2022 European Conference on Computing in Construction
Ixia, Rhodes, Greece
July 24-26, 2022

A CONCEPT OF AN AUTOMATED DAMAGE MANAGEMENT FOR THE MAINTENANCE OF BRIDGE STRUCTURES AS A LIFE CYCLE ORIENTED APPROACH

Jan-Iwo Jäkel[1], Robert Hartung[1] and Katharina Klemt-Albert[1]
[1]Institute for Construction Management, Digital Engineering and Robotics in Construction, RWTH Aachen University

Abstract

Despite the optimization of maintenance processes through digitalization, the inspection processes of bridges to determine damages are still analog. At the same time, damage data records are not organized and in a transparent and consistent manner so that all project participants can access and exchange the data interoperable. By combining innovative technologies and using open data exchange formats, this paper presents an approach that further optimizes and automates the process chain for damage management in the maintenance of bridge structures. In this context, a Cloud Computing system (CCS) serves as a central data hub for comprehensive and consistent storage and management of damage related data. A Common Data Environment (CDE) with an integrated digital building model, a damage library and an artificial intelligence (AI) module are implemented in the CSS. The concept exclusively uses open exchange formats to further integrate all project participants while improving collaboration in the maintenance phase and ensuring interoperability. In addition, robotics and artificial intelligence are used to automate the process chain of damage capturing and evaluation.

In this paper, the above aspects are highlighted and a concept for an automated damage management for the maintenance phase of bridge structures using walking robots and digital models is developed and realized as a mock-up.

Introduction

Bridge structures have a special significance for the economy and society for Germany and Europe. (Hartung et al., 2019) At the same time, the provision of resilient infrastructure is a challenging task with multidimensional complexity. (Klemt-Albert et al., 2018) Especially due to the long operating phase of bridges, the maintenance of bridge structures is of particular importance. (Hartung, 2021)

Maintenance processes in Germany run according to a defined standard DIN 1076 in fixed cycles. (Deutsches Institut für Normung e.V., 1999) Maintenance management processes are manually and require a lot of material and human resources. The use of digital methods and technologies has led to the first approaches to digital maintenance management. In the future, the maintenance of bridge structures should be predictive and not reactive. This allows potential damage to the structure to be detected before it occurs. In this way, the service life of bridges can be increased in the long term. (Hartung et al., 2019)

In order for the existing potentials to be experienced through the implementation of disruptive technologies for the maintenance of bridge structures, a reorientation of existing processes is required. For example, the use and linking of digital models, robotic systems, and artificial intelligence (AI) in the area of damage management can increase process efficiency and raise the level of automation. As a result, damages can be detected at an early stage and its impact minimized. This will make a significant contribution to future-oriented digital maintenance in the transport infrastructure. Furthermore, the chance is supported by the establishment and focus of uniform standards on an organizational, process-related and data-related level in the context of the openBIM approaches.

In this article, the above aspects are addressed and a concept for automated damage management for the maintenance phase of bridge structures using legged robots and digital models is developed and implemented in a mock-up. By applying the concept, damage assessment and interpretation can be made more efficient and automated. In addition, the use of a CDE and open exchange formats will strengthen and standardize collaboration between the parties involved in maintenance.

Methodology

The general approach is set up with three consecutive tasks - (i) the determination of the state of the art, (ii) concept development and (iii) mockup implementation. In the first step, the general state of the art is determined by a literature analysis. On the basis of this analysis, the concept for the automated damage management is developed using a legged robot and digital building models. The concept of damage management for the maintenance of bridge structures focuses on the representation of a holistic, automated process and interoperable data flow using open exchange formats like the Industry Foundation Classes (IFC) or the BIM Collaboration Format (BCF) based on the building information modeling method. The main process of the concept is divided into five individual subprocesses: Provision of the digital model, preparation of the inspection tour, image acquisition, image processing and the damage representation. In the next step, the individual components are implemented in a mock-up. This demonstrates and confirms the basic feasibility of the concept. At the end of the article, a critical review of the results is provided and an outlook on the resulting research questions is presented.

State of the Art

Mobile Robots

Mobile robots have a wide range of applications and special capabilities for navigating through unstructured and difficult terrain, as well as a significant potential for further automation of quality management processes. For these reasons, the fundamental interest in mobile robot systems has increased in recent years. Basically, there are different types of mobile robots, which can be distinguished according to the type of locomotion. (Lattanzi and Miller, 2017); (Zang et al., 2016); (Afsari et al., 2021) These types of mobile robots include unmanned aerial vehicle (UAV), wheeled robots, climbing and crawler robots, and legged robots. In particular, the field of legged robots offers great potential for use in difficult construction site environments and is more versatile than wheeled robots. (Hutter et al., 2017) For example, legged robots have better adaptability in rough terrain due to the increased degree of freedom of the legs (Fankhauser, 2018) and can achieve a higher locomotion speed. (Hutter et al., 2017) In addition, legged robots can detect obstacles, overcome height differences, and have many degrees of freedom in movement, regardless of the ground or leg position. (Afsari et al., 2021) (Grandia et al., 2020)

