 64-line quadrature encoder system utilizes a high energy neodymium magnet and provides an eight-bit digital resolution resulting in a total of 256 output pulses per revolution. The encoder provides 90-degree phase shifted A/B output channels along with a single index pulse for every complete shaft rotation. The encoder circuitry samples angular position at 10,000 samples per second for an output update every 100 microseconds. The 256 pulse magnetic encoder is an adequate replacement for optical encoders and is virtually immune to vibration, shock, dust and contaminants. The encoder can be operated using either a 3.3 V or 5 V input voltage. When combined with the Haydon 25000 series linear actuator, a robust, compact linear motion package is created.

For more information:

Haydon Kerk Motion Solutions, Inc.
1500 Meriden Road
Waterbury, CT 06705
Phone: (203) 756-7441
www.haydonkerk.com

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Boston Gear Motors

PROVIDE LONG-LASTING PERFORMANCE

Boston Gear has recently launched a new line of stainless steel motors which are value engineered for washdown performance. Exterior construction consists of 300 Series stainless steel housing, end bells, output shaft and conduit box. Motors are UL/ULc certified and conform to 2007 EISA efficiency standards. All units feature Class F insulation, Class B rise at 1.15 service factor, and epoxy-encapsulated windings. Internally-locked bearings eliminate unwanted axial movement. Other features include double lip shaft seals, rubber gasket seal on conduit cover, O-rings between end bells and housing, and smooth exterior with no mounting feet.

Stainless steel 230/460VAC, three-phase, 60 Hz (50 Hz) motors are totally enclosed and are available in seven sizes ranging from .5 hp to 3 hp. Fan-cooled and non-ventilated models are offered. These stainless steel motors are designed to provide long-lasting performance in harsh washdown environments where high-pressure caustic solvents and cleaners are utilized to help meet FDA bacteria and food contamination guidelines. Motors are suitable for food processing and packaging applications including dairy, meat and poultry, bakery and snacks, fruits and vegetables and candy.

For a complete washdown power transmission kit solution, these new stainless steel motors can be easily mounted to Boston Gear 700 Series stainless steel speed reducers.

For more information:

Boston Gear
701 Carrier Drive
Charlotte, NC 28216
Phone: (704) 588-5610
www.bostongear.com

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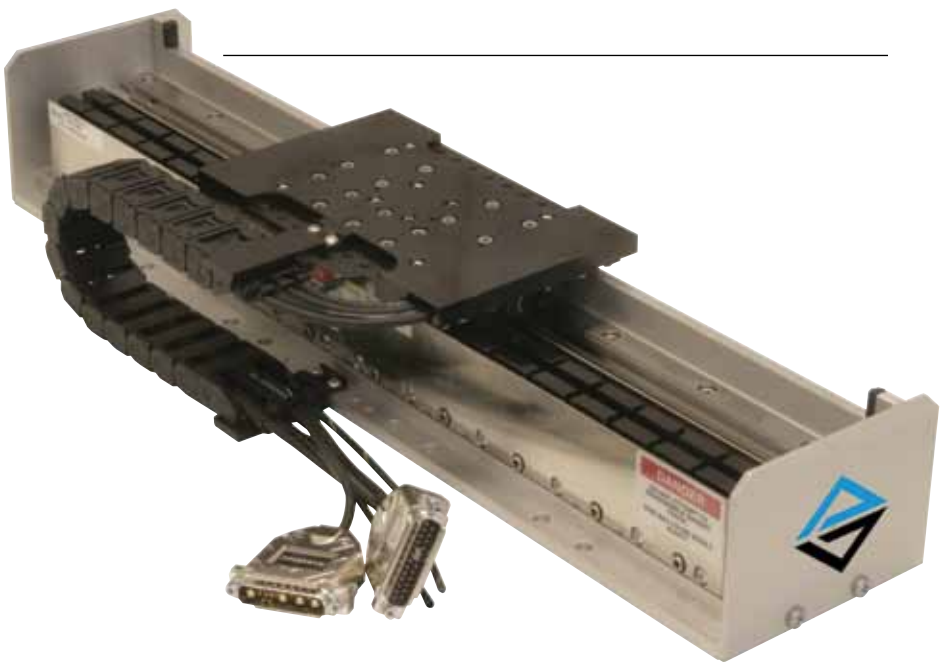

The ACT by Aerotech is a high performance, cost-effective linear-servomotor-driven actuator that is faster and more accurate than a ball screw or belt-drive without the costly, time-consuming maintenance ball screw or belt-drives typically require. Because the ACT is an integrated,

assembled mechanical system, it also eliminates the design complexity and guesswork in choosing and assembling individual components. It is suitable for applications including assembly, pick and place machines, electronic assembly and qualification, packaging, vision inspection, dispensing, life sciences, image scanning and processing and ink jet printing.

Aerotech's high-power, cog-free linear motors drive the ACT series to accelerations of 5 g and a top speed of 5 m/s, providing the solution to increase throughput. The stiff mechanical structure gives dynamic performance and reduces settling times, according to the company's press release. The non-magnetic forcer coil provides high force with zero cogging for smooth velocity and position control, and can be utilized for applications requiring outstanding contour accuracy and smooth velocity profiling. The linear motor has zero backlash, no windup, zero friction and outstanding system responsiveness, and the magnetic field is totally self-contained within the U-channel design.

Many high-performance applications cannot tolerate the stray magnetic fields generated by flat motor magnet tracks. Noncontact linear optical encoders with micron-level repeatabilities are standard on all ACT series actuators. Either a line-driver output or amplified sine-wave output encoder is available for maximum flexibility. Optional factory calibration further increases standard accuracy and repeatability.

Aerotech manufactures a wide range of matching drives and controls to provide a fully integrated and optimized motion solution. ACT actuators consist of noncontact linear motors and encoders, making them virtually maintenance-free. For applications requiring a complete solution, a cable management chain is provided. For OEM or applications requiring user-defined cable management, both cable pigtail and bulkhead termination options are available. Moveable limits allow easy adjustment of usable travel for varying applications.

For more information:

Aerotech, Inc.
101 Zeta Drive
Pittsburgh, PA 15238
Phone: (412) 963-7470
www.aerotech.com

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Motors Technology Update

Siemens

UNVEILS EXPANDED MOTOR RANGE AT HANNOVER FAIR

Redesigned 1FK7 Servo Motor Series. The Siemens Drive Technologies division has optimized the design of its 1FK7 servomotor series for standard motion control applications and extended its range of motors in the field of low-rated speeds. Mechanical decoupling of the encoders from the motor shaft increases both the ruggedness and serviceability of the motors, while improved integration of encoder interface electronics makes for a more compact motor design.

The servomotors are available in the basic "Compact" version, which offers the broadest range of sizes and versions. The "High Dynamic" version offers reduced rotor inertia, providing an efficient solution for tasks that involve maximum dynamics and low load inertia. The "High Inertia" design is designed for tasks that involve high load inertia.

High-efficiency Asynchronous Motors. Siemens now offers IEC motors across the efficiency classes IE2 and IE3, covering the application range of EU Regulation 640/2009 from 750 W to 375 kW. The motors are available in North America with EISA-certification in the energy efficiency and premium energy efficiency classes.

The minimum efficiency class IE2 will become mandatory in Europe after June 16 for all motors in the range of 0.75 to 375 kW. IE3 efficiency will be required beginning January 2015.

Siemens offers the new IEC motors in two different series: general purpose and severe duty. The general purpose motors come with aluminum housings and shaft heights between 80 and 160 mm and an output from 550 W to 22 kW. They are used mainly for pumps, fans and compressors. The severe duty version has a cast iron housing, making it suitable for conditions such as those found in the process industries. Severe duty motors are available from 2.2–375 kW, with shaft heights between 100 and 315 mm.

Extended Torque Motor Series. In addition to its previously available hollow-shaft motors, Siemens is now offering versions of the 1FW3 torque motor series with a plug-in shaft or a solid shaft. In addition, the rated speed range has been increased, which expands the torque motors' field of application to roller drives, cross cutters, winders and similar operations.

Previously the 1FW3 torque motors were available in hollow-shaft versions with axis heights of 150, 200 and 280 mm. The new plug-in shaft is available in the same configurations, while the

continued

solid shaft version is offered only for shaft heights of 150 and 200 mm.

The rated torque for all three versions remains 100–7,000 Nm, but the speed range has been increased. For example, at an axis height of 280 mm, the speed range has been increased from 250 to 600 rpm.

Asynchronous Motors With Cast Iron Housings. The 1LE1 series of asynchronous motors has been expanded to include a series of motors with cast iron housings for applications in the production and process industries.

The new severe duty series of 1LE1 motors are available in the power range from 2.2–200 kW, with shaft heights between 100 and 315 mm. They are

available in the European energy classes IE2 and IE3, as well as EISA-certified versions for the NAFTA market.

The series adopts the operating concept of the existing aluminum housing series, with terminal boxes divided at an angle, making the terminals easily accessible and reducing installation time. Specially designed versions are available for operation on frequency converters.

For more information:

Siemens Industry, Inc.
Drive Technologies - Motion Control
390 Kent Avenue
Elk Grove Village, IL 60007
Phone: (847) 640-1595
Fax: (847) 437-0784
www.siemens.com/motion control
www.siemens.com

ABB Motors

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ABB has been granted a license to use the IECEx Conformity Mark on qualified products and packaging and promotional materials related to those products. The mark shows that a product has been granted an IECEx Certificate of Conformity.

The IECEx Conformity Mark confirms that a product has the appropriate protection for use in explosive atmospheres, and that it has been manufactured under systems subject to ongoing surveillance by the certification body. It is recognized in all the countries participating in the IECEx system, and it means the product can be supplied to the market without the need for additional tests.

ABB has been granted IECEx certification for a wide range of low- and high-voltage motors. The hazardous area protection types provided by these motors include flameproof, non-sparking, pressurized and dust-tight protections.

For more information:

ABB Drives
16250 W. Glendale Drive
New Berlin, WI 53151
Phone: (262) 785-3200
Fax: (262) 785-0417
www.abb.com

Crouzet's Brushless DC Gearmotor

OFFERS
COMPACT SOLUTION
FOR VARIABLE SPEED
AND TORQUE CONTROL

Crouzet North America has introduced the 801 Series Brushless DC Gearmotor with integrated gearbox and electronics. The new all-in-one solution is designed to offer versatile control for

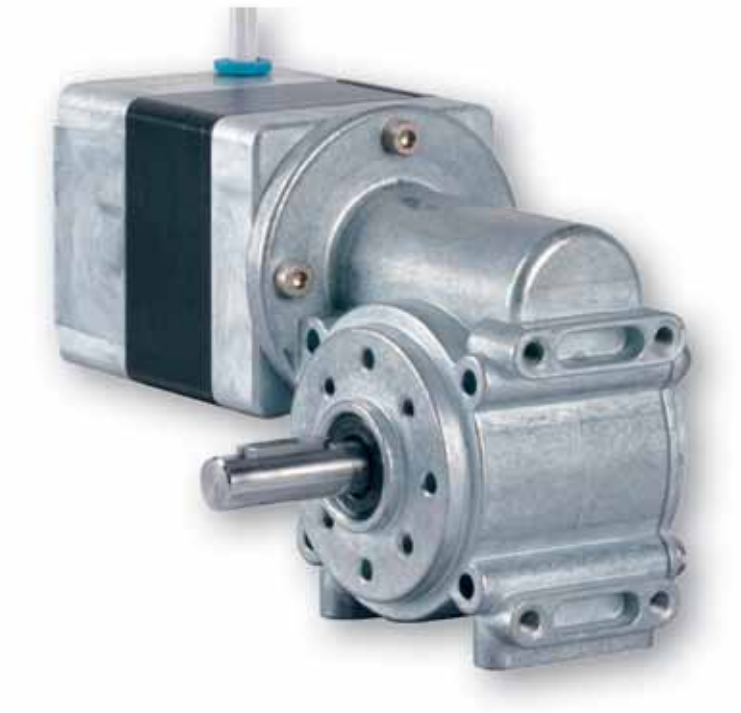
speed and torque in a compact, sealed package. With no brushes to wear out, it is well suited for medical equipment, lab automation and industrial applications where long product life and reliability are paramount.

"Typically, motors, gearboxes and controllers are purchased separately," says Jim McNamara, Crouzet application engineer. "With Crouzet's new integrated package, customers have a convenient way to purchase all three functions in one product from a single supplier."

With this product addition, Crouzet has increased its BLDC product line's power rating from 80 to 205 watts and torque range to 120 Nm, providing a significant expansion in capabilities. Other performance characteristics include speeds from 7 to 627 rpm for planetary models and 44 to 440 rpm for right-angle models. All 801 models include integrated electronics and standard IP54 sealing.

Compact in size, the new series measures 57 mm square. Sealed packaging allows for operation in harsh environments while the cast aluminum housing optimizes durability and robust operation. Crouzet's Custom Adaptation Center can modify any of the standard models to meet specific application requirements such as custom mounting options, higher IP seal ratings, or supplying without integrated controls.

The 801 Series is priced from $225.00 to $325.00 for the 40 watt, 10 Nm model, depending on volume. Delivery is eight weeks.



