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Long life structural health monitoring of selected bridges

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Abstract

The paper is focused on the structural health monitoring, current methodology of inspection in Slovakia for road and railway bridges. Consequently, the paper presents the advanced methods for monitoring and inspection of bridges using various types of robots and unnamed aerial vehicles. It describes two selected case studies, where all integrated system of structural health monitoring will be applied. Later, it defines the inspection and current condition of road arc bridge with stiffened beams and steel truss bridge.

Keywords: "bridge structure; digital twin; transport; security"

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1. Introduction

The scope of the project IRIS funded by SPS NATO is to develop an innovative integrated system for inspection and monitoring of essential structures (so called critical infrastructures – bridges, dams, offshore construction etc.) to ensure its security. Integrated systems will be developed to real time cooperation by digital environment reproducing degraded infrastructure and robots conducting inspection, maintenance and security actions performing novel sensing modalities, Dvořák et al. (2021).

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The developed model in the project will be used as digital twins (a living model, one that can be used for numerical simulations, visualizations, or just complex data management. Inspection data gets layered onto this model and then analysed) of the facilities with the purpose of life cycle management. The digital environment will consider both surface and underwater components of the structure. It will nclude both surface inspection robots, such as drones, ground robots as well as specifically underwater inspection robots, allowing parts of the structure lying under the water level. Data-driven models using data fusion and machine-learning for life cycle assessment of infrastructure will be developed.

2. Structural health monitoring

Existing structures need to be regularly inspected to detect any damage and to plan the necessary maintenance. The owner, or their designated facility managers, are responsible for ensuring that regular surveillance activities are carried out on the facility, which is the collection of a set of information about the facility in operation. The purpose of inspections and diagnostics is primarily to obtain information on the structural and technical condition of the building. On the basis of their evaluation, decisions are taken on traffic restrictions or closures, the carrying capacity of the facility is reviewed, and maintenance, repair or reconstruction of the facility is planned, Rinaldi (2021, 2022).

2.1. Currents methods in Slovakia

In Slovakia, inspections and diagnostics of road bridges are carried out according to the technical conditions issued by the Ministry of Transport, Construction and Regional Development of the Slovak Republic, Section of Road Transport and Land Communications. These are TP 059 - Commissioning and performance of bridge diagnostics (TP 059, 2012) and TP 060 - Inspection, maintenance and repair of roads (TP 060, 2012) issued by the private company Fidop s.r.o. and the Slovak Road Administration.

According to the inspection, bridge conditions are classified in seven condition classes depending on the level of damage: I – perfect, II – very good, III – good, IV – acceptable, V – bad, VI – very bad and VII – emergency condition.

These regulations lay down the basic rules for carrying out inspections and diagnostics of existing bridges using standard methods and procedures. The quantification of bridge failures and damages is carried out for road bridges according to TP 061 - Catalogue of failures of bridge structures on motorways, expressways and I. roads (TP 061, 2019). The results of inspections, diagnostics and further process of maintenance, repairs or reconstruction of bridges on roads in Slovakia are governed by the regulations of TP 075 - Registration of road bridges and footbridges (TP 075, 2013) and TP 014 - Bridge management system (TP 014, 2013) developed by private companies Fidop s.r.o. and Dopravoprojekt a.s. The whole process is largely affected by the financial under-budgeting of the Ministry of Transport. For this reason, in Slovakia, the diagnostics, repairs and reconstruction of bridges of the road network are dealt with only for objects in poor or disrepair condition.

A significant problem in the reconstruction and repair of road bridges is also the poor conception of the country's road infrastructure and the resulting detours are very long. As far as railway bridges in Slovakia are concerned, they all fall under the administration of the State Enterprise Railways of the Slovak Republic (ŽSR).

Diagnostic and maintenance inspections are governed by the internal regulations of TS5 (MANAGEMENT OF BRIDGES) and ŽSR VTP-UZŽMO (GENERAL TECHNICAL REQUIREMENTS, Determination of the load capacity of railway bridges on ŽSR). These tasks are exclusively with the competence of the professional staff of the state enterprise ŽSR. Levels of technical conditions for railways bridges are classified in classes: a) Grade 1 - excellent condition, b) Grade 2 - good condition, c) Grade 3 - fair condition, d) Grade 4 - limiting condition, e) Grade 5 - unsatisfactory condition. The lower structure and each supporting structure are assessed separately. With the local evaluations, an overall bridge evaluation shall be made. There is also an assessment according to the standard S5 in force which is a three-stage assessment 1 - without defects, 2 - with small defects, 3 - has to be reconstructed, which at the next assessment will be assessed in accordance with the Railway Infrastructure Regulations TS5. The periodicity of detailed bridge inspections is 3 years.

