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Hazards identification and risk assessment for UAV–assisted bridge inspections

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ABSTRACT

Unmanned Aerial Vehicles (UAV) technology has found its way into several civilian applications in the last 20 years, predominantly due to lower cost and tangible scientific improvements. In its application to structural bridge inspection, UAVs provide two main functions. The first, being the most common, detect damage through visual sensors. The 2 D image data can be used to quickly establish a basic knowledge of the structure's condition and is usually the first port of call. The second reconstructs 3D models to provide a permanent record of geometry for each bridge asset, which could be used for navigation and control purposes. However, there are various types of hazards and risks associated with the use of UAVs for bridge inspection, in particular, in a cold operating environment. In this study, a systematic methodology, which is an integration of hazard identification, expert judgment, and risk assessment for preliminary hazard analysis (PHA) in the UAV-assisted bridge inspection system is proposed. The proposed methodology is developed and exemplified via UAV-assisted inspection of Grimsøy bridge, a 71.3 m concrete bridge, located in the Viken county in eastern Norway.

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1. Introduction

Bridge inspections are conducted to identify potential changes from historical structural reports, as well as to assess the current conditioning of bridge elements to ensure the asset is safe and meets service requirements. Regular inspection also detects structural damage early, when it can be repaired at the lowest possible cost (NCHRP, 2017). However, different types of bridges require diverse inspection procedures and, pose different challenges. Further, the inability to effectively and systematically identify and measure damage in bridges can lead to acceleration and dangerous deterioration of the health state of these structures. In general, the issue can be categorised into two: the difficulty to visually identify damage; and, the late response and care of severe or irreparable damage (Ayele & Droguett, 2019; Jung, Lee, & Kim, 2018; Maldonado, Casas, & Canas, 2019). Several studies emphasize the need to contemplate advanced inspection and monitoring technologies to implement systematic inspection and permanent monitoring of the state of the bridge structures; see e.g. Yonas Zewdu Ayele (2019), Maldonado et al. (2019), Phares, Rolander, Graybeal, and Washer (2001), and Liu, Frangopol, and Kim (2009).

Unmanned Aerial Vehicles (UAV), commonly known as a drone, has found its way into several civilian applications in the last 20 years, predominantly due to lower cost and tangible scientific improvements. In its application to structural bridge inspection, UAVs provide two main functions. The first, being the most common, detect damage through visual sensors. The 2D image data can be used to quickly establish a basic knowledge of the structure's condition and is usually the first port of call. The second reconstructs 3D models to provide a permanent record of geometry for each bridge asset, which could be used for navigation and control purposes. The addition of 3D capabilities to bridge management allows navigation through a complex structure, providing visual identification of the area of concern rather than solely relying on reference names or numbers. Models can either be constructed through photogrammetry or by assembling a spatial point cloud using laser scanners. However, previous problems included low-quality image and video capabilities, are notably sensitive under poor lighting conditions and high wind speeds; see e.g. Jung et al. (2018) and Foreman, Favaró, Saleh, and Johnson (2015).

UAV–assisted bridge inspection will increasingly require interactions with an array of existing users of that airspace, such as general aviation aircraft, helicopters, etc. (Belcastro et al., 2017). However, the safety of these existing operations cannot be reduced by the introduction of the new UAV–assisted operations. Furthermore, humans are "designed" to operate in very narrow temperature range; and, thus, wind, icing, and darkness reduce the operational effectiveness considerably, and the possibility of mistakes or being inaccurate increases during UAV-flights (Ayele, Barabadi, & Barabady, 2016; Barabadi & Markeset, 2011; Gudmestad et al., 2007; Kumar, Barabady, Markeset, & Kumar, 2009; Markeset, 2008). In other words, the cold operational

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environments that are common for instance, in northern Europe, such as Norway, have a significant effect on the performance of the UAVs and UAV-pilots, and this magnifies the hazards associated with UAV–assisted bridge inspections.

