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The use of unmanned aerial vehicles to inspect bridges for Rijkswaterstaat

Colophon

Title:	The use of unmanned aerial vehicles to inspect bridges for Rijkswaterstaat
Educational institution:	University of Twente Faculty of Engineering Technology Civil Engineering Postbus 217 7500 AE Enschede www.utwente.nl/en/ce/
Author:	Alexander Jongerius alexander.jongerius@gmail.com
Supervisors:	Dr. A. Hartmann University of Twente Faculty of Engineering Technology
	Arie van Kersen Rijkswaterstaat Grote projecten en onderhoud
	Dr.ir. Martijn J. Booij University of Twente Water Engineering and Management
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List of abbreviations

3d	-	three-dimensional
DORA	-	Definitive object risk analysis
GPS	-	Global positioning system
ILT	-	Inspectie Leefomgeving en Transport
IORA	-	Initial object risk analysis
RWS	-	Rijkswaterstaat
SHM	-	Structural health monitoring
UAS	-	Unmanned aerial system
UAV	-	Unmanned aerial vehicle

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Summary

Within the Netherlands there are different types of bridge inspections that are conducted; from a small daily inspection to a full structure examination every six years. Within this full structure examination, every aspect of the bridge is being checked and damages are being identified. (Rijkswaterstaat, 2015) The process of using this damage identification and interpretation is referred to as structural health monitoring (SHM)(Farrar & Worden, 2007). In a general sense: structural health monitoring is used to analyse the physical fitness of our infrastructure.

Because of labour intensity and the objects' unavailability for users during some parts of the full structure inspection, Rijkswaterstaat (RWS) is considering alternative methods of data collection. One of these methods is using a drone to conduct (parts of) the field data collection, as they could be less labour intensive and provide less obstruction for the user during inspection.

In this research we first create an overview of what is known in literature about the use of unmanned aerial vehicles (UAVs) for bridge inspection. This information is supplemented with expert views obtained by the use of interviews. Next, a conventional bridge inspection report is analysed and a case study is executed to gather information about the feasibility of using UAVs to replicate the obtained results. The comparison will also give a complete overview on the limitations and possible areas of improvement.

We obtain that the quality of the imagery of present-day UAV's is comparable with imagery taken during conventional inspections. Besides that, a UAV can store multiple sensors and by this can gather additional information to furthermore improve the quality of asset management. However, UAV's are not able to inspect all parts of the bridge structure and are frankly not efficient on all parts of the structure. When using a UAV to inspect the surface or upper structures, in close distance to the bridge, full closure of the object is necessary. This makes the deployment of a UAV annoying for the users of the object.

As well as from literature and interviews we find that the visual inspection of full structure inspections could be executed up to five times faster using a UAV. The post-processing of the conventional visual inspection takes little time, as the amount of data is limited to the found damages. UAV's will also gather data on structurally saint parts of the structure. During post-processing, the data needs to be filtered to just the specific damages.

From this study, we obtain that UAV use for SHM data collection is a wildly studied alternative for conventional inspection methods. This study shows that indeed UAV's could prove to be a new, faster, cheaper, safer and more complete way of collecting data for SHM. Yet it also showed that a complete substitute for conventional methods is not possible, as additional research and access to certain locations is always a factor. There are also difficulties in post proccing of the UAV acquired field data. Due to strict legislation and limitations by external factors such as weather and battery life, deployment of UAV's is a complex undertaking and requires specific knowledge.

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1 Introduction

Rijkswaterstaat (RWS) is a part of the Dutch Ministry of Infrastructure and the Environment and responsible for the maintenance of the main infrastructure facilities in the Netherlands. These infrastructure facilities include: bridges, viaducts, locks (sluices) and dikes. To ensure the structural integrity of these objects, different inspections take place. These inspections range from a small daily inspection to a full structure examination every six years.(Rijkswaterstaat, 2015)

The inspections are conducted by independent companies contracted by RWS. Currently, these inspections are done manually using conventional methods such as visual inspection and direct measurements.

Because of labour intensity and the objects' unavailability for users during some parts of the inspection, Rijkswaterstaat (RWS) is considering alternative methods of data collection. One of these methods is using a drone to conduct (parts of) the field data collection, as they could be less labour intensive and provide less obstruction for the user during inspection. (Internal documentation Rijkswaterstaat).

1.1 Problem statement and research objectives

To explore the possibilities of using drones for the full structure examinations, RWS conducted some pilots-studies in which a drone was used to collect the data necessary for a full structure examination. From these reports, a complete view of the requirements and boundary conditions of using drones to perform these full structure inspections was lacking. Yet Rijkswaterstaat needs to catalogue these requirements and boundary conditions to fully explore the possibilities and create policy.

The problem is that RWS has no real view on the requirements when it comes to using drones for bridge inspection and thus lacking the right information to create policy.

The goal of this research is to map the possibilities and requirements for using UAV's to perform full structure inspections. The conclusions of this research can contribute to the writing of the new manual for the use of drones of Rijkswaterstaat. To achieve this goal the research will set out to answer the following main question with the help of three sub-questions:

What are the possibilities and requirements of using UAVs for performing full structure bridge inspections in the Netherlands?

A. what are possibilities and requirements of using UAVs for full structure inspections known in other countries?

Is there knowledge about UAV usage for conducting full structure inspections and what are the requirements that come forward.

B. What requirements are adjunct to full structure inspections in the Netherlands?

How is the SHM report currently structured, and what are the methods used, the area's inspected, and more important: what is the accuracy of these methods.

Important is to also map the requirements that are provided by RWS for performing a successful inspection.

C. To what extent do UAV’s cover these requirements?

Next, it will be mapped to what extent UAV’s can meet the found requirements and more important where UAV’s need extra development to meet the requirements.

2 Methodology

To achieve the goal of this research and to answer all the research questions, different methods of gathering information have been used. These methods can be found in figure 1. The different methods are summarized on the left side of the figure, in chronological order.

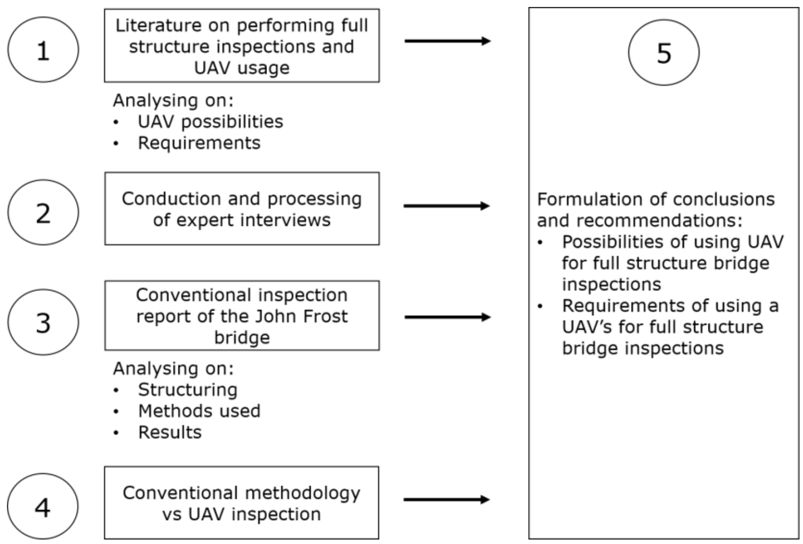

figure 1 - methodology flowchart

The first step is to create an overview of what is known in literature about the use of UAVs for bridge inspection. This information is supplemented with expert views obtained by the use of interviews. The companies that were interviewed for this research can be found in table 1.