Mobile and legged robots on construction sites

For direct use on the construction site, mobile robots, especially robots with wheels and legged robots, have so far been used mainly for activities in data acquisition for construction site documentation and construction progress control. For example, the papers of (Prieto et al., 2020) and (Karimi et al., 2021) investigated different development approaches based on a wheeled robot. Yan et. al. present the development of a wheeled robot for quality control inspections in the operation of existing buildings. (Yan et al., 2019) In contrast, there are also various publications that look at the use of legged robots in the construction industry. In (Afsari et al., 2021) for example, the general principles for the use of four-legged robots for construction progress control are explored. In addition, in (Halder et al., 2021) it has been discovered that the use of four-legged robots increases the efficiency, speed, and accuracy in the processes of data collection compared to manual execution. Furthermore, (Prieto et al., 2021) developed an approach of a construction site inspection system for the construction execution phase for autonomous quality assessment and progress monitoring. The focus of data acquisition is on the use of laser scan data. The use of laser scan data for reality recording with points clouds for scaffold monitoring using a legged robot as a mobile base is additionally described in (Kim et al., 2021). Although there are already initial approaches that deal with the use of legged robots on the construction site, the approaches are mostly limited to the recording and processing of data.

Robots for damage inspection on bridge structures

As described in detail in the previous chapter, wheeled and legged robots are mainly used to record the construction progress and for quality control in the field of building construction. On the other side, UAV systems, climbing robots and special robot systems are mostly used for inspecting damages on complex bridge structures.

Hallermann and Morgenthal present an approach for the use of UAVs for the inspection of large concrete bridge structures. (Hallermann and Morgenthal, 2014) The UAVs are equipped with RGB cameras and can acquire image data from different perspectives in a semi-automated process due to the high degree of freedom of the UAV in the air. Another approach for using drones to capture damage images with an RGB camera during the inspection process of concrete bridges is presented by (Seo, Duque, Wacker, 2018). The article presented an approach to increase the efficiency and degree of automation in the inspection processes. Additionally, (Tomiczek et al., 2019) show the added value of small UAV systems for inspection compared to the method with underbridge inspection vehicles. In addition to the application of drones on concrete bridges, there is also evidence for an efficient use of drones in the inspection of timber (Seo, Wacker, Duque, 2018). In addition to the prevalent use of drones for inspection processes, there are also use cases with climbing robots, wheeled robots, and or special systems. For example, (Liu and Liu, 2013) and (Zheng and Ding, 2019) developed different climbing robots for capturing damage images by camera when inspecting different types of bridge structures. In contrast, (La et al., 2019) and (Peel et al., 2018) presented different methods for inspecting bridges using an autonomous wheeled robot. Additionally, (Bui et al., 2020) explored an approach utilizing a hybrid robotic system for damage inspection.

From the analysis of the literature it can be concluded that the field of robotics offers a high potential of automatized data collection for various use cases. For a lifecycle-oriented approach, a holistic concept is required that includes both the end user as well as data aggregation processes.

Automated damage detection from image data on bridge structures

While in the past the recorded image data of the damage was evaluated in time-consuming processes using human resources, nowadays there is the possibility of automatic evaluation of damage images using artificial intelligence. For example, (Savino and Tondolo, 2021) used a Convolutional Neural Network (CNN) to correctly classify concrete damage from recorded damage images for infrastructure structures. Li et. al. developed a method for the detection of four concrete damages (cracks, spalling, efflorescence) at the pixel level using a Fully Convolutional Network (FCN). (Li et al., 2019) In (Qiao et al., 2021), a novel algorithm based on Artificial Neural Networks was developed to detect multiple damages on bridge structures from images. In addition, in (Saleem et al., 2021) an approach for automatic detection of crack damages was explored. This was done by combining an image capturing and geo-tagging approach with a CNN. The presented approaches can be used for a lifecycle-oriented process chain up to the linkage with a digital model using open exchange formats, which is not developed yet. An approach is needed that also uses digital models in an open exchange format for an automated damage management.

Concept of the automated damage management approach

Introduction of the holistic concept

The concept of automated damage management with mobile robots and a digital model is developed within the framework of a lifecycle-oriented approach. The focus is on the use of legged robots in combination with digital models and image cameras as recording medium. As a precondition, only open exchange formats IFC and BCF are used along the process chain. Hence, the data exchange becomes interoperable and available for project participants. The unique characteristic of the concept is the extended use of the CDE integrated in an additional cloud-based platform and the further linking with additional relevant data sources (e.g. damage library). This approach fulfills the requirements of the BIM development level 3 according to DIN 19650. Through the use of the CDE, all processes in the maintenance management of the operating phase run centrally via a platform and the collaboration and interoperability along the life cycle management is strengthened.