The identification of potential hazards and associated risks for the emerging UAV operations have been the subject of several publications; see e.g. Belcastro et al. (2017), Maldonado et al. (2019), Burdett, Stoker, and Simpson (2009), Wackwitz and Boedecker (2015), Hayhurst, Maddalon, Miner, DeWalt, and McCormick (2006), Clothier and Walker (2015). For instance, Belcastro et al. (2017) addressed the identification of current and future hazards associated with small unmanned aircraft systems (sUAS) operations within a UTM (UAS traffic management) system. Hayhurst et al. (2006) have discussed hazards associated with UAV operations, by categorizing the hazards into three domains – the UAV Design Domain, the UAV Flight Crew Domain, and the UAV Operational Domain. Moreover, Hashem Izadi, et al (Moud et al., 2018) have proposed a qualitative risk assessment for UAV flights by combining the Federal Aviation Administration (FAA) rules, regulations, and guidelines concerning UAV flights, with the safety needs and specifications of UAV flights on a construction job site. Furthermore, there are recent efforts to employ high-level AI techniques such as deep learning for hazard identifications, see e.g. (Cha, Choi, & Büyüköztürk, 2017; Cha, Choi, Suh, Mahmoudkhani, & Büyüköztürk, 2018; Kang & Cha, 2018).

However, in most of the available hazard and risk assessment literature discussed above, the operational hazard is the predominant factor considered; and there is a lack of consideration of the impact of the operating environment on the hazard and overall risk profile. This is considered a significant drawback, especially in a complex operational environment such as a cold operating environment. Further, there is a lack of detailed PHA for UAV-assisted bridge inspection, by considering operational, technical, and environmental-related potential hazards that affect the performance of UAVs and UAV-pilots directly. Moreover, those potential hazards that effects the performance of UAVs and UAV-pilots indirectly such as regulation are not highlighted enough. In addition, using UAVs for bridge inspection still considered being at an early stage from a practical point of view and more systematic and reliable hazard identification and risk assessment methods are needed, see e.g. (Ciampa, De Vito, & Pecce, 2019; Rakha & Gorodetsky, 2018; Seo, Wacker, & Duque, 2018).

Based on the above discussion, it is an important requirement to consider the impact of the operating environment when identifying hazards associated with UAV-assisted bridge inspection. In this paper, a new PHA methodology is proposed, which considers the complex nature of the cold operating environment. The proposed methodology is an integration of the analytical hierarchy process, expert judgment, and risk assessment for ranking the operational, technical, and environmental hazards associated with UAV-assisted bridge inspection. Moreover, the likelihood of the potential hazards and their consequence is estimated and presented in a structured format. Furthermore, the consistency index (CI), which is the index of the consistency, quality, and validity of expert judgments is presented, and discussed.

The rest of the paper is organized as follows: Section 2 discusses key stages in the proposed PHA methodology for UAV-assisted bridge inspection. Section 3 exemplifies the proposed PHA methodology via UAV-assisted inspection of Grimsøy bridge, a 71.3 m concrete bridge, located in the Viken county in eastern Norway. Lastly, Section 4 provides some concluding remarks.

2. Methodology for holistic preliminary hazard analysis of UAV-assisted bridge inspection

As such, a core requirement in Preliminary Hazard Analysis (PHA) is the identification of the hazards, which the UAV might encounter during its life cycle. In order to formulate combined hazard set, each of the potential hazards that have impact on the UAV systems and UAV pilots need to be determined. The term "hazard", in the context of this paper, is: "*any real or potential condition that can cause: injury, illness, or death to people; damage to or loss of a system, equipment, or property; or damage to the environment (*Belcastro et al., 2017*)*". Figure 1 illustrates the proposed PHA methodology; and, specific stages that help the hazard and risk analyst to: (i) identify all potential hazards and undesirable events that may lead to an accident, (ii) rank the identified undesirable events according to their probability and severity, (iii) identify required hazard controls and follow-up actions.

2.1. Stage 1: defining the goals and objectives

As mentioned above, in this study, the goal is to conduct a PHA for UAV-assisted bridge inspection. To achieve this goal, firstly the potential hazards need to be identified and then ranked based on their importance. Thereafter, focus would be on the most important hazard to find the most suitable plan of action and risk mitigation. Further, the PHA is mainly aiming the UAV operations in the cold operating environment. However, there is a lack of historical data in this particular operating environment. Henceforth, to conduct a PHA for UAV-assisted bridge inspection the concept of the Analytical Hierarchy Process (AHP) is used, and a team of experts is selected and their expert judgment and knowledge is aggregated. Also, the AHP is supported by available field data from past UAV bridge inspection.