Slovakia has not recorded a railway bridge collapse to date. Currently, extensive reconstruction-modernization of main railway corridors is underway due to increasing travel speed. As part of these large-scale interventions in the railway infrastructure, new bridges are being built and existing bridges are being reconstructed, in which monitoring systems are now being installed to monitor their structural and technical condition.

Surface defects and damages, quality and condition of surface finishes, traces of moisture, condition of surface layers of built-up building materials, cracks (their extent, distribution, direction), displacements and deformations on load-bearing and filling structures, failures of contacts and joints of structures and structural elements, possible cavities (they are detected by tapping) are detected. Visual inspections are carried out on an actual basis using inspection benches, lifting platforms and trained personnel working at height. However, such inspection methods are inadequate in inaccessible locations (such as over water, at high altitudes, etc.). The findings shall be recorded in a survey report in the form of a text document and photographs available to the facility manager.

Inspections are in major cases made only observing with naked eye.

2.2. New methods of monitoring

Use of unmanned aerial vehicles for inspections

The Unmanned Aerial Vehicles (UAVs) are known for their role in military applications but more recently, the potential use of UAVs as tools in civilian environments has gained significant attention. The aging and deterioration of structures such as bridges or buildings are becoming an urgent social issue; regular inspections for the preservation of the structures are needed, but it means high cost especially in terms of safety for workers due to the difficulty to access. Visual inspection of workers can be replaced by using basic UAVs, which share many advantages such as speed, safety for the workers, cost-effectiveness, inspection without traffic closure in some situations, share-ability with more stakeholders instantly, and maneuverability by making use of automated flights, Daponte et al. (2023).

A visual inspection made by UAVs is the first part of a complex survey campaign, and its use allows for planning experimental investigation for diagnostic (see Fig.1). For these tasks the UAV is equipped with a Video camera, and a GPS receiver.

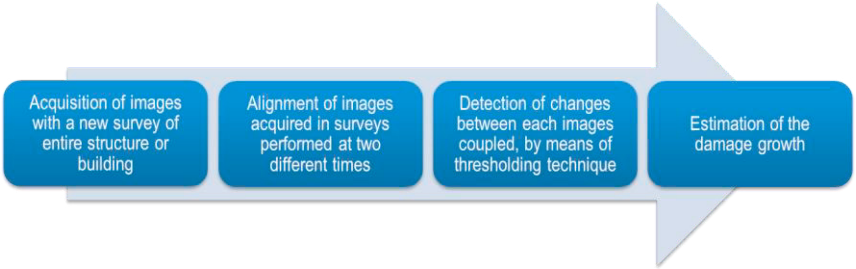

Fig. 1. Procedure for structural health monitoring by UAV.

From a measurement point of view, it is worth underlining that the luminosity changes can affect the performance of the thresholding technique, the minimum size of the damage that can be detected depends on the flight altitude, the position accuracy must be high enough to localize single damage, the detection is performed with post-processing methods.

The use of infrared thermography supported by a UAV is such a great non-destructive method which evaluates buildings without any contact and carry out rapid investigations. Its use is useful for discovering types of materials with which structures are made (masonry, concrete), discovering the presence of steel rebars, water leakages or humidity, or the thermal patterns within the building envelope as well as the movement through and across various building materials. The non-contact nature of infrared thermography is well-suited to projects that deal with historical buildings or to areas that have experienced catastrophic disasters. In addition, there is growing attention on the extraction of quantitative information from images in consequence of the identification of deterioration regions and crack detection. The ability to detect and measure concrete crack thickness and length using UAVs has already been researched. Using a specific software, it is possible to measure distances, specifically dimensions of structural elements, comparing them with project drawings. Moreover, it is possible to measure span deflections over the time on bridge or beams, caused by increasing loads or by long term effects, Ciampa (2019).

Since a UAV is equipped with electrical sensors like gyroscope and magnetometer, it can be affected by communication interference if there are magnetic sources around the UAV. Thus, the UAV takeoff location and flight path should be away from large metal objects or reinforced concrete structures. Weather conditions can affect the quality of the visual data collected: shadows and glare from reflective surface can affect the results of the 3D process.