For more information:

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Phone: (760) 597-6322
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mcnamaj@us.crouzet.com
www.crouzet.com

Maxon's EC40

PACKS POWER INTO SMALL SPACE

The EC40 is a new brushless DC motor that fits 170 Watts of power into a package measuring 40 mm diameter and 80 mm length. The motor is designed for industrial, logistics equipment, mobile robotics, packaging machinery, power tools or aerospace applications.

The EC40 was designed with high-quality materials in mind, according to the company's press release. It features a neodymium permanent magnet, stainless steel housing and welded flanges.

The motor presents a flat speed/torque gradient of about 3.6 rpm/mNm, speed up to 18,000 rpm and efficiency of 89 percent. Its ironless winding offers quieter running and higher stall torque than other motors.

The EC40 can be combined with other components, such as encoders, gears, or Maxon's new AB 32 permanent-magnet brake, which is designed for operating temperatures from –40 degrees C to 100 degrees C.

A wide range of compatible controllers is available, from 1-quadrant and 4-quadrant servo amplifiers to programmable positioning controllers.

For more information:

Maxon Precision Motors Inc.
101 Waldron Road
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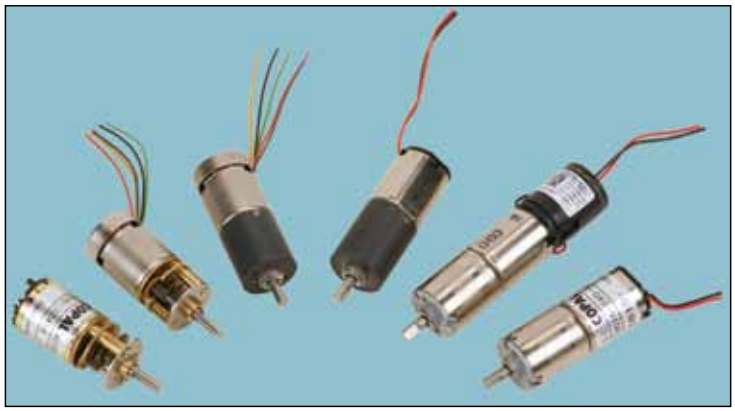
NIDEC-COPAL

INTRODUCES MINIATURE GEARMOTOR FAMILY



A new line of 16 mm miniature brush and brushless DC gearmotors and motors are designed for a wide range of office automation, medical devices and laboratory instrumentation. The motors are available with spur or planetary gearing, and planetary models are available with either metal or resin gears.

The Nidec-Copal 16 mm planetary resin models are designed for applications where lower noise is a requirement. Model HG16-XX-AA brush DC gearmotors are available in ratios of 30, 60, 120 or 240, with rated shaft speeds from 310 rpm down to 55 rpm, and torques ranging from 3.45 oz.-in. up to 6.94 oz.-in.

Models with planetary metal gearing are designed for applications requiring higher shock loads and torque. Ratios of 60, 120, 240, 300 and 500 are available. The brushless gearmotors models (LB16MG-XXX-CA and CB) and brush DC gearmotor model (MG16-XXX-AB) provide rated torques from 4.8–27.8 oz.-in. with rated shaft speeds from 164 rpm down to 21 rpm.

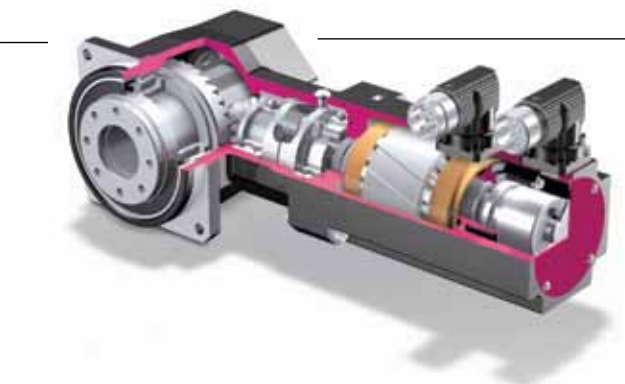
The Nidec-Copal spur 16 mm spur gear models are designed for applications with moderate loads where cost is a major concern. Gear ratios include 30, 60, 120 and 240 for the brushless HG16-XXX-AA and AB versions, while the brush LA16G-324XX gearmotors include ratios of 50 and 120.9. Rated torques for the spur gear models range from 3.47–6.94 oz.-in. Speeds vary from 230 down to 185 rpm for brush gearmotors, and 310 rpm down to 55 rpm for brushless.

For more information:

Nidec-Copal USA Corp.
373 Van Ness Ave., Suite 130
Torrance, CA 90501
Phone: (310) 782-6102
Fax: (310) 782-6821
info@nidec-copal.com
www.nidec-copal.com

STOBER KS SERVOMOTOR

RUNS EFFICIENTLY AT HIGH SPEEDS



The KS series of servomotors from Stober Drives Inc. are designed for low backlash and smooth running, while combining the gear unit and motor for a more compact unit.

The drives are designed to be suitable for all modern servo technology applications, especially those where high dynamic, continuous duty strength or high speeds are required, according to Adam Mellenkamp, product manager. The motors are available in three sizes, with torques up to 400 Nm, and three output shaft versions.

"High torques and speeds allow a higher number of cycles and therefore better machine performance," says Mellenkamp. "The synthesis of motor and gear unit eliminates the need for motor adapter and coupling, so the advantages are obvious—higher dynamics due to lower mass moments of inertia."

Removal of the motor adapter and coupling also mean that the size and weight can be reduced, resulting in higher power density in a smaller package.

The drives are designed for greater smoothness and efficiency than other models, due to their unique drive concept. The initial input at high drive speed is to a smooth-operating helical planetary stage. The output bevel stage revolves at much lower speeds than traditional solutions.

"The drive concept also provides the option of sealing on the smallest possible shaft diameter," Mellenkamp says. "With conventional bevel gears and hypoid gears, the input bevel pinion must be stable and supported due to the internal gearing forces. Sealing is over a relatively large diameter."

For more information:

Stober Drives Inc.
1781 Downing Drive
Maysville, KY 41056
Phone: (606) 759-3615
www.stober.com

MOTOR-MOUNTED VECTOR DRIVES

DESIGNED FOR DISTRIBUTED CONTROL

Nord's new SK200E line of motor-mounted vector drives is designed for distributed, decentralized control. This makes the SK200E more cost-effective than other solutions due to reduced wiring and panel costs, as well as more efficient space utilization. The SK200E is designed for applications such as conveyors and material handling systems.

The SK200E series is available in four model sizes, ranging from 0.33–10 hp (0.25–7.5 kW), 3-phase 230 V and 460 V, 1-phase 120 V and 230 V. The drives come standard with IP55 rating (NEMA 12), and IP66 (NEMA 4) versions are available for use in wet or washdown environments.

Full torque and accurate speed regulation can be achieved down to a 30:1 turndown ratio when operating in sensorless vector control mode, and 1,000:1 turndown in closed-loop vector control mode.

For more information:

Nord Drivesystems
800 Nord Drive
Waunakee, WI 53597
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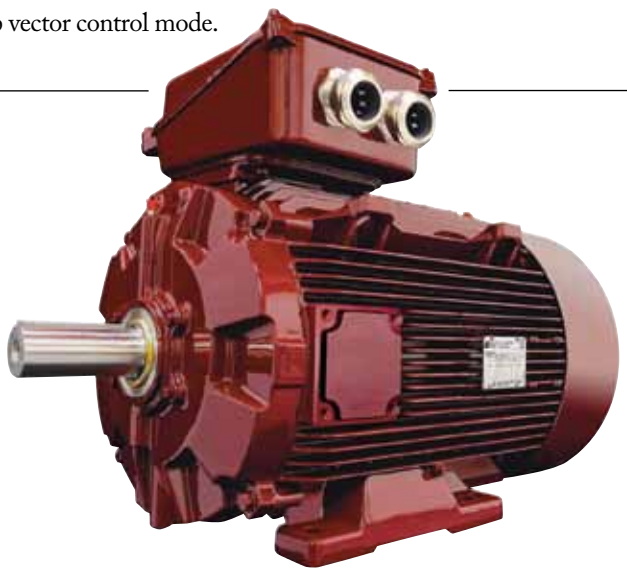


The Dyneo 3000 range of permanent-magnet synchronous geared motors from Leroy-Somer offer a possible torque gain of up to 30 percent within the same sized motor package. In addition, the Dyneo range has extended capacities up to 14,500 Nm and a variety of mounting options for fixed or variable speed operation in all types of applications and environments.

The Dyneo series features the LSRPM permanent magnet synchronous motor, which is designed for energy saving. According to company literature, the LSRPM can be combined with a variable speed drive to offer significantly greater efficiency than a class IE2 or IE3 asynchronous motor in all operating conditions (variable speed, fixed or variable load, constant or quadratic torque, constant power).

The gear technology, based on helical teeth, makes it possible to achieve mechanical efficiencies in excess of 95 percent. It also facilitates integration as close as possible to the transmission shaft, thus eliminating the need for any intermediate devices, such as pinion, chain or belt pulley.

Another advantage of these new drive solutions is a more compact geared motor. The size of the motor is roughly half that of conventional technologies, thus reducing overall weight by approximately 20 percent.

The Dyneo 3000 series is available in a variety of configurations. The Compabloc 3000 offers axial output in five sizes, with output torques from 210–3,150 Nm and power ratings from 4.8–80 kW. The Orthobloc 3000 helical-bevel series is available in eight sizes, with output torqes from 250–14,200 Nm and power ratings from 4.8–100 kW. The Manubloc 3000 with parallel output offers eight sizes, with output torques from 250–14,500 Nm and power ratings from 4.8–100 kW.

For more information:

Emerson Industrial Automation
8000 W. Florissant Ave.
P.O. Box 4100
St. Louis, MO 63136
Phone: (314) 553-2000
www.emersonindustrialautomation.com

Exploring All Motor Options

Matthew Jaster, Associate Editor

Siemens expanded line of 1FK7 servomotors allows for a 10 percent higher power output (courtesy of Siemens).

Harald Poesch

In 2010, Harald Poesch, product marketing manager, servomotors for Siemens Drive Technologies Division, published a technical paper on permanent-magnet, synchronous torque motors (*Ed's note: See* PTE August 2010 *for full article*). *PTE* recently caught up with Poesch to discuss the current and future state of the servomotor industry as well as some insight into the latest servomotor offerings from Siemens.

Briefly discuss the current state of the servomotor industry, specifically after emerging from the recent economic crisis? Our servomotor is coupled with the machine builder business. After the global economic crisis, this market is recovering well. Regions such as China were not as strongly affected as others. Europe, and especially Germany, is recovering very quickly. Looking forward, I see the servomotor business growing at a constant pace.

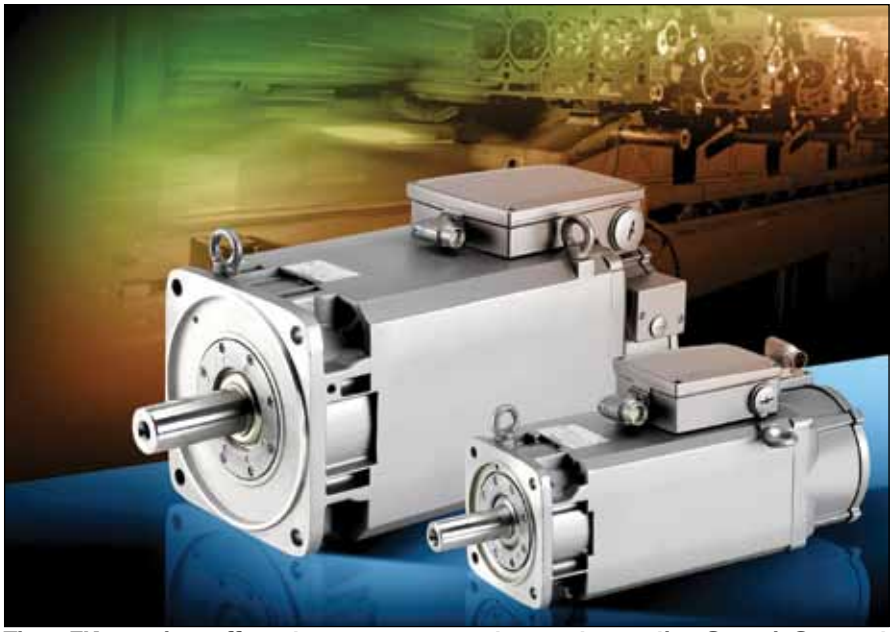
What industries will be the key to Siemens' continued success in motors—now and in the future? In addition to our presence in market segments like plastics, printing, machine tools, packaging, textiles, metalforming and others, we are active in cross segments such as converting, materials handling and safety-integrated drives. General motion control is also one of our focus segments. New markets such

as renewable energy or energy efficiency are part of our overall strategy—having already shown success in these areas. To be successful in the future means we have to be active in all different market segments. This means being the trusted partner in areas in which we are already active, along with developing new solutions in upcoming segments.

What are the most important factors in today's manufacturing environment that designers have to consider before selecting a motor? Besides the conventional approach—like motor type, speed, torque, accuracy and pricing, a machine builder, today, must consider additional aspects such as the machine's lifecycle—it's more important now than ever before. For example, energy savings and maintenance are two areas to consider. Highly efficient servomotors and maintenance-friendly motors with field-replaceable encoders, along with easy connection systems, are extremely important.