2.2. Stage 2: identification and categorization of potential hazards

When identifying and categorizing hazards, a reasonable effort has been made to identify those that will have the most significant implications on the strategic decision. Identifying hazards in the UAV-assisted bridge inspection involves finding things and situations that could potentially cause harm to people involved in the UAV system, etc. Hazards, during the UAV-assisted bridge inspection generally arise from the following aspects of work and their interaction: operators, physical work environment; equipment and materials used; inspection tasks and how they are performed; and bridge inspection design and management of UAVs. Further, when assessing hazards associated with the

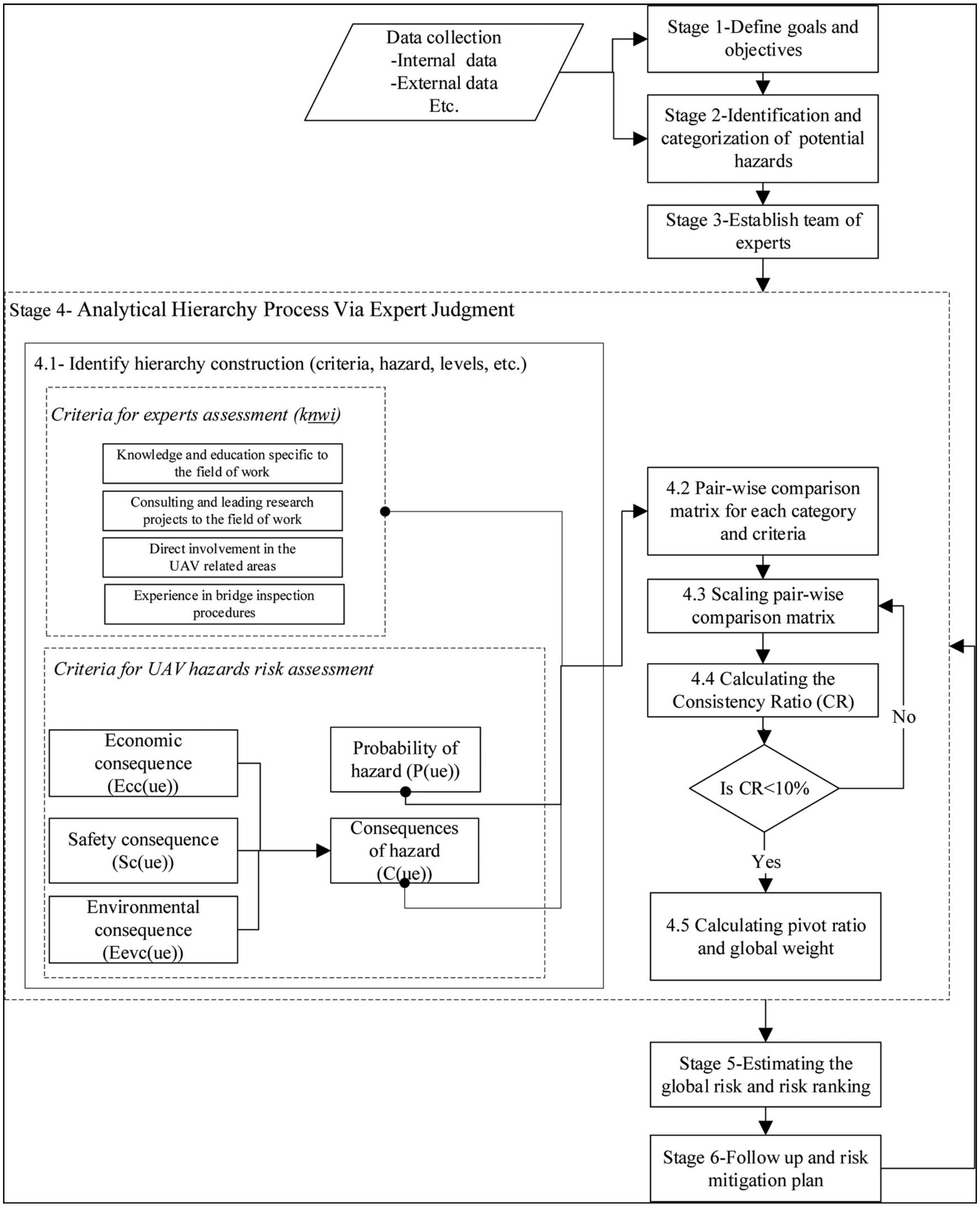

Figure 1. Methodology for preliminary hazard analysis for UAV-assisted bridge inspection based on the analytical hierarchy process.

