Robotic inspection of cable supported bridges

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ABSTRACT: In recent years there have been several developments to automate the inspection of the free cable length of cable supported bridges by means of robots. Robotic inspection of cable supported bridges requires a detailed cable investigation of the free cable length but also the anchorage zone. That applies to a broad variety of cable types like stranded cables, grouted parallel wire cables, full locked cables, or open spiral cables. This article will focus on the robotic detection of Local Faults (LF), the Loss of Metallic Area (LMA) due to wear and corrosion using the Magnetic Rope Testing (MRT) method and the visual detection of defects in the corrosion protection system of the free cable length (e.g. PE-duct) such as cracks and tears using robotic methods. The article will show how robotic solutions are increasingly becoming an integral part of cable inspection projects.

1 INTRODUCTION

Cables of cable supported bridges are exposed to aggressive weather conditions, excessive vibrations, corrosion, and unexpected loading events (NCHRP 2005]. To guarantee the operational safety of the cable system several non-destructive inspection methods can be applied. Technologies like the Magnetic Rope Testing (MRT) have been applied since 1937 by the mining industry and are well established (OIPEEC 2019), see Figure 1.

Figure 1. First MRT testing introduced in 1937, Germany (Otto 1937).

Whilst there is no global standard for discard criteria of structural cable systems existing, ISO 4309 (ISO 2017) combines research from bending tests for different rope configurations used at cranes to formulate discard criteria. Failure modes found in e.g. a stranded cable provide different challenges but at least from an MRT perspective they are based on the same physical principles as for ropes. The MRT method should support the periodic inspection and should always be associated with a visual inspection according to ISO 4309:2017.

2 REQUIRED SYSTEM FOR A COMPLETE CABLE INSPECTION OF CABLE SUPPORTED BRIDGES

Bridge cable inspection covers a wide range of non-destructive testing methods (NDT) for the inspection of cable supported bridges. Primarily, there is a basic visual inspection by a certified bridge inspector which is focused on critical positions e.g. the anchorage zone. This often requires the removal of the end caps on the sockets to perform a visual inspection of the anchorage and connected anchorage devices to see if there are moisture, corrosion, or other anomalies inside. Depending on the cable configuration the visual inspection includes detection of corrosion, mechanical damages, loosening of anchor components, detection of water ingress, and deterioration or dislocation of neoprene boots (Gimsing 2012).

If during a visual inspection severe surface deterioration or wire breakage is detected, a more detailed inspection of the cables using nondestructive testing techniques should be required to determine the extent of loss (AASHTO 2008).

Robotic inspection (e.g. magneto-inductive rope testing technology) cannot be applied in the anchorage zone. Inspection of the anchorage zone or connected piping resp. cable sheathing will use methods like borescope inspection or ultrasonic testing (UT) of the individual strands or parallel wires. UT is used to identify wire breaks within a limited range of the cable end. The limitations of UT depend on the accessibility of the cable end in the anchorage zone and the cable configuration. They must be carefully evaluated for every bridge.

High sensible vibration measurements allow a frequency analysis. Based on the measured Eigenfrequencies and considering the cable stiffness and bearing conditions a cable force can be calculated. This method can be used to globally assess the cable condition. As cable forces are impacted by temperature and life loads a direct comparison with previous measurements requires detailed analysis.

The free cable length can be inspected by using robotic technology. Here two methodologies go in hand: robotic visual inspection to inspect the cable condition from the outside and robotic magneto-inductive testing to analyze the condition of the cable from the inside.

3 ROBOTIC MAGNETO-INDUCTIVE INSPECTION OF BRIDGE CABLES

The magneto-inductive rope testing technology (MRT) has been successfully applied since mid 20^{th} century mainly for ropeways and mine hoists. First prototype devices have already been developed in 1989 in the US to inspect the free length of stay cables (NCHRP 2005).
The dimensions of these devices should be compact and they are designed to get close contact to the metallic cross section. MRT is one of the main non-destructive testing (NDT) methods applied for cables.