General process of the holistic concept

The concept is structured in five process stages, which are shown in Figure 1 in the context of the technical components: (a) provision of the digital building model, (b) preparation of the inspection tour, (c) image acquisition, (d) image processing, and (e) damage representation. The basis of the entire process chain is a cloud computing system (CCS). This CCS is based on a CDE with a stored digital model, which is linked to a damage library and an AI module. The CDE serves as a common project space for digital model in IFC format as a digital representation of the entire bridge structure manages all necessary geometric and semantic data. There is also a standardized damage library linked to the CDE for the central storage and management of damage images in the operating phase. The damage library contains information about standardized damage types and further information for different bridge types. For the concept in this paper, the damage library focuses on the four most relevant damage types of reinforced concrete bridges - cracks, spalling, corrosion, gravel pockets. The damage library uses the structure of infrastructure owners and can be extended by further damage patterns. The damage images consist of both historic data as well as records using robotic systems in an automated planning and execution of the inspection tour. The library is set up as a hybrid data store and consists of a relational database (SQL-DB) and a non-relational data base (NoSQL-DB) with standardized damage categories. The SQL-DB stores and manages structured data about unified damage types, the NoSQL-DB in contrast stores the image data for the respective damage types. For capturing the images of the bridge structure, a legged robot is used as a platform in conjunction with an RGB camera system for image acquisition.

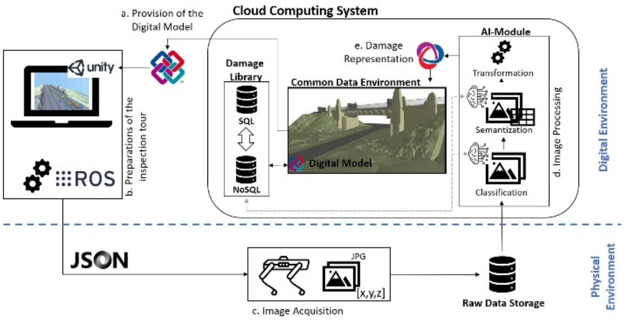
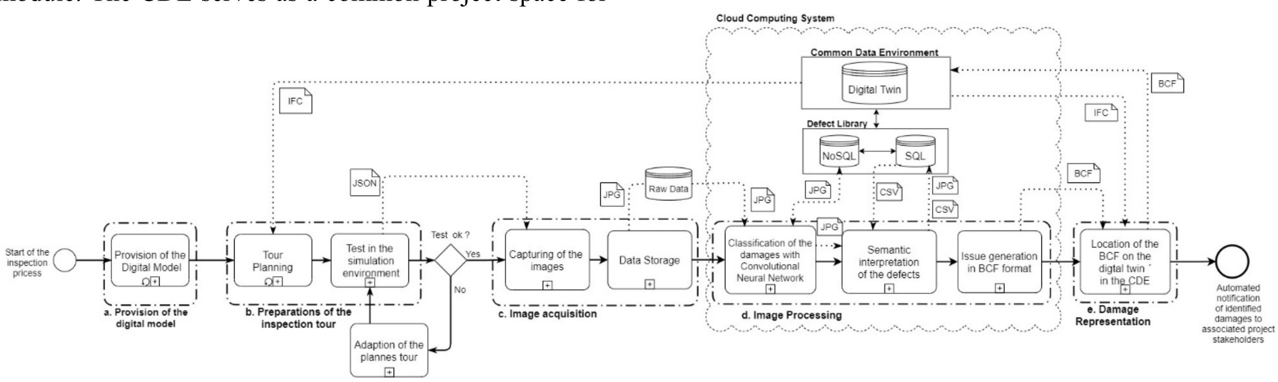


Figure 1 System Model of the Concept based on a common data environment

The digital model is provided in IFC format and will be transferred from the CDE to a Unity simulation environment for the planning of the inspection tour (s. Figure 2). The tour planning is done directly in the 3D environment and is then transferred to the robot via a ROS (Robotic



the maintenance of bridge structures (s. Figure 2). The

Figure 2 Process Model of the concept

Operating System) interface as a JSON file. This represents the transition from the digital environment to the real environment of the concept. In the following step, the legged robot walks through the planned tour and captures the entire structure per image. Each image includes the coordinates of the robot system at the defined points. Afterwards the data is stored in a raw data memory. Subsequently, the image files are imported into the AI-system for the classification and attribution. After that, the transformation in the damage file into the BCF format takes place. In the last step, the BCF damage file is then transmitted to the CDE as an issue and located at the appropriate point in the digital model. The individual process components from Figure 2 are specified in the following subsections and described on the basis of the mock-up implementation.

Provision of the digital model

The first process of the concept is the provision of the digital for the subsequent processes. The digital model of the bridge structure serves as the data basis for route planning and the subsequent presentation of the damage data in BCF format. The digital model acts as an "as-built" model and serves as a digital representation for the operational phase of the structure. All essential geometric and semantic data are stored in the model. By using a CDE as a central project space for data management and provision, all relevant data from the upstream lifecycle phases, planning and execution, are also available to the infrastructure owner in the operating phase in a non-proprietary data format. Another reason for using the IFC format as opposed to a native variant is the use of a uniform industry standard and predefined structuring of the model for maintenance of bridge structures. This ensures the independence of the concept across projects and the integration of every party involved in maintenance.