You wrote a technical article last year on the advantages of permanent magnet synchronous torque motors. Make a quick case for them once again. One reason to use a direct drive torque motor —when it comes to small windmills, a low-speed solution is necessary because the rotor is running at relatively low speeds. One solution for such windmills is using a reduction gearbox and a standard generator. By using a 1FW3 torque motor, the gearbox can be eliminated during the construction phase which gives you the advantage in the overall efficiency, product costs and maintenance costs. Another example using the advantage of the stiffness of a direct motor solution is a cast roll in film lines where very low speed ripple is required. By using a direct drive torque motor instead of a motor/gearbox combination, the overall ripple could be reduced.

Explain the significant differences (advantages/disadvantages) between a standard servomotor and a torque motor? The main difference between a standard servomotor and a torque motor is the amount of pole-pairs. A torque motor has a greater number of pole pairs and; therefore, runs at a lower speed. This is because power is comparable and the torque motors have a high output torque.



The 1FK7 series offers two new connector systems, the Speed Connect System and the Drive-CLiQ.

In a conventional solution, a gearbox is used to reduce the motor's speed and increase torque.

The advantages for using a direct drive solution include:

- Highest stiffness, no backlash—inertia-ratio up to 1:1,000 is possible
- Low torque ripple compared to the motor-gearbox combination
- Higher total efficiencies are possible
- The hollow shaft can be used for additional benefits such as cooling
- Cost advantages to a technically comparable motor-gearbox solution
- Very maintenance-friendly

Disadvantages include:

- Increased effort needed for the integration of a direct drive solution into the machine than using a motor/gearbox solution
- Mechatronics expertise is necessary, especially for built-in motors
- More expensive than a low-cost standard motor-standard gearbox combination

What is the key role that mechatronics now play in the direct drives market? Basic mechatronics knowledge is necessary when using direct drive technology. The reason being—it's no longer possible to separate the electrical part from the mechanical part of a machine. Direct drive motors are rigidly connected to the mechanical part of the machine. Additional considerations about the bearings, the machine and the motor are necessary. Increased expertise in mechatronics is needed when using built-in motors where the motor is deeply integrated in the machine—or in other words, the machine is actually the motor. In such cases, the machine builder kind of becomes a motor builder, so every bit of knowledge about encoder systems, bearings and cooling is required.

Siemens recently expanded its 1FK7 servomotor family. What are the main features/key capabilities of the new high-inertia style of servomotors? Siemens now has the second generation of the 1FK7 servomotor family, which is an innovation from the first generation. The advantages from the first-generation 1FK7 still exist and

continued

the mechanical connection is the same as before, which makes it easy to change over. The full range of the first generation 1FK7 servomotor is still available.

A major advantage for the second generation, however, is the mechanical and thermal decoupled encoder, which can easily be exchanged during maintenance without having to exchange the entire motor. Since the encoder is always the weakest part of a motor, it extends the motor's lifecycle. The encoder system is also decoupled from the shaft, which makes it more resistant to vibration. Another advantage of such a decoupled system is the thermal isolation of the encoder. It allows a 10 percent higher power output for some types of the 1FK7-series as compared with the first generation.

Other advantages include new encoder types with up to 24-bit resolution/turn, a Speed Connect system for the power connector and the Drive-CLiQ connector for the encoder itself. These two connector systems allow the quick and easy connection to the motor.

What does this motor line provide that a potential customer might not find from the competition? The 1FK7 servomotor is a very compact permanent-magnet servomotor. It is available for 230 V and 400 V, speeds up to 6,000 rpm, 0.08 up to 37 Nm torque and is available in three different variations—compact, high dynamic and high inertia. Together with the decoupled encoder, the speed connector for the power cable and the Drive-CLiQ encoder system with integrated electronic nameplate recognition for easy commissioning with our SINAMICS drive system make the 1FK7 an ideal motor for a variety of machines.

Describe the advantages from the customer's perspective on working with a company that offers an entire package of products and services for production machinery and machine tools? The biggest advantage is the system-tested interfaces. From the top level of an automation system, the process control systems to the control-

lers and HMIs—down to the drives and actuators, all of the interfaces are system-tested and defined—and they are still highly configurable. Our customers can also take advantage of our system-tested standard for a variety of applications. This will result in reduced development time, commissioning time, machine downtime and allows for easy maintenance.

What sort of emphasis does Siemens put on service and support for its motor products? Service and support is a very high priority in our company. In fact, Siemens can support its customers in every stage of a machine's lifecycle. From the planning and selection of components, to programming, commissioning and, of course, service. Customers have the entire Siemens global service network at their disposal. In fact, excellent service and support is not an option for Siemens, it is something that our customers can count on.

What has the response been like regarding Siemens' Sizer toolbox and 3-D CAD model-generating CAD-Creator package? Are there any other tools being implemented to assist customers with motor selection? The response has been phenomenal—especially for access to our CAD Creator. In the past, it was inconvenient for our customers to ask for the drawings. Today, everyone can easily access the database to get the 2-D-drawings or 3-D CAD model immediately. Sizer also has a great reputation in the marketplace. It makes it easy for customers to select the right products based upon simple specifications or even complicated mechanical constructions. It helps in the selection of the right motor, cables, drives, controllers and also the 24 V power supply. The output of Sizer is the entire project documentation with lists of order numbers, load curves, motor curves, motor data, wiring examples and even a sample cabinet. Instead of developing new tools for other tasks, we are extending the functionality of Sizer. For example, in the latest version, Siemens included an efficiency calculator. This calculator gives you an insight to all of the losses within the cabinet and at the motor for the selected operating point. This is a huge benefit to our customers optimizing their machines when it comes to the topic of energy efficiency.

What new or upcoming projects is Siemens working on or developing in the motor division? The motion control business of Siemens is working on completing its existing motor range. Two major projects are in development that we can talk about today: The 1PH8 motor series will be extended to shaft heights of 180 and 225. The 1PH8 is our newest main spindle motor. This motor type can be selected as servo or induction, water-cooled or forced-ventilated and can run up to 20,000 rpm for smaller shaft heights. The 1FW3 torque motor's series will be extended to a shafted version. The integration of a shafted torque motor in an existing machine design will be simplified with this design.

Where do you see the direction of the motors industry as a whole in the future? What will the emphasis be on regarding design and development? We can see several different trends, actually. One trend uses more-and-more direct drive technologies to increase the accuracy and the productivity in high-end production machines. We see this trend in different market segments all around the globe. Another trend is the development of electrical servomotors without permanent magnets. Because of the shortage of raw materials, the costs for high-density permanent magnets will increase in the future. Additionally, the demand for servomotors in hybrid vehicles and EV will rise. Several manufacturers are still using permanent magnets in their hybrid cars. Further investigations into servomotors without magnets or high-performance induction with similar characteristics as servomotors might be necessary.

(*See page 16 for Siemens contact info.*)

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Tuning a PID Controller

Guillermo J. Costa

Nomenclature

D_{out}	=	Derivative contribution parameter
$e\ (t)$	=	Error term with respect to time
I_{out}	=	Integral contribution parameter
K_d	=	Derivative gain
K_i	=	Integral gain
K_p	=	Proportional gain
K_u	=	Ultimate gain
L	=	Delay time, Ziegler-Nichols reaction curve method
P_{out}	=	Gain contribution parameter
T	=	Time constant, Ziegler-Nichols reaction curve method
T_u	=	Ultimate period
$V_m\ (t)$	=	Measured variable value with respect to time

Management Summary

This paper introduces the basic fundamentals of proportional-integral-derivative (PID) control theory, and provides a brief overview of control theory and the characteristics of each of the PID control loops. Because the reader is not expected to have a background in control theory, only the basic fundamentals are covered. Several methods for tuning a PID controller are given, along with some disadvantages and limitations of this type of control.

Introduction

The PID controller is a feedback mechanism widely used in a variety of applications. The controller calculates an "error" that is the difference between a measured process variable and the desired set-point value needed by the application. PID controllers will attempt to minimize the process error by continually adjusting the inputs. Although this is a powerful tool, the controllers must be correctly tuned if they are to be effective. Additionally, the limitations of a PID controller should be recognized in order to ensure that they are not used in applications that cannot make use of their unique advantages. This article covers the basics of PID controllers, as well as several methods for tuning them.

The most common question asked about the topic of PID controllers is, "Why learn to tune them?" The answer is simple. PID controllers are literally everywhere in industrial applications. For many applications, PID controllers are the optimum choice and will simply outperform almost any other control option. This is why they are currently used in over 95% of closed-loop processes worldwide (Ref. 1), governing everything from temperatures, flow rates, mixing rates, chemical compositions and pressures in a limitless number of applications. PID controllers can also be tuned by operators who do not possess a strong background in differential equations, electrical engineering or modern control theory; this grants PID controllers a very powerful ability to drastically

change a given process (called a "plant model") with a system that is very simple and robust.

Basics of Control Theory

A common example of a control system is a person adjusting the temperature of water coming from a faucet. This involves the mixing of two process streams—hot and cold water—which is followed by a person touching the water stream, measuring the process variable to gauge its temperature. Based upon this feedback, the person adjusts the amount of hot or cold water fed into the faucet until a desired temperature—the set-point value—is reached. However, this set-point value isn't reached immediately; there is usually an error value (*e*) between the measurement of the process variable and its set-point value. By measuring the process variable and calculating the error, the person will decide to change the positions of the hot and cold valves—the measured variables—by a certain amount until the water temperature resolves to its set-point value.

If the person only adjusts the position of the hot water valve, this is an example of proportional control. If the hot water does not arrive quickly enough, the person may open the hot water valve by an increasing amount as time goes by; this is an example of an integral control. By only using the proportional and integral methods (a PI controller), the water is likely to oscillate wildly between too hot and too cold because the valves are being adjusted too quickly and the process is overshooting the set-point. In order to dampen future oscillations, the person may wish to adjust the positions of the water valves more gradually, leading to a derivative control method.

This simple example is a wonderful demonstration of how a PID works. A PID controller involves three separate system parameters:

- ***Proportional (sometimes called the "gain")***: determines the reaction to the current error
- ***Integral:*** calculates the system reaction based on the sum of recent errors
- ***Derivative:*** calculates the rate at which the system error has been changing

The weighted sum of these three values is used to adjust a process by adjusting a control element, which could literally be nearly anything within the process. For instance, flow rates into or out of a mixing tank could be controlled through the position of a valve (as with the tap water example), or the output of a heating element could be controlled via its power supply. These three summed terms constitute the measured variable, i.e.—the aspect of the application that one is trying to manipulate:

$$V_m(t) = P_{out} + I_{out} + D_{out} \quad (1)$$

Where:

P_{out}, I_{out}, and D_{out} are the output contributions of each of the three PID parameters. These three outputs are given by their respective parameter loops, which are:

$$P_{out} = K_p e(t) \quad (2a)$$

$$I_{out} = K_i \int_0^t e(t)dt \quad (2b)$$

$$D_{out} = K_d \frac{d}{dt} e(t) \quad (2c)$$

Thus, the PID algorithm from Equation 1 can be rewritten in its final form as:

$$V_m(t) = K_p e(t) + K_i \int_0^t e(t)dt + Kd \frac{d}{dt} e(t) \quad (3)$$

As may be seen, there are quite a few options here for tuning the controller. Each of the characteristics of the three loops is discussed below.

Proportional (gain) loop. The purpose of the proportional gain is to create a change to the system's output that is directly proportional to the system's current error value. Stated another way, a gain can be thought of as an amplifier to the controller, as it only serves to multiply the current error value by a given gain value. A large gain value will yield a large change in a system's output for a given error, and thus gain can be used to amplify the speed with which a controller reacts to a certain state condition. However, if the gain is too large, the system can become unstable very quickly; conversely, if the gain value is too small, the controller will have a subsequently small response to an error value. This latter condition will result in a less-sensitive controller, which may not respond correctly to errors or disturbances.

In an ideal state—i.e., free of any disturbances—a purely proportional control system will not settle at the set-point value, but will retain a steady error that is a function of the proportional and process gain. However, despite the presence of the steady-state offset, it is common practice to design control systems wherein the greatest amount of control response is provided by the controller's proportional gain. An example of this steady-state error is shown in Figure 1.