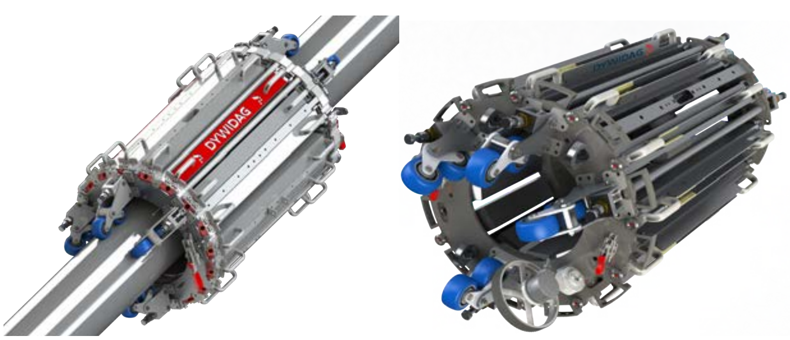

Figure 2. R315 - The world's largest bridge cable MRT device - modular design by DYWIDAG (left), R250 MRT device - modular design by DYWIDAG (right).

ISO 4309:2017 states that MRT should be used where defects might exist which cannot be identified by visual inspection alone (ISO 2017).

With the latest technology this approach has been taken a step further in order to inspect large metallic cross-sections of cables where a closeness to the metallic cross-section is not always given (e.g. strands surrounded by a not completely filled pipe). This requires a new approach for both sensor technology as well as modular device design (Figure 2) to allow an on-site setup by rope access technicians with minimum impact to the traffic.

3.1 *MRT Technology*

The MRT method magnetizes the metallic cross-section of the rope locally along the cable path. This can be achieved either by applying large permanent magnets around the circumference of the cable or by the usage of an electromagnetic exciter coil.

In accordance to DIN EN 12927-8 (DIN EN 2019) a magnetic flux density of at least 1.9 T but not more than 2.3 T is required to properly detect defects across the full metallic cross-section. The required magnetic flux density must expand at 0.5 · cable diameter in both axial directions of the metallic cross-section (Figure 3). This technology can be used for different ferromagnetic cable types (e.g., stranded, full locked, etc.). A defect which is located inside of the cable only causes the magnetic field lines to be distorted locally within the cable if the magnetic flux density is below 1.9 T. This means the defect signal cannot be picked up by the Hall or coil sensors. In Figure 8 it is shown that a magnetic field > 1.9 T distorts the magnetic field lines across the entire cross-section and therefore causes a leakage of a stray field outside of the cable which is measurable by the sensors.

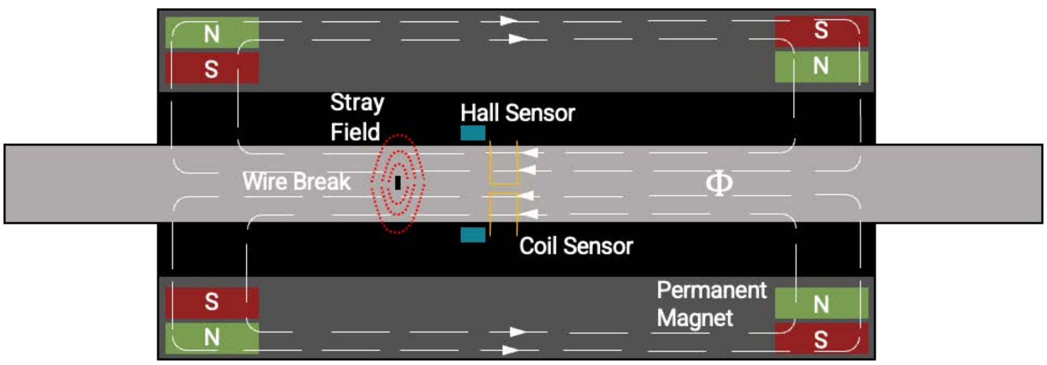

Figure 3. Principal setup of a MRT device.

