CUTTING BLADE, COMPUTER VISION AND CONTROL SYSTEM

Cable splicing, the process of joining two electric cables, is essential for the expansion of the power grid. Automation of this procedure allows for fewer quality-related connector failures and can potentially speed up the grid expansion needed to facilitate the energy transition. This article proposes the design of a robotic system for automatically removing the semiconducting insulation shield of medium-voltage cables. The article discusses the conceptual design of the robot and the mechanism for propulsion around the cable, as well as a system for automatically adjusting the cutting-blade depth using computer-vision and control algorithms.

TIM ELDERHORST, EDWIN DERTIEN AND LUC NIES

Introduction

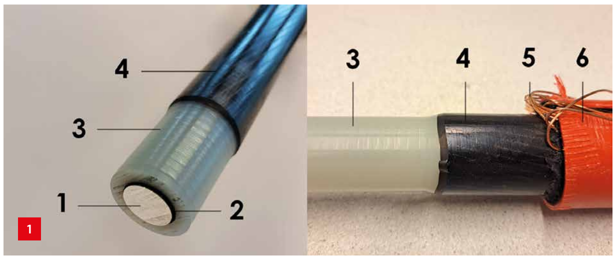
Numerous robots have been developed for the inspection and maintenance of power cables, primarily for the high-voltage grid. [1][2][3][4] Automation of the cable-splicing process is a novel research topic, as the only known cable-splicing robot is a machine prototype by ULC Technologies. [5] This paper shows a novel approach for the autonomous removal of the semiconducting insulation shield of underground medium-voltage cables, with the ultimate goal of automating the entire medium-voltage cable-splicing process. The project has been carried out at the Robotics and Mechatronics group at the University of Twente, in collaboration with Dutch distribution system operator Alliander. [6]

Analysis

Cable splicing is the process in which two cable ends are joined together in order to create a single continuous cable. It is vital in electrical power transmission and distribution, as it is required for repair and expansion of the power grid. In order to meet the goals for the Dutch energy transition, Alliander should double the size of its power grid before 2050, which requires the installation of 250.000 novel cable joints on the medium-voltage grid. [7] One of the main hurdles in this process is the lack of skilled cable-splicing technicians. A possible solution for solving personnel shortages in the energy industry is the use of robotics. [8]

Cable splicing is a difficult process, prone to failure. Cable-splicing technicians require a practical education of four years before they are eligible for performing this task. Splicing of medium-voltage cables takes roughly three hours to complete. After cutting the two cables that are to be joined, the different layers of the cables should be peeled off in such a way that each layer can be connected to the corresponding layer on the second cable. A connecting part is installed to join the conductors of both cables. Afterwards, the various layers of both cables are reconstructed to ensure proper insulation, as well as containment of the electric field. Finally, a heat shrink is installed as a replacement for the outer sheath, to prevent water from entering the cable joint.

The medium-voltage grid is used to transport electricity underground at a voltage of 3-25 kV, with most medium-voltage cables having a voltage of 20 kV. Medium-voltage cables used by Alliander contain six primary layers, as shown in Figure 1. First of all, each cable has one or three aluminium conductor cores for transportation of electricity. Secondly, each core contains an insulating layer for electrically insulating the conductor cores from each other and the environment. Each core contains a conductor shield and insulation shield, with the purpose of homogenising the electric field around the cable core. [9] The shielding and insulation layers are made from cross-linked polyethylene



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Schematic drawing of the primary layers of a medium-voltage XLPE cable, showing 1) conductor core, 2) conductor shield, 3) insulation, 4) semiconducting insulation shield, 5) grounding, and 6) outer sheath.

AUTHORS' NOTE

Tim Elderhorst (EngD candidate) and Edwin Dertien (assistant professor) are associated with the Robotics and Mechatronics (RaM) group at University of Twente, Enschede (NL). Luc Nies is principal researcher at the Research Center for Digital Technologies at Alliander, Arnhem (NL).

t.r.elderhorst@utwente.nl
www.ram.eemcs.utwente.nl

Liander technicians performing cable splicing in the field.

(XLPE), where the shielding layers are semiconductors with a higher conductivity than the insulation layer. The three layers (Figure 1: layers 2, 3 and 4) are melted together during manufacturing to form a single mechanical layer, but their conductive properties remain distinct. Lastly, the cable is surrounded by a layer of copper grounding and an outer layer of PVC for mechanical protection.

