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Preliminary estimates of the viability of UAV-based bridge inspections in Switzerland

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ABSTRACT: Unmanned aerial vehicles (UAVs) are gaining popularity as sensor platforms for different inspection purposes. Additionally, due to the developments in flight control systems, the effort of learning how to control a UAV is steadily decreasing. This opens up a number of possibilities on how these UAVs can assist in the inspection of civil engineering infrastructure. Furthermore, intelligent flight control algorithms allow for autonomous flight, obstacle avoidance and dynamic flight path calculation and as such increase the possibilities for potential use even more. This paper investigates the boundary conditions of the use of UAVs for bridge inspections in order to give more insight to the infrastructure manager on which conditions in the network advocate the use of UAVs as a beneficial tool for performing inspections. The work is based on an analysis of the viability of using a UAV in visual inspections of three bridges in Switzerland. Based on these investigations a decision flow chart is developed that can be used to help decide whether or not UAVs should be used. The paper is a summary of the work presented in (Romer, 2016)

1 INTRODUCTION

Inspections are an important part of infrastructure management, as is determining the optimal balance between the amount of information collected and the cost of collecting it (Adey et al., 2012). With this in mind, unmanned aerial vehicles (UAVs) are gaining popularity as sensor platforms for different inspection purposes. Additionally, due to the developments in flight control systems, the effort of learning how to control a UAV is steadily decreasing. This opens up a number of possibilities on how these UAVs can assist in the inspection of civil engineering infrastructure. From a scientific point of view, the theoretical usefulness has already been proven (Derkx, 2008). However, from an infrastructure managers' point of view, the general usefulness is a necessary but not in itself sufficient as there are also other factors to be investigated than a general usefulness. For example, legal requirements limit the possibilities for autonomous flight, or forbid flight over certain areas with exceptions not always possible. This paper investigates the boundary conditions of the use of UAVs for bridge inspections in a Swiss context in order to give more insight to infrastructure managers on which conditions advocate the use of UAVs as a beneficial tool for performing inspections. Although this paper focuses specifically on Switzerland, the results can still be used as a guideline to implement UAV-based Bridge inspections in other countries as well.

2 LITERATURE REVIEW

Literature about the viability of UAV-based inspections can be separated into three parts: 1) literature about UAV-based inspections itself, 2) literature about legal aspects of UAV flights and 3) literature about legal aspects concerning inspections.

For UAV-based inspections, the general viability has already been demonstrated by Derkx and Sorin (2008), and Hallermann (2014), which both provide information about flight patterns and general requirements, as well as the expected results. Derkx and Sorin (2008) mention that as of 2008, any UAVs in France were considered as normal aircraft, and as such a 6-week training was needed to be legally allowed to fly the UAV. In Switzerland, the legal requirements for UAVs (DETEC, 2015) can be summarised as follows: No special permit is needed, given that 1) the take-off weight does not exceed 30 kg, the UAV is permanently in line of sight, a distance of 5'000 m to airport runways is kept at all times, and an insurance cover of at least 1 Million Swiss Francs (approx. 1 Mio US$) is provided. For all other situations, a special permit is required which will be issued on a case-by-case examination by the FOCA (Federal Office of Civil Aviation). However, not only UAV flights are regulated. In Switzerland, the inspection of bridges is governed by the guidelines given in (Steiger and Stutz 2000; Dieterle et al., 2005), which define the description of defects, condition states, but also the method of performing an inspection. Steiger and Stutz (2000) state that all 5 senses should be used for an inspection in the following hierarchical order: 1) sight, 2) hearing, 3) touch, 4) smell, and 5) taste. UAVs, of course, can only provide (1) and to a limited extent (2). Recent research from Rossi et al. (2014) shows potential for also providing gas detection i.e. (4 - smell), but is at the moment bound by the capabilities to detect specific chemical substances. Therefore, UAVs can only be seen as a tool that complements the infrastructure inspection, but not as a single means of inspection. There is, however, still great potential as the inspector can chose to stop at any point in the list if it is clear that all defects are already found.