Two sensor technologies are installed to detect defects such as wire breaks or corrosion pitting in the cable. Coil sensors are the traditional sensor type that was applied first (Figure 1). A coil sensor requires a relative movement between the cable and the detector to record a voltage V that is induced following the Faraday's Law which is proportional to the field variation. In this case a voltage represents the derivative of the magnetic field B and its variations (e.g. caused by defects).

$$V = k \cdot \frac{dB}{dt} \quad (1)$$

k = Constant geometry factor

This signal is proportional to the relative speed between device and the rope. Therefore, a high and constant velocity of the device is desired to achieve a good signal quality.

The second sensor type applied are Hall effect sensors which are passive sensors. If a conductor with a current I_{dc} flowing in one direction is introduced perpendicular to a magnetic field B a voltage V can be measured.

$$V = \frac{R_h \cdot I_{dc} \cdot B}{D} \quad (2)$$

D = Thickness of Hall effect sensor

R_h=Hall constant

The voltage mirrors the magnetic induction in the rope and its variations (caused by defects). The output signal is a sum of different frequencies which constitute the rope information. Filter technology is applied to achieve a good ratio between peak identification caused by defect and the signal base level representative for the rope conditions.

Given a sufficient sample rate low pass and band pass filters are applied to the signal. To clearly filter the signal a good understanding of the defect types and expected failure modes is required. Modern MRT technology is usually applied to detect two types of defects by generating separate signals for each defect type. Both defect types will be explained in the following sections.

3.2 *Local Fault (LF)*

The first defect is a quantitative determination of discontinuities in the cable such as wire breaks, corrosion pits or any other physical condition that degrades the integrity of the cable in a localized manner. They are called Local Faults (LF).

A signal to record such defects measures the leakage of magnetic flux, caused by a defect on a magnetized cable (detected by both coil and Hall effect sensor). The basic characteristics in the signal caused by irregularities of the rope are not to be mistaken for signal noise.

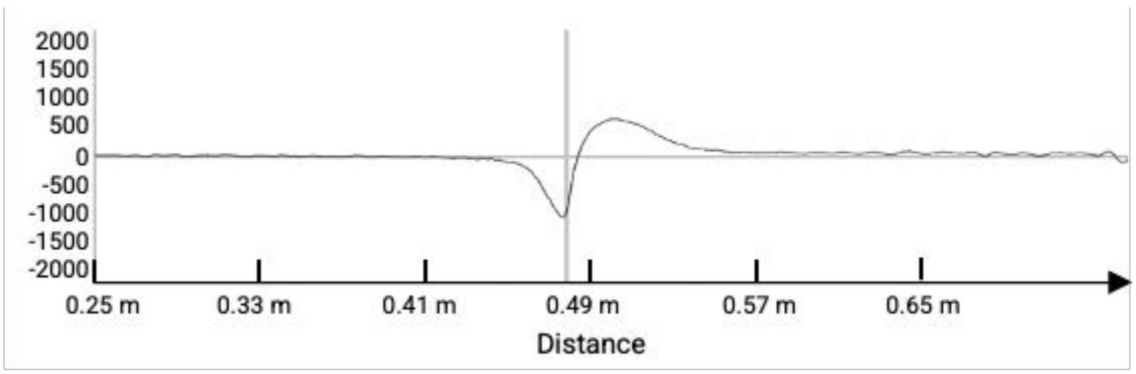

Figure 4. Characteristic magnetic flux leakage signature from a coil signal, with the shape representing the defect.

A wire break is characterized by two distinct peaks in the signal, with an amplitude well above the basic signal. The amplitude of the signal is internally normalized and is not equipped with a physical unit (Figure 4). The size and shape of the defect can be derived from the signal. Defect parameters that disturb the distribution of the leakage flux (and therefore the signal shape) are sharpness, depth, width, length at the edge (Kaur 2017).

Reliable defect detection requires a lot of experience as signals recorded on large cables usually do not show defects as clear as shown in Figure 4.