Preparation of the inspection tour

The second process step is the preparation of the inspection tour. Preparation includes planning the walk and the mandatory pre-test of the planned walk in a simulated digital environment. The planning of the tour is based on the approaches of previous research results according to (Prieto et al., 2021), (Prieto et al., 2020) and (Halder et al., 2021). The basis of the tour planning and the only input to the entire subprocess of the concept is the digital model in IFC format. The model provides sufficient information about the geometric dimensions of the structure or floor and additional semantic attributes for planning the tour. The entire tour planning is done in a 3D environment. In the first step, the digital model for optimal tour planning is integrated into a Unity virtual simulation environment in conjunction with a ROS interface to the legged robot. In the next sub-step, waypoints are defined manually in the digital model. Individual routes are planned for image acquisition of the substructure (s. Fig. 3) or the superstructure (s. Fig. 4) of the bridge. In addition, the tour planning can also be used for image acquisition inside the bridge structure (e.g. for a box girder bridge). The waypoints are defined in such a way that the legged robot can capture the complete bridge structure. The defined waypoints serve on the one hand as orientation points for the robot and at the same time as breakpoints for taking photos of the bridge structure. The walkable route is determined directly in the Unity environment using the integrated NavMesh function. (Unity Technologies, 2022); (Halder et al., 2021) Subsequently, an optimal route for the legged robot is planned on the basis of the defined points. The final planning of the optimal route is again done using the Nav-Mesh function, according to the results of (Halder et al., 2021). After the completion of the route planning, the walk-through is performed in a simulation as a pre-test in the virtual environment. In this simulation test, it is checked once again whether the robot system reaches all waypoints and whether the camera system also reaches all essential components of the bridge structure. Assuming that the test was successful and no gross errors occurred in the virtual walk simulation, the planned tour is played to the robot unit as a JSON file and the image acquisition in the real environment can be started.

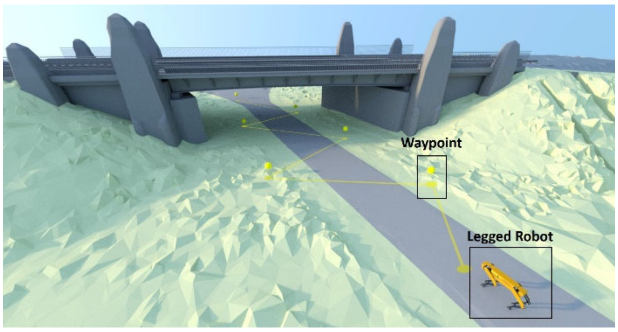


Figure 3 3D tour planning for inspection of the bridge substructures

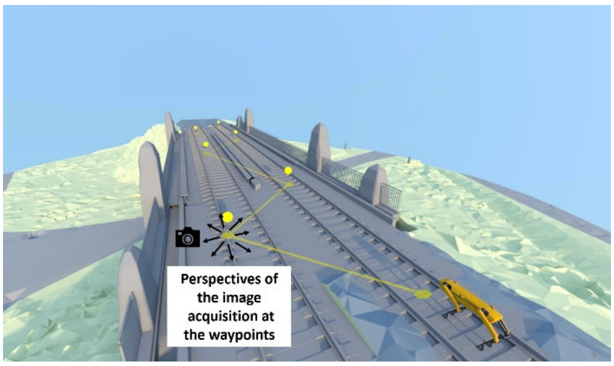


Figure 4 3D tour planning for inspection of the bridge superstructures

Image acquisition

The image acquisition is the third process stage in the concept and is subdivided into the subprocesses of recording the damage images during the inspection and data storage. A legged robot is used for the acquisition of damage images. For the recording of these damage images, a RGB-camera systems is used, inspired by the approach of (Prieto et al., 2020). The legged robot follows the planned inspection tour of the pre-process, stopping at the defined waypoints and taking images of the structure from different perspectives to provide sufficient material for the AI-system. QR codes attached to the location of the defined waypoint are used to orient the robot in the real environment, according to (Halder et al., 2021). These QR-codes are scanned by the robot and transmitting the exact coordinates of the location and can be used for any upcoming inspection. The coordinates of the waypoints, implemented in the QR-code allows the robot to capture all defined corridors of the building structure and at the same time the photo is assigned a specific position with corresponding coordinates in the model. This facilitates the later localization of the detected damages in the digital model. For the later classification of the data by the AI-system, the use of open image file formats, either as raster graphics (.jpg, .gif, .png, etc.) or vector graphics (e.g. EPS, SVG, PDF, PSD) is necessary. In the concept, the image format JPG is used for recording and further post-processing in the successive stages of the process. The image data obtained forms the basis for the next process step of the concept, data processing.