3 INVESTIGATION OF VIABILITY

As showed in section 2, UAVs can be used for bridge inspections in Switzerland, albeit only as a supporting tool due to legal requirements. Therefore, the investigation of viability is based on the assumption that the UAV is used as a complementary tool in inspections. This paper presents a 2-stage flowchart (section 4) that helps in deciding 1) whether a UAV can be used, and 2) how much information can be gained by employing a UAV. To create this flowchart, three bridges have been investigated (described in section 3.1). The specifications of the UAV are given in section 3.2. The investigation is described, together with a short summary of the processes used to investigate the viability in section 3.3. The final flowcharts and the conclusion are presented in sections 4 and 5, respectively.

3.1 Bridges

The investigated bridges are shown in table 1.

Table 1. Investigated bridges

Name	Construction type	Span	Height
Pont sur la Lienne	Arched reinforced concrete	55 m	20 m
Pont de Chippis	Steel girder	50 m	14 m
Pont des Gorges du Dala	Steel composite	174 m	51 m

All three bridges share the properties, that they are located at places, where a traditional inspection is rather difficult: The «Pont sur la Lienne» crosses a deep canyon (more than 100m deep) that is not accessible without climbing equipment. Additionally, the bridge deck is very narrow (useable width 5.2m), so that a crane-based inspection interrupts traffic on the bridge. The «Pont de Chippis» is a steel girder bridge, that crosses the river Rhône, with only approx. 2.5m clearance below. Therefore, any inspection of the outer side has to be performed by moving the inspection crane through holes in the girder structure. This requires repositioning of the crane with full retraction of the inspection gondola during an inspection approximately 20 times (in contrast to other bridges, where the crane can be repositioned with the inspection gondola extended. The «Pont des Gorges du Dala» also crosses a deep canyon, and with its significant height of 50m, it is beyond reach of a standard inspection crane. In summary, all three bridges provide good opportunities for UAV-based inspections as a beneficial tool that can improve the inspection workflow.

3.2 UAV

The UAV used was a DJI Inspire 1 Pro. The technical details are shown in table 2.

Table 2. UAV and camera specifications

UAV		Camera System	
Model	DJI Inspire 1 pro	Model	Zenmuse X5 / DJI 15mm
Max. take-off weight	3500 g	Sensor	MFT CMOS
Service ceiling	4500 m	Effective pixels	16M
Wind speed resistance	10 m/s	Video resolution	4K@25p, 1080@60p
Max. speed	18 m/s	Lens	15mm f1.7 asph.
Flight time	18 min	Angular vibration	±0.02°
Operating temperature	-10°C…40°C		
Diagonal distance (largest dimension)	559 mm		

The flight control software of this UAV allows for fully automated flight (i.e. with a pre-loaded flight plan, the UAV is able to fly to all programmed waypoints automatically), assisted flight (i.e. the control software stabilizes the UAV and calculates drift and inertia compensation automatically), manual flight (control inputs are direct, without stabilization and compensation) and special flight modes (circling, follow-me, keep orientation, etc).

3.3 Investigation

The investigation into the viability was performed, using 4 elements: 1) the general requirements of inspections for bridges, 2) the optical detectability of defects, 3) a case study to verify the results of the optical detectability, and 4) a fault tree analysis of the UAV flight in order to assess the financial viability.

3.3.1 Requirements for inspections

In Switzerland, due to the country's topology, bridges serve a key purpose in road and rail infrastructure. These bridges have to be monitored in order to detect possible problems in a timely manner. The first level of monitoring is the simple observation, where employees of the road management agency report any apparent defects they encounter during their everyday tasks. The second level of monitoring is the inspection, with three subcategories: 1) the main inspection, performed in regular intervals (5 years). Here, the whole bridge is inspected in considerable detail. Essential structural components have to be inspected "in hand distance", i.e. from closer than one meter. 2) the interim inspection, performed on components that have been marked as "in critical state" during the main inspection. The monitoring interval is set on a case-by-case basis. 3) the special inspection, only performed after hazard events, such as flooding, earthquakes, etc.) (Dieterle et al. 2005)

The main goal of a visual inspection is to identify increasing damage, to clarify the causes and to estimate the extent. In order to achieve this, the entire structure is examined and the results are recorded both in writing and imagery. An inspector should perceive the structure through all his organs of sense, i.e. vision, hearing, feeling, smelling and tasting. (Steiger and Stutz, 2000). As a UAV, however, only has the possibility to provide visual images to deliver inspection information, the optical detectability of defects, presented in the next section, plays an important role.