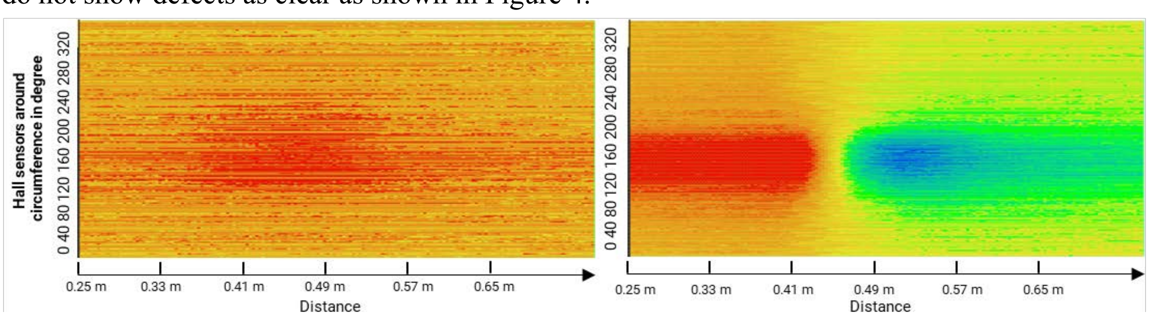

Figure 5. Heatmap generated from Hall effect sensors for defect located in the cable center of a 127-strand cable, magnetization in the center 1.425 T (left), magnetization in the center 1.9 T (right).

An advanced method for defect detection based on Hall effect sensor technology is displayed in Figure 5. The display of the cable cross-section in the format of a 3-D heatmap requires a high number of Hall effect sensors to be evenly distributed around the circumference.

The Y axis displays the position around the cable circumference. In X axis the distance along the cable is displayed. Provided with sufficient magnetization an indication of the defect distance to the cable center is recorded. Whitest a defect found on the outer layer of e.g. a parallel wire cable will only be picked up by a small number of Hall effect sensors, a defect being located in the center of the metallic cross-section would theoretically be picked up by every Hall effect sensor. Depending on how the defect stands out against the base signal the size, shape and type of the defect can be analyzed.

For LF ISO 4309:2017 provides discard criteria. A calculation of a loss of metallic area resulting from wire breaks needs to be made and cross checked with Table 1.

Table 1. LF-MRT discard criteria, based on ISO 4309, Annex C (ISO 2017)

	LMA %
Over a length of 6d	6
Over a length of 30d	10
d = nominal diameter of cable	

It must be highlighted that ISO 4309:2017 was developed for wire ropes and due to different cable configurations (e.g., strand or parallel wire) discard criteria can differ. Therefore, further guidelines or standards with adapted discard criteria for bridge cable systems must be created.

3.3 *Loss of Metallic Area (LMA)*

The concept of LMA serves the purpose of giving the inspector an opportunity to quantify defects that occur in a cable usually caused by corrosion (internal or external) and wear. This can be a gradual change along the cable length. For this signal the measurement of the full metallic cross-section according to DIN EN 12927-8 is required. For the measurement the LMA signal Hall effect sensors must be physically inserted into the magnetic flux path (Weischedel 1985).

The generated output will provide the LMA of the metallic cross-section of a cable as percentage, with respect to a reference point on the cable representing the maximum metallic cross-sectional area (ASTM 1993).

Recording of the LMA signal requires calibration of the device according to DIN EN 12927-8 (DIN EN 2019).

An increase of broken or corroded wires will cause more obstacles to the flow of the magnetic flux. In case of corrosion in a defected area metal has been replaced by air, modifying the total value of the resistance in the cable. This will correspond to a higher reluctance.

If the defect area is longer than the device, the Loss of Metallic Volume (LMV) and Loss of Metallic Area (LMA) is proportional. If the defect is shorter than the device, the signal gets smaller. This is why the LMA signal is used primarily for long defects like wear or corrosion - not for wire breaks.

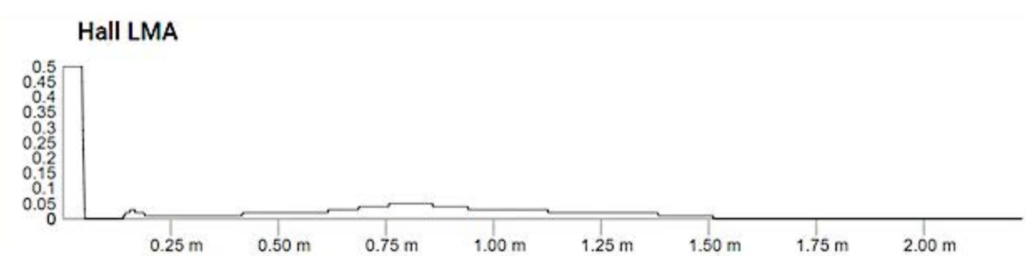

Figure 6. Hall-LMA Signal showing cross-section reduction in percentage.