Automatic removal of the insulation shield was the main concern for this project because this task is prone to errors, making it one of the most difficult tasks in the cable-splicing process. This is caused by the necessity to remove a layer of 0.7 mm with a maximum resolution of 0.1 mm in a challenging work environment. Cable splicing is performed outside and in small excavated holes half a meter below ground level (as shown in Figure 2), which makes the process difficult for technicians.

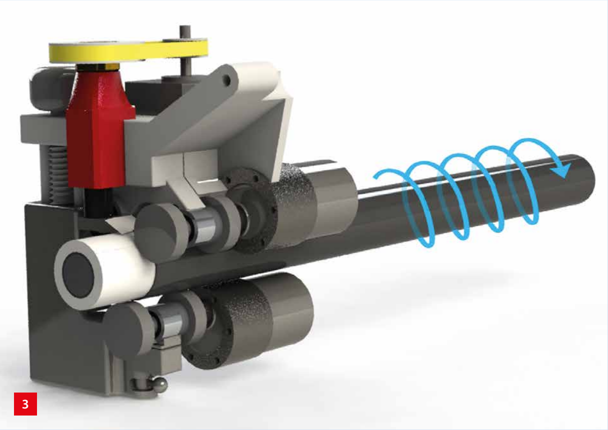
Removal of the semiconducting insulation shield is done by peeling off the semiconductor, along with a small outer part of the insulation layer. Any remaining patches of semiconductor on the cable will result in cable failure. On the other hand, removing too much of the insulation material reduces the resistance to electric stress within the layer, causing the cable to wear out faster. Furthermore, it is important that the cutting depth remains constant in order to ensure a smooth outer surface of the insulation layer. Inconsistencies in the outer layer lead to difficulties in the attachment of the connector body to the cable.

Current practice involves the use of mechanical cutting tools that contain screw actuators for adjusting the blade depth with 0.1 mm resolution. Still, the process of removing the insulation shield remains prone to failure. For this reason, the robotic system presented here contains a subsystem for automatically adjusting the cutting-blade depth.

Implementation

Conceptual design

The most important requirement for the robotic system is the precision and accuracy with which the insulation shield is removed. Any remaining patch of insulation shield on the cable will disturb the homogeneity of the electric field, which results in burning at the location of the remaining patches of shielding. [9] The edge of the semiconducting layer should be perpendicular to the cable axis in order to not disturb the electric field lines. This poses a challenge, as medium-voltage cables are coiled during transportation and bent during the splicing process, resulting in unpredictable curvature of the cables. Additionally, it was found that the insulated and shielded cores of medium-voltage cables are not perfectly circular, but slightly elliptical instead.



CAD model of the robotic system operating on a cable core, showing the desired robot trajectory.

To address these challenges, the robot is fixed to the cable; see the CAD model in Figure 3. This allows the robot to follow the curvature and position of the cable axis, resulting in a higher cutting precision. The system contains three sets of two wheels, which are used to align the robotic system with the cable axis, constraining all degrees of freedom except for the desired robot trajectory. If all wheels are placed at equal distance from the axis of rotation, the tool blade will always be at the correct position with respect to the cable core, irrespective of the cable size. Moreover, the axis of rotation for the robot will align with the cable axis at any point along the cable. As the position of the tool blade is fixed to the position of the robot, this construction allows the robot to cut nearly perfect circles, irrespective of variations in layer thickness, position and angular deviation of the cable core.

Drive train

A drive-train system was designed which allows the robot to propel itself over the cable, following a helical trajectory around and along the cable core, removing any insulation shield along the way. For this, the robot should be driven with sufficient torque to provide the required cutting forces, while also counteracting friction forces and inertia. A design was made for the drive train using two sets of actuated wheels and one set of unactuated wheels; see the prototype in Figure 4. The two sets of actuated wheels

