Automation in industry II

Motors and controllers

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Summary

Whether you want to position a tool or move products from A to B, automation requires a complex assembly of mechanical components, a drive and a control system.

In the past, this complexity has resulted in high development costs that have made automation too expensive for many applications. Electrical components and the programming of digital controllers have turned out to be particularly major cost drivers. However, advances in technology mean that automation solutions can now be planned faster, installed more easily and commissioned without any problems. Today, thanks to carefully coordinated components, automation can be used in a whole range of application areas.

How this White Paper can help

This White Paper focuses on the electrical components used in automation solutions. It complements the White Paper “Automation in industry I”, which centres on the principles of the mechanical elements (linear drives and guides). The aim is to help users accurately select and evaluate components. Indeed, when it comes to motors, gearboxes, encoder systems and controllers, a whole host of technologies are available. In some cases, different approaches can produce similar results, so it is important to weigh up the advantages and disadvantages.

Automation projects require the perfect combination of linear unit, motor, gearbox and controller so that tools or workpieces can be moved with maximum speed and precision.

Automation and drive technology

Humans have been using machines to enhance their own capabilities for more than 2700 years. This process of development has had two particularly important focal points: The first concerns mechanics, i.e. the means of actually performing the task in question. Early machines included pumps, mechanical looms and lathes. The other focal point is the drive, i.e. replacing muscle power with water or wind power.

When the steam engine was invented in the early 18th century, it offered a mobile drive source that could be put to use whenever needed. Mechanical systems also got a boost at this time, with British inventors John Kay and Edmund Cartwright gradually paving the way to the first automatic loom around 1740, for example. This invention could produce a simple fabric faster than a manual worker.

It was French silk weaver Joseph-Marie Jacquard who ultimately achieved the decisive breakthrough. In 1805, he patented a loom that could weave various patterns via punched cards. This succeeded in replicating the last advantage of manual weaving – the weaver's specialisation in reproducing a desired pattern to order. When brought together, mechanics, a drive and a control system made machines better cloth makers than their human counterparts.

To this day, the interplay between mechanics, drive and control system continues to be of crucial importance in automation. While the mechanics deliver the added value in the production process, it is the drive and control system that provide the precision and flexibility.

State-of-the-art drive technology is about more than simply transmitting power to create motion. The targeted actuation of various drive elements ensures that complex motions can be executed and that information from supporting sensors can be processed. The combination of mechanical, electrical and digital components is also referred to as mechatronics. However, in the context of industrial production, the terms automation or automation technology are more common.

This White Paper highlights the key components in drive technology for machinery, specifically electric motors, gearboxes and controllers. The mechanical components of linear units, such as linear drives and linear guides, are covered in the Automation I White Paper.

Electric motors come in a range of sizes and designs so that the ideal configuration can be achieved for each application.

Electric motors

An electric motor converts electrical energy into mechanical energy. During braking procedures, however, it acts as a generator, recovering electrical energy from the motion of the system.

Electric motors utilise the Lorentz force. Dutch Nobel prize-winner Hendrik Lorentz (1853 – 1928) described the physical effect of a force acting on a moving charge in a magnetic or electric field. According to the left-hand rule, this force acts in a predictable direction, which means controlled motion can be achieved on an electrically charged conductor in a magnetic field, while simple means can be used to achieve rotation.

The key components of an electric motor are the rotor (usually a rotating coil with a metal core) and stator (usually a stationary permanent magnet or exciter coil). Depending on the design of the electric motor, other parts may be necessary, such as a commutator, which reverses the current direction.

When the rotor is exposed to the magnetic field of the stator, a voltage is induced in the coils or short-circuited conductors of the rotor. This flow of current in turn generates its own magnetic field that interacts with the field of the stator. The Lorenz force thus produced causes the rotor to rotate.

Due to the very wide range of requirements that electric motors have to meet, various designs have emerged over time. The following sections examine their suitability for automation applications.

Direct-current motors

Direct-current motors are controlled by voltage level and polarity, which enables very efficient speed control. Direct-current motors are used when a very high speed and low torque are required.

However, there is one design-based disadvantage to them: The electrical energy for the rotor is transmitted via a commutator and friction contacts (usually carbon brushes). The commutator is a polarity changer that reverses the polarity of the rotor after each half turn of the rotor. This ensures that the magnetic field of the stator maintains movement. If it weren't for the commutator switching polarity, the rotor would not move.