For the determination of the LMA the whole metallic cable cross-section is used. ISO 4309:2017 provides discard criteria according to Table 2.

Table 2. LMA-MRT discard criteria, based on ISO 4309, Annex C (ISO 2017).

	LMA %
Over a length of 30d	10
d = nominal diameter of cable	

3.4 *MRT Devices*

Current MRT technology covers a diameter range from 18 mm to 315 mm cable diameter (this equals an inspectable metallic cross-section of max. $19500\,mm^2$). Large devices for bridge inspection are typically based on a modular permanent magnet system (Figure 7). This means that the robot consists of a lightweight chassis that can be installed and operated by two operators. The permanent magnets are then installed and handled separately. The number of magnets scales with the device size. The weight per unit is below 20 kg. The devices are pulled passively by a winch. Wheel drive systems need to be designed to accommodate changes in diameter up to 30 mm which can include radial rings, helical fillets or ovalization of the cable sheathing. The wheel drives are designed to be adjusted for different cables sizes whilst different sensor heads are equipped suited for the measured cable diameter. Modern MRT devices can be operated wirelessly. The measurement is continued even if the connection is interrupted.

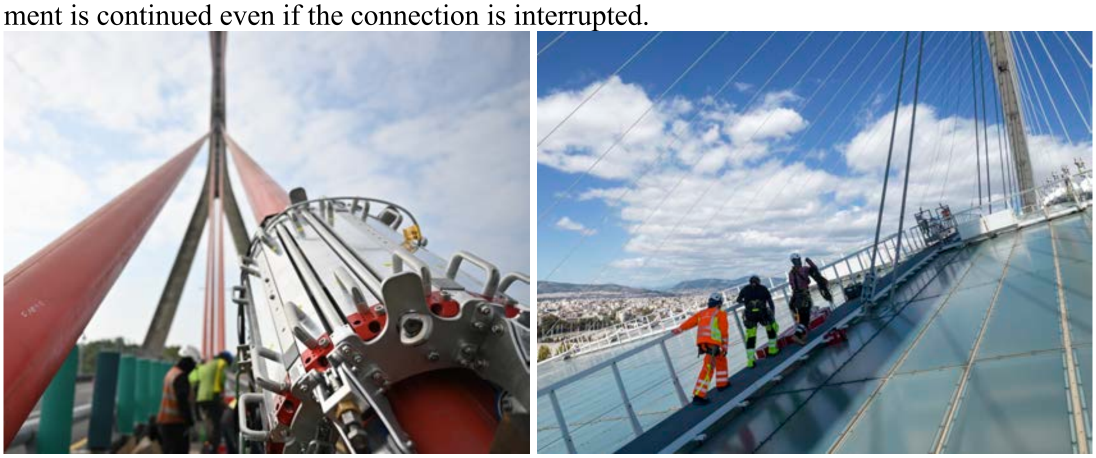

Figure 7. Application of the R315 MRT device designed by DYWIDAG at Kao Ping Bridge -Taiwan (left), application of the R140 MRT device designed by DYWIDAG at Olympic Stadium Athens – Greece (right).

MRT devices can be certified based on DIN EN12927-8. This means the devices must pass a specified accuracy test and receive an according certification. The test requires defect a detection of a failure with a section loss caused by the defects lower than 0.5 % with a maximum distance from the device (at the cable center). For this reason, EN12927-8 is a strong proof of the sensitivity of a device. The equipment must completely saturate the rope and it must report a well-defined signal, with a signal to noise ratio:

$$\frac{signal}{noise} > 2 \tag{3}$$

MRT devices typically record three different channels / signals. A coil signal to detect Local Faults (LF), a Hall signal to detect Local Faults (LF) and Hall signal to calculate the loss of metallic area (LMA). All data stored include the position in axial direction along the cable which is recorded with a measurement wheel at the device. MRT devices are equipped with up to 500 Hall effect sensors which enable the computing of a detailed 3-D heatmap around the circumference (Figure 8). The 3-D heatmap can be used locally to differentiate between defect selections from the 2-D Hall- or coil signal. It can also be used as a 3-D localization tool for defects. The recorded data of all four channels can be viewed in parallel in a viewer. Modern viewer tools can provide an automated defect detection. Detected defects can then be analyzed and annotated for each cable. After the data is analyzed a report can be generated automatically.