Integral (reset) loop. The value contributed from the integral loop is proportional to both the magnitude and duration of the error. Summing the recent error values over time (integrating the error) gives the offset value that should have been previously corrected. This accumulated-error value is then multiplied by the integral gain (which defines the magnitude of the contribution of the integral loop) and added to the

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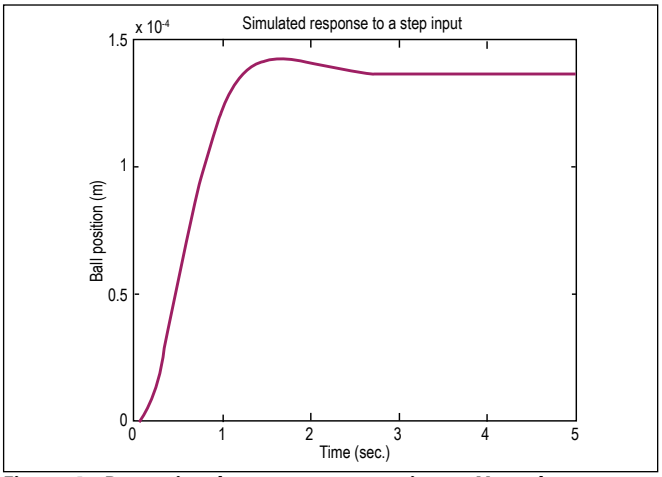

Figure 1—Proportional response to step input. Note the presence of a steady-state error value. (Image copyright Carnegie Mellon University)

controller output. When added to the proportional term, the integral loop accelerates the response of the process towards the set-point value and eliminates the residual steady-state error of a proportional-only controller. The integral loop is only responding to the summation of recent errors, however, which will cause the response to overshoot the set-point value and thus create an error in the opposite direction. Left alone, this PI controller may eventually settle on the set-point value over time, but there are many applications—such as stability control systems in aircraft—where rapidly settling upon the set-point value without oscillation is both desirable and necessary. Figure 2 shows the effects of adding an integral loop to a proportional controller. Note how changing the value of the integral gain affects the response of the system. Although a PI controller will not resolve to a steady-state error (as a proportional-only will), the amount of overshoot is directly related to the value of the integral gain. Notice in Figure 2 that the highest value of integral gain gave the fastest response to the step input (as evidenced by the steep slope of $K_i = 2$, relative to the other values), but also required the most amount of oscillations and the longest amount of time to resolve to the set-point value. By contrast, the red line of $K_i = 0.5$ has the slowest response time of the three options, but notice that it resolves to the set-point value with no noticeable overshoot.

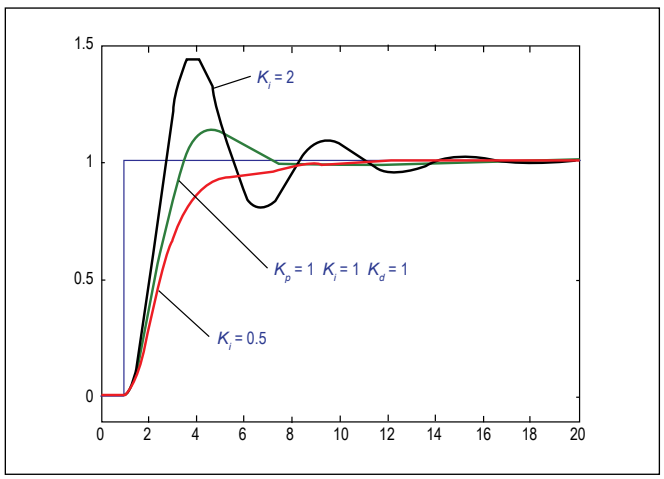

Figure 2—Controller response to step input with proportional and derivative values held constant. (Image copyright Wikipedia)

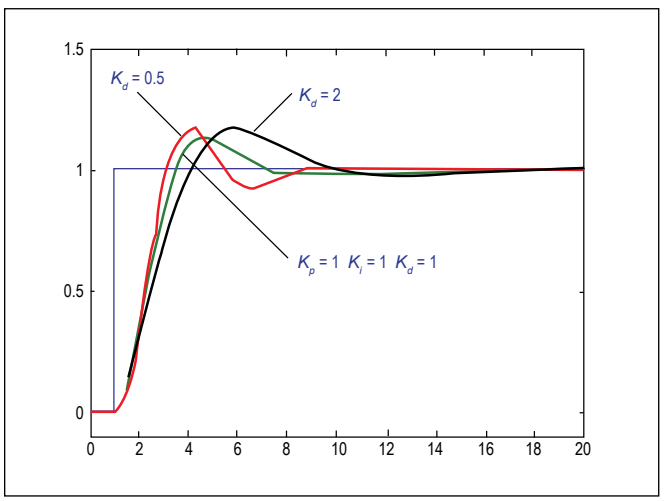

Figure 3— Controller response to step input with proportional and integral values held constant. (Image copyright Wikipedia)

Which response is "best" for a given application will of course depend on the application in question, but it is common practice to limit the number of response oscillations while still maintaining an acceptable response time. This is also done via the derivative gain, as discussed below.

Derivative (rate) loop. With a PI control, the system is able to settle to its set-point value through the use of a steady-state proportional response and the summation of past errors. But how fast have those previous errors been changing with respect to time? In Figure 2, the rate at which the errors change is relatively constant—especially with K_i equal to 2. To increase response time and minimize errors, a term is needed to calculate the rate at which the error term is changing. This is done through a derivative loop, sometimes called a "rate loop."

The derivative loop calculates the rate at which the error is changing by calculating the slope of the error. In essence, this is done by calculating the change in error (rise) over time (run)—the first derivative of the error function. This value is multiplied by a derivative gain K_d to obtain the derivative contribution to the system. As with the proportional and integral loops, the derivative gain can have a great impact on the system's response (Fig. 3). The derivative loop controls the rate at which the controller's response overshoots a given input value—produced by the proportional and integral loops—and is most noticeable when the process variable is close to the set-point. However, derivative loops amplify noise and are thus very sensitive to noise in the error term. For this reason, it is best to use attenuation filters with derivative loops, lest the presence of noise combined with a high value of derivative gain drive the system to instability. Note in Figure 3 that the behavior of the derivative term relative to its gain is the direct opposite of the integral term's response to an identical gain value.

Loop Tuning

Tuning a PID controller involves the control of four variables:

- ***Rise time***: the amount of time necessary for the system's initial output to rise past 90% of its desired value
- ***Overshoot***: the amount by which the initial response exceeds the set-point value
- ***Resolving time***: the amount of time required by the system to converge to the set-point value.
- ***Steady-state error***: the measured difference between the system output and the set-point value

The goal of a PID controller is to take an input value and maintain it at a given set-point over time. But if the values for the three loops of a PID controller are chosen incorrectly, the system will become unstable through any one of a number of failure modes. Typically, these involve an output that diverges—with or without oscillation—and is limited by the physical characteristics of the control mechanisms, including actuators breaking, sensors and encoders burning out, etc. The process of tuning a controller involves adjusting its control parameters—proportional band, integral gain and

Table 1—Three Typical Methods for Tuning a PID Controller.		
Method	**Advantages**	**Disadvantages**
Manual	No math required; online options available	Requires experience in controll tuning
Ziegler-Nichols	Proven method; online options available	Some process upsetting involved; can be a very aggressive tuning method
Software	Consistent tuning options available; multiple valve and sensor inputs can be simulated and tested before applying to application	Acquisition costs of software (such as *MATLAB*) can be prohibitive for some organizations; software training required

Table 2—Effects of PID Tuning on System.					
Variable Change	**Rise Time**	**Overshoot**	**Resolving Time**	**Steady-State Error Change**	**System Stability**
Increase K_p	Decrease	Increase	Small Decrease	Decrease	Decrease
Increase K_i	Small Decrease	Increase	Increase	Large Increase	Decrease
Increase K_d	Small Decrease	Decrease	Decrease	Minor effect	Increase for small values of K_d
Decrease K_p	Increase	Decrease	Small Increase	Increase	Increase
Decrease K_i	Small Decrease	Decrease	Decrease	Large Decrease	Increase

derivative gain—in response to a given input until the desired response is attained. This desired response is almost entirely application-driven. For instance, a controller must not allow any overshoot or oscillation if such things would create a hazardous condition within the application (and would yield response graphs similar to the red line in Figure 2). Other applications are inherently non-linear, rendering parameters that are ideal at full-load and maximum-RPM conditions undesirable when starting from zero-load conditions.

There are, generally speaking, three main methods of tuning a PID controller (Table 1).

The most important aspect to remember about control tuning is that it is a bit of an art form, requiring training and practice. Some knowledge of control theory is required—which is why it was introduced earlier in this paper's Basics of Control Theory section—as well as a systems-level understanding of the process in question. For instance, a large change in response to a small error results in a high-gain controller and leads to overshoot. Combining this with the oscillations introduced by an integral loop would result in the system oscillating about the set-point—rather than reaching it—with the system responding as a decaying, constant or increasing sinusoid. These determine the stability of the system, i.e.—stable, marginally stable or unstable, respectively. Initially, this concept may be difficult to grasp, although we humans "tune" our own control processes automatically. Recalling the tap water example, the person is able to learn from past actions, and so does not have to "oscillate" around the desired temperature of the water because a human being is a form of adaptive controller. A simple PID controller, however, does not have this ability to learn from process history and thus must be tuned correctly.

Before deciding on a tuning strategy, it is essential to understand how changing the gain, integral and derivative loops will affect the system as a whole. Table 2 shows the effects (Ref. 2) that tuning these loops independently have on the behavior of the system.

It should be noted that the philosophy of increasing derivative gain to increase system stability is a common belief, but real-world applications may behave in a fashion contrary to this assumption if there is a transport delay present (Ref. 3). This may lead some users to exclude the derivative term entirely from their control system, thus denying themselves a powerful tool in the design of their control system.

Manual tuning. Manual tuning is best used when a system must remain online during the tuning process. The four-step process is as follows:

- Set K_i and K_d to zero
- Increase K_p until the loop output begins to oscillate
- Reduce K_p to one-half of this value to obtain a quarter-wave decay
- Increase K_i to adjust the behavior of the offset so that the system will resolve in an acceptable amount of time (how much resolving time is acceptable will be governed by the process in question)

Note that increasing the integral gain by too great an amount will cause system instability (Table 2). The derivative gain should then be adjusted until the system resolves to its set-point value with acceptable alacrity after experiencing

continued

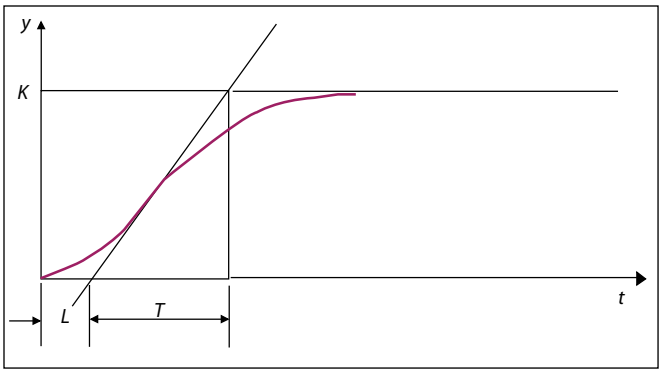

Figure 4—Reaction curve used for Ziegler-Nichols tuning. (Image

Table 3—Ziegler-Nichols Turning Values.

Control Type	K_p	K_i	K_d
P	$0.5\ K_u$	-	-
PI	$0.45\ K_u$	$\frac{1.2K_p}{T_u}$	-
PID	$0.6\ K_u$	$\frac{2K_p}{T_u}$	$\frac{K_p T_u}{8}$

Table 4—Ziegler-Nichols Turning Values: Reaction Curve Method.

Controller Type	K_p	K_i	K_d
P	$\frac{T}{L}$	-	-
PI	$0.9\ \frac{T}{L}$	$0.27\ \frac{T}{L^2}$	-
PID	$1.2\ \frac{T}{L}$	$0.6\ \frac{T}{L^2}$	$0.6T$

a load disturbance. This is simulated with a step doublet or "stick rap"—a step input from 0 to one, followed by a step input from one to 0—or with the sinusoidal or ramp input equivalents. Note that a fast PID loop will usually require a slight overshoot to resolve to the set-point more quickly. But if the system cannot accept an overshoot, an over-damped system will be required. In these instances the K_p value will be less than half of the value causing oscillation.

Ziegler-Nichols tuning. The Ziegler-Nichols tuning method is a very powerful way to resolve a system to its set-point value while circumventing a great deal of the mathematical calculations required to find an initial estimation of the PID values. This is especially useful when the system is unknown or when creating state matrices for the system is impractical or impossible. As with manual tuning, with Ziegler-Nichols tuning the integral and derivative gain values are first set to zero. The proportional gain is then increased from zero until the system reaches an oscillatory state, as above. This proportional gain value should be marked K_u, or ultimate gain. The system's oscillatory period at this gain value should also be marked T_u, or ultimate period. These two ultimate values are then used to set the proportional, integral and derivative gain values (Table 3; Ref. 4).

There are, however, limitations to Ziegler-Nichols tuning. It will permit some fluctuation in the controller response as long as each successive oscillation peak is no more than one-fourth the amplitude of the previous peak (Ref. 5)—or, the so-called, "quarter-wave decay." Applications requiring less fluctuation or a faster resolving time will require further tuning.

A second Ziegler-Nichols tuning method is used for plant models with step responses resembling an S-shaped curve (or "reaction curve"), with no overshoot. This is ideally suited for processes that cannot tolerate overshoot or oscillations. A typical reaction curve is shown in Figure 4. The delay time L and constant time T are found by drawing a tangent line to the reaction curve through its inflection point $\left(\frac{d^2y}{dx^2} = 0\right)$ and finding the intersection points with the time axis and the set-point line. Once these intercepts are determined, the values from Table 3 are recalculated (Table 4; Ref. 6).

The parameters in Table 4 will give a system response with an overshoot of approximately 25%, and the system will resolve to the set-point value within polynomial time (Ref. 7).