Image processing

The next process stage of image processing is divided into a total of four subprocesses. The first sub-process is the detection of damage and its classification in the previously acquired images of the entire bridge structure. The AI-system analyzes all recorded image data and identifies standardized damage patterns on the basis of image recognition. These damage images are then automatically enriched with further semantic attributes. For this process, the concept of a Convolutional Neural Network (CNN) was developed according to the approach of (Özgenel and Sorguç, 2018) and implemented in the mock-up. According to (Dörn, 2018), a CNN is the most suitable artificial neural network for processing and classifying the image files due to the integrated convolutional algorithm. (Dörn, 2018) The AI-system is integrated as an additional module in the CCS and uses the damage library as an additional knowledge source during classification and attribution. A supervised learning approach was chosen for the preliminary training of the CNN. A combined and pre-classified dataset with images of unblemished concrete walls and images of concrete damage (cracks, spalling, holes) served as training data. This dataset consisted of images from the approach of (Özgenel and Sorguç, 2018) and images acquired by the researchers of concrete damages. The captured images are imported from the raw database in JPG format into the developed CNN and classified automatically. A result of the classification process is shown in Figure 5 using the example of a damage on a concrete wall of the bridge structure. The damage in the image detected by the AI-system, in this case the damage type hole, was detected and highlighted by a red marking of the damage area. From this marking, for example, with a further development of the CNN, the approximate size can be determined in addition to the damage classification. In addition to the classification of the damage, a certain inaccuracy is nevertheless also recognizable in the illustration. The red marking of the damage in Figure 5 does not exactly outline the area of the damage, but also smaller secondary areas with imperfections where the color is merely not perfect. Due to slight deficiencies in automated damage detection, deviations also result in the calculation of the further parameters of the damage, such as the area size of the damage, the consequential costs or the resources required for remediation. In order to further improve the accuracy of the AI system, it is necessary to use a higher amount of training data.

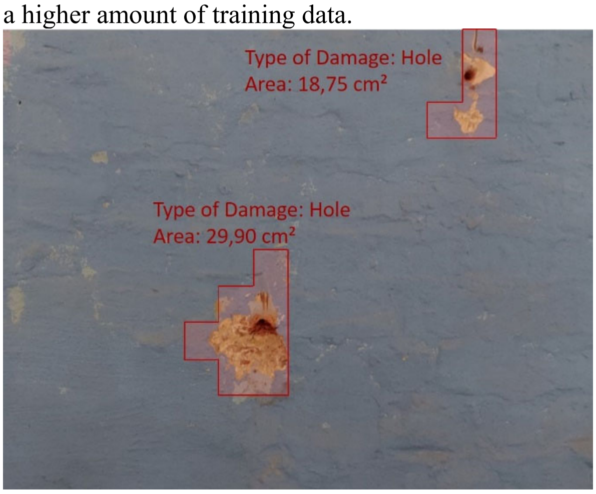
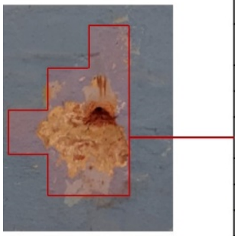


Figure 5 Classification of the damage images

After the successful classification, the semantic interpretation is the next step using the AI-system. The previously classified damage images are enriched with additional information on the basis of the damage library. The basis for the semantic enrichment is the existing data on standardized attributes of the damage types in the damage library embedded in the CCS. Due to the existing link to the damage library the AI-system can automatically identify the appropriate attribute assets for the damage image. This adds important additional information to the damage image as semantic attribute parameters for further specification, which is shown in Figure 5.



Damage	
Damage-ID:	000001
Damage-Name:	Hole
Description:	Hole in the concrete wall due to impact of blunt force
Cause:	Force applied by an object
Union:	Structural Work
Responsibility:	Structural work / concrete construction
Location:	Concrete wall
Priority:	High
Surface Area:	29,90 cm²
Calc. Extra Costs	3500,00 €
Calc. Delay	4,0 Days
Calc. Extra Labor	2 Persons
Damage_Image.-No.:	000001

Figure 6 Semantic interpretation of the damage

The Figure shows the parameters defined for the uniform attribution and specification of the damage during attribution by the AI-system. These parameters are the basis for the BCF extension in connection with the later transformation into the BCF format. Attributes such as cost and duration of rework are additionally calculated by the system on the basis of the SQL database. In the last step of the data processing stage, the damage image file is converted into an issue in the BIM Collaboration Format (BCF). The structure of the issue is based on the XML 3.0 specification for BCF-format from buildingSMART. (buildingSMART International, 2022) The basic structure of the BCF is retained and extended by additional parameters in the context of damage management. These parameters enable a recognized and attributed damage to be identified and interpreted uniformly in the BCF format as well.

Damage representation

After the successful transformation of the damage data, the BCF with all information and the inclusive viewpoint coordinates is transferred to the CDE, then automatically positioned at the correct component location and shared with all project stakeholders in the project space (s. Figure 7).