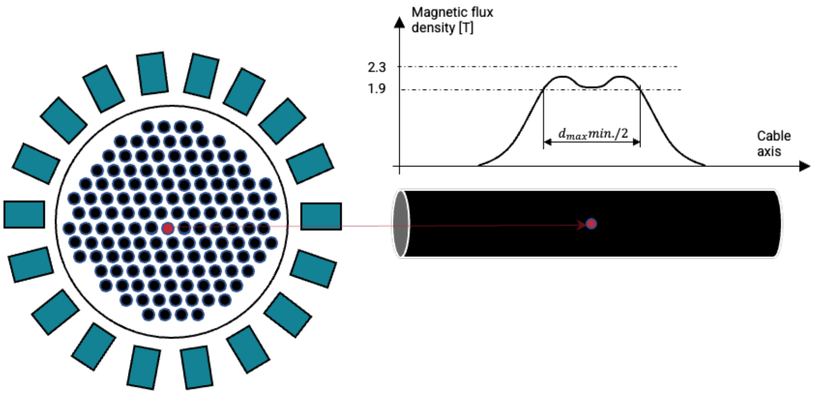

Figure 8. Cable cross-section with permanent magnet array (left), cable in axial direction with magnetic flux density plot according to DIN EN 12927-8 (DIN EN 2019).

4 ROBOTIC VISUAL INSPECTION OF BRIDGE CABLES

Robotic visual inspection is an advanced method to inspect difficult accessible parts of the bridge structure, in accordance with DIN 1076 (DIN 1999).

By robotic visual inspection longitudinal or transverse cracking of the stay cable sheathing, leakages, defects of coating, corrosion or wire breaks of the outer wires can be detected and appropriately recorded. Latest robotic inspection devices shown in Figure 9 can generate and store full panoramic images of the free cable length. The devices adopt to different cable diameters and are available for a diameter range between 50 mm and 450 mm.

Figure 9. Inspection Bot (new generation) Size L by DYWIDAG (left), application of the Inspection Bot (first generation) Size M by DYWIDAG at Obere Argen Bridge, Germany, 2012 (right) (Kuhn 2008).

For an accurate assessment of the cable condition an isolation from external lighting conditions at the cable is required. Light modules must be placed around the circumference to shield and illuminate the cable. There is a first generation of self-driven cable powered systems (Figure 9, right) as well as a new generation of self-driven battery powered systems (Figure 9, left) which are capable to inspect bridge cables up to 600 m of length without any need of lane closures.

The drive systems have to accommodate for a change in diameter of 30 mm (e.g. radial rings, helical fillets, sudden changes in diameter or ovalization of the cable sheathing). Self driven robotic devices for cable inspection have to be able to provide sufficient traction of the wheel drives on cable surfaces whilst still having enough system elasticity to accommodate for the diameter changes. The devices displayed in Figure 9 are equipped with a special spring-damping system to achieve this.