Wear and maintenance requirements for the brushes make direct-current motors less appealing for long-term use in automation systems. Due to safety concerns, the flying sparks caused by the brushes are also undesirable in production environments.

When using electric motors, separate cables are usually needed for the power supply (shown in orange here) and data from the encoder system.

Three-phase AC motors

Three-phase AC motors utilise the continuous polarity reversal of alternating current. They use this to generate a rotary field – without needing a commutator. Three-phase AC motors are therefore largely maintenance-free. They are not susceptible to electrical or mechanical overload either, which makes them the most frequently used electric motors in industrial production.

Three-phase AC motors use at least three coils (or a multiple of this to increase the pole count) that are arranged at 120° to each other. This generates a rotary field that turns with the frequency of the alternating current. At an alternating current of 50 Hz, a single-pole motor can achieve a speed of 3000 rpm. A two-pole motor delivers 1500 revolutions per minute.

To control the motor, a frequency converter is used to adjust the mains frequency and thus achieve the desired speed. The control system must be adapted to the motor, its pole pair and the gearbox. For example, a single-pole motor needs a different mains frequency to a three-pole motor in order to achieve 500 revolutions per minute. An encoder system monitors the position of the rotor during operation and thus determines the actual speed.

Three-phase AC motors come in various designs, with asynchronous, synchronous and stepper motors the most important.

Asynchronous motors

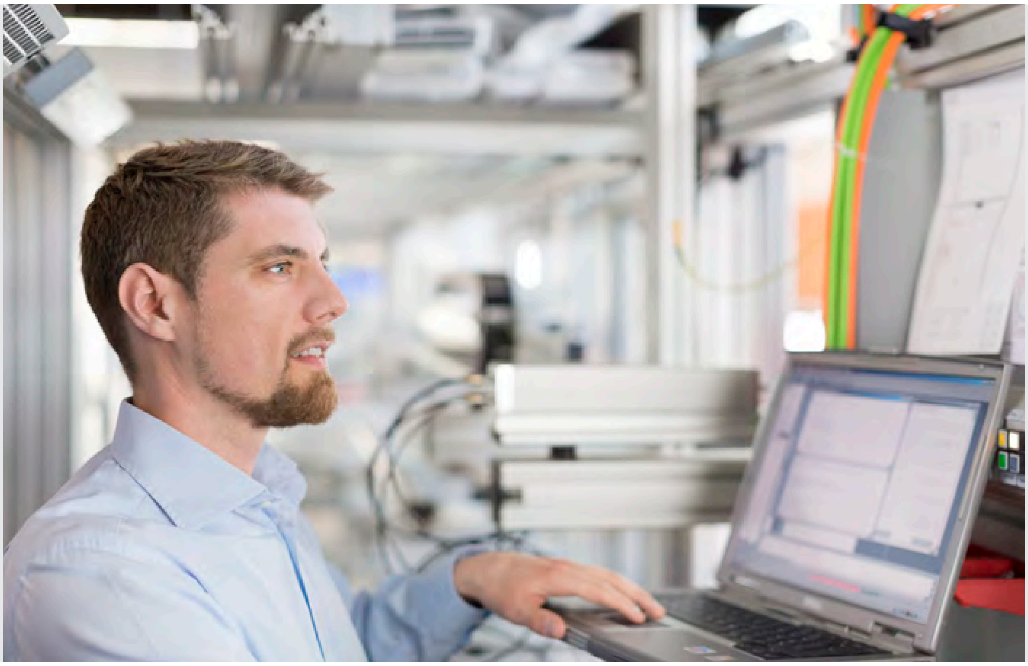
Asynchronous motors are robust three-phase AC motors with rotors that do not move in sync with the rotary field. Torque develops when the rotor speed deviates from the speed of the rotary field. Due to the slip that occurs owing to the basic principle of their design, asynchronous motors do not achieve full speed, but rather lag behind it by up to 8 percent, depending on the load.

The most common design type is the short-circuit squirrel-cage motor. This uses conductive bars that are set or cast into grooves on the rotor. Shorting rings connect these bars at both ends to form a closed rotor winding.

Asynchronous motors often produce disagreeable noises during start-up and at low speeds. This can be mitigated if the grooves of the rotor are arranged diagonally to the shaft axis. Other disadvantages include the high starting current and the constant rotor current during operation.