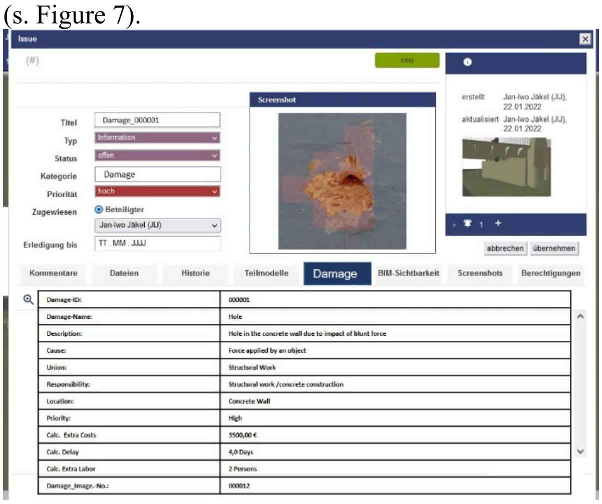


Figure 7 Representation of the BCF-Issue

The figure shows the representation of the BCF-issue as damage in the user interface of a CDE implemented in a mock-up. The correct localization of the BCF-Issue at the corresponding position in the digital model is based on coordinates stored in the file and the identified objects. The coordination is based on the sensors of the robot in combination with the stored program of the inspection, which is integrated into the image file as additional information during the acquisition. Thus, all identified damages can be shared with all project participants in the open BCF format while at the same time making damage management more transparent and consistent in the maintenance phase. Since the responsibility for the damage is stored directly in the BCF file as information, the responsible company is automatically informed about the new damage and requested to plan a removal. The responsible person can report the damage removal directly in the CDE. During the next inspection, the legged robot can then recheck the removal of the released damage. If the damage has really been removed in acceptable quality and the AI-system no longer detects any damage, the clearance report is confirmed.

Discussion

The concept illustrates the basic feasibility of the process chain by its implementation in a mock-up. By using legged robots, digital models and artificial intelligence, the process chain from damage assessment and interpretation to implantation into the CDE as an BCF-issue can be made more efficient and the degree of automation can be increased. This can lead to a reduction in the workload of skilled personnel in the maintenance phase and a reduction in the occurrence of damages, while at the same time increasing the period of use and resilience of the bridge structure. The deployment of open exchange formats and a CDE in damage management promotes the openBIM idea beyond the planning and execution phase and into the maintenance of infrastructure systems. The recording and management of damage images by means of BCF-issues on a digital model in a CDE becomes more structured, consistent and transparent. This makes damage management in the maintenance of bridge structures comprehensible for all project participants. Moreover, all project participants have access to the data throughout the entire lifecycle. The pure use of open exchange formats also increases the interoperability of damage management, eliminates existing interface problems and uses existing standards and defined structures. Furthermore, the use of open exchange formats (BCF and IFC) and open source frameworks (ROS) reinforces the independence of the concept and transferability to other building structures (e.g. tunnels, dams or buildings) or mobile robotic systems (wheeled robots, UAV). Moreover, the concept contributes to the future achievement of BIM development level 3 according to DIN 19650 in maintenance management for infrastructure systems. (Deutsches Institut für Normung e.V., 2019)

Although the basic functionality of the concept is illustrated in this paper, it may also have some limitations. For example, the mock-up needs to be prototyped and the fully automated process chain has to be validated in further research. As a result, there is the possibility of hurdles arising in the interfaces between the individual application systems. These interface problems can be uncovered and eliminated in future prototyping so that the process chain can ensure interoperability. The mock-up has further limitations in the classification of damage patterns. The CNN in the mock-up has so far only been trained to identify only one type of damage. Learning additional damage patterns is possible, but requires a large amount of training data. This is because a high classification rate in the output can only be achieved by a training data set with many precise damage images. There are other limitations to path planning with a legged robot. For example, although legged robots can record, process and execute the route planning in JSON format, there are limitations to the orientation of the robot system in free space during the course of route walking without the inclusion of further GPS data.

Future research activities shall prototype and validate the individual technical components in all stages of the process chain. Furthermore, the interfaces between the individual process stages and technical components should be investigated and tested to ensure an interoperable data flow. Furthermore, the extensibility of the concept will be investigated in further research. Therefore, the concept will be tested on other structures of transport infrastructure, e.g. tunnels, dams, locks, weirs, etc. Additionally, the concept can also be used for measurements on or in the structure with sensor systems instead of recording damage images. In addition, there is the possibility of using laser scanning systems as a recording medium. Another extension being tested is the use of other types of mobile robotics, e.g. wheeled robots or drones, as a moving platform for the recording process or the use of several types of robots as autonomous swarm intelligence for simultaneous inspections from the air and the ground.

Conclusion

This paper presents a concept for automated damage management using legged robots and digital models in the context of a lifecycle-oriented single source of truth approach to bridge structure maintenance. Using a process model, the holistic approach and its single components of the concept are presented.