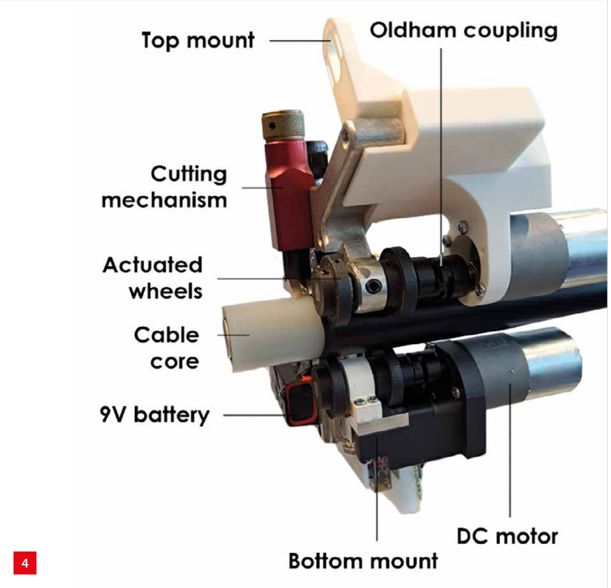


Photo of the drive system prototype.

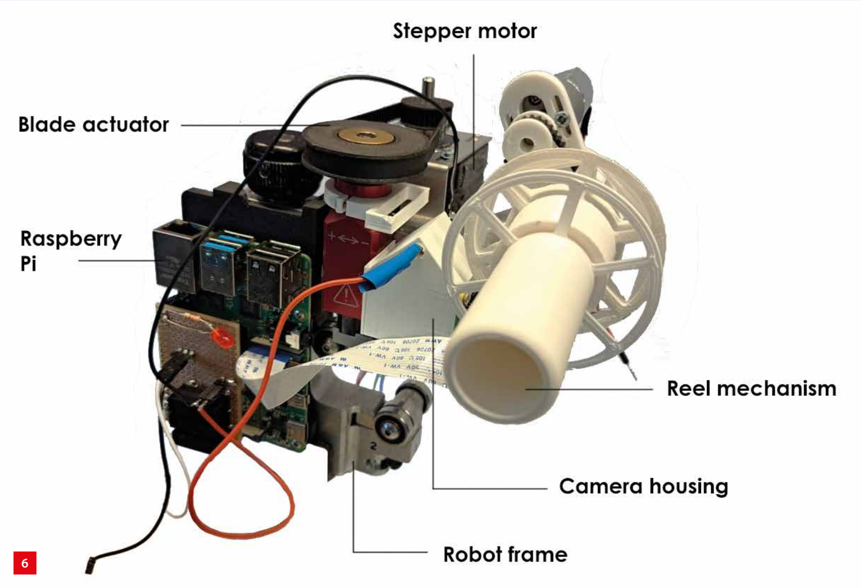


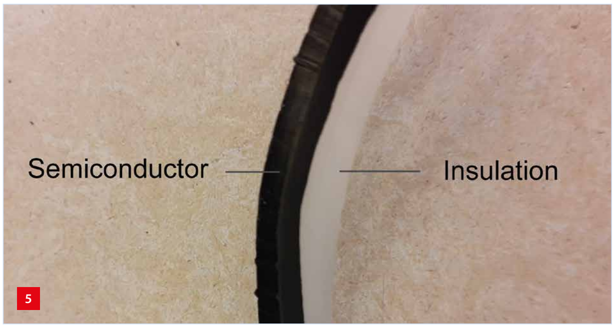
Photo of the blade-depth control system prototype. The vision system is included.

are fixed to two axes, both of which are driven by a DC gear motor through an Oldham coupling. In the initial prototypes, the cutting system was substituted by an existing cable-splicing tool; in this case the Ripley US02-7000.

Blade-depth control

In current practice, cable technicians visually inspect the peel of semiconducting and insulating material (Figure 5) in order to determine the appropriate blade depth. The ratio of the semiconductor width compared to the total width of the peel (which we call the chip ratio) varies due to elliptical disturbance of the cable and other variations. The chip ratio should be close to 67% on average, as this has been shown to provide sufficient margin of error for the cutting process. The visual inspection process can also be automated, using a camera, a computer-vision algorithm, a controller and a blade-depth actuator.