UAV-assisted bridge inspection in cold regions, including Norway, the effect of the operating environment needs to be analysed thoroughly. This is because the cold operating environment is one of the dominant factors, which influences the performance of the inspectors, the function of UAVs, and then consequently increases the hazards.

2.3. Stage 3: establishing the team of experts

The core for the AHP is to set up a team of experts to identify the potential hazards and conduct risk assessment by estimating the probabilities and consequences of the potential hazards, etc.

2.3.1. Selecting the experts

One can use the criteria suggested by Ortiz et al. (1991) regarding how to select experts. Based on Ortiz et al. (1991) experts should be sellected collectively to represent a wide variety of backgrounds and knowledge. Based on this, here the experts have been chosen by referring to their: (i) knowledge and education specific to the field of work, (ii) consulting and leading research projects to the field of work, (iii) direct involvement in the UAV related areas and, (iv) experience in bridge inspection procedures.

2.3.2. Posing questions to the experts

At this stage, the questionnaires should be stetted by describing the potential hazards and undesirable events. Some of the factors that need to be taking into account while preparing the questionnaires are detailed.

2.3.3. The quality of the expert judgements

Hora (2009) has pointed out that degree-of-belief probabilities are personal. In addtion, these probabilities differ from expert to expert and from time to time. This leads us that there is no "true" probability that one might use as a measure of the accurateness of a single elicited probability. Thus, for crosschecking the goodness of the probabilities from experts, one can employ the Consistency Ratio (CR), see Section 2.4.4.

2.3.4. Aggregating the expert judgements

There are several methods to aggregate individual opinions exist based on specific usage and specific goal, see e.g. (Benamara, Kaci, & Pigozzi, 2010; Lu, Lan, & Wang, 2006; Ramanathan & Ganesh, 1994). For example, one of the most used methods is Aggregation of Individual Judgments (AIJ), where once the individual comparison matrices of every agent in a concrete node are known, it is possible to calculate an aggregated comparison matrix for the group at this node.

2.4. Stage 4: analytical hierarchy process (AHP) via expert judgment

AHP refers to the decomposing of elements related to decision making into goals, criteria, and hazards. The AHP is more suitable for the target system with hierarchical interlaced evaluation indicators, and the target value is difficult to quantitatively describe the problem. The overall hierarchy process is explained in the following key steps.

2.4.1. Identify hierarchy construction and defining criteria

In this step, one should specify the criteria that are important to reach the stated goal. To construct the hierarchy of AHP in this stage, the criteria for risk assessment of identified potential hazards as probability and consequences of potential hazards (see Figure 1) are identified. Also, for consequences of potential hazards are categorized into three sub-criteria: (i) safety consequences, (ii) economic consequences and (iii) environmental consequences. Each criterion is pairwise compared to gets an average overall score (total weight of criteria k, see Section 2.4.5). On the other hand, four criteria for expert assessment are used: (i) knowledge and education specific to the field of work, (ii) consulting and leading research projects to the field of work, (iii) direct involvement in the UAV related areas and, (iv) experience in bridge inspection procedures. Each expert is pairwise compared to each of these criteria and gets an average overall score (see section 3.3.1). In this way, one can construct the hierarchy of analytical process based on identified goals and criteria. Thereafter, based on the overall hierarchy of AHP, one can quantify the importance of each criterion and rank them accordingly.

2.4.2. Pair-wise comparison matrix for each category

As mentioned above, the main idea of the analytic hierarchy process is to compare the importance degree between the two factors to establish a judgment matrix where the dimensions of the matrix depend on the number of criteria. In this paper, it is suggested to establish two matrices; one for expert assessment and one for risk assessment criteria. In general, a comparison judgment matrix, A, can be expressed as:

$$A = (a_{ji})_{n\times n} = \begin{bmatrix} a_{11} & \cdots & a_{1i} \\ \vdots & \ddots & \vdots \\ a_{j1} & \cdots & a_{ji} \end{bmatrix} \quad (1)$$

where:

- a_{ji} is the comparison weight between criteria i and j.

