Robotic maintenance of cable-supported bridges

F. Förster, J. Laukner, W. Brand & C. Gläser
DYWIDAG-Systems International GmbH, Leipzig, Germany

ABSTRACT: When it comes to maintenance of the free cable length of cable supported bridges and structures there has been a strong development in the recent years for semi-automated and fully automated robotic solutions. That applies to a broad variety of cable types like stranded cables, parallel-strand cables, parallel-wire cables, full-locked cables, or open spiral cables. Focus of this article is on corrosion & UV protection of bridge cables by automated robotic wrapping of a multilayer butyl rubber tape system. The advantages of the wrapping are highlighted such as faster execution times, reduced impact on traffic and lane closures, reduced environmental impact as well as the durability of the solution. In addition, cable wrapping also other robotic supported maintenance services are described such as robotic welding of PE stay pipes as well as automated cable cleaning. Using example projects across the globe, it is made clear how robotic solutions are increasingly becoming an integral part of cable maintenance projects and which role they play within the entire scope of bridge cable maintenance.

1 INTRODUCTION

The use of bridge cables has revolutionized bridge construction worldwide in terms of span, structural and economic efficiency, and aesthetics (Svensson 2011). Regarding inspection & maintenance, the accessibility of the free cable length is a particular challenge, regardless of whether the structures are suspension bridges, cable-stayed bridges, arch bridges, or even other cable-supported structures like arena roofings, masts or high flares.

For this reason, the development of robotic technology has made enormous progress over the last two decades, Figure 1. The advantages are obvious: with the use of fully automated or semi-automated systems – controlled by special trained rope access technicians (RATs) – the inspection and maintenance work can be carried out in much less time, without the need for scaffolding and with significantly reduced road closures, which reduces the cost of the work as well as the impact on traffic (Kuhn 2008).


Cable Wrapping
Cable Welding
Cable Inspection

Figure 1. Robotic technology for inspection & maintenance of bridge cables. Modular system of linear transportation modules and functional modules for different tasks. Left: Configuration for cable wrapping (butyl rubber tape system). Center: Configuration for welding of PE stay pipes. Right: Configuration for visual cable inspection of the outer cable surface (ATIS 2010).

2 ROBOTIC CABLE WRAPPING

This chapter is giving an overview about corrosion & UV protection of stay cables based on a butyl rubber tape system which can be robotically applied. After a short introduction to the topic (see Section 2.1) and a description of the tape system (see Section 2.2) the robotic application technology is presented (see Section 2.3 and 2.4). Executional & environmental aspects are then highlighted (see Section 2.5). Finally, the testing and approval of the system is described (see Section 2.6).

2.1 *Corrosion & UV protection of bridge cables*

Bridge cables as central load-bearing elements must be efficiently protected against corrosion. The type of corrosion protection used depends on the cable type of the bridge, mainly defined by the main tension-resisting elements (MTE) (NCHRP 2005). In the case of stranded cables, parallel-strand cables or parallel-wire cables the single wires or strands are either galvanized or coated with epoxy, with or without an additional PE sheathing or sheathed directly with PE, while the external stay pipe ensures mechanical protection and dimensional stability. Alternatively, the corrosion protection can be realized by grouting or waxing the entire cross section within the outer pipe (Gimsing & Georgakis 2012). For full-locked cables an additional external corrosion protection by various layers of anti-corrosion paint has been state of the art for decades (Saul & Nützel 2010). Same applies for open spiral cables – mainly used for smaller bridges like foot bridges. Corrosion protection via paint application has several requirements such as:

- preparation of the cable surface (by brushing, sweeping, blasting)
- application of several (4 to 8) layers of paint
- sufficient time needed for hardening of each layer before applying the next one
- minimum surface temperature of 5°C; 3 K above dew point
- housing of the application area to ensure environmental protection

Those requirements result in the need for scaffolding during the manual application process as well as long execution times which especially in case of maintenance of existing bridges leads to traffic restrictions and high project cost. As painting is a manual process it is subject to local imperfections. Additionally, the outer cable surface per definition is always exposed to weathering & UV radiation which leads to aging and therefore a need of maintenance / renewal after a certain time.