Synchronous motors

Synchronous motors are robust three-phase AC motors with rotors that move in constant sync with the rotary field. Due to the low moment of inertia on the rotor, starting torque is high even when the speed is low. When under load, the motor immediately builds up torque, which leads to very low slip and ensures good control over speed. Synchronous motors combine high torque and high speeds with a low-maintenance design. They are therefore ideal for applications that are highly dynamic and require powerful acceleration.

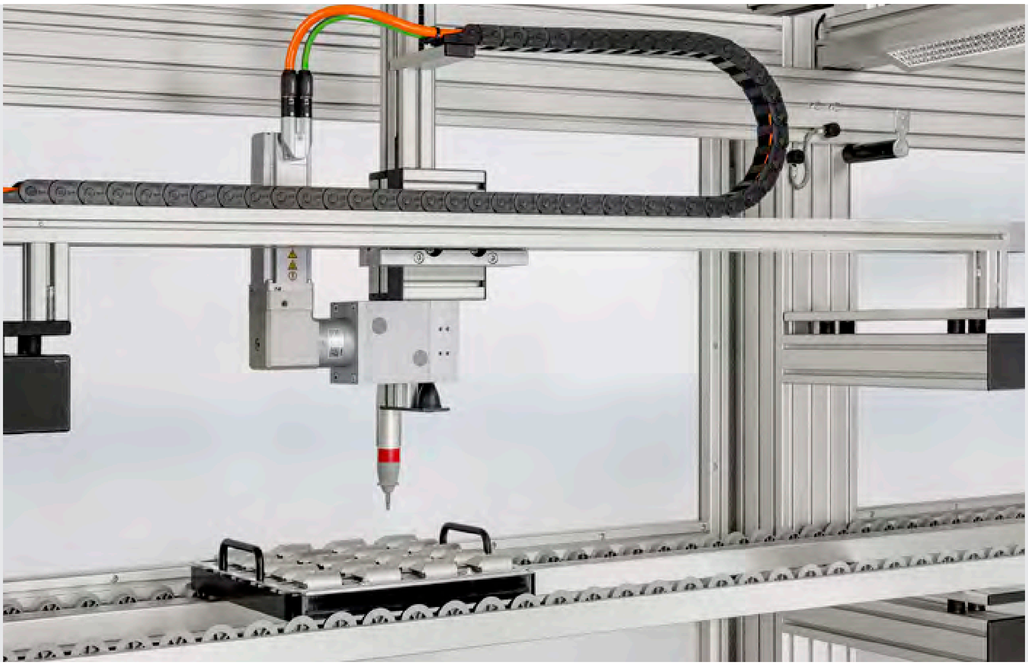


The control system ensures that an electric motor works to its optimum capacity in every motion phase. Programming is often a key cost factor.

Stepper motors

Stepper motors are robust, three-phase AC motors with rotors that can be turned precisely around a defined angle. This means the position of the rotor can be monitored very accurately without relying on sensors, which makes the system easier to control.

Stepper motors work in a similar way to synchronous motors but usually need a high number of pole pairs, which means their design is more complex. Furthermore, during rapid starting or braking actions, stepper motors can lose one or more steps, which influences the precision of the motion. The torque generated by stepper motors noticeably drops as speed increases. This results in poor efficiency, particularly when under partial load.



Among other things, gearboxes equalise the different mass inertia of the rotor and the mass that is to be moved. This ensures that even large masses can be moved dynamically.

Gearboxes

According to Guideline 2127 of the Association of German Engineers (VDI): “Gearboxes are used to transmit and transform motions, energy and/or forces.” In automation, they act as a torque converter between the motor and linear drive. They usually increase torque while reducing speed, thereby equalising the mass inertia ratio between the rotor and the mass that is to be moved.

Gearboxes can also change the direction of rotation. By arranging the gears at an angle, a motor can be installed at a 90° angle, for example, which saves space because the motor casing then runs parallel to the linear unit. Bevel gearboxes have a slightly lower efficiency rating than axial gearboxes. Overall efficiency is dictated primarily by design.

In automation applications, linear units can also be connected directly to the motor, with no gearbox in between. The bigger the mass that is to be transported, the more worthwhile it is to use a gearbox to increase torque. It is often cheaper to use a smaller, high-speed electric motor than a larger motor that generates high torque.