3.3.2 Optical detectability of defects

In order to investigate the optical capabilities of the used UAV, a Koren Lens test (Koren, 2003) was performed from various distances, in order to find the maximum distance, the UAV can be away from a defect with given size in order to detect it. The test examines a pattern of black/white lines with logarithmically increasing width for the response in the black value of the optical sensor. As soon as there is a clear high-low response, (corresponding to a clear distinction between black and white), a line is deemed detectable. The test was performed outdoor, in overcast condition. The result of the test is shown in figure 1, a black-white response is shown in figure 2.

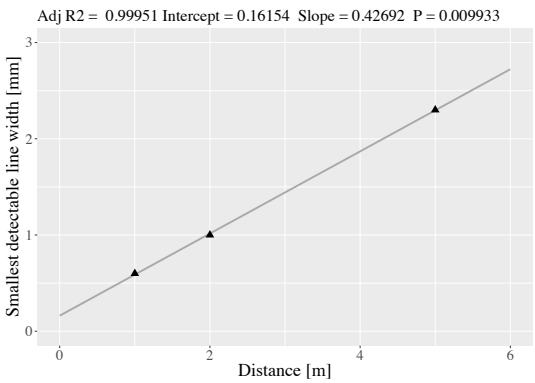

Figure 1. Koren lens test result.

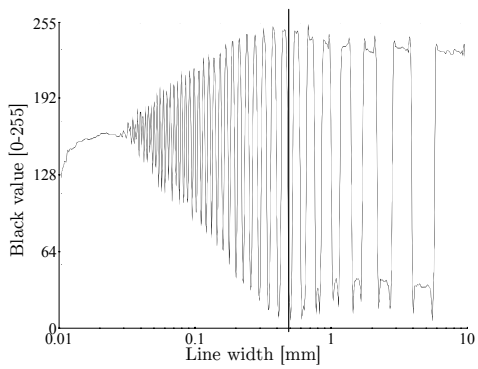

Figure 2. Black-white response for 1m distance.

It can be seen, that there is a linear relationship between the distance and the detectable defect size, as expected. The trend line crosses the y-axis at 0.16 mm, because the camera is mounted at the center of the UAV, but the safety-relevant distance between UAV and object is measured from the nearest edge of the UAV (which is approx. 40 cm away from the camera).

3.3.3 Requirements for UAV operations

In order to operate a UAV safely, several requirements have to be met. These requirements can be divided into two groups: 1) legal requirements of the FOCA, and 2) precautions that ensure a safe flight[1]. They are listed and explained in table 3.

Table 3. Requirements for UAV operations

Requirement	Source	Comment
No flight near crowds	FOCA	In order to prevent injuries due to the UAV crashing in a mass gathering scenario (concert etc.) Not applicable.
Operation in line-of-sight only	FOCA	For bridges, where the inspection can only be performed from the bridge deck, this can be a prohibiting factor, as the underside of the bridge can only be inspected diagonally from the outside.
Landing spot	Safe flight	The take-off and landing spot has to be large and close enough in order to facilitate repeated landings if the flight battery has to be changed.
Third parties	Safe flight	If the possibility exists, that the UAV crashes on land owned by third parties, these should be informed in order to recover the UAV in a crash scenario without delay.
GPS shadowing	Safe flight	As both the automated and the assisted flight rely on GPS positioning, special attention has to be paid during the flight, if high obstacles “shade” the UAV from proper GPS reception

3.3.4 Case study on bridges

With all considerations from sections 3.3.1 to 3.3.3, a case study was performed using the aforementioned bridges. This case study is described in detail in (Romer, 2016). For the sake of brevity, only one significant image, showing the capabilities is presented:

Figure 3. Corrosion marks on steel girder, magnified from top left hi-res image.