2.2 *Use of butyl rubber tapes for corrosion & UV protection*

As an alternative to using paint as external protection against corrosion, there is a method of helical wrapping of butyl rubber tapes around bridge cables which first has been introduced at Passelrelle des Deux Rives – a stay cable bridge between Strasbourg (France) & Kehl (Germany) in 2008 (Saul & Nützel 2012). The tape system consists of a base layer and a top layer. Both layers are wrapped around the cable in a helical manner and with 50 % overlap so in the end the entire system is build up by 4 layers of tape with a total thickness of 2.6 mm (Figure 2, top left) (Nürnberger 2010). The tape itself also has a multi-layer structure. The base layer consists of a stabilized PR-carrier film which on both sides has a layer of butyl rubber attached. Butyl rubber and PE are coextruded during manufacturing process of the tape which results in an insoluble compound of the two materials. By helical wrapping and overlapping the butyl rubber of the base layer connects to itself. By this time an interdiffusion process (cold welding) is started which results in an irreversible merging of the base layer to itself, see Figure 2, bottom left. At this stage the corrosion protection of the cable is functional already. The butyl rubber also adapts well to the cable surface by adhesion and is filling fine structures perfectly (Saul 2010).

The top layer of the tape system also consists of a PE-carrier film (UV-stabilized) with coextruded butyl rubber only on one side. By simultaneous wrapping of base and top layer the butyl rubber of both layers also cold welds which connects the two layers to each other (Figure 2, right).

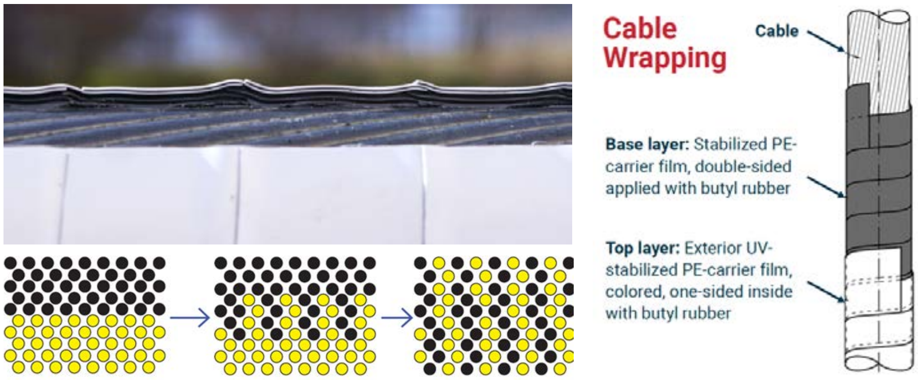

Figure 2. Butyl rubber tape system ATIS Cableskin®. Top left: Cross-section of the tape system wrapped around a spiral cable. Tape section cut out for demonstration. Bottom left: Schematic view of the interdiffusion process (cold welding) of the butyl rubber molecules between two single tape layers. Right: Schematic view of the helical wrapping of the base layer and the top layer – each with 50 % overlap.

Both layers are wrapped with a defined tape tension which results in a constant hoop stress around the cable avoiding unintentional folding of the tape. The wrapping can be done either manually with specialized hand-wrapping devices or automatically by using robotic wrapping technology (see Section 2.3, 2.4). This ensures constant tape tension, constant hoop stress, constant overlapping which in the end is resulting in a homogenous wrapping pattern.

The PE foil of the top layer is colored which allows bridge cables in all color variants. At this point it should be mentioned that a light tape color is always preferable in order to minimize surface temperatures when exposed to sunlight. The temperature difference between a white and a black cable surface can easily be around 30 K. Minimizing temperature differences minimizes mechanical stress of the entire cable which helps enhancing its lifetime (Svensson 2011).

As bridge cables not only have a free cable length but also connect to other constructive parts like anchorages to the bridge deck and pylons, hanger clamps or damper elements, proper wrapping of those connection points is critical in order to guarantee the protective functionality of the entire system. Figure 3 shows an example of the wrapping to a cable damper clamp as well as a schematic view of the situation. In this case the rectangular corner between the cable and the clamp is filled with butyl mastic. Afterwards the tape layers are applied one after the other. The resulting hoop stress of the tape is directing pressure directly towards the corner forcing the mastic to always seal the system.