Measurements can be estimated from images, but tactile functions (e.g. cleaning, sounding, measuring, and testing) equivalent to a hands-on inspection cannot be replicated using drones. It is worth to underline the need of a qualified person to pilot a UAV, liability, insurance, flight permission by national Civil Aviation Authority and property permission to fly on private soil.

The use of UAVs should be considered as an assistive tool for routine inspections to improve the quality of the inspection by obtaining information and details that may not be readily obtained without expensive access methods and sometime the interruption of the service is required. This technology can aid structural engineers in performing different nondestructive tests and plan future destructive ones.

Use of robots for inspections

Inspection is crucial activity to be performed to assess structural deterioration of structures and infrastructures, due to several factors, such as high pollution, lack of inspection and maintenance activities. As a results, sometimes structures may become obsolete even before their intended lifetime. Performing periodic inspection is costly and sometimes dangerous moreover, the inspection process requires workers who are well-trained, as described in Solla et al. (2015).

Therefore, solutions involving automatic, guided inspections by robotic systems have started to be developed to increase safety of the operators reducing the exposure to the risks related to the operations to carry out, as described by Figuli (2021), Leitner (2021) and Rea (2017). The application of autonomous and tele-operated robots for monitoring infrastructures is becoming feasible due to the development, enhancing, and merging of technologies such as computing, communication, instrumentation, and others. Robotics for inspection allows the automation of operations related to the inspection and maintenance of scenarios that involve risks for operators. There are difficult-to-access or dangerous environments for humans, such as nuclear power plants, the chemical industry where toxic substances are handled, or places where there is a danger of collapse, among others.

Unmanned robot systems, both autonomous and tele-operated, are composed by a mechanical part, which is devoted to the interaction with the environment, power supply, actuators, control, and communication systems. Additional specialized units, such as cameras, grippers, and others, are included in order to build a main system to accomplish a predetermined task, Rea et al. (2018); Gonçalves et al. (2018). Robots for inspection can be firstly classified according to the task, and the environment and very often many solutions can be considered bioinspired, as reported in Sandin, (2003). Robots can be classified as UAV (Unmanned Aerial Vehicle), UGV (Unmanned Ground Vehicle), Climbing Robots, and Underwater rovers.

UAVs consists of mobile systems that fly in a certain aerial space (airplanes, helicopters, drones, rockets, animal-mimicking flying systems. Ground mobile systems are those that negotiate with the ground, they can be further classified in wheeled/tracked, legged, of hybrid solutions. Climbing robots are those able to negotiate with vertical surfaces or pipes. Water and underwater systems are ships, boats, autonomous underwater vehicles.

Referring to ground mobile systems wheeled or tracked are the most common types of locomotion to almost flat surfaces, when the obstacles sized are almost of the same size of the wheels radius. These systems have low energy consumption and easily outfitted with large payloads, including sensor packages, robotic arms, or custom accessories, and of course batteries, Gibb et al. (2018), Bruzzone et al. (2012).

When negotiating with uneven terrain, legged robots have broad mobility, which makes them suitable for many applications both in structured environments and on unstructured environment. However, they are relatively slow and high energy consuming. Legged robots have many actuators and a complex control system. The development of legged mobile robots is often biologically inspired, there are robots with two legs (inspired by humans), with four legs (inspired by quadrupeds), and with more than four legs (inspired by insects), examples are found in Raibert et al.(2008). Hybrid mobile robots have been developed to exploit the advantages of both previous locomotion types, Ottaviano et al., (2014). They can be composed by legs combined with wheels/tracks, being able to overpassing a large number and types of obstacles, Ottaviano et al. (2013).

Steel structures and steel bridges, constituting a major part of civil infrastructure, require adequate maintenance and health monitoring. Currently, steel infrastructure inspection activities require a great amount of human effort along with expensive and specialized equipment. There have been a significant number of studies related to using advanced technologies for bridge inspection and maintenance. Certain climbing and crawling mechanisms, some of which are bio-mimetic, have been developed for movement on vertical walls or uneven surfaces of steel structures. Examples include gecko-like locomotion that can climb on smooth surfaces using directional adhesion, a vacuum-creating suction adhesion, and a climbing mechanism using adhesive materials. Moreover, very specific designs are required for pipe inspection. A bioinspired robot was proposed in Kanada et al. (2019), climbing robot designs are well suited for wind turbines inspection, as it was proposed in BladeBug, (2023).

In the context of inspection of bridges, most of the time, UAVs are the most suited solution, although it is evident that they work properly in outdoor environment. Indeed, for box girder bridges other solutions have to be considered.