No.	Company	Function
1	IV Infra BV	Project manager, Project leader
2	Nebest BV	Productmanager maintenance analysis
3	Arcadis NV	Senior advisor technical asset management
4	Richtlijn Geodesie BV	Owner

table 1 - conducted interviews

Next, a conventional bridge inspection report is analysed and a case study is executed to gather information about the feasibility of using drones to replicate the obtained results. The comparison will also give a complete overview on the limitations and possible areas of improvement. The final step is to bundle all information and formulate conclusions about the possibilities and requirements of using UAVs for bridge inspections.

3 Structural health monitoring and unmanned aerial vehicles

In this chapter, literature is analysed on the following subjects: structural health monitoring (SHM), unmanned aerial vehicles (UAVs) and lastly combining these subjects by reviewing how UAVs can be used in SHM.

3.1 Structural health monitoring

Within the Netherlands there are different types of bridge inspections that are conducted; from a small daily inspection to a full structure examination every six years. Within this full structure examination, every aspect of the bridge is being checked and damages are identified. (Rijkswaterstaat, 2015) The process of using this damage identification and interpretation is referred to as structural health monitoring (SHM)(Farrar & Worden, 2007). In a general sense: structural health monitoring is used to analyse the physical fitness of our infrastructure.

In essence, SHM consists of two parts: data acquisition on an infrastructural object and post-processing of the acquired field data. The quality of the collected data and the general way in which the date is collected are important. From initial talks with Rijkswaterstaat we defined the subjects that are important to SHM, which can be found in table 2. These criteria will be used to structure the results throughout the report.

Data acquisition	**Data interpretation**
1. Data quality The quality of the data that is gathered 2. Equipment & access Equipment used to acquire the data and/or equipment used to gain access to the locations of acquirement. Also consisting of other factors that limit access e.g. weather 3. Nuisance The nuisance that is experienced by the users of the object during data acquisition 4. Time The time it took to acquire the data 5. Cost The costs that are related to the data acquisition	6. Post-processing Everything that is involved in the processing of the acquired data.

table 2 - Important subjects SHM

3.2 Unmanned aerial vehicles

Unmanned aerial vehicles are aircrafts without a human pilot onboard, and operate with various degrees of autonomy. (International Civil Aviation Organization, 2011) While the early users were mostly military, more peaceful applications of these systems are being investigated in border patrol, search and rescue, damage investigations, locating forest fires or farmland frost conditions, mining activities and scientific surveys. (Anand, 2007)

The most common system used for civil purposes is the multi-copter platform, consisting of four or more brushless motors. The advantage of these multi-copters is the capability of vertical take-off and landing. The improved manoeuvrability of UAV technology allows flights to be conducted in difficult-to-access areas as well as indoors. (Jordan et al., 2018)

figure 2 - Example of simple multi-copter platform, DJI Phantom 2 (Irizarry & Costa, 2016)

UAVs can be equipped with various generic sensors, such as video or still-image cameras (including far and near infrared), radar or laser-based rangefinders. (Karan et al., 2014) The great diversity in sensors in combination with flexible deployment and easy to use platforms make that UAVs are being developed at a rapid pace. Simultaneously, the development of sensors and instruments that can be used on these platforms is growing exponentially. (Pajares, 2015) One of the fields that are also heavily in development is the research concerning UAVs in SHM data acquisition.

3.3 UAV's in SHM

We find that UAVs are already widely tested for acquiring data for SHM. For example, the Minnesota Department of Transportation developed a demonstration project to evaluate the technology, safety and effectiveness of UAVs as a tool for bridge inspection (Lovelace, 2015). This report also sparked interest across the United States, including the peaked interest of other states' transportation departments, who are eager to reduce the costs and safety concerns associated with such work (Zink, 2016). There are also a lot of smaller scale tests and studies that research the use of UAVs for SHM. For example, (Morgenthal & Hallermann, 2014) where the possibilities of small-scale UAVs for the inspection of buildings were tested.

The information obtained from the literature study will be structured following the subjects listed in table 2.

3.3.1 Quality

There are questions about the quality of the inspection data when UAV's are used (Lovelace, 2015). Is it possible to achieve the same level of inspection quality with a UAV's relative to a conventional inspection? This question led to the comparison report of Rijkswaterstaat (Keesmaat, 2017) and the report commissioned by the Minnesota Department of Transportation (Lovelace, 2015). The first report, states that the level of detail obtained from a UAV can be compared with images from a conventional inspection, since: 'Defects can be identified and viewed with a level of detail equivalent to a close-up photo' (Lovelace, 2015). However, this is not in line with the conclusions drawn from the report of RWS were one of the conclusions is that(Keesmaat, 2017): 'the large inspection distance and limited view make it more difficult to estimate the relevance of the damages'.

Another quality issue that came forward from (Keesmaat, 2017) is that most of found cracks need to be measured. Again this is also the case in Minnesota, where they found that (Lovelace, 2015): '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 UAVs'. which in line with the statements made in the comparison study executed by IV Infra. Yet new UAV's are already available that are designed especially for inspections and that can deliver a resolution of 1mm^2/pixel from a distance of 6 meters (Lovelace, 2015). These UAV's could provide the accuracy that is necessary to measure certain crack lengths, measuring the crack width remains a problem with current available hardware and legislation (distance to an object).

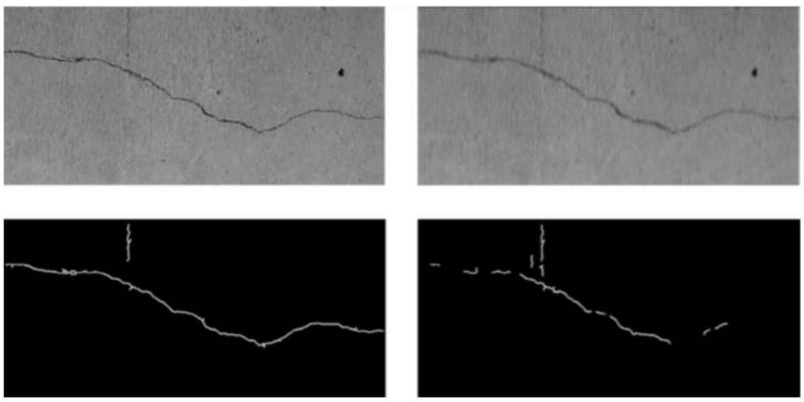

figure 3 Automatic crack detection. With normal photo (left) and blurred photo (right) (Morgenthal & Hallermann, 2014)

Studies show that even measuring crack width will be possible in the future if image quality (resolution) is large enough. (Kim et al., 2017) shows that a specialist UAV system can detect and correctly measure cracks with a width up to 0,25mm. In the future, this could provide a fast, reliable and cost-efficient method for mapping cracks in concrete structures and therefore making the need for human interaction to measure the cracks in most cases obsolete.

3.3.2 Equipment & access

The legislation concerning the deployment of UAVs is limiting the possibilities and deployment in practice as (Keesmaat, 2017) and (Lovelace, 2015) state clearly in their conclusions, which is supported by Chan et al. (2015). Weather conditions are also proven to be a limiting factor for deploying UAVs as UAVs are only able to operate in a limited set of weather conditions. (Morgenthal & Hallermann, 2014) and (Cho, 2017).

Another important feature needed on UAV's for practical use is (Lovelace, 2015): 'the ability to direct cameras upward and the ability to fly without a GPS signal are important features when using this technology as an inspection tool' Also stated by (Al-Kaff et al., 2017).