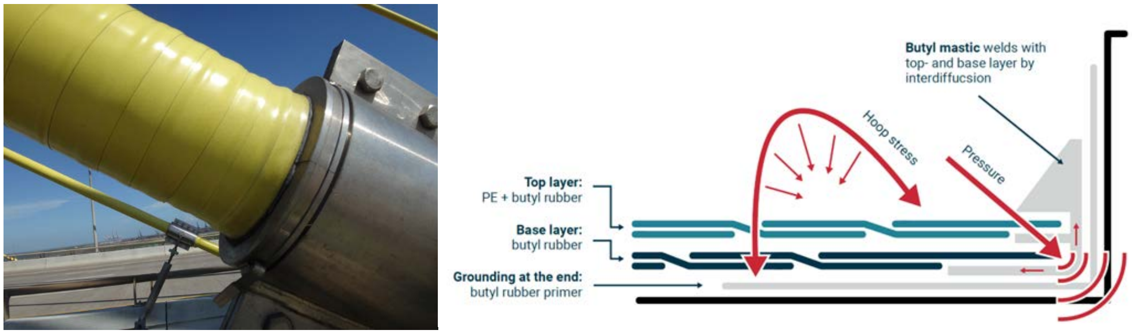

Figure 3. Wrapping of connection points such as anchor zones, cable dampers or hanger clamps. Left: Example of butyl rubber system ATIS Cableskin® wrapped to a cable damper clamp at Fred Hartman Bridge, Texas, US, 2015. Right: Schematic view of wrapping to a connection point.

This concept also applies for other connection points like anchorages. In comparison to paint the butyl mastic always stay flexible which guarantees the sealing of connection points even under small relative movements and therefore represents a crucial advantage.

In case of an external damage the corrosion protection effect of the butyl rubber tape system is retained as long as the base layer remains intact. A local repair easily can be done by overwrapping the damaged area with base and top layer.

2.3 *Fully automated wrapping*

Already at the first bridge that was wrapped with butyl rubber tape in 2008 (see Section 2.2) robotic technology was used to apply the tape. This first generation of wrapping robots is based on a modular platform consisting of a linear belt-driven transportation module and a rotating wrapping module. The helical unwinding of the tape is made possible by the superposition of linear and rotating movement. The robot is carrying two tape rolls with 50 mm width which are synchronously wound off. The wrapping process itself is working fully automatically. If the tape is empty the robot is coming down and gets refilled manually. In a first step the base layer is applied, the top layer is applied afterwards in a second step. This first wrapping robot generation has been used for a broad variety of cable supported structures (bridges, stadium roofs, masts) in the recent years, see Figure 4.

Figure 4. Fully automated wrapping of ATIS Cableskin®. Left: Passerelle Des Deux Rives, France / Germany, 76 stay cables, 2500 m², 2008. Right: Assembly Hall Indiana University, US, 8 supporting cables, 2019.

2.4 *Semi-automated wrapping*

With increasing size (span, pylon height, cable length, cable diameter) of stay cable bridges the fully automated first wrapping robot generation (see Section 2.3) was increasingly reaching its limits. In addition to the maximally wrappable cable diameter (150 mm), one operational parameter was increasingly problematic: Since the robots can only be loaded with two tape roles at once, the time to come down to the bridge deck for refilling the robot increases the longer the stay cables get.

To meet this challenge, a new generation of semi-automated wrapping robots has been developed, see Figure 5.

Figure 5. Second generation of wrapping robots. Wrapping for UV protection and color renewal of 192 stay cables, 12,000 m² at Fred Hartman Bridge, Texas, US, 2015. Left: Platform setup. Right: Wrapping robot remote controlled by a rope access technician.

Those devices are travelling in a helical motion by wheel drives which can be adjusted in angle. They are capable for wrapping larger cable diameters (90 – 340 mm). Furthermore, the devices are battery-powered and operated by a rope access technician (RAT) via remote control.

The RAT is moving in front of the robot in a specialized light weight gantry which is capable to carry a significant amount of spare tape rolls (tape width 100 mm). In this way the RAT can refill the machine on the spot which makes the entire process extremely time efficient. Additional tape can be directly pulled vertically to the gantry using an additional electric winch.

While with the first-generation robots base layer and top layer are wrapped in two consecutive operational steps now both tape layers are wrapped simultaneously by having a base layer tape located at the front and a top layer behind it in the center of the robot. In this way, the entire tape system is applied completely in just one operation.

Within the most recent development step further improvements have been implemented to the wrapping robots of the third generation in 2021, Figure 6.