The key factor is the gear ratio. This indicates the ratio of motor revolutions (drive input) to axle revolutions on the linear unit (drive output). A ratio of $i = 3$ means that the drive output completes one whole turn for every three revolutions of the drive input. This can also be stated as a ratio of 1:3. When the ratio is $i < 1$, we talk about a reduction ratio.

Gearboxes come in various designs that often represent variations on a basic principle. Different designations are also used for similar gearbox types, which can easily cause confusion. Gearboxes with fixed gear ratios are usually used for automation solutions because motion can be controlled simply by varying the speed of the motor. The following sections set out the most important types of gearbox.

Tip: Designing an automation solution is a complex affair. The requirements associated with the mass that needs to be moved must be coordinated with the characteristics of the drive. However, you can avoid having to carry out all the calculations yourself by using software such as item MotionDesigner®. This program factors in the optimum interplay between electric motor and gearbox when designing the overall system.

Spur gears

The simplest form of a spur gear consists of two gear wheels with external gearing on parallel axes. Due to their high efficiency and simple design, these gears are still very widely used today.

To achieve the desired torque, the motor here (right) is connected via a compact planetary gearbox. The drive shaft continues to run thereafter into the drive of the linear unit (left).

In practice, the low maximum gear ratio associated with this configuration can be problematic. Without additional design input, the limit is around 1:6. For mechanical reasons, spur gears with a high gear ratio take up a lot of space and are comparatively heavy. What's more, they generate more noise than other gears. Although additional gearwheels can help achieve graduated power transmission, complicating the design in this way sacrifices one of its main advantages – simplicity.

Spur gears with gearwheels that feature angled gearing run more smoothly and quietly and compensate better for problems caused by vibrations or misalignment. On the down side, they generate slightly higher levels of friction, which reduces their efficiency.

Worm gears

In a worm gear, there are no gearwheels in contact with the drive shaft. Instead, there is a screw-like indentation that moves the gearwheel of the output side. The movement of this "worm" results in continuous contact with the gearwheel. As a consequence, worm gears run very smoothly and without any of the jolts that can occur when gearwheels intermesh.

The biggest disadvantages are, on the one hand, the heat that is generated by the longer period of contact and, on the other, the lower efficiency that results from the friction. Friction losses mean that worm gears quickly hit their limits when it comes to large gear ratios. However, they perform well where reduction is required.

Bevel gears

Instead of conventional gearwheels, bevel gears use bevelled gearwheels that are geared on the side. The larger contact area ensures they run smoothly and are not susceptible to jolts. Bevel gears really come into their own when very large torques need to be transmitted.

The drive and output shafts are usually arranged at a 90° angle to each other. Bevel gearwheels can be used as a simple means of achieving different angles. As in the case of worm gears, high gear ratios and increased friction can prove problematic when using this type of gearing.

Planetary gears

In planetary gearboxes, two or more gearwheels run around a central gearwheel with external gearing, connecting it to another gearwheel with internal gearing. The planetary wheels revolve around the central shaft on fixed trajectories, rather like planets orbit a sun. Planetary gears are compact and enable efficient power transmission. They can transmit high torques because load is distributed over several planetary wheels. The planetary gears also ensure contact is sound even when the shafts are under load and deliver a high level of efficiency coupled with exceptionally smooth running. Planetary gears also support a space-saving design.

Because the internal and external gearwheels have different diameters and the planetary gears are located between the two, planetary gears are also ideal for high gear ratios. The disadvantages to this type of gear include the more complex design, which requires high production quality.

The installation space of a machine can often be used more efficiently by installing a gearbox that turns through 90°. This means the motor can then be fitted parallel to the linear unit.

Encoder systems

In an automation solution, the rotation of the motor axis is translated into another motion, such as the turning of a timing belt that moves the carriage on a linear unit. This action is controlled directly by regulating the motor. Start-up, acceleration and precise braking all depend on reliable data about the position of the rotor (see section on “Electric motors”).

Capturing that data is the job of the encoder system. A rotary encoder will tell the control unit what angle the rotor is at and support calculations as to how many revolutions are needed to achieve the desired position. Monitoring and checking movement increases precision, as errors caused by slip can be corrected faster. The encoder system is installed directly in the electric motor. Data is often transmitted over separate cables, with industrial fieldbuses also supporting the transmission of position data.