The number of available dedicated inspection UAV's is increasing rapidly. (Yamada et al., 2017) developed a UAV that is completely dedicated to the inspection of bridges. Recently Intel has presented an UAV for inspection purposes that can withstand higher wind speeds, and is able to fly during light rain (Cho, 2017).

Within the Netherlands, there are currently some limitations in legislation regarding the professional deployment of UAVs. Figure 4 depicts the no-fly zones within the Netherlands. It is not allowed to deploy UAVs without a transponder (which communicates with local air traffic control) in these areas. Besides these no-fly zones, the following rules must be observed when it comes to inspecting large infrastructural objects (Keesmaat, 2017):

1. A minimum distance of 150 meters between human beings (in all three dimensions).
2. Altitude limitation of 120 meters.
3. No flying within three kilometres of airports.
4. No flying above roads (speed limit 60km/h or higher) and a minimum distance of 150 meters to these roads.
5. Roads with a speed limit beneath 60km/h have a minimum flying distance of 50 meters.
6. No flying within 150 meters of railway lines.

With permission from Inspectie Leefomgeving en Transport (ILT) there is a possibility to divert from the set rules.

figure 4 - No-fly zones in the Netherlands

3.3.3 Nuisance
The comparison report executed by Nebest states that during their flight the bridge had to be fully shut down, this is also the case in the report of IV infra where (Keesmaat, 2017) states: 'in most cases, complete closure of the object is necessary, during conventional inspection only partial closure is sufficient'. This closure is due to location in which the UAV is deployed in relation to the object. When a UAV is deployed below the road surface of the object, closure of the object is not necessary, this also applies to possible water traffic that crosses below the object. (Keesmaat, 2017)

3.3.4 Time
In the reports commissioned by Rijkswaterstaat, we find that the time investment between conventional methods and inspection with the use of UAV´s is about the same as concluded in the comparison study of Nebest. From the comparison of (Kadamkulangara Balagopalan, 2018) we obtain another point of view, represented in figure 5. Here we find a simulated time comparison between conventional methods and UAV data collection. In this comparison, the post-processing has also been taken into account. And as (Kadamkulangara Balagopalan, 2018) concludes: ʼʼ unmanned aerial system (UAS) assisted bridge inspections would be the preferred choice versus the conventional approach. Inspection time was reduced by almost 80% with the introduction of UAS inspections in certain cases.ʼʼ From this research, we also find that the conventional methods that are used within the geographical study area can be compared with conventional methods used in the Netherlands.

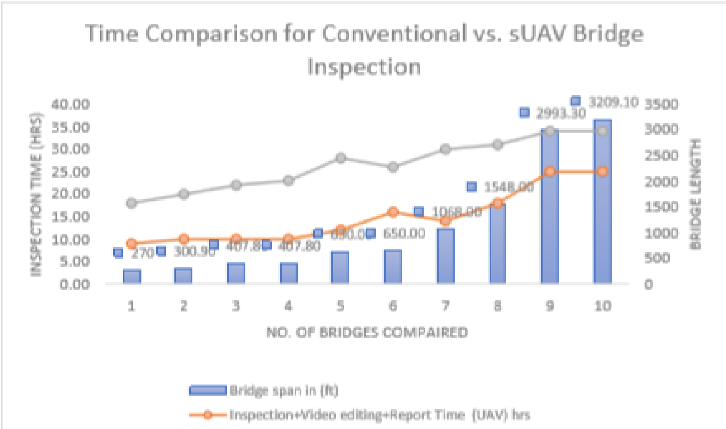

figure 5 - simulated time comparison for conventional vs UAV bridge inspection (Kadamkulangara Balagopalan, 2018)

3.3.5 Costs

From the comparison studies commissioned by RWS we find that an inspection with the use of a UAV is more costly and time-consuming than a conventional inspection. This is partially in line with the report of the Minnesota Department of Transportation, where they state that the problem is that (Lovelace, 2015): 'obtaining the approval is significant and cost prohibitive'. But they also state that when this problem is solved UAV's can provide a cost-effective way to obtain detailed information that may not normally be obtained during routine inspections. Adding to this (Zink, 2016) states that when it comes to very large bridges a cost reduction of 66% could potentially be achieved. These statements are being supported by (Kadamkulangara Balagopalan, 2018), in figure 6 a simulated price comparison can be found. The reduction that are achieved in this simulation differs for each bridge type and length, yet it shows the great potential of cost savings that could be achieved when using UAVs. (Kadamkulangara Balagopalan, 2018)

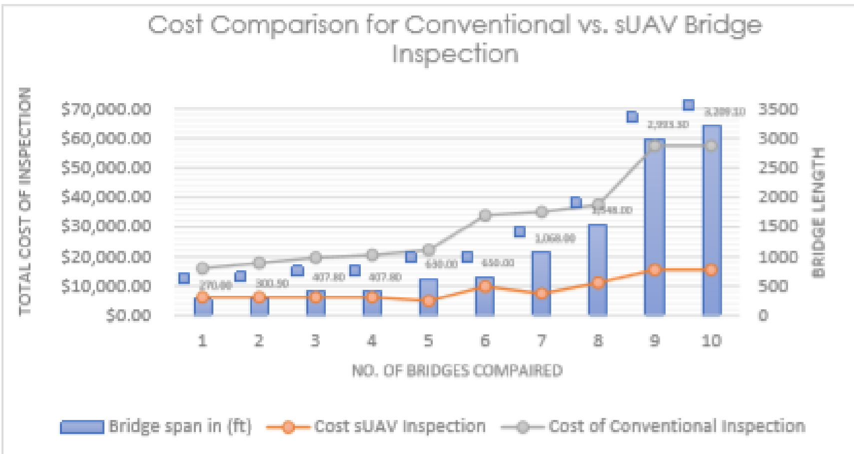

figure 6 - simulated cost comparison for conventional vs UAV bridge inspection (Kadamkulangara Balagopalan, 2018)

3.3.6 Post processing

The use of UAVs for inspection adds the possibility to analyse images with the use of dedicated software, this could drastically bring back manual processing time of taken images of an object.. This technique could offer a solution for some of the problems stated by the comparison study of Rijkswaterstaat, namely the fact that the processing time of the images is very costly and is one of the main reason UAV inspections are more costly. (Keesmaat, 2017) This is in line with (Khaloo et al., 2018) where they state that: 'Standardisation of the mission planning and data analysis processes are needed as well if UAV inspections are to become an integrated part of the National Bridge Inspection Standards process'. Certain software packages could offer a faster way of analysing all the data and selecting important images. Generating a complete 3d model of the structure could also offer a solution. The comparison can be found in figure 7. Although the potential, this is still a technique that is yet to be used in practice

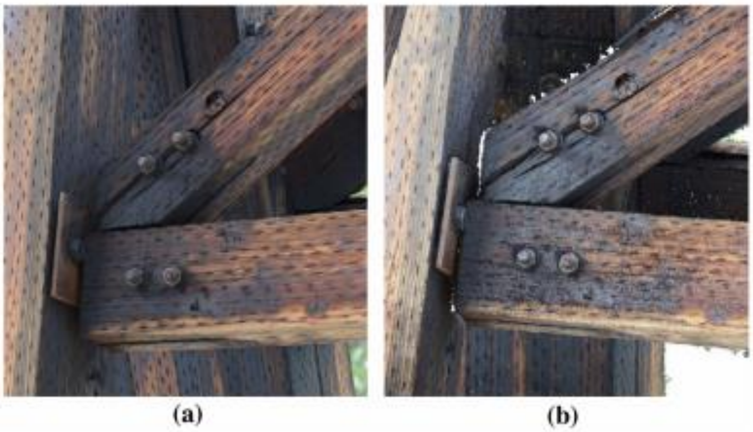

Figure 7 - Damage on field photo (left) and same damage from the complete 3d model (right) (Khaloo et al., 2018)