3. Case studies

For the purpose of the research, two case studies in Slovakia were selected. One railway and road bridge, where all integrated system of structural health monitoring will be applied.

3.1. Railway viaduct Ružín

In 1963-1970 on the river Hornád southeast of the village of Margecany in easter part of Slovakia a Ružín dam reservoir was built. Is a system of two hydraulic structures Ružín I and Ružín II, source of water for industry and thermal power generator. The reservoir has a storage volume of 45.3 million cubic metres and the flooded area is 3.9 square kilometres. The length of the dam is 14 kilometres The railway viaduct Ružín N°2601 cross the reservoir in km 125,541.

Fig. 2. View on the bridge and situation. https://ismcs.cdb.sk/

Current conditions of the bridge

The last detailed inspection of the bridge was made in December 2020. On the lower chord of the beam there is inspection bench (Fig. 3) which allows safe movement inside the construction. The steel construction shows normal abrasion.

(a) (b) (c) (d)

Fig. 3. (a) horizontal surface corrosion, (b) exposed areas with corrosion, (c) joints stringer to transversal weakened by the corrosion (d) loosened rivet

Anti-corrosion protection degrades on horizontal surfaces and in exposed areas of the structure (connections stringers, crossbeam, and main girders, joints plates) where steel corrosion occurs. More significant failures - cracks and weakening by corrosion is in the wall plates of the connection of the longitudinal member to the transversal beam. In rare cases, rivets and screws are loosened. Rare fatigue cracks on the upper flanges of the stringers in the bearing of the bridge decks are present. Bearings are functional with surface corrosion. Concrete parts of the substructure is damaged with surface cracks. Facing stone are locally not jointed with the present of the local dimensional deviations. The current condition of the bridge is evaluated according to the ŽSR TS5 regulation as grade 3 - satisfactory for supporting structure and clearence gauge and as 2 good for bridge foundations and sleepers.

3.2. Road bridge Bytča

The second bridge is part of the road N° 10 (I/10) in the route from Bytča to Makov in the direction to the state border with Czech Republic (see Fig.4). Identification number of the bridge is M2109. The bridge is designed as beam stiffened by arch (so called Langer beam) with the lower bridge deck with the total length of 105. 21m. Axial distance of beams 13,4m and maximum height is 15,802m. Bridge was constructed in 1991.

Fig. 4. View on the bridge and situation.

Current conditions of the bridge

According to the last deep inspection of the bridge, the current class of the bridge condition was categorised as class 3, what in good condition TP 08/2012 (2012). The bridge defects not affect the load-carrying capacity but reduce the service life. Major defects are damaged railings, damaged protective plaster, damaged pavement of roadway, presented vegetation in the bridge in small extent, damaged cornices, damaged surface treatment of light alloy structures or their surface is oxidised, unrestored coatings with the first signs of rusting of the steel structure, subsidence of the embankment. Connections on the right and left side of bridge decks are with the corrosion, the lower part of bearing is shrivelled (see Fig.5)

The current normal load capacity is 26 t, exclusive load capacity is 80 t and exceptional load capacity is 196 t.

Fig. 5. (a) corrosion of the connections, (b) shrivelled part of bearing, (c) inspection bench and the view on the longitudinal and transversal beam of bridge deck.

4. Discussion and conclusions

Presented work is the part of research project IRIS. The core of the proposed IRIS project relates to the development of new technologies to fully automate the use of robotized systems and sensor networks in data acquisition for survey, inspection and monitoring. Two case studies were selected. The initial step was to make the first inspection of bridges, consequently the BIM model as design, based on the original technical drawings, will be created. Consequently, the new methods presented in the chapter 2 will be applied. Bridges will be scanned by LIDAR using of unmanned aerial vehicles and robots. One of the robot will monitor internal part of the Bytča bridge arch. UAVs will be selected to monitor bridges as well as to carry Lidar for 3 d scanning. Point cloud geometry reconstruction through 3D scanning will be made with the modified BIM model as built. Accordingly, mechanical modelling using finite element model (FEM) will be created where inputs from damage detection with image processing will be involve. The interaction between data acquisition and storage is so managed by the construction of advanced models which are the Digital Twins (DT) of the infrastructure updated in real time.

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TS5 MANAGEMENT OF BRIDGES, internal standard

ŽSR VTP-UZŽMO - GENERAL TECHNICAL REQUIREMENTS, internal standard

ŽSR VTP-UZŽMO - Determination of the load capacity of railway bridges on ŽSR, internal standard