2.4.3. Scaling pairwise comparison matrix

To derive the priorities matrix, verbal statements (comparisons) need to be converted into integers. Different scales for pairwise comparison in AHP can be used such as standard AHP linear scale, logarithmic scale, root square scale, power scale, geometric scale, and fuzzy scales. There is no theoretical reason to be restricted to these fundamental AHP scales and verbal gradations, one can have its scales based on some specific logic. Moreover, in this study for defining the scale criteria, there is a need to define the system's mission. The system's mission can be defined as the ability of a given UAV to carry on visual inspection of any bridge within a certain time and a certain standard. The success and failure of the mission can be defined as follows:

- Mission success: UAV completes the mission and gathers the required data within the acceptable standards and return to base intact.
- Mission failure: UAV cannot fulfil the minimum data required for the inspection process or the UAV is destroyed during the mission.

2.4.4. Calculating the consistency ratio (CR)

Unfortunately, decision-makers do not normally make "perfect" judgements, and therefore it is necessary to check if judgements are logically consistent. In the AHP, consistency index (CI), which is the index of the consistency of judgements across all pairwise comparisons measures the quality of expert judgments (Lootsma, 1991). To explain consistency in a simple word, consider a person who likes banana twice apple and orange twice banana, in logical way he would like orange four times higher than apple, if he ranks apple higher than orange in second comparison he is inconsistent in his judgment. Many researches have shown that when $CR < 0.1$ it is considered that the judgment matrix is consistent, otherwise pairwise comparison matrix need to be appropriately corrected (Tummala & Ling, 1996, 1998; Tummala & Wan, 1994; Tung & Tang, 1998). CR can be estimated as follows:

$$CR = \frac{CI}{RI} \tag{2}$$

where:

- CI is the consistency indicator,
- RI is random index (see in Supplementary Material Appendix I).

In the same approach, one can estimate the CI as follows:

$$CI = \frac{\lambda - n}{n - 1} \tag{3}$$

where:

- λ is the maximum eigenvalue,
- n is the number of criteria.

For instance, if any given expert is consistent in his/her evaluation, then the matrix A will be equal to p, which is an eigenvector. In addition, the eigenvector corresponding to the largest eigenvalue of the matrix (λ) as the importance degree of different criteria can be estimated as follows:

$$Ap = \lambda p \Rightarrow |A - \lambda I| = 0 \tag{4}$$

where:

- p is the eigenvector of the comparison judgment matrix,
- I is the identity matrix.

Having λ the CR can be calculated and check if it is less than 10% then, the normalized average weight of each criterion can be used as its importance weight.

2.4.5. Calculating pivot ratio and global weight

Since experts are scaling each category separately to unify the results from different experts, in this step, a pivot ratio should be estimated. Pivot ratio (Pvr) is calculated by putting one representative hazard from one category to another category and compare it pairwise by all the hazards in that category. By dividing the average weight of the same representative hazard into two different categories. The pivot ratio that connects the importance of both categories related to each other can be estimated as follows:

$$Pvr_{ij} = \frac{Ca_i}{Ca_j} \tag{5}$$

where:

- Pvr_{ij} is the pivot ratio of criteria k between categories i and j,
- ca_i is the average weight of representative criteria in category i,
- ca_i is the average weight of representative criteria in category j.

Thereafter, one can estimate the total weight of criteria k, Wc_k as follows:

$$Wc_k = \frac{AWc_k}{\prod_{i=1}^{j} Pvr_{ij}} \tag{6}$$

where:

- Wc_k is the total weight of criteria k,
- AWc_k is the average weight of criteria k in category i,
- Pvr_{ij} is the pivot ratio of criteria k between categories i and j.

Subsequently, the global weight (Gr_k) which is the total importance weight of criteria k can be estimated as follows:

$$Gr_k = \sum_{k=1}^{k} \sum_{i=1}^{i} k_{nwi} * Wc_k \tag{7}$$

where:

- k_{nwi} is the total weight of expert i,
- Wc_k is the total weight of criteria k.

2.5. Stage 5: risk assessment

In this stage, one can describe the risk as a function of undesirable events, subjective probability of the undesirable events, consequences of the undesirable events, etc. Such description of the risk is beneficial, in particular in the cold operating environment, since there is lack of data and information. The risk function can then be estimated as follows, based on Aven, Renn, and Rosa (2011):

$$\text{Risk} = f\left(A, C, P_f^*, U\left(P_f^*\right), U, K\right) \tag{8}$$

where:

- A represents the potential hazard,
- C the consequences of A,
- P_f^* is a estimation of P_f,
- $U\left(P_f^*\right)$ refers to an uncertainty description of P_f^* relative to the true value P_f,
- U refers to uncertainty factors not covered by $U\left(P_f^*\right)$,
- K is the background knowledge that the estimate and uncertainty description is based on.