A feedback control algorithm was designed that adjusts the blade depth based on camera images of the XLPE peel. The peel that has been removed by the robot is fed along a camera, where a computer-vision algorithm inspects the chip ratio. After filtering out elliptical disturbance, the ratio found by the computer-vision algorithm is compared to the setpoint of 67% in order to compute the signal offset error. The error is used as input for a proportional controller. When the error reaches a certain threshold, a command is sent to the blade-depth actuator to increase or decrease the blade depth by 0.1 mm. The actuator is temporarily locked after each action in order to improve stability of the control system.



Peeled layer consisting of XLPE insulation and semiconducting insulation shield.

The actuator consists of a screw actuator that is driven by a stepper motor, both of which are connected by a belt-drive transmission; see the prototype in Figure 6. A reel mechanism collects the XLPE peel, after it has been inspected by the vision system.

Computer-vision algorithm

Cutting away the semiconducting layer results in a peel that consists of both semiconducting and insulating material. In the robotic system, this peel is fed along a camera, after which it is collected on a reel. The peel is fed along a green background sheet, where a camera captures images of the peel, which are subsequently processed by a computer-vision (CV) algorithm on a Raspberry Pi. The CV system for this project has been developed by R. van den Berg. [10]

The CV algorithm segments the image using Bayesian classification, as shown in Figure 7. [11] Since it is unknown where the peel will be located on the image in the beginning, the prior probability is uniformly distributed. The first segmentation iteration will result in a noisy segmented image, as the algorithm has difficulty distinguishing the insulation and background segment. Since the semiconducting material is black, this segment is easily detected by the algorithm during the first attempt, as this layer can clearly be distinguished from the background and insulation layer. New prior probability distributions are constructed based on the semiconductor segment. Afterwards, the image can be segmented for a second iteration, which results in a more accurately segmented image. The chip ratio of the peel can be calculated by dividing the semiconductor segment by the semiconductor and insulation segments combined, using the following equation:

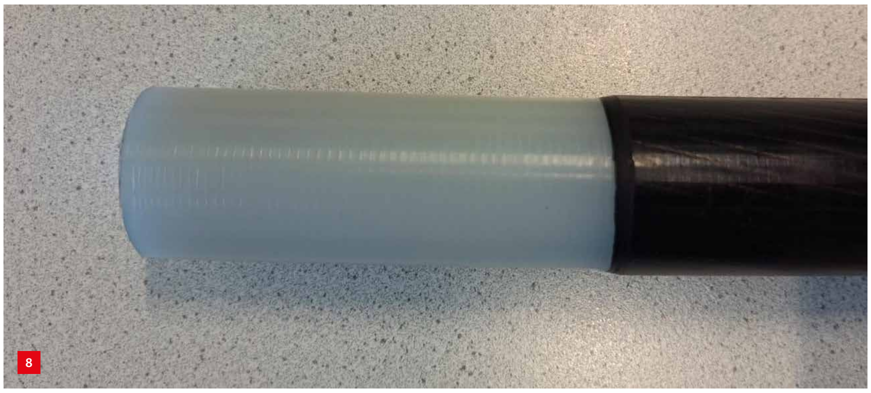
$$Ratio = \frac{N_{semicon}}{N_{semicon} + N_{insulation}}$$

Here, *N* is the number of pixels of the respective segment. This chip ratio is used as input for the blade-depth control system, as well as for monitoring the quality of the peeling process.

Results

A prototype was made for the drive system, as well as a prototype for the blade-depth control and CV system. The prototype of the drive system was used to successfully remove the semiconducting layer of a single-core medium-voltage cable, while meeting the requirements for surface quality. The prototype was able to achieve a velocity of 32 rpm while removing the semiconducting layer. The end result can be observed in Figure 8.

An experiment was performed to evaluate the blade-depth control system in combination with the CV system. The chip ratio, averaged ratio, control error and blade depth are plotted in Figure 9. An IMU (inertial measurement unit) was connected to a rotating cable core. Estimations of the position and velocity based on accelerometer data are shown in Figure 10. Figures 9 and 10 were both collected during the same experiment, where Figure 10 shows that the velocity was stable. At the beginning of the experiment, the blade depth was deliberately set too shallow. It can be seen that the chip ratio reaches 100% between 5 and 10 seconds, which triggers a response of the stepper motor around $t = 9$ s and $t = 14$ s. After two adjustments of 0.1 mm, the control error stabilises around approximately 0%. It can be seen that the blade depth is successfully adjusted when the control error becomes too large.