[1] These precautions were imposed during obtaining the case-by-case permission for a specific drone flight

It can be seen, that due to the high resolution (original image in the top left corner), accurate detection of damages is possible.

3.3.5 Fault tree analysis

To be able to calculate the financial benefits, a fault tree analysis was performed in (Romer, 2016), in order to estimate the crash probability, taking into account the UAV-side crash probability, as well as, the human error side from the pilot, using NASA's CREAM[2] tables (Vesely, 2002) that estimate the human factor in flight related tasks. Using these tables, a crash probability of 2.47%, i.e. 1 crash in 40 flights was estimated, which puts the expected repair costs in a feasible range. For more details see (Romer, 2016).

3.4 Results

Summing up sections 3.1 to 3.3, the viability has been investigated in the areas of requirements for inspections, optical detectability, and requirements for UAV operation. The viability has been tested on three bridges. Additionally, a fault tree analysis has shown, that the financial viability is demonstrated for the investigated UAV. Therefore, it is deemed viable that a UAV is one of an inspectors' tools. It is not, however, beneficial to use them for all bridges for all types of monitoring. For this reason, section 4 introduces a two-stage flowchart that helps infrastructure managers decide, whether UAV-based inspections are beneficial.

4 DECISION FLOWCHART

From the investigation, the following two flow charts have been developed: 1) A Yes/No flowchart, that determines if it is possible to use a UAV for inspections. 2) Given that the result of the first flowchart is "Yes", the second flow chart provides an estimate of the amount of benefit that can be gained from UAV-inspections.

The first flow chart is shown in figure 4

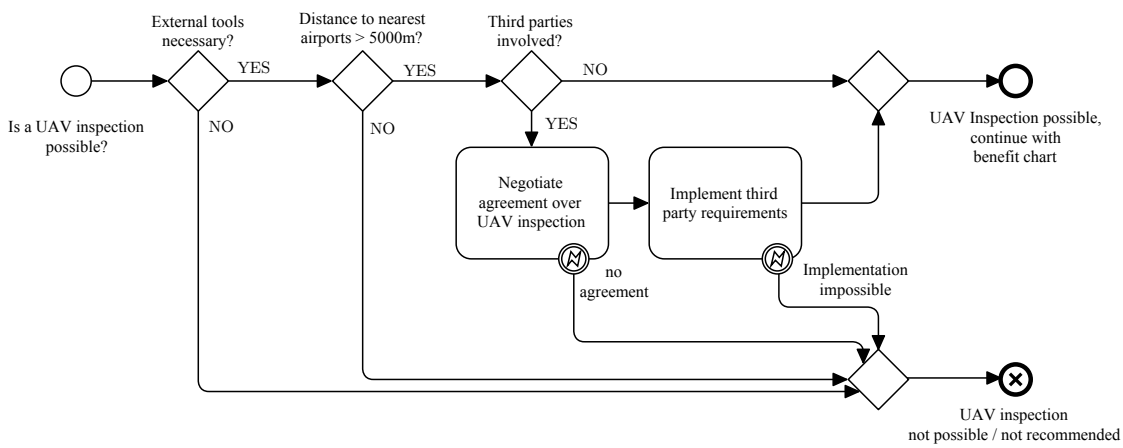

Figure 4. Flowchart for UAV inspection possibility.

[2] Cognitive Reliability and Error Analysis Method

The flowchart begins with the question, if external tools (such as a UAV, or a mobile crane) are needed. If not, a UAV is not beneficial. If yes, it has to be checked, if the flight is legal (for bridges, this means that the nearest airport has to be further away than 5 km.) If third parties are involved, negotiations are perhaps needed in order to get permission to fly over their property. Requirements may be imposed by the third parties. If either the negotiations fail or the requirements are not possible to implement, a UAV inspection is not possible. Otherwise, it can be continued to the estimation chart shown in figure 5.