2.6. Stage 6: follow up and risk mitigation plan

Once the global risk has been estimated, in this stage, the risk mitigations or safeguards need to be in place. Safeguards could be a course of action that needs to be implemented for reducing the impact of potential hazards. For instance, in the case of low temperature, one can put safeguards measures such as preheating the battery of the drone to prevent the battery from dying while flying. In the same aspect, the drone operator can use personal protective equipment for reducing the negative impact of low temperature.

Key bridge data	
Id	01-0137
Municipality	Sarpsborg
County	*Viken*
Built in	1950
Material	*Concrete*
Length (m)	71.3
AADT (Annual average daily traffic)	533

Figure 2. Overall view and location and structure description of Grimsøy bridge.

3. An illustrative case study - Grimsøy bridge, Norway

The proposed methodology is exemplified via UAV–assisted bridge inspection of Grimsøy bridge, which is located in the Viken county, in the eastern part of Norway. Grimsøy bridge ensures road connection out to Grimsøy, which is a peninsula in Skjeberg, Viken county. It is situated at Latitude: 59.1355° or 59° 8′ 7.7" north and Longitude: 11.2011° or 11° 12′ 3.9" east, and with Elevation: 15 meters above sea level. The bridge is a concrete slab bridge supported by concrete pillars in the relatively shallow water. The bridge is constructed in a typical coastal landscape but lies in a wedge without exposure to the sea. Figure 2 illustrates an overall view and location and structure description of Grimsøy Bridge.

3.1. Stage 1: defining the goals and objectives

The basic assumptions in this study are a year-round UAV operational window and, the fact that the UAV-assisted inspection is carried out in Norway. Since employing UAV for bridge inspection is relatively new, there is a lack of historical failure rate data for the UAV system. Hence, judgments provided by those people with expertise in identifying potential hazards and risks of undesirable events are utilized at various stages of this hazard analysis to perform effective hazard identification and quantification. Their expertise is used to analyses historical information, define and analyses potential hazards, and evaluate the probability, consequence, and risk of undesirable events.

3.1.1. Data collection – UAV flights

The DJI Matrice 100 drone with Zenmuse Z3 aerial zoom camera with 7X zoom capacity is used, for carrying out the drone-assisted inspection. This particular drone was chosen based upon distinctive features such as flight time, camera resolution, video resolution, and others. Trailed autonomous control is tested by using Z3 cameras and sensors, which can help the drone to autonomously avoid obstacles or simply hold altitude in a GPS-denied environment. Other equipment used are DJI Phantom 4 Pro V2.0, DJI remote controllers, landing platform, GPS antenna & handheld, total stations, tripods, spare batteries, blades; I-pad & connection wires to drone remotes; safety helmets, safety boots & reflective jackets, and tapes & markers. Figure 3 depicts tools and equipment used during the drone-assisted inspection. Figure 4 illustrates the level of details obtained from the drone-based imaging for Grimsøy bridge.

3.2. Stage 2: identification and categorization of potential hazards

Based on the data collection stage from different sources as well as data from the field identified potential hazards were categorized into two categories, direct group and indirect group. Direct groups include those potential hazards that have a direct physical connection with the UAV-assisted bridge inspection system. The indirect group includes those potential hazards that do not have a direct physical connection with the UAV-assisted bridge inspection system but their decisions and actions will affect the UAV-assisted bridge inspection system. The indirect group category includes: (i) regulatory agencies, (ii) insurance companies and (iii) third parties which are anyone who is interested and using the bridges in the indirect group (see Table 1).

3.3. Stage 3: establishing the team of experts

3.3.1. Selecting the experts

As mentioned in the Section 2.4.1 four criteria for expert assessment are used including; i) knowledge and education specific to the field of work, ii) consulting and leading research projects to the field of work, iii) direct involvement in the UAV related areas and, iv) experience in bridge inspection procedures. Therefore, to calculate the global weight for each expert can be done by adding each criteria weight for an expert i using the following equation:

$$k_{nw_i} = \sum_{k=1}^{k} k_{nwk} \tag{9}$$

where:

- k_{nwk} is the average weight criteria k for expert i,
- k_{nw_i} is the total weight for an expert (i) based on identified criteria k.