3.4 Results

The above conducted literature allowed us to derive several broad requirements for UAV usage in SHM projects, which are listed below. However, as of now, the exact specifics of these requirements are hard to pin-point, since, the usage of UAVs in large civil project is a recent phenomenon (Lovelace, 2015). The comparison studies of RWS are only partially in line with other literature. The broad requirements derived are the following:

1. The ability to direct cameras upward and the ability to fly without a GPS signal.
2. UAV must be able to photograph from close enough distance to obtain a right resolution, resolution of 1mm/pixel is shown to enough to obtain detail images that are comparable with close-up photos. For accurate crack measurement, this resolution needs to even better.
3. UAV must be able to fly in different sets of weather conditions, to estimate conditions permits should be issued faster and/or UAV's should handle conditions better.
4. Location of the UAV's, and thus its photos relative to the object should be clear to obtain better knowledge on the location of the photos as some elements of bridges are much alike.
5. Currently when using UAV's for inspection complete closing of the object is necessary, this provides similar or even more nuisance than a conventional inspection.
6. Standardisation of the mission planning and data analysis processes are needed
7. Currently due to legislation, when performing an inspection with use of a UAV, it is still necessary for the object to be fully closed for users. This is limiting wider use.

4 Expert views

To complement the information obtained from literature and to give a complete view on the requirements that are applicable for situation in the Netherlands, interviews with experts from four different companies were conducted. These experts have experience in using UAVs for bridge inspections. The interviews that were conducted can be found in appendix A, the companies that have been interviewed can be found in table 1.

From the interviews it becomes clear that companies see and use UAVs as a tool for specific data acquisition. However, three out of four companies state that there is a lot of development necessary before UAVs can be used for more general ways of data acquisition for SHM. Challenges these companies run into are mostly concerning: legislation, knowledge, processing software and processing time.

The complete results of the interviews can be found in Appendix B and are structured according to the subjects defined in section 1.2. A summation of the found requirements in combination with an explanation can be found below:

1. Inspectors should be able to steer the camera to capture the right images/data.
2. Maintaining visual contact with the drone is obligated by law, which in some situation limits the benefits as the base station cannot be fixed.
3. Road closure when flying above the road surface is obligated by law. This full road closure is diminishing benefits compared to conventional methods, which can operate with partial closing.
4. From images alone it is hard to observe the difference between, for example, a spider web and a crack. Sensor data should be more complete to be able to distinguish the difference.
5. Lots of data is acquired during flight, this data should be analysed in an efficient way.
6. Permits should be issued faster to be able to be flexible in terms of weather conditions and planning.
7. UAV's with the possibility of upward facing cameras are necessary to be able to inspect the underside of a bridge.
8. Automatic image processing is necessary, currently photos are viewed piece by piece which takes a lot of man-hours and is therefore costly and time consuming.

While three out of four respondents state that data analysis should be more efficient, there were no clear indications on how this efficiency can be achieved. We find this trend, where the respondents are not able to provide specific requirements and/or boundary conditions, in all the interviews.

5 Conventional inspection

The type of inspections this research focusses on are full structure inspections as these are deemed most interesting for UAV usage by RWS. These inspections are performed every six years to measure the state of an object. To perform this analysis within the scope of this research, one full structure report is analysed, a recent report on the John Frost bridge in Arnhem. This report is selected because of the size of the object in combination with age as according to RWS, these kinds of object are the most ideal for inspection by UAV and therefore a suitable case study.

During this case study the focus will lay on the methods that are used, and the results that are obtained during the visual inspection phase of the full structure inspection report. The details of the John Forst bridge report that will be researched are the following:

Name: John Frost bridge
Location: Arnhem
Function: bridge crossing the Rhine
Year of construction: 1932
Total Length: 601m
Roads: N344
Details:
Foot and bicycle lane
Three lanes (traffic)
Foot and bicycle lane

figure 8 - John Frost bridge

5.1 Build-up

The fundamental idea of a conventional full structure inspection is that all risks to the objects and its users are contained, making sure the object is safe for use. This means that the final report states all the uncontained risks and offers a solution to each of corresponding risks in order to make the object safe for use again.

The starting point of the inspection is done by gathering all previous data on the object and creating an initial object risk analysis (IORA). In this IORA all substructures of the object and all possible ways of failure of these substructures are specified. Some of the risks of failures can be eliminated using previous data on the object yet most of the risks need visual inspection or additional research to be eliminated or to be contained. In figure 9 a flowchart of this method can be found.

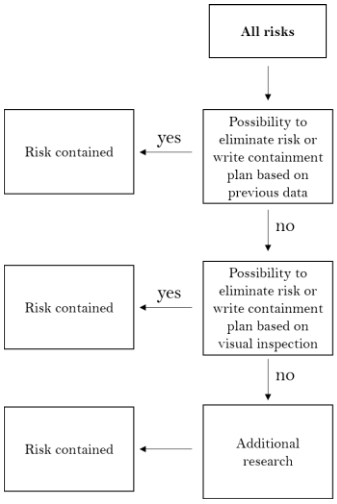

figure 9 - flowchart risk-based inspection

This risk analysis then leads to the focusing area's during the inspection, a full flowchart of an inspection build-up can be found in figure 10. The focus of the case study is to gather information about to the extent to which UAVs are able to replicate the results of the conventional visual inspection. This will be done by making a comparison in chapter 6.

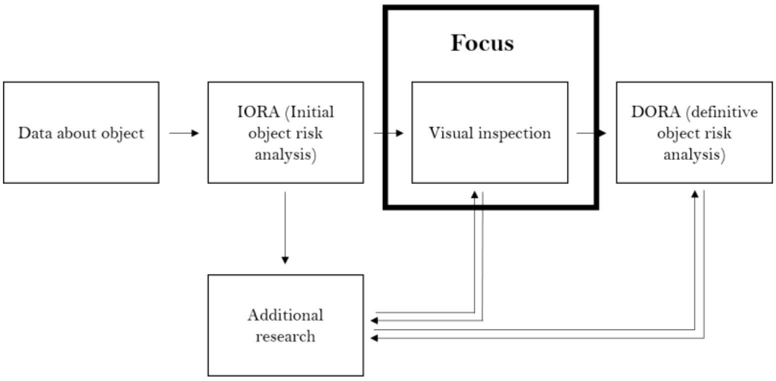

figure 10 - flow chart full structure inspection

5.2 Substructures

From an initial object specific risk analysis (IROA), key and high risk substructures and the necessary equipment are derived which are listed in detail in appendix C & D. In this overview, we shortly summarize the specific substructures and needed equipment regarding the John Frost bridge:

1. Main construction concrete
2. Main construction steel
3. Water drain
4. Handrail
5. Supports
6. Road sides
7. Wear layer
8. Pillars
9. Hardening
10. Expansion junction

During the visual inspection, these substructures were inspected using standard equipment consisting of: inspection hammer, photo camera, protective clothing, measuring tape, crack width measuring possibilities and a ladder. Some substructures require the usage of additional equipment , which can be found in table 3.