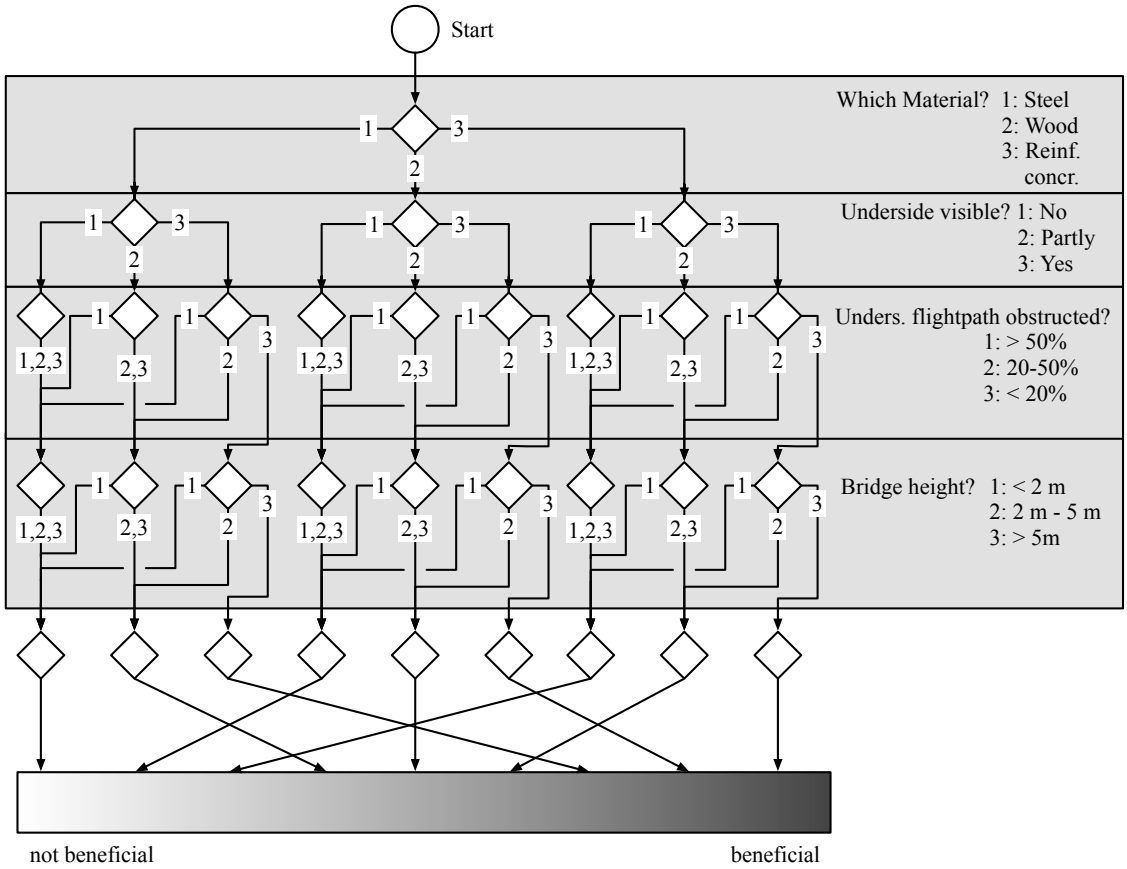

Figure 5. Benefit estimation chart.

This chart helps in estimating the benefit obtained from a UAV inspection in contrast to a normal visual inspection. The chart has to be followed from element to element, by asking the question in the respective row, and following the numbers of the answer. For example, for a wood bridge with the underside visible, and an underside flight path obstruction of less than 20%, combined with a bridge height of 7m, the path would follow 2→3→3→2 and would land in the middle of the benefit estimation bar, signifying that a UAV inspection would bring additional benefit in comparison to a normal visual inspection.

With that information, the infrastructure manager can then decide whether the cost for the UAV inspection is worth it.

5 CONCLUSION

In this paper, the viability of UAV inspections in a Swiss context was investigated, both from the legal and the practical side. Two flowcharts are presented that assist infrastructure managers in deciding whether the use of UAV based inspections is possible and indicated. Future research should refine the benefit flowchart, as it is at the moment only a qualitative estimation of the benefit. Nevertheless, it acts as a useful guide upon which infrastructure managers can base their decisions.

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