Software tuning. As it has with most other aspects of life, technology has rendered a great many number of control tuning methods irrelevant. A very large number of modern facilities forego tuning their controllers using the manual calculation methods mentioned previously. Rather, tuning and optimization software are used to ensure that optimum results are obtained in short order. Of course, for some systems—such as those with response times measured in minutes or hours—mathematical tuning is still recommended, as tuning by pure trial-and-error can literally take hours or days. *MATLAB* and *SimuLink* are the most common tools used to design and tune control systems, and they have found widespread use in a variety of industries. Other software packages such as *PIDeasy*, *AdvaControl Tuner*, *IMCTune* and others can often produce optimal responses from either online or offline inputs, and are plug-and-play ready—often with no need of subsequent controller refinements. Many of the features of PID tuning software are also designed directly into the hardware of the controller, most often from the "Big Four" of control vendors—ABB, Honeywell, Foxboro and Yokogawa. Because of the number of variables involved in software tuning, it is recommended that it be done on a case-by-case basis.

Limitations of PID Control

Although a PID controller provides an optimum solution to many processes, it is not a panacea for all control problems that may be encountered. This is especially true for processes with ramp-style changes in set-point values or slow disturbances (Ref. 8). PID controllers can also perform poorly when the gain values must be greatly reduced in order to prevent a constant oscillation—or "hunting"—about the set-point value. Furthermore, PID controllers are linear and so care must be taken when using them with inherently nonlinear systems—i.e., systems that do not satisfy the superposition principle or systems with an output that is not proportional to its input, such as air handling and mixing applications.

For nonlinear systems, gain scheduling—where utilizing a family of linear controllers that are independently activated based upon the values of scheduling variables determines the

current operating region of the system—is most often used. Which scheduling variables are used will depend on the system in question. For example, a flight control system on an aircraft might use altitude and true airspeed as its scheduling variables, whereas an air handling application might use mass flow rate and impeller RPM. Nonlinear systems might be controllable with linear control systems if enough data and a sufficiently high sampling rate are known. Oftentimes, however, the use of gain scheduling may be more cost-effective.

Feed-forward control is found in a number of applications, including perceptron (*Ed.'s note: a binary classifier that maps its input x—a real-valued vector—to an output value f (x)—a single binary value—across the matrix) and long distance telephony (L-carrier transmission system of the 1970s*). Feed-forward control can also be used to improve the performance of a PID controller if certain qualities about the system are known beforehand and can be fed forward into the PID controller. This feed-forward value can greatly impact the performance of the controller; best of all, because feed-forward input is not affected by the feedback of the system, the feed-forward value can never cause the control system to oscillate, thus improving controller response and overall system stability.

Because the derivative loop is susceptible to process noise, it is also important to employ low-pass filters, if needed. However, the use of low-pass filters with derivative control can result in one filter negating the effect of another. For this reason, proper instrumentation or the use of a median filter may be a better option for improving both filter efficiency and overall performance of the controller (Ref. 9). Additionally, the differential loop can be turned off completely—$K_d = 0$—thereby using the PID controller as a PI controller. Note that this may require retuning the proportional and integral loops by utilizing one of the methods discussed in the previous Loop Tuning section.

Conclusion

PID controllers are a widespread control solution due to their simple architecture, generally acceptable control performance and ease of use. Unlike other control options, PID controllers do not require the user to have an extensive background in mathematics, control theory or electrical engineering to understand them. They are found in a wide variety of applications, and if properly tuned will outperform almost any other control option. It is in tuning the controllers that the greatest gains in performance may be found. A wide variety of tuning methods exist, although of the three discussed in this article, the Ziegler-Nichols method provides the most effective "quick- and-dirty" approach to tuning a controller. Software tuning has several advantages over the Ziegler-Nichols method, including the ability to run multiple iterations of tuning variables through process simulations to ensure optimum performance before the control logic of the process is updated. However, this type of tuning requires knowledge of the system's state properties and extensive knowledge of the software in use, with the latter necessitating acquisition and training costs that the organization might not be able to justify. In contrast, the Ziegler-Nichols method requires very little training or specialized knowledge beyond basic algebra, and offers results that are acceptable for the majority of applications. The Ziegler-Nichols method is also advantageous to use when the state properties of the system are unknown or in situations when the determination of these state properties is impossible or impractical.

As mentioned, the Ziegler-Nichols method is not without its disadvantages. Systems that require a very fast rise time and/or zero overshoot require a response other than quarter-wave decay, and as such cannot be tuned with the Ziegler-Nichols methods. Ultimately, it is imperative that the user have a clear understanding of the requirements of the system, and to select the appropriate tuning method as it applies to their own, unique needs.

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Development of the Upgraded DC Brush Gearmotor

FOR SPACEBUS PLATFORMS

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(Proceedings of the 40th Aerospace Mechanisms Symposium, NASA Kennedy Space Center, May 12-14, 2010; NASA/CP-2010-216272)

Management Summary

The obsolescence of materials and processes used in the manufacture of traditional DC brush gearmotors has necessitated the development of an upgraded DC brush gearmotor (UBGM). The current traditional DC brush gearmotor (BGM) design was evaluated using the Six-Sigma process to identify potential design and production process improvements. The development effort resulted in a qualified UBGM design that improved manufacturability and reduced production costs. Using Six-Sigma processes and incorporating lessons learned during the development process also improved motor performance for the UBGM, making it a more viable option for future use as a deployment mechanism in space flight applications.

Introduction

DC brush gearmotors have been used for several years in various spaceflight applications because of their many favorable design features. They are extremely efficient at converting electrical energy into mechanical energy, using only simple control electronics. Existing, qualified DC brush gearmotors for space flight applications, however, use some obsolete materials and processes in their design and construc-

Figure 1—Existing brush gearmotor (BGM).

tion. The intent of this presentation is to review the existing BGM design, using the Six-Sigma process to identify potential design improvements and to select replacements for the obsolete materials and processes. This paper documents the development and qualification of a UBGM for use as a solar array deployment mechanism on the Spacebus satellite platform that maximizes motor performance, lowers overall drag and optimizes manufacturability.

The BGM has to operate in hostile environmental conditions during test and flight. The proper selection of materials is critical. Factors that must be considered include:

- Operate in ambient air, up to 55% relative humidity
- Survive random vibration (32.3 G rms)
- Survive in vacuum (1.0 x 10^{-5} torr)
- Operate in vacuum (1.0 x 10^{-5} torr) from –50° C to +80° C
- Survive in vacuum (1.0 x 10^{-5} torr) from –50° C to +125° C

Background

The qualified BGM (Fig. 1) consisted of a DC brush motor and a multi-stage planetary geartrain. The design used brush material that has since been discontinued and other obsolete materials and employed non-forgiving process-driven steps that resulted in high manufacturing costs. The redesign addresses materials and processes, manufacturing changes and test tooling improvements that are necessary for future successful production of the new, upgraded DC brush gearmotors.

Purpose of redesign:

- Enhanced producibility
- Improved functional performance characteristics
- Reduced delivery schedules
- Increased robustness

Development

The existing BGM design was analyzed and a 3-D CAD model was created in Unigraphics. Prior failures and manufacturing problems were reviewed for areas of improvement. A Six-Sigma product assurance process was conducted. Trade studies were performed on major assemblies and a detailed tolerance analysis was completed to identify potential interferences.

A Six-Sigma process improvement team was established. Process walkthroughs were completed on six assemblies and three piece parts from the existing manufacturing and build cycles. Personnel were interviewed and fabrication, assembly and test processes of the existing BGM units were observed. Forty eight items were identified for improvement. Trade studies were initiated on all sub-assemblies and major components. Design and manufacturing process changes were completed to address all identified issues. The following major areas of potential improvement were identified:

Process improvements:

- Commutator soldering and inspection

continued

- Armature paint integrity
- Armature insulation

Performance improvements:

- Optimized motor speed and motor torque
- Predictable gearhead drag

A gearhead trade study was completed to develop a consistently producible design with predictable gear drag over the required temperature range. Review of the existing gearhead design and a detailed tolerance analysis showed: a potential interference at cold temperatures; high drag in the first- and second-stage bushings; a material combination prone to galling (same gear material used on mating gear teeth); and a high sensitivity to gear center distance shift. The following trade study criteria were selected for gearhead design improvement:

- Provide similar gear ratio
- Non-binding operation at extreme temperatures
- Manageable internal loss
- Robust design
- Non-galling material combinations

Three different gearhead concepts were selected for design and testing:

1. Completely redesigned gearhead
2. Harmonic drive gearhead
3. Modified existing gearhead using radial ball bearings

Engineering models of each concept were fabricated and tested. The redesigned gearhead (concept 1) had higher and inconsistent drag over the required temperature range; the harmonic drive gearhead (concept 2) exhibited significantly higher drag at ambient temperatures, so no further testing was required; the modified gearhead using radial ball bearings (concept 3) was ultimately selected, based on its low and consistent drag over the required temperature range. Table 1 lists gearhead drag of engineering models over the required temperature range. The modified gearhead does not exhibit interference over the required temperature range, has reduced drag in the first and second stages, has no galling material combinations and uses a one-piece ring gear to minimize sensitivity to gear center distance shift.

A new brush material was identified and selected at the conclusion of the motor trade study. A detailed review of

Table 1—Gear Head Drag

		Gear Drag @ 450 RPM (N-cm)			Gear Drag @ 450 RPM (in-oz)		
	Description	-50°C	+23°C	+80°C	-50°C	+23°C	+80°C
SN042	Existing Design Drive	0.22	0.06	0.07	0.31	0.09	0.10
Option #1	Redesign Drive	1.78	0.60	0.44	2.52	0.85	0.63
Option #2	Harmonic Drive		3.53			5.00	
Option #3	Radial Bearing Drive	0.16	0.01	0.02	0.23	0.02	0.03

Table 2—Brush Performance

	Motor Torque	Brush							Commulator
Brush Material	SN0042 N-cm (in-oz)	Wear in Atmosphere	Wear In Vacuum	Drag N-cm (in-oz)	Debris	Smearing	Resistance (Ω)	Yield	Wear
1	1.77 (2.50)	Good	Good	0.29 (0.41)	Moderate	None	0.13	Good	Excellent
2	1.20 (1.70)	N/A	N/A	0.23 (0.33)	N/A	N/A	0.21	Good	N/A
3	0.85 (1.20)	N/A	N/A	0.25 (0.35)	N/A	N/A	0.20	Good	N/A
4	1.77 (2.50)	Good	Poor	0.41 (0.58)	Moderate	None	0.16	Excellent	Excellent
Existing	1.77 (2.50)	Excellent	Excellent	0.46 (0.65)	Light	Light	0.56	Good	Good

Table 3—Motor Performance

Motor Torque (N-cm / in-oz)					
Unit	Brush Material #1	Brush Material #2	Brush Material #3	Brush Material #4	Existing
SN 0042	1.8 (2.5)	1.2 (1.7)	0.85 (1.2)	1.8 (2.5)	1.6 (2.2)
EM 0001	2.4 (3.4)	N/A	N/A	2.3 (3.3)	1.9 (2.7)

Figure 2—Upgraded brush gearmotor (UBGM).

the existing motor design revealed inefficient processes, high brush drag and use of discontinued brush material.

The brush assembly consists of a carbon-composite brush, shunt wire, cap and spring. Eight different brush materials were considered and four were selected for testing. All brushes were tested for motor performance, resistance, drag, spring force, brush wear, commutator wear, smearing, debris and manufacturing yield. Brush material options 2 and 3 were eliminated due to low motor torque. Brush material option 1 was selected due to poor performance of option 4 in a vacuum. Table 2 lists development brush performance. The selected brush material is softer than the existing brush material, resulting in higher motor torque, lower brush drag and less commutator wear.

The motor trade study considered all assemblies and machined parts. The producibility of the existing motor is poor, due to the need for frequent rework resulting in high production costs. Stack fabrication, coating and attachment methodology were upgraded to current Moog procedures. All uncontrollable and unnecessary processes were replaced or eliminated. For instance, existing BGM commutators are machined after final armature assembly, putting the completed armature at risk. UBGM commutator processing was moved to the piece part level to lower the risk to hardware. The soldering process was updated to the current standard. Table 3 shows increased motor torque with new brush materials, design and manufacturing changes.

The overall development of the upgraded brush gearmotor was successful. All issues discovered during the Six-Sigma process were addressed. After development was completed, a qualification unit (Fig. 2) was fabricated to specification, using production processes and tooling. The unit was subjected to qualification testing that included vibration, thermal-vacuum exposure and life tests. The qualification unit successfully passed all qualification and life tests with no findings.

Lessons Learned

While the upgraded brush motor development and qualification were successful, the methodology in some areas needs improvement. The following documents the major lessons learned during development and qualification:

Understand derived requirements. A firm understanding of the requirements (actual and derived) is needed prior to development. At the onset of the development process, the gearhead bushings were identified as a cause of BGM performance problems. A total redesign of the gearhead was started, with heritage design practices, processes and software utilized in the new gearhead. Gear design parameters were optimized to allow for greater allowable tolerances and used compatible material combinations to reduce galling and thermal expansion issues. Optimization of the gearhead for producibility adversely affected performance, however.