Absolute encoders

Absolute encoders determine the precise position of the rotor and issue an unequivocal numerical value. This means the precise position is known immediately on start-up, so there is no need to carry out a homing run. State-of-the-art absolute encoders can transmit other data besides distance travelled and current position, such as the temperature of the motor. Their internal digital data processing technology makes absolute encoders relatively complex and expensive.

Incremental encoders

Incremental encoders capture changes in rotor angle. The measurement process involves monitoring a rotating disk that features graduations. Each time one of these graduations is passed, the measured value either increases or decreases. Since it is only possible to capture changes from the point when measurement starts, an incremental encoder cannot identify the current position on start-up and therefore requires an initial motion. Heating and soiling can have a detrimental impact on the accuracy of measurements.

Resolvers

Resolvers calculate the angle of the rotor by taking an electromagnetic measurement. Installing angle encoders at several points means that the movement of the rotor can be monitored very accurately. Resolvers are extremely robust and provide reliable measurement results even when temperatures fluctuate widely. They also feature a design that is not susceptible to soiling.

State-of-the-art controllers are easy to program and feature a modular design that supports a range of fieldbuses.

Controllers

Industrial control technology distinguishes between different hierarchy levels in automation. These range from company level, such as recording orders for a particular product, to actuator level, where a specific motor is activated as part of the production process for a component of the product in question.

When it comes to the actual production process itself, the controller and field levels of the automation pyramid are most relevant. Although German Standard DIN 19226 differentiates between open-loop and closed-loop control, the boundaries are largely fluid today. Thanks to their processors and programmable interfaces, cutting-edge servo controllers – which are actually intended as a subordinate level to the technical production process – can take over the functions of the controller level. In practice, the generic term controller has become widely used to refer to all programmable systems. In the past, this function required an overarching PLC (programmable logic controller) that actuated the individual controllers.

Historically, a distinction has been made between hardwired and programmable controllers. Since production costs for industrial-grade digital technology have dropped significantly, programmable solutions with on-board memory have become the norm.

The controller has two main tasks. The first is to collate the digital and/or analogue signals from motors, sensors, etc. are collated. The controller thus regulates the circumferential speed of an electric motor from start-up until the braking action when the carriage of the linear unit has reached the desired position.

The motor and controller must be coordinated because each motor has its own specific characteristics. At the same, the controller processes signals from limit switches, etc.

Cascaded solutions are sometimes used, in which a digital controller talks to a servo controller that in turn acts as the electrical interface to the electric motor. This means controllers can be used to coordinate different electric motors in one solution. However, the use of an overarching control system increases complexity.

The second task of a controller is to execute a program. In automation, a transport task has to be described as a sequence of steps. Describing this sequence in general terms such as “move the carriage 350 mm to the right” is not good enough. Can the transported goods be accelerated and decelerated using the maximum speed of the motor? Is a gentle start-up needed? Is start-up time-controlled or triggered by a signal?

Setting up a controller is a key cost factor in automation projects due to the many different factors involved, and because every controller uses its own system for programming. Additional experts often need to be brought on board because mechanical engineers frequently don’t have the necessary programming skills.

Since several sensors and drives are required for the open-loop or closed-loop control of an automation solution, a controller needs the corresponding connections for processing analogue and digital signals. Despite all the efforts that have been made

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to achieve standardisation, there is still a wide range of interfaces available. State-of-the-art controllers therefore have a modular design so that the desired interfaces can be added.

Fieldbuses are used to ensure dependable communication in an industrial environment. Depending on their design, they help to establish communication with production planning or between machines and machine parts.

Tip: State-of-the-art solutions such as item linear motion units® do not require programming expertise. They ensure users can define a transport task by following a clear and user-friendly process. The software then translates the planned sequence into actual programming and sets the control parameters. As a result, many tasks don’t require any additional expertise.

Fieldbuses

A fieldbus is a bus system that connects together various devices in an industrial automation system. In an office environment, connection standards such as USB or Ethernet are used, but these are not designed for the harsh demands of a production environment. Fieldbuses set more stringent requirements when it comes to resisting sources of interference and ensuring reliable data transfer.

Fieldbuses were developed in the 1980s to create one shared network to replace the growing number of dedicated lines. All devices were to be capable of sending and receiving data via one bundle of cables to simplify cabling and development. Different fieldbuses became established owing to the range of requirements.