Equipment used for accessibility	**Substructures**
Platform	Main construction concrete, main construction steel, supports, pillars and expansion junctions
Inspection wagon (part of bridge structure underneath the main span, can move along the complete span)	River span of: main construction concrete, main construction steel, supports, pillars and expansion junctions
None	Water drain, handrail, road sides, wear layer and hardening

table 3 - accessibility equipment

5.3 Inspection results

Next, we will discuss some of the damages found to certain substructures during the conventional visual inspection, the complete results of the visual inspection can be found in appendix E.

During the conventional visual inspection of the main concrete construction six different damages have been found. The severity of each of these damages varies from low to high. The severest damage is to the concrete construction of the underside of the concrete slabs that support the bridge deck. In figure 11 an example of one of the damages is given. In this case two to four small cracks have been found in the underside of the bridge deck with a width that is smaller than 0,2mm (middle photo). Another six cracks have been found on the bridge deck, with width varying between 2-3mm (right photo). Both observed cracks are placed within the "cracks in the main construction concrete" group.

figure 11 - one damage type to the main bearing construction concrete

Apart from damages on the main concrete construction, the visual inspection reported failures on all other substructures except the handrail. Another example of one of these damages is corrosion cracking (fatigue) due to the thermal expansion/closure of joints. This process will result in material decay over time. The corrosion damage photos can be found in figure 12. Again, the overview photo of the substructure is on the left and two photos of the damages on the right. No measurements have been made on this damage type.

figure 12 - one damage type to the expansion junction

The last example of a found damage is to the supports, this is the only damage type that is found during inspection. In this case the supports show signs of corrosion, mostly showing on the points of contact. The overview photo (left) and the damages (right) can be found in figure 13. The damage has been classified as normal considering the age of the structure.

figure 13 - one damage type to the supports

The complete overview of the found damages can be found in table 4. The full specifications of these damages can be found in Appendix E.

Track. ID	Substructure	Number of noteworthy damages types found	Severity
1	Main bearing construction (concrete)	6	high
2	Main bearing construction (steel)	2	low
3	Water drain	1	low
4	Handrail	-	-
5	Supports	1	Low
6	Road sides	1	Low
7	Top layer asphalt	1	Medium
8	Pillars	1	Low
9	hardening	1	Low
10	Expansion junction	2	medium

table 4 - number & severity of damages found during visual inspection

In order to compare the data quality between conventional methods and data acquisition using a UAV, all the damages have been scaled for each substructure to the smallest level of detail that was obtained during the conventional inspection. In this way information on quality feasibility when using a UAV for data acquisition can be specified to each of the substructures. We use the following levels of detail that came forward as important from analysis of the damages:

- Large (> 0,5 meters)
- Close-up (0,5m – 0,1m)
- Detailed (0,1m-0,01m)
- Measured (<0,01m)

Each of the damages found in the conventional report will be specified to the level of detail that is obtained during the visual inspection. This overview can be found in Appendix F.

From the data we obtain that the areas that must be examined the closest are: the main baring construction (concrete) and the expansion junctions. In table 5 the smallest level of detail and required additional equipment (if any) for each of the substructure is given. It should be noted that the level of detail specified in table 5 only applies to the case study presented in this report, hence the John Frost Bridge.

Track. ID	**Substructure**	**Level of detail obtained during conventional inspection (smallest)**	**Equipment needed**
1	Main construction (concrete)	Measured	Standard + platform + inspection wagon
2	Main construction (steel)	Measured	Standard + platform + inspection wagon
3	Water drain	Large	Standard
4	Handrail	-	Standard
5	Supports	Large/close-up	Standard + platform + inspection wagon
6	Road sides	Large/close-up	Standard
7	Top layer asphalt	Large/close-up	Standard
8	Pillars	Detailed	Standard+ platform + inspection wagon
9	hardening	Detailed	Standard
10	Expansion junction	Measured	Standard+ platform + inspection wagon

table 5 - the level of detail and equipment needed during the visual inspection

6 Conventional vs UAV inspection

In order to compare the conventional visual inspection to a theoretical inspection with the use of a UAV, we group some of the substructures, this division is made within the vertical axis of the bridge as most substructures are lengthwise oriented. Firstly, we consider the parts that are below road height. Next, we group substructures that are located at road height. The last group we consider are substructures that are located above the road height. An overview of this distribution can be found in table 6.

Name	**Consisting of**
Lower structures	Main construction concrete, main construction steel (except arch), supports and the pillars.
Road surface structures	water drain, handrail, road sides, top layer asphalt, hardening and expansion junction.
Upper structures	Steel arch of the bridge

table 6 - grouping of substructures

The different substructure groups will be compared with the data collected from literature and expert interviews. The subjects on which they will be compared on are the subjects of 2.1.

6.1 Results comparison study

In this chapter the results are presented; these consist of an overview of the obtained information from the comparison study. The results specified for each of the subcategories (lower, road level and upper structures) can be found in Appendix G. In table 7 a short score summary is disclosed, in which red is negative in comparison to conventional methods, yellow is neutral and green is positive.

Subject	**UAV score**
Quality	+-
Equipment & access	+-
Nuisance	-
Time	+
Costs	+
Post processing	-

table 7 - UAV vs conventional inspection

6.1.1 Quality

We obtain that the quality of the imagery of present day UAV's is comparable with imagery taken during conventional inspections. We find that all the substructure groups could quality wise be inspected with a UAV. Furthermore, an UAV can store multiple sensors and this can gather additional information simultaneously, which can greatly enhance the quality of the acquired data, assuming compatible asset management. Yet the UAV also has limitations, as it is not able to physically touch the object. This makes it impossible to remove coting, dust or spiderwebs.

6.1.2 Equipment & access

UAVs are not able to inspect all parts of the bridge structure and are frankly not efficient on all parts of the structure. This becomes most visible on the bridge deck. Substructures like the expansion joints are almost impossible to inspect with use of UAVs. Other substructures on the bridge deck can be conventionally inspected without the use of equipment to gain access.

6.1.3 Nuisance

During the conventional inspection of the John Frost bridge, nuisance was created during the inspection of the upper part of the structure. In this case, one lane of the bridge was closed for traffic. When using an UAV to inspect the bridge surface or upper structures, in close distance to the bridge, full closure is necessary. This makes the deployment of a UAV more annoying for the users of the object than the conventional method. Inspection using an UAV from a distance is also one of the possibilities, yet this has a diminishing effect on the quality of the acquired images. Using an UAV to inspect the lower structures of the bridge does not result in any form of Nuisance to the users.

6.1.4 Time

For the John Frost bridge a comparison could not be made between the time taken to complete the conventional inspection and inspection with UAVs as, as there is no disclosure of the amount of time the visual inspection took. However, both the consulted literature and interviews state that the visual inspection using UAVs could result in inspections being executed up to five times faster.

6.1.5 Costs

Within the conservation report no prices are disclosed of the visual inspection nor prices of the equipment used to gain access. From literature and interviews, we know that a UAV can compete with conventional methods and could potentially even reduce costs.

6.1.6 Post processing

The post processing of the conventional visual inspection takes little time, as the amount of data is limited to the found damages. UAVs will also gather data on structurally saint parts of the structure. During post processing, the data needs to be filtered to just the specific damages, which most likely requires trained personal and dedicated software. However, from the interviews we also obtain that smart sensors are being developed that could offer a solution to the problem of post processing and junk data.