Since the BGM motor torque output is relatively low, it

continued

Table 4—Brush Wear

				
New Brush	A1	A2	B1	B2
Percent Reduction	~14%	~14%	~14%	~17%

Table 5—UBGM vs BGM Performance Comparison

		UBGM						BGM					
		-50°C		+23°C		+80°C		-50°C		+23°C		+80°C	
Test Description	Units	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn
Drag torque only (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.15 (0.21)		0.06 (0.09)		0.04 (0.05)		0.15 (0.21)		0.06 (0.09)		0.04 (0.05)	
Drag torque tooling only (torque to start)	N-cm (in-oz)	0.18 (0.25)		0.06 (0.08)		0.05 (0.07)		0.18 (0.25)		0.06 (0.08)		0.05 (0.07)	
Drag torque gearbox (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.31 (0.44)		0.08 (0.11)		0.06 (0.08)		0.37 (0.52)		0.13 (0.18)		0.11 (0.05)	
Drag torque gearbox (torque to start)	N-cm (in-oz)	0.18 (0.26)		0.06 (0.08)		0.04 (0.06)		0.18 (0.26)		0.07 (0.10)		0.06 (0.08)	
Tool drag removed													
Drag torque gearbox (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.16 (0.23)		0.01 (0.02)		0.02 (0.03)		0.22 (0.31)		0.06 (0.09)		0.07 (0.10)	
Drag torque gearbox (torque to start)	N-cm (in-oz)	0.01 (0.02)		0.00 (0.00)		0.00 (0.00)		0.01 (0.02)		0.01 (0.02)		0.07 (0.01)	

		UBGM						BGM					
		-50°C		+23°C		+80°C		-50°C		+23°C		+80°C	
Test Description	Units	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn	Max	Mn
Drag torque motor (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.99 (1.40)		0.99 (1.40)		0.99 (1.40)		0.85 (1.20)		0.81 (1.15)		0.78 (1.10)	
Drag torque gearbox (dynamic torque @ 450 RPM)	N-cm (in-oz)	0.16 (0.23)		0.01 (0.02)		0.02 (0.03)		0.22 (0.31)		0.06 (0.09)		0.07 (0.10)	
Drag torque motor (torque to start)	N-cm (in-oz)	1.31 (1.85)		1.31 (1.85)		1.31 (1.85)		2.8 (4.0)		2.8 (4.0)		2.8 (4.0)	
Drag torque gearbox (torque to start)	N-cm (in-oz)	0.01 (0.2)		0.00 (0.00)		0.00 (0.00)		0.01 (0.02)		0.01 (0.02)		0.007 (0.01)	
No load speed (motor with 6.0V)	rpm	588	571	549	505	572	563	440	405	480	455	515	470
No load speed (motor with 6.0V)	amps	0.081	0.080	0.077	0.072	0.065	0.062	0.100	0.095	0.098	0.095	0.078	0.075
Time to rotate 90 degrees (motor and gearbox with 6.6V)	sec	78.5	75.5	82	76.75	78.75	74.25	68.00	65.00			74.00	72.00
No load speed (motor and gearbox with 6.6V)	rpm	0.19	0.20	0.18	0.20	0.19	0.20	0.01	0.231			0.203	0.208
No load speed (motor and gearbox with 6.6V)	amps	0.101	0.099	0.093	0.084	0.084	0.078	0.01	0.070			0.086	0.083
Stall torque (motor with 6.0)	N-cm (in-oz)	3.2 (4.5)	3.2 (4.5)	2.4 (3.4)	2.4 (3.3)	2.0 (2.9)	1.9 (2.7)	2.1 (3.0)	1.6 (2.2)	1.2 (1.7)	0.76 (1.1)	1.1 (1.6)	0.78 (1.1)
Stall torque (motor and gearbox with 6.6V)	N-cm (in-oz)	48.0 47.5	47.5 (420)	50.6 (488)	49.5 (438)	48.0 (425)	47.5 (420)	36.2 (320)	33.9 (300)	29.0 (257)	28.8 (255)	33.1 (293)	29.9 (265)

Tested at 6.0 V

is sensitive to drag torque. Valuable time was spent on developing a new gearhead that had a gear drag greater than the motor could produce. If the BGM gear drag data had been available, it would have been realized that there was little chance to design a new gearhead with significantly lower drag.

Understand test capabilities. At the start of development it was determined we would test all gearheads before they were integrated into the BGM. It was assumed we would use our standard test setup, tooling and test equipment. But during initial gear drag testing it was discovered that minor misalignment caused major shifts in the drag torque measurement. Thermal expansion of the tooling was enough to double or triple drag torque measurements. In response, a standardized process was developed to consistently adjust the alignment before each test.

Verify performance at every environment. During testing it was observed that brush drag and wear were different in vacuum than at ambient pressure. The leading brush material was eliminated after vacuum testing. Almost no wear was observed during ambient and initial vacuum testing, but during extended vacuum testing the brush was completely worn away.

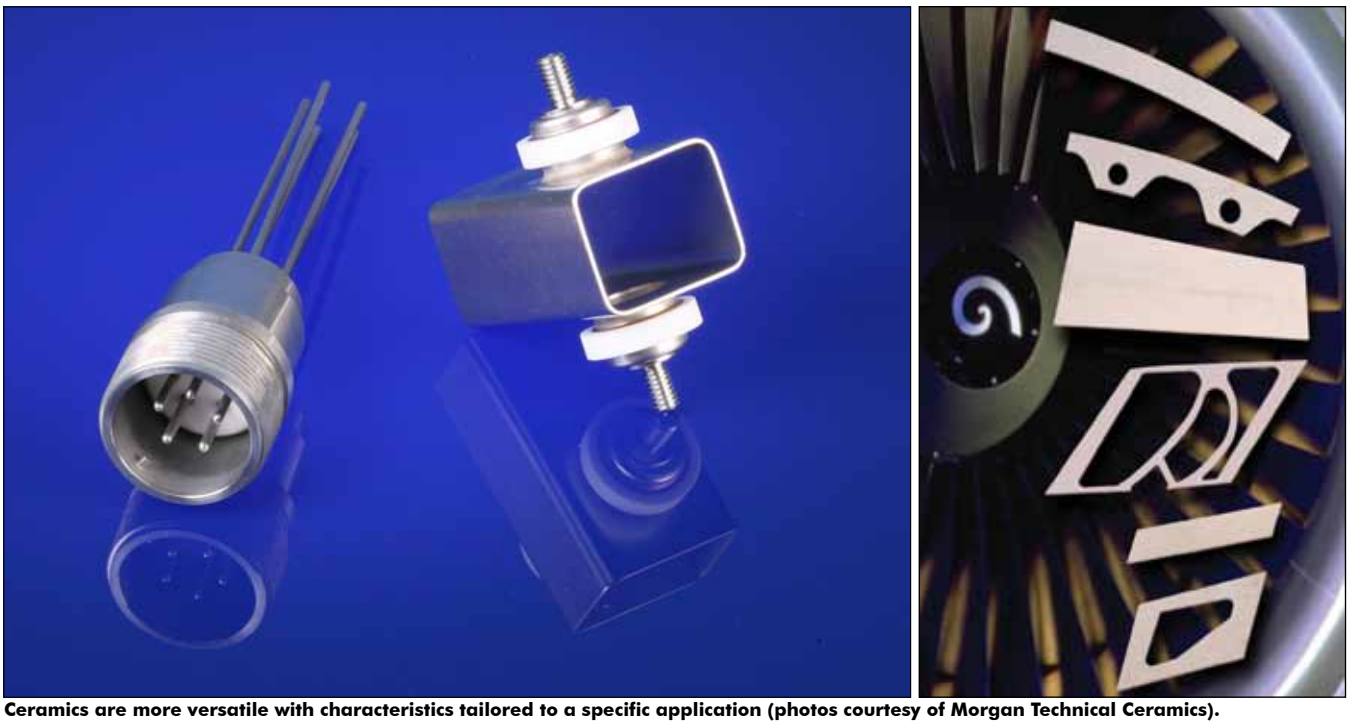
Work with suppliers to understand procured part requirements. One brush manufacturer's brush shunt wire broke significantly more than the others. The brush shunt attachment had to be redesigned to address yield issues. The initial design used an eyelet to keep the solder from wicking down the shunt wire (their internal requirement). The eyelet damaged the wire strands, causing them to fail. The eyelet was removed and replaced with a braided shunt wire. The redesigned brushes were installed into the engineering model for functional and vibration testing. The redesigned brushes successfully completed testing without any broken shunt wires.

The issues involved with the "lessons learned" were not catastrophic, but each one of them could have had serious consequences. The upgraded brush gearmotor was successful because these issues were identified and addressed soon enough to enable meeting program schedule dates.

After development was completed, a qualification unit was fabricated to per production specification using production processes and tooling. The unit was subjected to qualification testing that included vibration, thermal vacuum exposures and life tests. The qualification unit successfully passed all qualification and life tests with no findings. After qualification and life testing, the unit was disassembled and cleaned. All parts were inspected and showed minimal wear and no signs of damage.

The new brush material meets all design requirements, and brush wear was consistent with wear observed during engineering testing. An estimated loss of 17% of usable brush material was observed.

Successful qualification was a direct result of the trade study development. The Six-Sigma process and trade study identified the driving requirements. DC brush gearmotor performance was improved, resulting in an approximately 11 N-m (100 in-lb) torque increase at the output. The upgraded gearhead assembly is a robust design with lower drag, non-binding operation at all temperatures and non-galling material combinations. The risk of damage to hardware during assembly was lowered due to design simplification. The new qualified DC brush gearmotor is a robust design capable of handling all environmental conditions with consistent, predictable performance.



Ceramics are more versatile with characteristics tailored to a specific application (photos courtesy of Morgan Technical Ceramics).

The Expanding Role of Advanced Ceramics in the Aerospace Industry

Keith Parker, Marketing Director, Morgan Technical Ceramics

Aerospace manufacturers face extreme pressure to lower costs while increasing performance and satisfying stringent safety standards. Producers in the commercial airline, defense and space exploration sectors continually seek new materials that are reliable, robust and meet the needs of highly specialized applications. Advanced ceramics, such as alumina, silicon nitride and aluminum nitride, are currently being used to manufacture critical aerospace components because they have several advantageous physical properties. These inorganic, non-metallic materials retain dimensional stability through a range of high temperatures and exhibit very high mechanical strength. They also demonstrate excellent chemical resistance and stiffness-to-weight ratio, thereby providing manufacturers with the ability to design components that offer optimal performance in their intended application.

With the growing use of advanced ceramics in the manufacture of aerospace components, Morgan Technical Ceramics is playing a key role in this industry. Morgan Technical Ceramics, comprised of Morgan Advanced Ceramics and Morgan Electro Ceramics, is a manufacturer of innovative products made from a range of ceramic, glass, precious metal, piezoelectric and dielectric materials.

Instrumentation and Control Systems

Developments in material science, as well as recently introduced manufacturing techniques, have led to the development of advanced ceramics that serve critical functions in aircraft instrumentation and control systems, missile guidance systems, satellite positioning equipment, ignition systems, fire detection and suppression, instrument displays and engine monitoring equipment. Electro ceramic materials (piezo-electric and dielectric) are used in aerospace transducers and sensors such as accelerometers (for measurement of vibration), gyroscopes (for measurement of the acceleration and pitch of aircraft, missiles and satellites) and level sensors (e.g., fuel tanks). The term "piezo-electric" refers to the effect of mechanical pressure causing a crystalline structure to produce a voltage proportional to the pressure. Conversely, when an electric field is applied, the structure changes shape, producing dimensional changes in the material. Engineered piezo-electric polycrystalline ceramics offer several advantages over natural piezo-electric crystals, such as quartz, Rochelle salt and tourmaline. Ceramics are more versatile with physical, chemical and piezo-electric

characteristics that can be precisely tailored to specific applications.

One of the most successful commercial aircrafts in recent times, the Boeing 777, uses piezo-ceramic material within the 60 ultrasonic fuel tank probes located on each aircraft. The ultrasonic transducers are installed at a variety of locations in each fuel tank. A pulsed electric field is applied to the piezo-ceramic material, which then responds by oscillating. The resulting sound waves are reflected off the surface of the fuel and picked up by the piezo-electric ceramic transducer. A digital signal processor interprets the 'time of flight' measurement of the sound waves in order to continually indicate the amount of fuel present. Similar ultrasonic fuel probes are also used in fighter aircraft and other level-sensing applications because of their ability to provide highly accurate readings, regardless of the orientation of the aircraft.

Seals and Thermocouples

Advanced ceramics are also suited for aerospace applications that provide a physical interface between different components, due to their ability to withstand the high temperatures, vibration and mechanical shock typically found in aircraft engines and other high-stress locations. Ceramics are commonly found in seals for gas turbine engines, fuel line assembly and thermocouples. Where ceramic/metal assemblies are required, joining the two materials generally involves metallizing the ceramic surface and then brazing the components together.

Aero Engine Component Repair

Research into the development of advanced brazing materials for aero engine component repair has also led to the development of brazing materials suitable for the repair of gas turbine engine components. One example is the use of pre-sintered preforms (PSPs) for high-temperature braze repair applications. With turbine temperatures reaching up to 1,300 degrees C (2,350 degrees F) and the presence of hot corrosive gases, components experience considerable erosion and wear.