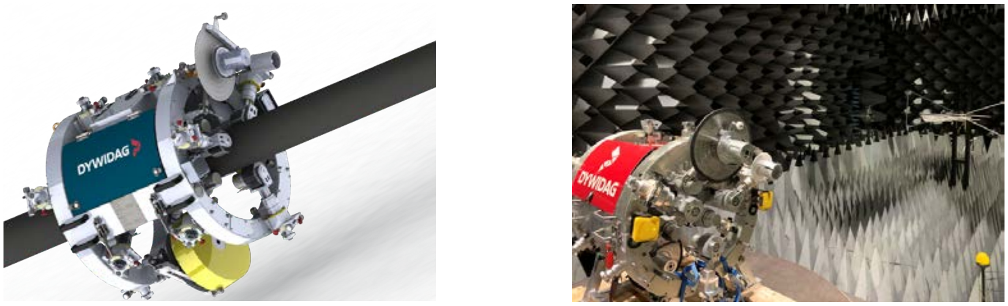

Figure 6. Third generation of wrapping robots of DYWIDAG-Systems International GmbH. Left: CAD-visualization of the new wrapping concept. Right: Final prototype in EMC testing laboratory to achieve CE-conformity.

A complete rework of the chassis, wheel drives, control electronics, battery system and remote control has led to higher operational speed (max. rotation speed of 1 ms^{-1}) and higher reliability of the devices during operation. Safety features like a three-way safety button on the remote control or a redundant radar personal protection system as well as a full-scale EMC testing of the robot guarantee a maximum of operational safety.

2.5 *Executional & environmental aspects*

The robotic application of the butyl rubber tape system ATIS Cableskin® for corrosion protection and UV protection of stay cables has a variety of advantages compared to classical paint. Above all, the elimination of the need for housing or scaffolding has a tremendous positive effect on project execution. This becomes visible when comparing two corrosion protection projects carried out at the same time in Germany in 2012 / 2013. While in case of the Rhine Bridge Speyer a massive scaffolding has been needed to carry out the painting works, in case of Obere Argen Bridge by using fully automated wrapping the scaffolding could be eliminated completely. This led to much faster project execution times of about 2 months in case of Obere Argen Bridge project compared to about 2 years on the Rhine Bridge Speyer project, see Figure 7.

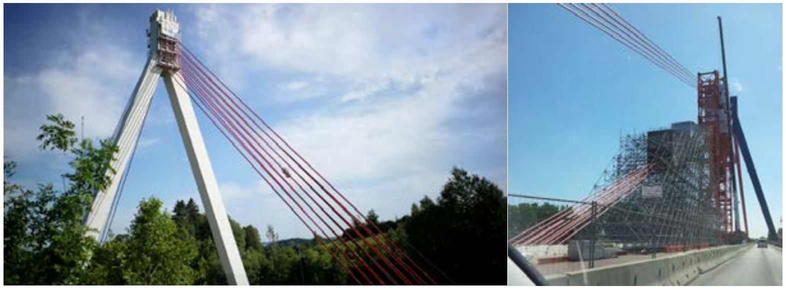

Figure 7. Comparison of stay cable corrosion protection. Left: Fully automated robotic cable wrapping of ATIS Cableskin®, Obere Argen Bridge, Germany, 2012. Right: Classical paint-based corrosion protection with use of scaffolding, Rhine Bridge Speyer, Germany, 2012-2013.

2.6 *Testing & Approvals of ATIS Cableskin®*

The butyl rubber system ATIS Cableskin® itself has a European technical assessment (ETA-13/0171) (DIBt 2019) as well a German technical approval (Z-30.11-41) (DIBt 2022). To achieve those approvals an intensive testing of the butyl rubber tape system has been executed according to DIN (EN ISO) standards in 2007 at Materialprüfanstalt Universität Stuttgart (see Table 1) (MPA 2007). Same tests were repeated according to ASTM standards in 2022 at Institut für Korrosionsschutz Dresden (IKS 2022).