7 Discussion

The set-out goal of this research was to map the requirements that come with the usage of UAVs for SHM data collection. From the literature study and the interviews, we obtain a lot of overlap in the results. UAVs with the ability to face the camera upwards come forward from the literature study as well as from the respondents of the interviews. From both studies, we also find that resolution of the current cameras is sufficient to compare data with conventional methods. Both the literature study and the consulted experts indicated that complete road closure during an UAV inspection and additional post-flight data processing are defined as the biggest drawbacks with respect to the conventional methods. However, the consulted experts also state UAV's are being used in the field, and can result in benefits as found by specific case studies.

This research provides an overview of the pain points when using UAVs for SHM. However, due to the novelty of this specific application of UAVs, the specific requirements and boundary conditions that are linked to these pain points can, in most cases, not be pin pointed. One way to explain this pattern is that there a still a lot of uncertainties and a lack of maturity in this domain. High perceived risks would disincentive investment in the current state of the market, as Nebest states: 'the market is currently not that motivated to invest, as there are a lot of uncertainties'. Low market maturity would also explain the gaps in the literature, namely the hard to specify exact requirements for UAV use. A parallel effect might be that companies within SHM have a stable modus operandi which in combination with high perceived risks might decrease incentives to invest and change their current operation methods.

In a way a vicious circle is created, were investment and development in using UAVs for SHM is being suppressed in the Netherlands. From the interviews and the study of the conventional report it becomes clear that RWS has a leading role in the way SHM is executed. The current state of affairs is not leaning towards deployment of UAVs apart from very specific use. From the interviews it also becomes clear that UAVs have the ability to gather data that could give a completely different spin on the way asset management is arranged at Rijkswaterstaat.

8 Conclusions

From this study, we obtain that UAV use for SHM data collection is a broadly studied alternative for conventional inspection methods. This study shows that indeed UAVs could prove to be a new, faster, cheaper, safer and more complete way of collecting data for SHM. Yet it also showed that a complete substitute for conventional methods is not possible, as additional research and access to certain locations is always a factor. There are also difficulties in post proccing of the UAV acquired field data. Due to strict legislation and limitations by external factors such as weather and battery life, deployment of UAVs are a complex undertaking and requires specific knowledge.

From this study we can conclude the following requirements are linked to usage of UAVs for SHM data collection:

1. UAVs with the ability to direct cameras upward and the ability to fly without a GPS signal.
2. UAV must be able to photograph from close enough distance to obtain a right resolution, resolution of 1mm/pixel is shown to enough to obtain detail images that are comparable with close-up photos. For accurate crack measurement, this resolution needs to even better.
3. UAVs must be able to fly in different sets of weather conditions, current limitation weather wise are not flexible enough for year wide use.
4. Location of the UAV's, and thus its photos relative to the object should be clear to obtain better knowledge on the location of the photos as some elements of bridges are much alike.
5. Standardisation of the mission planning and data analysis processes are needed to efficiently cope with the amount of data and planning.
6. Inspectors should be able to steer the camera to capture the right images/data.
7. Maintaining visual contact with the drone is obligated by law, which in some situation limits the benefits as the base station can't be fixed.
8. Legislation around infrastructural objects should be changed to avoid full closure of the object. The full road closure is diminishing benefits compared to conventional methods, which can operate with partial closing.
9. On images alone it is hard to observe the difference between for example a spider web and a crack. Sensor data should be more complete to be able to distinguish the difference.
10. Certain permits should be issued faster to be able to be flexible in terms of weather and conditions during the inspection.

9 Recommendations & future research

From this research it becomes clear that a lot of research has been conducted concerning the deployment of UAVs for Structural health monitoring data collection. Standardisation of mission planning and post-processing is one of the key requirements that came forward from literature as well as expert interviews. Due to Rijkswaterstaats' powerful position as client for bridge inspection, a change in modus operandi almost has to be started by Rijkswaterstaat.

To fully explore the possibilities I can recommend more research in the potential benefits of using UAV's for SHM data acquisition. Currently the Dutch studies that were conducted are solitary and did not go into standardisation of flight planning and data processing or exploring full benefits of the technology. New studies should take different modus operandi into account instead of using the current modus operandi in combination with UAVs for data collection.

I can also recommend more research in the standardisation of the flight planning and data processing. Additional research in the functionality of different sensors is also important to the contribution of UAVs for SHM data collection.

For Rijkswaterstaat it is important to take a leading role in the development of standardised flight planning and data processing. Furthermore the possibilities of developing new ways of asset management are for Rijkswaterstaat to initiate.

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Appendix A – Conducted interviews

Gedurende dit interview zal getracht worden in kaart te brengen wat complicaties zijn voor het toepassen van drones ten behoeve van het uitvoeren van instandhoudingsinspecties. Het doel van het onderzoek waar deze interviews aan bijdragen is het in kaart brengen van de eisen en randvoorwaarden die het gebruik van drones voor inspectiedoeleinden met zich meebrengen. Daarnaast wordt er getracht in kaart te brengen welke problemen bedrijven momenteel ondervinden bij het gebruik van deze nieuwe methoden.

Het eerste deel van de vragen zal zich focussen op de conventionele manier van inspecteren. Hier zal de focus vooral liggen op de kwaliteit van de aangeleverde data en de manier waarop conclusies worden onderbouwt. Het tweede deel richt zich op het gebruik van drones en eventuele complicaties die worden ondervonden bij het gebruiken van de techniek. Hier zullen we ook onderscheid maken tussen verschillende categorieën en zal de focus ook liggen op veranderingen die nodig zijn om effectieve inzet haalbaar te maken.

De vragen zullen betrekking hebben op een uitvoering van een instandhoudingsinspectie van een groot kunstwerk, de leidraad voor dit onderzoek is een inspectie uitgevoerd bij de John Frost brug in Arnhem.

Conventionele inspectie methoden

1. Welke informatie dient verzameld te worden om tot een correcte instandhoudingsrapportage te komen? *Eventuele naderonderzoeken blijven hier buiten beschouwing, informatie die leidt tot het uitvoeren van een nader onderzoek niet.*

Opmerkingen….

2. Welk niveau van nauwkeurigheid moet aangeleverd worden om tot een juiste rapportage te komen? *Het gaat hier om locatie en detail niveau van de informatie.*

Opmerkingen….

3. Hoe wordt een keuze gemaakt om door te gaan naar een nader onderzoek? *Het gaat hier vooral over de kwaliteit van de informatie die nodig is en hoe deze gepresenteerd wordt.*

Opmerkingen….

4. Welke eisen en randvoorwaarden zijn er verbonden aan het afleveren van een goede instandhoudingsinspectie? *Hier maken we onderscheid tussen de volgende categorieën: technische, omgevings, kwaliteits, veiligheids en efficientie eisen en randvoorwaarden.*

Opmerkingen….

5. Welke materialen zijn er nodig voor het uitvoeren van een conventionele inspectie, en tot welke overlast leidt de inzet van deze materialen? *Eventuele hinder die voorkomt bij het uitvoeren van een inspectie zonder de inzet van materialen valt hier ook onder.*

Opmerkingen….

Het gebruik van drones

1. Kun je een voorbeeld noemen van een door jullie uitgevoerde inspectie doormiddel van drones? *hoe vaak is het toegepast en soorten objecten, Meer background, wat voorn personeel (speciaal voor drones,) grootte en dergelijken.*

Opmerkingen….

2. Wat waren hier de belangrijkste bevindingen als het aankomt op: nauwkeurigheid, efficiëntie (snel uit kunnen voeren van een inspectie), veiligheid en overlast? *(specifiek bij die brug of ook bij andere bruggen?)*

Opmerkingen….