The pre-sintered preforms consist of a blend of superalloy and low melting point braze, and are customized to fit the shape of the component and then to be tack-welded into place and brazed. The ability to provide a range of near net thicknesses can eliminate the need for most post-braze machining and extend the life of engine components by up to 300 percent, making it a more reliable and cost effective method than traditional welding, which requires post-braze machining or grinding.

Ion Propulsion

Advanced ceramics are playing a critical role in the development of highly-efficient and cost-effective new technologies for space travel. Morgan Technical Ceramics' division in Erlangen, Germany has been working with a European space development program for a number of years to support its research of ion propulsion systems. A lightweight alternative to traditional chemical propulsion, ion engines have the potential to push spacecraft up to ten times faster with the same fuel consumption, thereby significantly decreasing vehicle size and increasing travel distance.

Ion propulsion technology, which uses electricity to charge heavy gas atoms that accelerate from the spacecraft at high velocity and push it forwards, traditionally incorporated quartz discharge vessels. Quartz has now been replaced by alumina because of the need for a material with the same dielectric properties but with higher structural stability. Alumina is easier to fabricate and offers good thermal shock resistance, ensuring that the chamber can withstand the extremes of temperature that occur during plasma ignition. It is also lighter, which reduces the costs associated with each launch.

Driven by the aerospace industry's demand for higher performance and lower costs, material scientists and ceramics component manufacturers will continue to develop new materials and processes that take advantage of the powerful physical, thermal and electrical properties of advanced ceramic materials.

For more information:

Morgan Technical Ceramics
26 Madison Road
Fairfield, NJ 07004
Phone: (800) 433-0638
www.morgantechnicalceramics.com

Pre-sintered preforms (PSPs) are suitable for high-temp braze repair applications.

IFPE Focuses on Return to Growth

OPTIMISTIC TRADE SHOW HINTS AT U.S. MANUFACTURING UPTURN

While the neighborhoods outside of Las Vegas depict the unsettling realities of the struggling U.S. housing market, the construction materials, fluid power, power transmission and motion control industries converged downtown to examine the latest equipment and product technologies—and the general mood was one of optimism.

CONEXPO-CON/AGG and IFPE 2011 attracted nearly 120,000 attendees, down from the 144,000+ at the record-setting 2008 edition, but nevertheless exciting given the current state of the construction industry. Exhibitors cited the high quality of customers and reported strong purchases and sales leads from March 23–26 in Las Vegas.

"The construction industry has been through some very tough times, with record unemployment, since the last show in March 2008. With these positive numbers and the industry support of the shows, we're optimistic about the future and looking forward to seeing these new sales orders fulfilled," said Megan Tanel, AEM vice president of exhibition and events.

IFPE alone featured exhibit pavilions from AGMA and the PTDA as well as an international presence with pavilions from China, Italy and Taiwan. While the floor traffic wasn't as massive as the crowds outdoors, the south hall stayed busy throughout the duration of the show.

"I was very impressed with the number of people walking around IFPE," said Bob Lennon, vice president of sales and marketing at Centa Corporation. "We received a good number of highly qualified visitors to our booth and have several projects already moving forward—one already placed the PO yesterday. All things considered, a good week in Vegas."

Melissa Magestro, IFPE show director, stated, "IFPE-related markets have fared somewhat better than construction and there definitely was a lot of positive momentum and interaction on the show floor. At both shows, attendees told us this was the place they needed to be to check out what's new and get up to speed on the latest industry trends."

Larger exhibitors like Bosch Rexroth and Parker Hannifin saw a significant amount of foot traffic throughout the duration of the exhibition as the companies focused on short presentations and brief product tutorials with engineers. Rexroth emphasized its BlueHydraulics line while Parker demonstrated its Hydraulic Start/Stop system.

The 52nd National Conference on Fluid Power featured 114 presentations and the Innovations Theater offered 14 sessions developed from abstract submissions for the conference. For the 2011 edition of IFPE, leading industry and university researchers gave keynote presentations, and college-level courses were offered.

While enthusiasm for the market was up, overall attendance levels were down 12 percent compared to 2008. International attendees, however, rose to 24 percent, up from 19 percent in 2008.

"The increased global participation by attendees and exhibitors underscores the importance of world markets to our industry," Tanel said. "The U.S. economy is slowly improving and we have a ways to go, especially in construction, but after 18 to 24 months there is more pent-up demand for equipment to be ready for the upturn."

And the exhibitors are ready as well. Many that *PTE* spoke with during the trade show felt that the bearing, coupling and gear drive markets were gaining significant momentum in early 2011 with sales figures that resemble those found just before the economic recession.

The next edition of the CONEXPO-CON/AGG and IFPE expositions will be held in 2014 from March 18–22 at the Las Vegas Convention Center. For more information, visit *www.ifpe.com*. Here's hoping there's even better news to report by 2014.

calendar

April 29–May 3—BSA 2011 Annual Convention. Austin, Texas. Celebrating 45 years of industry leadership, the Bearing Specialist Association (BSA) 2011 Annual Convention will feature a variety of speakers and presentations, including "Growing with People" by Connie Podesta, "Growing with Energy/ Sustainability Opportunities," by Dr. Michael Webber and "Growing with Motivation" by Andy Andrews. Carl James, CEO of BDI Group, will give an update on the bearing industry from the distributor perspective while L. Jeffrey Manzagol, president of Kaydon Bearings Division, will update the bearing industry from the perspective of the American Bearings Manufacturers Association (ABMA). The schedule also includes conference table sessions, one-on-one meetings and informal networking opportunities. For more information, visit *www.bsaconventions.org*.

May 3–6—Control 2011. Stuttgart, Germany. 20,369 expert visitors from all over the world—which corresponds to 8 percent growth in comparison with 2009—gathered information at Control 2010 regarding all quality assurance-relevant technologies, products and subsystems, as well as complete hardware and software solutions. In 2011, Control is celebrating its 25th anniversary with events like "Contactless Measuring Technology" promoted by the Fraunhofer Vision Alliance, an Event Forum offered by the Fraunhofer IPA, a theme park for "Quality Assurance in Medical Engineering" and other focal points with regard to new developments and technologies. For more information, visit *www.control-messe.com/en/control*.

May 6–8—Gears, Motors and Controls Expo. Bombay Exhibition Centre, Mumbai, India. GMC 2011 is a showcase of gears, motors, controls and allied products scheduled to be organized from May 6–8, 2011. The 3rd edition of the event builds on the success of the earlier editions held in Chennai & Mumbai. It will be held in conjunction with Pumps, Valves & Compressors Expo 2011. The three-day event will be promoted extensively across India and the region, and visitors will comprise key decision makers from nearly every industry segment. With customer satisfaction at the heart of the trade show's strategy, GMC 2011 hopes to build on previous efforts and deliver maximum rewards to the participants. Bonfiglioli and Elecon are industry partners for the 2011 event.

May 22–25—Windpower Conference and Exhibition. Anaheim, California. Organized by the American Wind Energy Association (AWEA), Windpower brings together thought leaders, industry experts and investors to capture the energy of the expanding wind market. AWEA uses revenues generated from the trade show to support the interests of the wind industry through business strategies that deliver results through policy promotion, renewable energy legislation and advocacy and grassroots campaigns. This year's attractions and events include an outdoor equipment and demonstration area, a wind-themed, custom-built motorcycle on display from Perewitz Cycle Fabrication, a special guest celebrity and more than 50 wind-related educational sessions. For more information, visit *www.windpowerexpo.org*.

June 6–8—Sensors Expo and Conference. Rosemont, Illinois. The Sensors Expo is the North American industry event exclusively focused on sensors and sensor integrated systems. Providing more than 25 years of technical innovation and thought leadership, the trade show is dedicated to exploring the most up-to-date innovations in sensor technology, including MEMS, energy harvesting, wireless sensor data and networks, measurement and detection and more. Sensors Expo identifies industry trends, explores them in an information-packed conference program and reflects those trends throughout the exhibit floor with new product announcements and a showcase of hundreds of products and services. Co-located with the Embedded Systems Conference, an event for the global electronics industry, Sensors Expo allows exhibitors to reach more than 4,000 engineering professionals from around the world. For more information, visit *www.sensorsexpo.com*.

June 23–25—9th Shenzhen China International Small Motor Exhibition and Electric Machinery Exhibition. Shenzhen Convention and Exhibition Centre. The ninth installment of this trade show features forums, general assemblies, product conferences and technology seminars taking place in eight exhibition halls. Co-located events include the International Magnetic Materials and Equipment Exhibition; the International Magnet Wired Insulating Materials Exhibition; International Electronic Equipment, Components, Photonics and Laser Exhibition; and the 17th China International Power Supply Exhibition. Exhibits cover a broad scope including motor technology, test equipment, manufacturing apparatus, parts and auxiliary products, motor control systems and devices, servo systems, digital control devices, frequency converters, switch devices and more. For additional information, visit *www.motor-expo.cn/en/dj.asp*.

June 21–24—Expo Pack Mexico 2011. CentroBanamex, Mexico City. Expo Pack will showcase the latest solutions in packaging and processing machinery, materials, containers and other related goods and services. It offers direct access to the packaging and processing industries in Latin America, attracting buyers from throughout the region including professionals from the food, beverage, pharmaceutical, personal care, graphic arts, medical, chemical and automotive industries. Expo Pack Verde, returning for a second year, will display sustainable packaging technologies and the new Procesa pavilion will feature the latest developments in processing machinery and technology. The new Containers and Materials pavilion will include innovations that increase visual impact, enhance convenience and maximize shelf life. For more information, visit *www.expopack.com.mx*.

WEG

WINS MOTOR CONTRACT IN SAUDI ARABIA

WEG Germany has won a major contract from Outotec for a total of 21 MV motors, including slip ring types up to 5,200 kW, 24 WEG transformers, six liquid rheostat starters and project management to install and commission the package. The equipment is being installed and commissioned in the world's largest sulfuric acid (SA) production facility, currently under construction at Ras Az Zawr, a mining and industrial city in the kingdom of Saudia Arabia.

Ras Az Zawr is an industrial city/zone on the Arabian/Persian Gulf coast in a region that is one of the richest natural and mineral resources areas in the world. One of the key activities within the Ras Az Zawr zone is processing of phosphates for use in fertilizers. This involves phosphate concentrate being processed in a fertilizer production facility, consisting of a phosphoric acid plant, a sulfuric acid production facility, an ammonia plant, a DAP granulation plant and co-generation and desalination plants.

Outotec was successful in winning the contact for the SA segment of the project, the largest production facility of its type in one phase in the world. The total investment in the production facility, which includes three SA plants, is approximately $240 million. When complete, the three plants will have a total production capacity of 13,500 tons of sulfuric acid per day. Due to the remoteness of Ras Az Zawr, and the possibilities for issues with multiple suppliers should problems occur, Outotec insisted on single suppliers for each element of the project.

"We didn't have a previous track record with Outotec in Germany, but we had already done business with the company—successfully—in Brazil and Australia, although there was no specific reference to this type of plant," commented WEG general manager energy business, Andreas Schulte Mesum. "However, our project management single contact, allied with the single supplier argument, was definitely the key to our winning the bid."

The project started in 2006, and is only today nearing completion. The MGWs and HGF type motors are used in the boiler feed water and circulation pumps of the sulfuric acid plant. The higher power (5,200 kW) MAW units are slip ring motors that drive the main blowers in the plant. WEG decided to use slip ring motors controlled by liquid rheostat starters for this application, as the blower inertia was large and starting current was an issue. The benefit of starting the main blowers in this way is that the customer can easily control the starting current of the blowers, at the same time handling the very high torques involved.

In addition to the motors and starters, a total of 24 WEG transformers are used to supply and condition electricity to all types of equipment across the whole SA plant, including the WEG MV motors. In common with the MV motors the WEG transformers are designed for use in some of the most demanding operating conditions worldwide in hydroelectric plants, desalination systems, oil and gas installations, mining, marine and many more. As evidence of this, WEG recently manufactured and supplied 200-ton transformers—the largest step-up power transformers ever made by the company—for the world's largest hydroelectric plant, Itaipu Binacional, on the Brazil/Paraguay border.

In terms of project support, WEG was active during the project management stage at Ras Az Zawr, managing three different suppliers, and also coordinated with Outotec to ensure that several technical modifications required by the main contractor were acted on promptly and with the required level of customer support. Now that the project is in its start-up phase, WEG is, once again, heavily involved, its coordination expertise and technical support being much in demand.

"Once again in a major global flagship project, WEG has demonstrated its ability to provide a package of key products and the project expertise to integrate them at the highest level," Mesum says. "As a result of this, and other similar successes, no one can deny our credentials as a premier global supplier of integrated supply, control and automation solutions to key commodity markets across the world."

PTDA Market Forecast

FREE TO MEMBERS

Alan Beaulieu

The Power Transmission Distributors Association (PTDA) added a forecasting tool to the list of benefits it provides to greatly enhance the competitive advantage of its members. In response to member demand for market trend information, PTDA is working with Alan Beaulieu, president of the Institute for Trend Research, to provide 400 distributors and manufacturers of power transmission/motion control products with the new PTDA Market Forecast at no additional cost. To be issued quarterly, the PTDA Market Forecast combines three targeted economic forecasts into one comprehensive report including macroeconomic analysis for the United States and Canada, forecasts for 10 of the most important North American customer markets served by PTDA members and a webinar facilitated by Beaulieu to help members use the market trend data in their business planning.