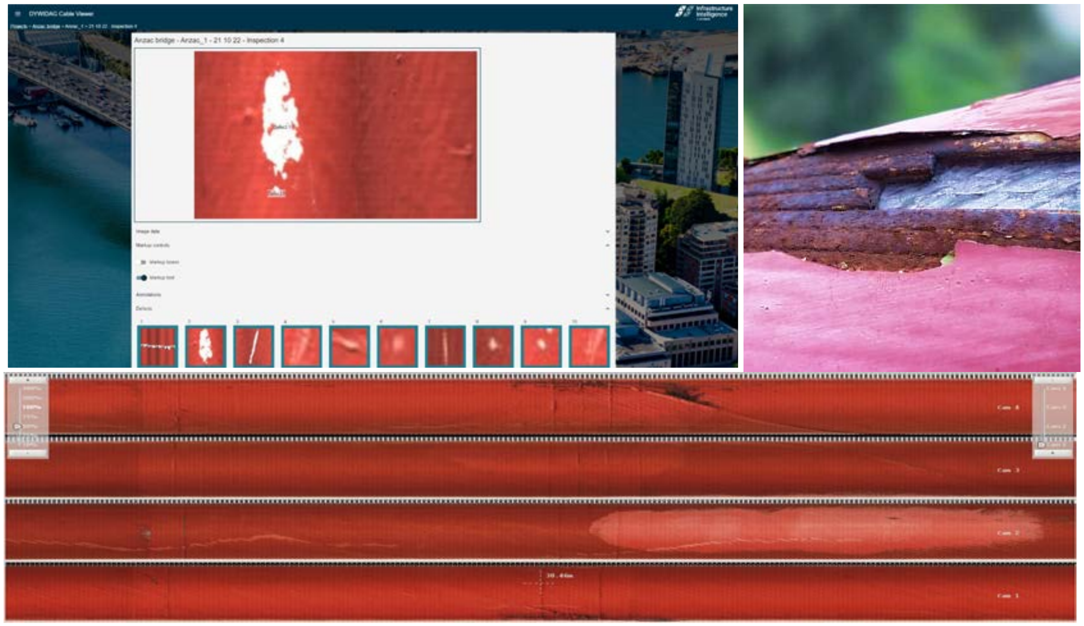

Figure 10. Visual inspection data viewer with automated defect detection by DYWIDAG.

Self-driven robotic inspection devices have to be equipped with brake systems to quickly react in case of a loss of traction (e.g. caused by unexpected rain). The devices itself achieve a IP 54 rating (in accordance to DIN EN 60529) but are neither used on a wet cable surface or when temperatures are bellow dew point. The devices are remote controlled from the bridge deck whilst the inspection data is stored automatically.

The panoramic images are generated with a resolution up to $10\ \frac{pixel}{mm}$ in axial direction by industrial cameras. Then the files are automatically stitched and corrected of their barrel and cylindrical distortion. A further camera equipped to the front of the device is used for device navigation but can also be used to inspect transition zones or the pylon. Modern data viewers are designed to enable easy navigation through the history of inspections of different bridges but also the compare the development of the cable condition for one bridge. Specific areas of the recorded panoramic images can be picked out and directly compared to recordings from previous inspections e.g. 6 years ago, annotated and stored for reporting purposes. The data can also be correlated with data recorded from a MRT inspection (see Section 3.4). This is especially useful for defects where the root cause e.g. a crack in the sheathing of a stay cable system and the subsequent corrosion issue can initiate defects inside of the cable. Through data correlation consequent measures can be taken. Reports of the annotated data are generated automatically. The software displayed in Figure 10 can also make an artificial intelligence (AI) based preselection of defects which can aid the inspector to find the defects quicker and more reliable. To improve the AI capability for finding a wide variety of defects inspection data is constantly collected and categorized.

5 CONCLUSIONS

With the latest developments of robotic technology bridge inspections can be made much faster whilst reporting the bridge condition way more detailed than it was possible in the past. Inspections become more repeatable and – based on a much deeper understanding of the current bridge condition – also allow the prediction of the future development of the bridge condition.

Like it was shown in chapter 2 it is important to understand how the different inspection technologies are to be used in conjunction. Robotic inspection is very useful especially for parts of the bridge which are difficult to access, but they can only be applied on the free cable length for now which requires corresponding technologies like the ultrasonic testing to inspect parts of the cable that can’t be entered by a robot.

Although these are great achievements for the inspection of bridges, still there is a lot of work to be done. As this technology is still very new in the bridge context, current standards don't cover all common cable systems and are not designed specifically for the failure criteria that are common for bridge cable systems. This requires bridge experts internationally to gather and collaborate on a new standard for bridge inspection criteria.

The application of robotic inspection for bridges will become more popular in the upcoming years which will make bridges much safer.

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