Table 1. Material testing of ATIS Cableskin® according to DIN and ASTM standards

Test	DIN (EN ISO)	ASTM
Peal Resistance	DIN EN 12068*	no corresponding standard
Condensed Water	DIN EN ISO 6270-2*	ASTM D-2247**
Neutral Salt Spray	DIN EN ISO 9927*	ASTM B-117**
Condensation + Sulphur Dioxide SO_2	DIN EN ISO 3231*	ASTM G-87**
Artificial Weathering Xenon Arc Radiation	DIN EN ISO 4892-2*	ASTM G155**
Fire Resistance	DIN EN ISO 11925*	no corresponding standard

* Tested at Materialprüfanstalt Universität Stuttgart (MPA 2007)
** Tested at Institut für Korrosionsschutz Dresden (IKS 2022)

In summary, it can be stated that ATIS Cableskin® is a well-tested and approved system, which from an engineering point of view represents an excellent alternative to classic corrosion protection. The durability of the tape system is usually higher than that of traditional multilayer coating systems and additionally to this there are several executional advantages.

3 ROBOTIC CABLE PE-WELDING

In this chapter it is shortly described how robotic technology can be used for the maintenance of the PE stay pipes of stay cables either for repair works (see Section 3.1) or for improving the aerodynamic behavior (see Section 3.2).

3.1 *Cable repair*

PE stay pipes can be damaged for various reasons such as external mechanical impacts, pre-damaging during bridge construction, aging of the PE due to weathering and UV radiation or cyclic load changes due to temperature changes (day/night or winter/summer). In some cases, therefore it is necessary to attach additional PE stay pipes around the existing damaged pipe or even partially replace entire PE pipe segments. This work can be done with a combination of rope access works and semi-automated welding. Figure 8 shows a semi-automated welding device which was used for PE pipe repair works at Puente Ingeniero Carlos Fernández Casado in 2016.

Figure 8. Semi-automated welding for PE repair works of stay pipes. Left: Detail of PE extruder in front of the device. Right: Device welding a longitudinal welding seam at Puente Ingeniero Carlos Fernández Casado, Spain, 2016.

The stay pipes at this bridge had been pre-damaged during construction already due to excessive pressure of the injected grout. Because of the black surface of the PE pipes associated with the strong solar radiation in this region the pipes had been under heavy temperature induced mechanical tension over the years causing the cracking. Parts of the grout became loose, and water could penetrate the cables initiating corrosion of the outer strands which did not have any further corrosion protection.

For repair of the cables the damaged PE pipe sections have been cut radial and replaced by new PE pipe segments. This work has been carried out by RATs. To achieve a constant and reproducible quality of the welding seams the semi-automated welding device was used which is capable to weld longitudinal as well as radial seams of full 360° with constant thickness due to the constant linear or rotational speed of the welding device. After repair of the sheathings was completed, the new pipes were injected with a thixotropic flexible filler.

3.2 *Cable aerodynamics*

One of the classic phenomena of fluid mechanics is the flow around a cylinder – which is perfectly represented by stay cables. To mitigate rain-wind induced vibrations (RWIV) helical fillets on cable sheathings have been introduced to stay cable bridge design for the first time at Pont de Normandie Bridge, France (Christiansen et al. 2018). Even though Anzac Bridge in Australia was built at about the same time the PE pipes of its stay cables initially had not been equipped with helical fillets. When actual RWIV-related issues arose at the bridge it was decided for a retrofit solution (Oates et al. 2012).

All of the 128 stay cables have been retrofitted with helical fillets by the use of a fully automated welding robot which is based on the same modular concept as the fully automated wrapping robot (see Section 2.3) but this time having a welding module – which is also used for semi-automated PE repair works (see Section 3.1) – attached to the linear transportation module. As in case of wrapping, the pitch of the helical motion results from a superposition of linear and rotating movement. By constantly travelling down the cable the helical fillet is welded by a PE extruder carried by the robot, Figure 9. In order to ensure a constant thickness and geometry of the helical fillet a constant contact pressure of the PE extruder to the cable surface must be guaranteed in addition to a constant traversing speed. This is achieved via a special balancing mechanism, which compensates for the variable gravitational vector within a full 360° rotation.

Figure 9. Fully automated welding for retrofit of helical fillets to improve cable aerodynamics and reduce rain-wind induced cable vibrations, Anzac Bridge, Australia, 2012. Left: Cable-powered welding robot travelling down while welding a helical fillet. Right: Detail of the modular welding robot consisting of linear transportation unit, rotating unit and welding device including PE extruder.

4 ROBOTIC CABLE SURFACE ENHANCEMENT

In this chapter it is shortly described how robotic technology can be used for the maintenance of the stay pipes of stay cables either for cleaning works (see Section 4.1) or for surface enhancement by polishing for stay pipes made of stainless steel (see Section 4.2).