Result of the drive system test. The insulation will be partly removed at a later stage.

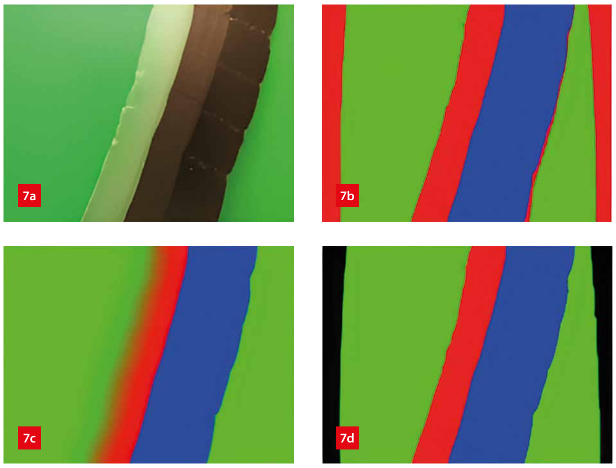
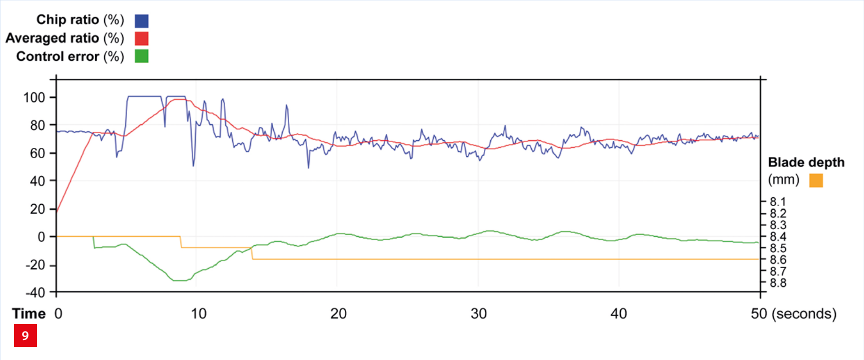


Image segmentation; the insulation is shown in red, semiconductor in blue, and background in green.
(a) Input of the XLPE peel.
(b) After initial segmentation.
(c) Probability density after initial segmentation.
(d) After second segmentation.

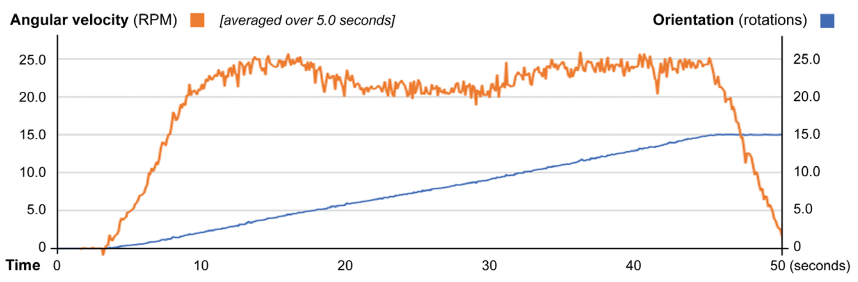
Conclusion

Testing of the blade-depth control system in combination with the CV system and reel system showed that the control system appropriately adjusts to errors in the chip ratio. It was found that the CV system sometimes incorrectly segments the insulation segment at chip ratios higher than 90%, incorrectly measuring a chip ratio of 100%. In practice this is not problematic, as in both cases the blade depth should be increased to reach the goal state of 67% chip ratio. It was shown that the control system has sufficient tolerance for variations in cutting velocity.

It was found that the drive mechanism offers sufficient torque and velocity to successfully remove the semi-conducting layer in one step. Moreover, using 0.1 mm increments of blade depth, it was possible to achieve



Chip ratio (blue), averaged ratio (red), control error (green) and blade depth (orange) measured during the blade-depth control system test.



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An estimate of angular velocity (orange) and orientation of the cable core (blue) during the blade-depth control system test, based on accelerometer data.

the required surface finish, which was confirmed by technical specialists from Alliander. It was found that the cutting system can fail when the blade deflection exceeds 11.2 millidegrees. Therefore, it is recommended that the blade deflection does not exceed 5.6 millidegrees during operation. To achieve this, it is recommended that the rotational stiffness of the cutting mechanism be increased by 150% in future prototypes.