3. De bovengenoemde eisen (conventionele methoden), zijn die haalbaar door middel van het gebruiken van een drone zo niet, waar liggen deze problemen?

Opmerkingen….

4. Wat zijn belangrijke eisen en eisen voor het gebruiken van een drone voor instandhoudingsinspecties? *Hierbij maken we opnieuw onderscheid tussen:*

(technische, omgevings, kwaliteits, veiligheids en efficientie eisen, gebruiken voor doorvragen en niet in de vraag) en randvoorwaarden.

Opmerkingen….

5. Wat zijn belangrijke randvoorwaarden voor het gebruiken van een drone voor instandhoudingsinspecties

Opmerkingen….

6. Wat zijn de redenen dat jullie momenteel geen of weinig gebruik maken van drones? Of zo ja waarom wel. Kan ook in algemenere zin.

Opmerkingen….

7. Wat zou er nog moeten veranderen om drones meer inzetbaar te maken. Waar zien jullie veranderingsbehoefte? *zijn drones uberhaubt een alternatief voor de traditionele manier*

Opmerkingen….

Appendix B – interview results

1. Data quality

The quality of the data that is gathered.

	interview 1	interview 2	interview 3	interview 4
Global condition can become clear from images	x	x		
DORA could not be completed on UAV imagery alone	x	x	x	
Development of (smart) sensors is a must to contribute to more qualitive data	x		x	
Resolution of imagery is compairable with close-up photos	x	x		x

2. Equipment & access

Equipment used to acquire the data and/or equipment used to gain access to the locations of acquirement. Also consisting of other factors that limit access eg. weather

	interview 1	interview 2	interview 3	interview 4
Communication with the pilot is still hard, as the inspector is not able to fly the drone	x	x		
Maintaining visual contact with the UAV is still nessesary so the base station has to be mobile	x	x		
Some places, that allmost always need visual inspection, cant be reached with the UAV	x	x	x	x
In safety aspects much better than conventional methods			x	x
Lots of no-fly zones within the netherlands	x		x	
limitions by weather, espessialy in the Netherlands, make deployment an issue	x	x	x	
battery duration whas to short, UAV had to return to the bas station a lot	x			

3. Nuisance

The nuisance that is experienced by the users of the object during data acquisition

	interview 1	interview 2	interview 3	interview 4
restriction on road traffic nessisary when inspecting above roadlevel	x	x	x	
Inspection from a distance is possible without roadrestrictions				x

4. **Time**

The time it took to acquire the data.

	interview 1	interview 2	interview 3	interview 4
Very time-consuming, lots of repositioning needed and short battery life	x			
On specific project about 5 times faster than conventional methods			x	
Comperable or faster than conventional methods				x
For small objects conventional method is much faster		x	x	
Hard when sicking to a schedule, as there are a lot of different parameters		x		

5. **Cost**

The costs that are related to the data acquisition.

	interview 1	interview 2	interview 3	interview 4
Lot of personel needed: inspector, pilot and observer	x			
Relatively expencive, esspesialy for smaller objects	x	x	x	
Usage is currently quite cheap and is becoming ever cheaper				x

6. Post processing

Everything that is involved in the processing of the acquired data.

	interview 1	interview 2	interview 3	interview 4
Lot of data aqusition is taking place, this makes processing the data very cost and timely	x	x	x	
Currently different sensor usage in this field is underdeveloped		x	x	
Smart sensors nessesary to reduce the amount of junk data		x	x	
Lots of different ways of data acquisition and prosessing are currenly possible				x
Collected data should be intergrated in assetmangengement systems so better estimates of maintance can be made				x

Appendix C – inspection plan

Track. ID	Substructure	Risk level	Possibility to inspect from distance	Equipment needed to reach object for inspection	Equipment usage
1	Main bearing construction (concrete)	High	No	Yes	Inspection within arm's reach with use of platform
2	Main bearing construction (steel)	High	No	Yes	Inspection within arm's reach with use of platform
3	Water drain	Medium	Yes	No	Inspection within arm's reach, no equipment needed
4	Handrail	Medium	No	No	Inspection within arm's reach, no equipment needed
5	Supports	Medium	No	Yes	Inspection within arm's reach with use of platform and inspection wagon
6	Road sides	Medium	Yes	No	Inspection within arm's reach, no equipment needed
7	Top layer asphalt	Medium	Yes	No	Inspection within arm's reach, no equipment needed
8	Pillars	Medium	No	Yes	Inspection within arm's reach with use of platform, ladder and inspection wagon
9	hardening	Medium	Yes	Yes	Visual inspection from biking lanes
10	Expansion junction	Medium	No	Yes	Inspection within arm's reach with use of platform and inspection wagon

Appendix D – bridge substructures

1. main construction concrete
description: concrete parts of the structure on which the roads are constructed.
location: whole span, on top of steel framework
substructures:

- Road bicycle lane, concrete
- Road cars, concrete

2. main construction steel
description: complete baring construction of the span and framework that supports the concrete structure above (roads).
location: complete span.
substructures:

- Arch, steel
- Console, steel
- Diagonal, steel
- Vertical element (arch), steel
- Main baring construction, steel
- Length bearers, steel
- Wind strengthens, steel

3. water drain
description: water drainage elements
location: throughout the span
substructures:

- Water drainage, steel

4. handrail
description: handrail along both outer sides of the bridge
location: outer sides of the bridge, along the whole span
substructures:

- Handrail general, steel
- Handrail vertical elements, steel

5. supports
description: main supports of the bridge
location: both sides of the arch located in the Rhine
substructures:

- Support block, concrete
- Supports general, concrete
- Supports general, concrete
- Support cradle, steel

6. Road sides
description: barrier to holdback road waste
location: on each sides of the road and bicycle lane.
substructures:

- Road sides general, concrete

7. wear layer
description: top layer of road deck.
location: top of both the bicycle lanes.
substructures:

- Wear layer general bicycle lane, synthetic material
- Wear layer general car lane, synthetic material

8. pillars
description: bridge supports for non-arch construction.
location: from both sides of the arch towards land heads.
substructures:

- Ladder, steel
- Bridge head, concrete
- Pilar, concrete
- Stairs, concrete
- Floor, concrete
- Wall, concrete

9. hardening
description: top layer of the road deck.
location: main road.
substructures:

- Hardening, asphalt

10. expansion junction
description: transition from bridge to land structures.
location: Three locations, complete width of the bridge structures
substructures:

- Expansion junction general, steel
- Expansion junction general, rubber

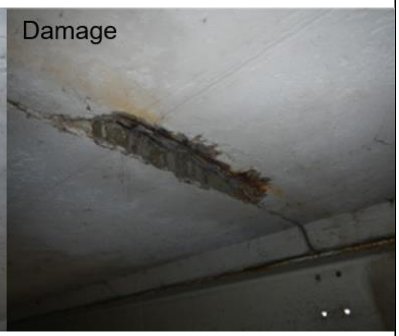
Appendix E – found damages

1. main construction concrete

Underside of the road bearing concrete slabs show rupture/broken off concrete, damage is of around 0,5 meter.

Severity: severe damage.

Corrosion areas on the concrete slabs with exposed reinforcement. About 20 locations along the outer side of the bridge deck. Coverage on reinforcement is 1,5-2cm came forward from additional research.



Severity: severe damage.

Rips in concrete slabs (underneath) in width direction of the bridge, about 2-4 cracks. The width of these cracks is very small (<0,2mm). Also on the bridge surface detected 6 cracks with a width of 2-3mm.