Adding the average weights of each criterion for expert assessment, which is coming from a consistent normalized matrix, total weight for each expert can be estimated.

3.3.2. Posing questions to the experts

To facilitate the AHP the surveys are set by reciting the likely hazards and unwanted events. An excel file with all identified potential hazards matrices in different categories based on identified criteria for example environmental and operator-related hazards was prepared to get the data from each expert. The hazards risk assessment criteria are used as guidance, in the term of probability and consequences (safety, economic, and environmental consequences). Then after, a step by step guideline was established for experts to understand how correctly fill the excel file was distributed. In addition experts would be guided when there was ambiguity for them.

3.3.3. The quality of the expert judgements

As mentioned above, for crosschecking the goodness of expert judgments, one can estimate the Consistency Ratio (CR). The CR which is an indicator for the consistency of the experts while assigning the probabilities for each potential hazard is used to approve the judgment of experts (see Figure 5).

3.3.4. Aggregating the expert judgements

In this study, the criteria for risk assessment are probability and consequences (safety, economic, and environmental consequences). In this study, weights of sub-criteria are used to infer the total consequences of each potential hazard. Therefore, the global weights for probability, $P_{ue}(ue)$ and consequences criteria, $C_{ue}(ue)$ are estimated, respectively, as:

$$P_{ue}(ue) = \sum_{i=1}^{n} k_{nw_i} P_{ue_i}(ue_i) \tag{10}$$

$$C_{ue}(ue) = \sum_{i=1}^{n} k_{nw_i} (Sc_{ue_i} * \ Ecc_{ue_i} * Eevc_{ue_i}) \ (ue_i) \tag{11}$$

where:

- $P_{ue}(ue)$ is the aggregated judgment of the probability of n expert for each hazard,
- $C_{ue}(ue)$ is the aggregated judgment of the consequences of n expert for each hazard,
- $Sc_{ue}(ue)$ is the aggregated judgment of the safety consequences of n expert for each hazard,

Figure 3. Tools and equipment used during drone-assisted inspection.