"This new member benefit is putting relevant and timely data in our members' hands, so they can anticipate the performance of their most critical customer markets," said David Mayer, PTDA's president in 2011 and vice president of marketing for Kaman Industrial Technologies Corporation. "Access to this information is generally out of reach for the average PTDA member. By leveraging its resources, PTDA is able to provide all members, regardless of their budgets, with tools they can apply to make a tangible difference in their operations."

Hydraulic Institute

ANNOUNCES 2011 BOARD OF DIRECTORS AND OFFICERS

The Hydraulic Institute (HI), the largest association of pump manufacturers and suppliers to the pump industry in North America, recently announced its 2011 board of directors and officers during its 94th Annual Meeting held in Scottsdale, Arizona. The new board will be primarily responsible for providing organizational oversight to the institute and guiding the direction of its strategic plan. Ken Napolitano, president, ITT- residential and commercial water, is the newly elected chairman of the board. Napolitano served as 2010 president of HI and received the prestigious "President's Award" at the gala in recognition for his efforts and leadership in that capacity. Dean Douglas, president, Dover Pump Solutions Group, will assume the HI presidency. Douglas previously served HI as vice president, member services in 2010, and was recognized for this service and received HI's highly respected "Vice President's Award." The new board also includes three vice presidents: Dave McKinstry, vice president, IMO Colfax, was re-elected as vice president of technical affairs; Dave Roland, president, Pentair Water - Engineered Flow GBU, vice president, member services; and Mike Medaska, vice president, ARO Fluid Products, new vice president, knowledge and education.

Additional board members include:

- Rich Heppe, president, Nidec Motor Corporation
- Chad Tuttle, COO Americas, CLYDEUNION
- Dave Brockway, president, Intelliquip, Inc.
- Tom Conroy, vice president and general manager, Chempump-A Division of Teikoku USA Inc.
- Bob Hendricks, vice president, Flowserve
- Suellen Torregrosa, vice president and general manager, Hamilton/Sundstrand
- Dennis Wierzbicki, general manager, Grundfos, USA

Past presidents of the Hydraulic Institute, Al Huber, president, Paterson Pump Company, John Miersma, vice president, CFO and COO, Iwaki America, Inc. and Dennis Ziegler, president and CEO, GIW Industries, Inc., will continue active participation in the organization as ex-officio members of board.

AST Bearings

NAMED JOHN DEERE PARTNER-LEVEL SUPPLIER

Pictured left to right Dan Fox, Dale Kaminski, Steve Vandervinne and Mark Davis.

AST Bearings, an international supplier of bearing products and services, has earned recognition as a Partner-Level Supplier for 2010 and was also inducted into the Supplier Hall of Fame in the John Deere Achieving Excellence Program. The Partner-Level status is Deere & Company's highest supplier rating and was awarded to AST Bearings for outstanding supplier performance. The prestigious Hall of Fame status is only given by Deere after a supplier attains a Partner-Level rating for five consecutive years.

The Montville, New Jersey-based company was selected for these awards in recognition of its dedication to providing products and service of outstanding quality as well as its commitment to continuous improvement. The awards were presented to Dale Kaminski (CEO), Dan Fox (vice president, sales and marketing), and Mark Davis (regional sales manager) during formal ceremonies held March 1, 2011 in Davenport, Iowa.

AST Bearings earned their distinction as a supplier of bearings to the Agriculture and Turf and the Construction and Forestry divisions of John Deere operating in Moline, Illinois, and Davenport, Iowa, respectively. "AST is very proud to have been awarded this prestigious honor by one of our valued customers," said Kaminski.. "Our goal is to provide all of our customers 'value beyond the part.' In this regard, the awards we received from Deere demonstrate how AST continues to improve the ways in which we partner with our customers to develop measurable solutions in an efficient and cost-effective way."

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3) Name:_____ Job Title/Position: _____
(print)

4) Signature _____ Date: _____

5) Please tell us about your company:

Company Name:_____
Company Address:_____
_____
City:_____
State/Province:_____
ZIP/Postal Code:_____
Telephone:_____ Fax:_____
E-mail:_____
Co. Internet Address:_____

6) How is THIS LOCATION involved with power transmission products?
(Check all that apply)
☐ WE MAKE power transmission products (10)
☐ WE BUY power transmission products (12)
☐ WE SELL power transmission products (Distributors, sales reps. etc.) (14)
☐ WE DESIGN products with power transmission components in them. (16)
☐ Other (please describe) (15)_____
_____

7) Which of the following products and services do you personally specify, recommend or purchase? (Check all that apply)

- ❑ Actuators (30)
- ❑ Adjustable-Variable Speed Drives (31)
- ❑ Bearings (32)
- ❑ Belting and Belt Drives (33)
- ❑ Brakes (34)
- ❑ Clutches (35)
- ❑ Controls (36)
- ❑ Chain & Chain Drives (37)
- ❑ Couplings & U-Joints (38)
- ❑ Gears (39)
- ❑ Gear Drives (40)
- ❑ Gear Mfg. Services (41)
- ❑ Hydraulic Power (42)
- ❑ Linear Motion (43)
- ❑ Motors (44)
- ❑ PT Accessories (45)
- ❑ Sensors (46)

8) What is your primary job function responsibility? (Check one)

- ❑ Corporate Management (1)
- ❑ Plant Engineering (2)
- ❑ Design Engineering (3)
- ❑ Marketing & Sales (4)
- ❑ Manufacturing Engineering (5)
- ❑ Purchasing (6)
- ❑ Quality Control (7)
- ❑ Factory Automation (8)
- ❑ Maintenance (9)
- ❑ Other (10) _____

9) What is the principal product manufactured or service performed at **THIS LOCATION?**
_____

10) How many employees are at THIS LOCATION (Check one)
☐ 1-19 ☐ 20-49 ☐ 50-99 ☐ 100-499 ☐ 500+

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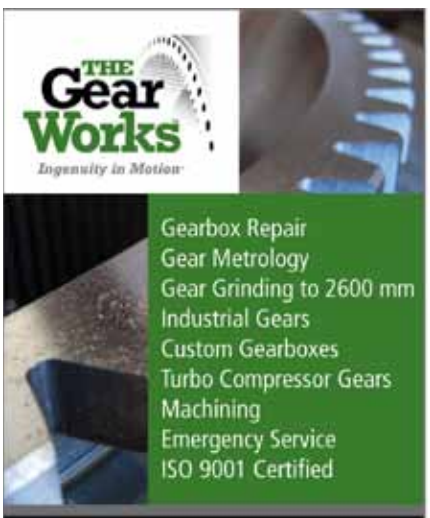

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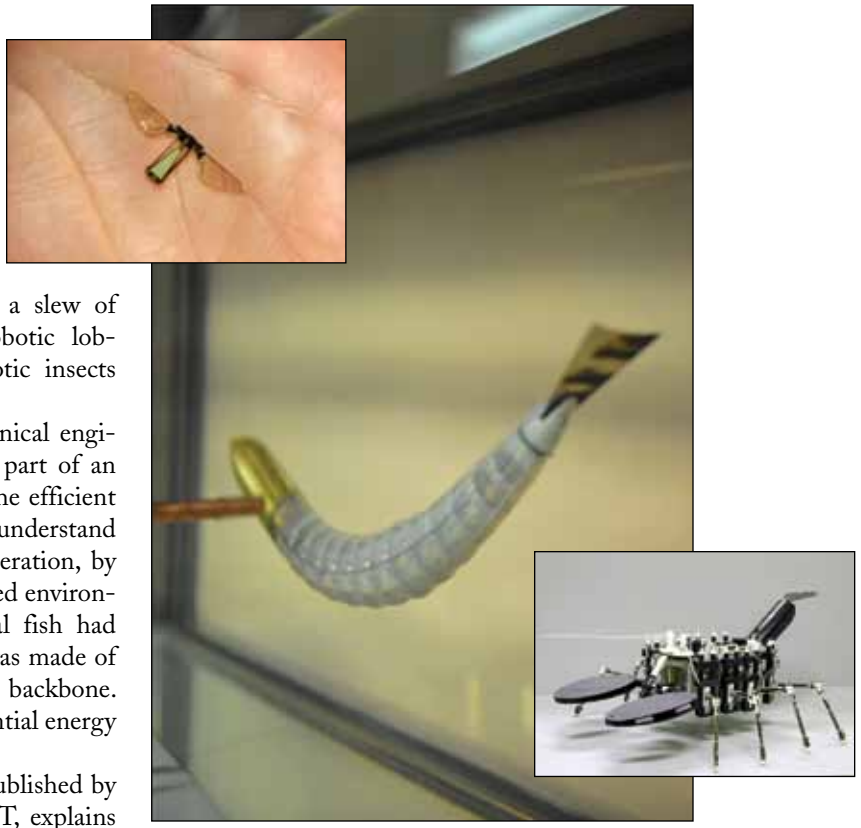
When (Robotic) Animals Rule The Earth …

Flip through the pages of *Wired* or *Popular Science* and you're sure to find an article or two about robots. Not so much the kind that shoot lasers from their eyes, but the compact, programmable taskmasters engineered to take on dangerous functions such as clearing land mines, inspecting nuclear reactors or trolling around Mars.

Furthermore, you'll find scientists and engineers "creating" micro-robotic creatures for a slew of fascinating research projects. These include robotic lobsters (Northeastern University), free-flying robotic insects (Harvard University) and mechanical fish.



Robotic insects, fish and lobsters are just a few of the micro-robotic creatures you'll find on college campuses.

Yahya Modarres-Sadeghi, professor of mechanical engineering at the University of Massachusetts, was part of an MIT team that developed such a fish to mimic the efficient start time of a pike. "The main purpose was to understand the basic physics behind a pike's very high acceleration, by emulating their fast-start mechanism in a controlled environment," says Modarres-Sadeghi. "Our mechanical fish had three parts: a head, a body and a tail. The body was made of a soft rubber material cast around a spring steel backbone. When bent to a C-shape, the body stores the potential energy which is necessary for the fast start."

An article in *Bioinspiration and Biomimetics*, published by Modarres-Sadeghi and four colleagues from MIT, explains the concept in detail: "The system consists of a thin metal beam covered by a urethane rubber, the fish body and an appropriately shaped tail. The body form of the mechanical fish was modeled after a pike species and selected because it is a widely-studied fast-start specialist. The mechanical fish was held in curvature and hung in water by two restraining lines, which were simultaneously released by a pneumatic cutting mechanism. The potential energy in the beam was transferred into the fluid, thereby accelerating the fish."

Modarres-Sadeghi says the maximum acceleration of the mechanical fish is around 40 m/s^2, with the maximum final velocity around 1.2 m/s (acceleration just over four g underwater, fast and furious for those playing the home game).

"By using our mechanical fish we can understand the fundamentals of fast-start, which can be used when designing future autonomous underwater vehicles," Modarres-Sadeghi says. "Also, with the help of biologists, we can relate these fundamental understandings to the evolutionary changes of the live fish."

Today, Modarres-Sadeghi and his colleagues are designing a new mechanical fish concept using internal machinery instead of an external actuator and clamping mechanism. Currently in the design phase at the University of Massachusetts in Amherst, the project aims to place servomotors close to the head with pull strings attached to the tail through the body.

"We have built a preliminary version of this fish, and currently we are testing it to finalize our design," Modarres-Sadeghi says. "We will use this new fish to study various methods of achieving high accelerations."

Although the mechanical fish will probably never shoot lasers from its eyes (fingers crossed!), it's a safe bet scientists will continue to identify areas where robotic engineering can enhance productivity in everyday life.

For more information on this and other mechanical engineering projects, visit *http://mielsvr1.ecs.umass.edu/fsi/index.htm*.

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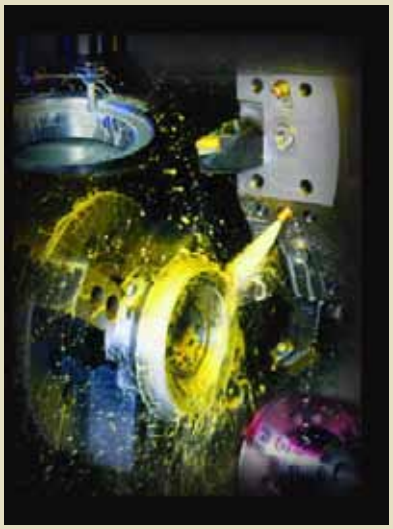

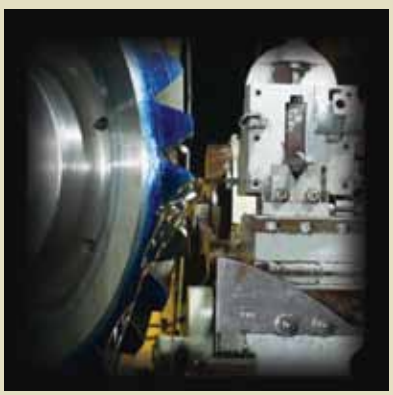

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