In further research, the integration of the drive system, blade-depth control system and position-tracking system [12] should be verified. Some of the subsystems should be redesigned to increase the system autonomy, including the chip collection system and the software architecture.

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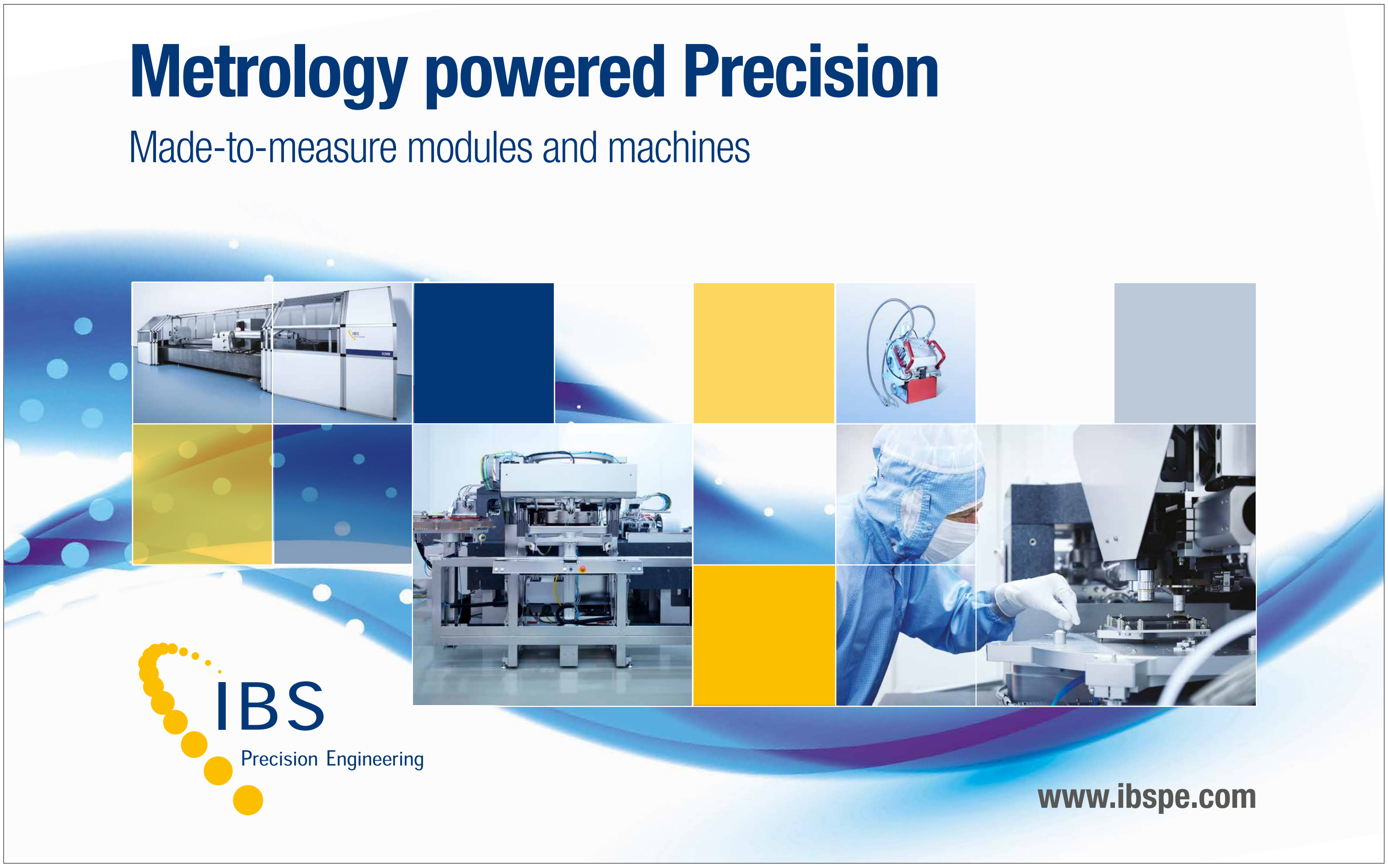
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