The individual components are described in detail in the technical article and implemented in a mock-up for better comprehensibility. Subsequently, the concept approach was discussed, limitations were highlighted and future research activities identified.

The concept serves to advance the damage management by linking innovative technologies and digital methods in the maintenance phase of existing bridge structures. Furthermore, the automated process chain optimizes the recording, detection and management of damages in the maintenance phase of bridge structures and makes them more transparent.

Further research activities and the prototyping and validation of the concept in the near future will increase process efficiency and the degree of automation in damage management as well as the cooperation of all project participants in maintenance.

Acknowledgments

This research is supported by the Federal Ministry for Digital and Transport (BMDV) in the funding program mFUND in the project mdfBIM^{+} (FKZ: 19FS2021A)

References

Afsari, K., Halder, S., Ensafi, M., DeVito, S. and Serdakowski, J. (2021) 'Fundamentals and Prospects of Four-Legged Robot Application in Construction Progress Monitoring', EasyChair, 274-263.

Bui, H.-D., Nguyen, S., Billah, U.-H., Le, C., Tavakkoli, A. and La, H. M. (2020) 'Control Framework for a Hybrid-steel Bridge Inspection Robot', 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). Las Vegas, NV, USA, 10/24/2020 - 1/24/2021. Piscataway, NJ, IEEE, pp. 2585–2591.

buildingSMART International (2022) GitHub - buildingSMART/BCF-XML: XML specification for BIM Collaboration Format [Online]. Available at https://github.com/buildingSMART/BCF-XML, (Accessed 5 February 2022).

Deutsches Institut für Normung e.V. (1999) DIN 1076: Ingenieurbauwerke im Zuge von Straßen und Wegen, Berlin, Beuth Verlag GmbH.

Deutsches Institut für Normung e.V. (2019) DIN EN ISO 19650-1:2019-08: Organisation und Digitalisierung von Informationen zu Bauwerken und Ingenieurleistungen, einschließlich Bauwerksinfomationsmodellierung (BIM) - Informationsmanagement; Deutsche Fassung EN ISO 19650-1:2018, Berlin, Beuth Verlag GmbH.

Dörn, S. (2018) Programmieren für Ingenieure und Naturwissenschaftler: Intelligente Algorithmen und digitale Technologien, Berlin, Heidelberg, Springer Berlin Heidelberg.

Fankhauser, P. (2018) Perceptive Locomotion for Legged Robots in Rough Terrain, ETH Zurich.

Grandia, R., Taylor, A. J., Ames, A. D. and Hutter, M. (2020) 'Multi-Layered Safety for Legged Robots via Control Barrier Functions and Model Predictive Control', IEEE International Conference on Robotics and Automation (ICRA) [Online]. Available at https://arxiv.org/pdf/2011.00032.

Halder, S., Afsari, K., Serdakowski, J. and DeVito, S. (2021) 'A Methodology for BIM-enabled Automated Reality Capture in Construction Inspection with Quadruped Robots', Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC). Dubai, UAE, 11/2/2021 - 11/4/2021.

Hallermann, N. and Morgenthal, G. (2014) 'Visual inspection strategies for large bridges using Unmanned Aerial Vehicles (UAV)', in Chen, A. (ed) Bridge maintenance, safety, management and life extension: Proceedings of the Seventh International Conference of Bridge Maintenance, Safety and Management, 7-11 July 2014, Shanghai, China, Boca Ration, Fla., CRC Press, pp. 661–667.

Hartung, R. (2021) Vorgehensweise zur Bewertung von Schäden an Ingenieurbauwerken auf Basis objektorientierter Bauwerksmodelle, Dissertation, Gottfried Wilhelm Leibniz Universität Hannover.

Hartung, R., Senger, L. and Klemt-Albert, K. (2019) 'Linking Building Information Modeling and Structural Health Monitoring for Reliable Railway Infrastructure', Proceedings of the 29th European Safety and Reliability Conference (ESREL): 22-26 September

2019, Hannover, Germany, 9/22/2019 - 9/26/2019. Europe, Singapore, European Safety and Reliability Association; Research Publishing Services, pp. 596–603.

Hutter, M., Gehring, C., Lauber, A., Gunther, F., Bellicoso, C. D., Tsounis, V., Fankhauser, P., Diethelm, R., Bachmann, S., Bloesch, M., Kolvenbach, H., Bjelonic, M., Isler, L. and Meyer, K. (2017) 'ANYmal - toward legged robots for harsh environments', Advanced Robotics, vol. 31, no. 17, pp. 918–931.

Karimi, S., Braga, R. G., Iordanova, I. and St-Onge, D. (eds) (2021) Semantic Optimal Robot Navigation Using Building Information on Construction Sites.

Kim, J., Chung, D., Kim, Y. and Kim, H. (eds) (2021) Semantic segmentation of 3D point cloud data acquired from robot dog for scaffold monitoring.