4.1 *Cable cleaning*

Pollution caused by traffic as well as climatic environmental conditions can result in soiling of cable surfaces over the years. Especially under humid conditions, thick mossy layers can accumulate, which have a negative impact on the visual appearance of the bridge, but in worst case can also have a negative effect on the cable aerodynamics.

For cleaning of the PE pipes of Puente Centenario in Panama a special high-pressure cleaning device was developed (Figure 10). Water is pumped from a high-pressure unit which is located on the bridge deck to the device via high-pressure hoses. In the device itself, the water is divided into a series of high-pressure nozzles, which distribute the water around the entire stay cable circumference. The cleaning effect is achieved solely by the parameters pressure and volume flow.

Only pure water without any cleaning additives is used, which makes the cleaning process environmentally friendly. Due to the weight of the high-pressure hoses and the water within them, as well as the massive water impact directly around the cleaning device, this cleaning concept is based on a purely mechanical device. Instead of being self-propelled the device is passively pulled with a textile rope which runs via a deflection point on the pylon to a winch located near the pylon base on the bridge deck.

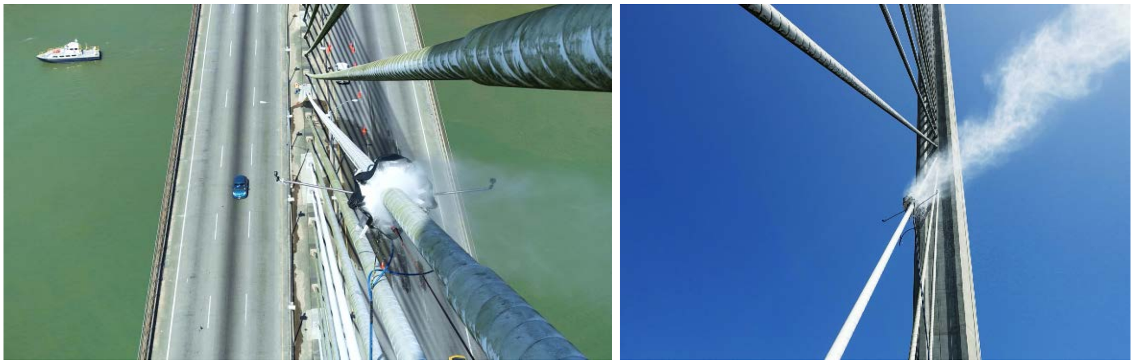

Figure 10. High-pressure cleaning device travelling along a stay cable of Puente Centenario, Panama, 2018. Left: View from pylon to bridge deck. Device being pulled upwards. Right: View from bridge deck to pylon. Clearly recognizable difference between cleaned white stay pipe and non-cleaned stay pipes.

4.2 *Cable polishing*

A project with a certain rarity serves as the last example of possible uses for robotic maintenance technology of cable supported bridges and structures. For the construction of the Mersch Red Bridge in Luxembourg it was decided to go for cable sheathing made of stainless steel (Figure 11).

Due to manual contact during installation process, the stainless-steel surface had tarnished irregularly, which resulted in an inhomogeneous and dull appearance of the stays which made subsequent surface polishing necessary.

Therefore, the modular robotic concept already presented for the fully automated cable welding was again modified just by replacement of the tool at the rotating module. Instead of a single PE extruder two polishing tools were attached 180° opposite to each other. A constant contact pressure of the polishing discs is crucial for a uniform result. This is achieved by modification of the balancing mechanism, which compensates for the variable gravitational vector like for the welding application (see Section 3.2).

Figure 11. Fully automated polishing robot travelling along a stay cable of Mersch Red Bridge, Luxembourg, 2016. Left: Device traveling downwards while polishing the stainless-steel surface. Right: Detail. Polishing module rotated about 90° compared to the left image.

5 CONCLUSIONS

This article has shown that the use of robotic technology for maintaining cable supported bridges and structures has already successfully proven itself in practice for a wide range of services. While some applications are implemented fully automatically, in others the synergy lies in an intelligent combination of rope access works and semi-automated devices. The advantages of constant and reproducible execution quality, reduced impact on traffic, shorter execution times and therefore reduced project costs are obvious. In addition to all of this, work safety is increased significantly. Thus, it can be assumed that the use of robotic technology for stay cable maintenance will continue to expand to also other fields of application, such as stay cable deicing.

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