The IEC 61158 standard was introduced in 1999 with the aim of bringing order to the confusion of fieldbuses. Numerous solutions have now been standardised. Although this doesn’t necessarily make it easier for users to choose between solutions, it does ensure the various solutions are mutually compatible.

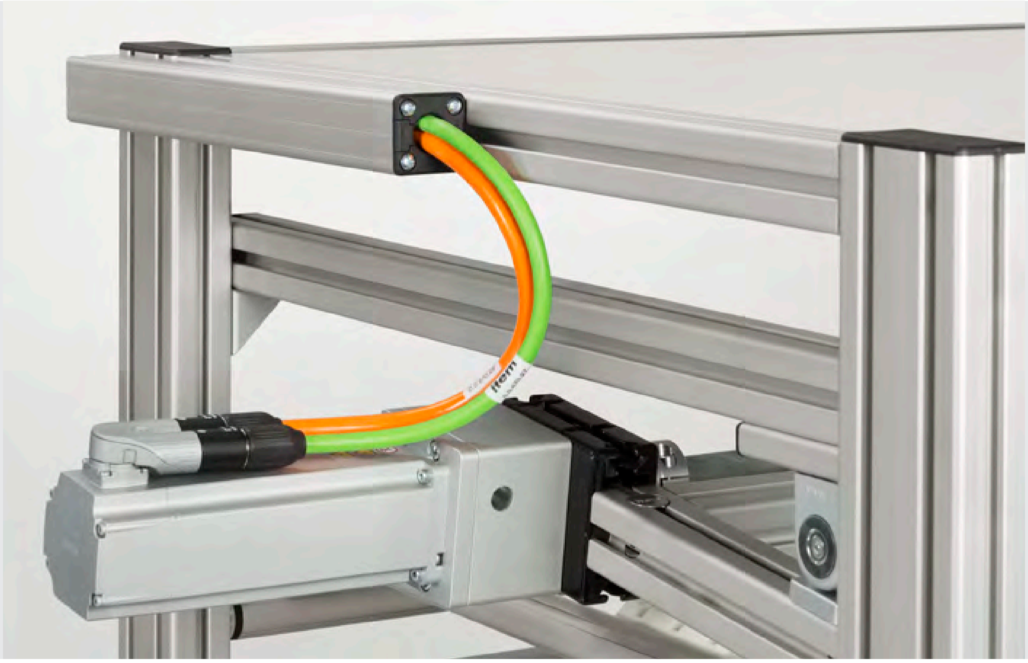
CAN bus / CANopen

The CAN (Controller Area Network) bus is one of the oldest fieldbuses and has become established in various designs. The typical variants of the CAN bus are the high-speed and low-speed CAN.

To improve compatibility, CANopen offers a universal software interface, which means developers don’t have to grapple directly with the hardware. This makes CANopen applications easier to network with each other.

EtherCAT

EtherCAT (Ethernet for Control Automation Technology) is a real-time-capable Ethernet solution for industrial applications. It is standardised in line with IEC 61158. EtherCAT offers short cycle times.



Fieldbuses standardise the transmission of data between drives, controllers, sensors, etc. They are designed to meet industrial requirements.

PROFIBUS

PROFIBUS (Process Field Bus) is a fieldbus that was developed in the late 1980s with support from the German Federal Ministry of Research. More than 20 companies and institutes were represented on the committee behind the development. PROFIBUS uses a proprietary network protocol and a dedicated PROFIBUS FMS (Fieldbus Message Specification) communication protocol.

PROFINET

PROFINET (Process Field Network) builds on PROFIBUS but uses open network protocols such as TCP/IP. PROFINET is real-time capable.

Summary

Automation solutions are some of the most complex applications in industry. As they require expertise from a range of specialist areas, the question often arises as to whether the end result is worth all the effort.

However, advances in control technology are making automation solutions more attractive for simpler applications. They don't always need to be complex workflows. Since setting up controllers is much easier, and doesn't require complex programming, they can be used for endurance tests or partial automation in assembly lines. Linear units can guide products, lift goods and open doors.

It is worthwhile comparing overall engineering costs. Carefully coordinated solutions reduce the outlay for planning, installation and commissioning. This in turn lowers the costs associated with automation and thus opens up new application areas.

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