Klemt-Albert, K., Hartung, R. and Bahlau, S. (2018) 'Enhancing Resilience of Traffic Networks with a Focus on Impacts of Neuralgic Points Like Urban Tunnels', Resilience Engineering for Urban Tunnels. Reston, Virginia, USA, September 1, 2016. Reston, American Society of Civil Engineers, pp. 55–70.

La, H. M., Dinh, T. H., Pham, N. H., Ha, Q. P. and Pham, A. Q. (2019) 'Automated robotic monitoring and inspection of steel structures and bridges', Robotica, vol. 37, no. 5, pp. 947–967.

Lattanzi, D. and Miller, G. (2017) 'Review of Robotic Infrastructure Inspection Systems', Journal of Infrastructure Systems, vol. 23, no. 3, p. 4017004.

Li, S., Zhao, X. and Zhou, G. (2019) 'Automatic pixel-level multiple damage detection of concrete structure using fully convolutional network', Computer-Aided Civil and Infrastructure Engineering, vol. 34, no. 7, pp. 616–634.

Liu, Q. and Liu, Y. (2013) 'An approach for auto bridge inspection based on climbing robot', 2013 IEEE International Conference on Robotics and Biomimetics (ROBIO 2013): Shenzhen, China, 12 - 14 December 2013. Shenzhen, China, 12/12/2013 - 12/14/2013. Piscataway, NJ, IEEE, pp. 2581–2586.

Özgenel, Ç. F. and Sorguç, A. G. (2018) 'Performance Comparison of Pretrained Convolutional Neural Networks on Crack Detection in Buildings', Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC). Taipei, Taiwan, 6/28/2017 - 7/1/2017.

Peel, H., Luo, S., Cohn, A. G. and Fuentes, R. (2018) 'Localisation of a mobile robot for bridge bearing inspection', Automation in Construction, vol. 94, pp. 244–256.

Prieto, S. A., Garcia de Soto, B. and Adan, A. (2020) 'A Methodology to Monitor Construction Progress Using Autonomous Robots', Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC). Kitakyushu, Japan, 10/27/2020 - 10/29/2020.

Prieto, S. A., Giakoumidis, N. and García de Soto, B. (2021) 'AutoCIS: An Automated Construction Inspection System for Quality Inspection of Buildings', Proceedings of the 38th International Symposium on Automation and Robotics in Construction (ISARC). Dubai, UAE, 11/2/2021 - 11/4/2021.

Qiao, W., Ma, B., Liu, Q., Wu, X. and Li, G. (2021) 'Computer Vision-Based Bridge Damage Detection Using Deep Convolutional Networks with Expectation Maximum Attention Module', Sensors (Basel, Switzerland), vol. 21, no. 3.

Saleem, M. R., Park, J.-W., Lee, J.-H., Jung, H.-J. and Sarwar, M. Z. (2021) 'Instant bridge visual inspection using an unmanned aerial vehicle by image capturing and geo-tagging system and deep convolutional neural network', Structural Health Monitoring, vol. 20, no. 4, pp. 1760–1777.

Savino, P. and Tondolo, F. (2021) 'Automated classification of civil structure defects based on convolutional neural network', Frontiers of Structural and Civil Engineering, vol. 15, no. 2, pp. 305–317.

Seo, J., Duque, L. and Wacker, J. (2018) 'Drone-enabled bridge inspection methodology and application', Automation in Construction, vol. 94, pp. 112–126.

Seo, J., Wacker, J. P. and Duque, L. (2018) Evaluating the use of drones for timber bridge inspection.

Tomiczek, A. P., Whitley, T. J., Bridge, J. A. and Ifju, P. G. (2019) 'Bridge Inspections with Small Unmanned Aircraft Systems: Case Studies', Journal of Bridge Engineering, vol. 24, no. 4, p. 5019003.

Unity Technologies (2022) Inner Workings of the Navigation System: Inner Workings of the Navigation System [Online]. Available at https://docs.unity3d.com/2021.2/Documentation/Manual/nav-InnerWorkings.html (Accessed 29 January 2022).

Yan, R.-J., Kayacan, E., Chen, I.-M., Tiong, L. K. and Wu, J. (2019) 'QuicaBot: Quality Inspection and Assessment Robot', IEEE Transactions on Automation Science and Engineering, vol. 16, no. 2, pp. 506–517.

Zang, X., Lui, Y., Lin, Z., Zheng, C. and Iqbal, S. (2016) 'Two multi-linked rescue robots: design, construction and field tests', Journal of Advanced Mechanical Design, Systems, and Manufacturing, vol. 10, no. 6.

Zheng, Z. and Ding, N. (2019) 'Design and Implementation of CCRobot-II: a Palm-based Cable Climbing Robot for Cable-stayed Bridge Inspection', 2019 International Conference on Robotics and Automation (ICRA). Montreal, QC, Canada, 5/20/2019 - 5/24/2019. Piscataway, NJ, IEEE, pp. 9747–9753.