Severity: severe damage

Concrete slabs for the bicycle lane have little thickness (8cm), in combinations with the damages the slabs lose structural safety.

Severity: severe damages

Transversal rips in concrete slabs, with shows of calcium spout at about 8 locations. Width of the cracks is <2mm.

Severity: minor damage

Concrete connection joints losing material over a length of about 50 meters as a result of water corrosion. Depth of the material loss is about 5 centimeters.

Severity: severe damage

2. main construction steel

Longitudinal beams show local corrosion on connection with concrete slabs.

Severity: minor damage

Arch shows corrosion on connection areas and some rivets are corroded (about 30). On about 5 locations there is material decay and slight compression (0,5-1mm)

Severity: minor damage

3. water drain

Drains are block, causing water to reach the supports.

Severity: minor damage

4. handrail

No damages found on the handrail.

5. supports

All supports show signs of corrosion, mostly showing on the points of contact.

Severity: minor damage

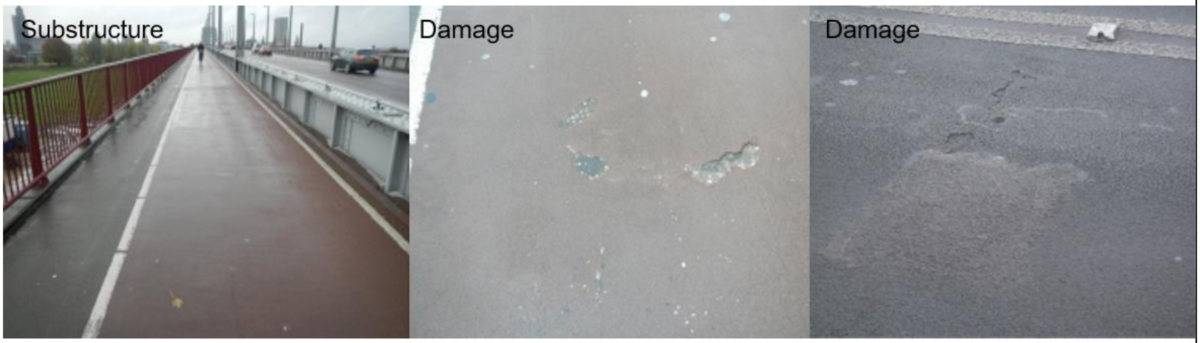
6. Road sides

Damages on Road sides at about 40 locations with a total length of 50 meters.

Severity: minor damage

7. wear layer

Wear layer shows several different types of damages at an area of about 10 square meters.



Severity: severe damage

8. pillars

Natural stone on the upper side of the pillars show silted up mortar at about 125 natural stones.

Severity: minor damage

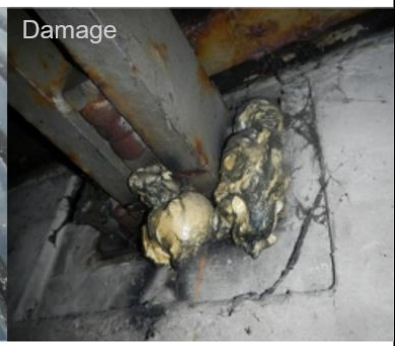
9. hardening

Asphalt shows several different types of damages at an area of about 12 square meters. There is also rut formation on the complete deck with a depth of about 1cm.

Severity: minor damage

10. expansion junction

Tearing of rubber of junctions, besides slight settlement in the middle of around 0,5 cm.



Severity: minor damage

Junctions are showing corrosion on all lower parts and show slight material decay as result.

Severity: heightened

Appendix F – summation of found damages

Track. ID	Substructure	Damage id and damage	Level of detail
1	Main bearing construction (concrete)	1.1rupture/broken off concrete 1.2corrosion over 20 locations 1.3about 10 cracks from top and underneath 1.4bicycle lane deck has little thickness 1.5Transversal rips in concrete slabs 1.6Concrete connection joints losing material	1.1Large 1.2Large 1.3Measured 1.4Detailed 1.5Measured 1.6Detailed
2	Main bearing construction (steel)	2.1 Longitudinal beams show local corrosion 2.2 material decay on arch	2.1 close-up/ detailed 2.2 measured
3	Water drain	3.1 drains are blocked	3.1 large
4	Handrail	-	-
5	Supports	5.1 supports show signs of corrosion	5.1 Large/close-up
6	Road sides	6.1 decay of material	6.1 Large/close-up
7	Top layer asphalt	7.1 several types of damages	7.1 Large/close-up
8	Pillars	8.1 silted up mortar	8.1 detailed
9	hardening	9.1 several types of damages 9.2 rut forming	9.1 large/close-up 9.2 detailed
10	Expansion junction	10.1 tearing of rubber and settlement 10.2 corrosion and material decay	10.1 measured 10.2 close -up

Appendix G – Comparison results

In this appendix you will find the benefits and disadvantages of using UAV in comparison with conventional methods. The comparison is made for each of the three substructure groups: lower, road surface and upper. The data is presented in an Italian flag diagram style.

Lower structures

Subject	**Conventional**	**UAV benefits**	**UAV neutral**	**UAV disadvantages**
Quality	Close-up photo quality Obtains cracks up to 0,2 mm possibility to remove coting	Possibility to gather different types of data in one flight	Close-up photo quality measure cracks up to 0,25 mm	No possibility to remove coting
Equipment & access	Standard basic equipment Platform used for lower parts inspection wagon for river span	No platform or inspection wagon necessary	UAV able to access all locations	Complex undertaking drone + planning + observer + pilot
Nuisance	No limitations, means of access do not use road			Full road closure necessary to fly under the bridge
Time	Unknown for the John Frost bridge and differs for each substructure	Data acquisition in the field could prove up to 5 times faster		
Costs	Unknown for the John Frost bridge	Cost reduction of could potentially be achieved		
Post processing	Clear processing data is right size			Currently inefficient post processing

Road surface structures

Subject	**Conventional**	**UAV benefits**	**UAV neutral**	**UAV disadvantages**
Quality	Close-up photo quality	Possibility to gather different types of data in one flight	Close-up photo quality	
Equipment & access	Standard basic equipment Platform only used for underside expansion junctions			Complex undertaking drone + planning + observer + pilot Still a platform is necessary as the UAV cannot inspect the expansion junctions
Nuisance	No limitations, means of access do not use road			Full road closure necessary to fly above the road
Time	Unknown for the John Frost bridge and differs for each substructure	Data acquisition in the field could prove up to 5 times faster		
Costs	Unknown for the John Frost bridge			Expensive drone equipment against little means of accessibility during convention inspection
Post processing	Clear processing data is right size			Currently inefficient post processing

Upper structures

Subject	Conventional	UAV benefits	UAV neutral	UAV disadvantages
Quality	Close-up photo quality Obtains cracks up to 0,2 mm possibility to remove coting	Possibility to gather different types of data in one flight	Close-up photo quality measure cracks up to 0,25 mm	No possibility to remove coting
Equipment & access	Standard basic equipment Platform used	No platform necessary	UAV able to access all locations	Complex undertaking drone + planning + observer + pilot
Nuisance	Depends, possible only closure of one lane.			Full road closure necessary to fly above and around the arch
Time	Unknown for the John Frost bridge and differs for each substructure	Data acquisition in the field could prove up to 5 times faster		
Costs	Unknown for the John Frost bridge	Cost reduction of could potentially be achieved		
Post processing	Clear processing data is right size			Currently inefficient post processing