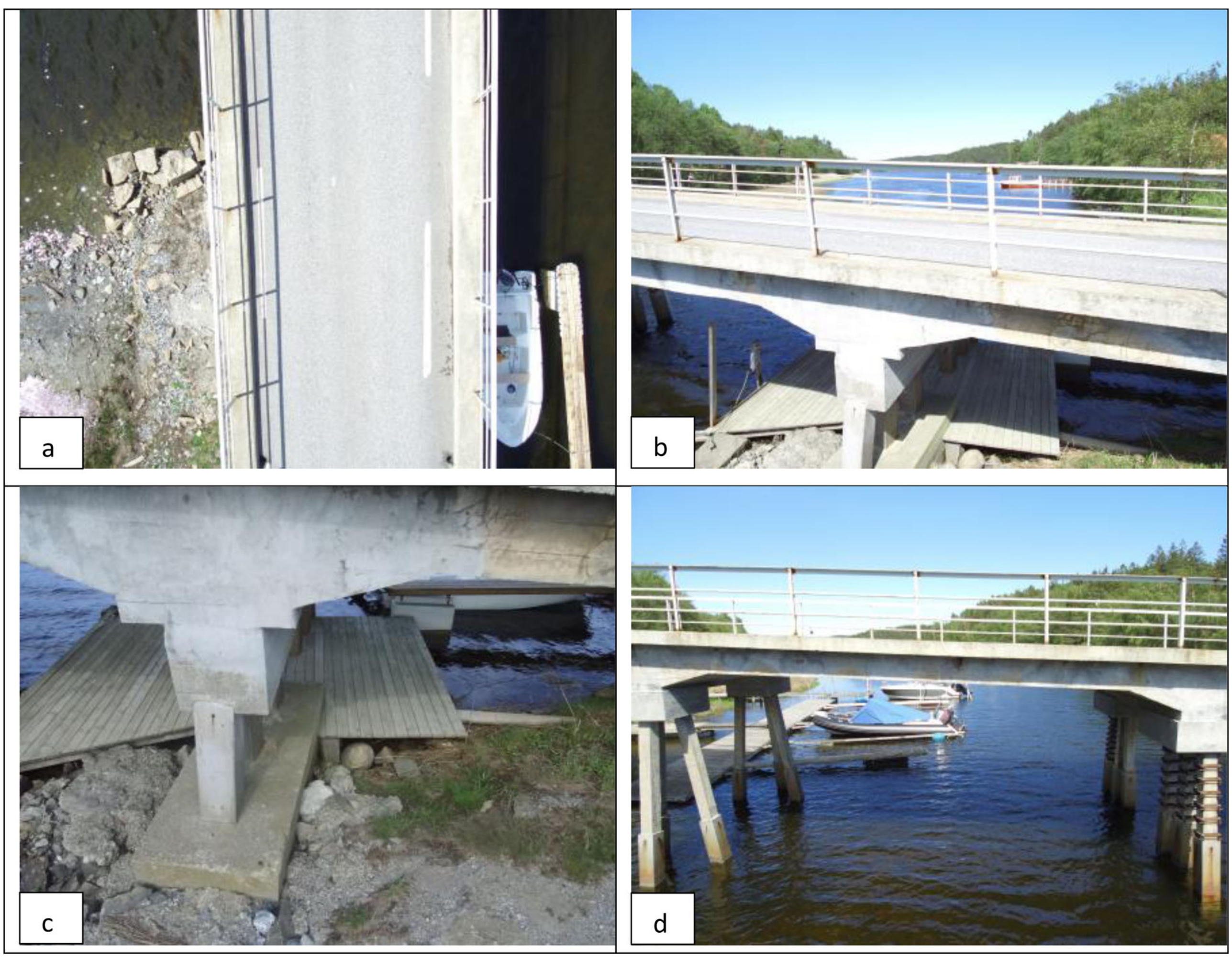

Figure 4. (a) Grimsøy Bridge top view; (b) UAV image of Grimsøy Bridge near top deck; (c) UAV image of Grimsøy Bridge near foundation; (d) UAV image of Grimsøy bridge showing bridge columns and supports.

- $Ecc_{ue}(ue)$ is the aggregated judgment of the economic consequences of n expert for each hazard,
- $Eevc_{ue}(ue)$ is the aggregated judgement of environmental consequences of n expert for each hazard,
- k_{nw_i} is the total weight for expert i based on identified criteria.

3.4. Stage 4: analytical hierarchy process via expert judgment

Based on methodology proposed in previous section, those steps will be followed to conduct a PHA for UAV-assisted bridge inspection system.

Table 1. The predominant direct and indirect actors and categorization of potential hazards.

	Potential hazard			Description
Direct group actors	*Environment related hazards*		*Low temperatures*	- Creates a problem for the endurance of the UAVs and will possibly decrease the battery life of the UAV. - Performance decrements of UAV-pilots due to cold hands, cold muscles or general cooling or due to hinders caused by protective clothing against cold such as weight, bulk, friction, etc. - Lack of concentration, due cold environment, during UAV-assisted bridge inspection can causes fatal accidents.
			Ice and Snow accretion	- Ice and snow accretion on the body of the UAVs; and, this cause problems for the rotary blades, loss of control of the UAV, degraded performance of the UAV, and instrument and sensor malfunctions.
			Darkness	- Insufficient visibility due to darkness increases the hazards during the UAV-assisted bridge inspection - It can have effects on vision and target detection of the UAV and, it can degrade the operator's performance.
			High Winds and Vortex ring state	- Wind is a common hazard in most parts of Norway, especially on bridges, which are in contact with the sea, or rivers and open areas the probability of high winds is much higher. - It can cause loss of control during landing and navigation of the UAV. It also can degrade the UAV operator's performance. - The vortex ring state, also known as settling with power, is a dangerous aerodynamic condition that may arise in drone flight. This is due to disruption to the airflow around rotor disks, is considered as a significant risk for bridge inspections using UAVs. It mainly occurs close to abutments and in enclosed girder spaces, or when it positioned low above the ground/water surface. This can result in turbulent airflow and loss of rotor efficiency of the UAV. - The probability of entering the vortex ring state and recovering from it is dependent on UAV frame design, size and power (Seddon & Newman, 2011). This state particularly affects smaller size drones. Further, drones without ability to maintain level altitude are also more likely to succumb to operator error, where the operator drops the UAV too fast and into its own prop wash (Richard DeYoung, Dec 17, 2018) . Therefore, the scenario UAV spiralling out of control.
			Noise	- The noise generated by the quadrotor's blades can be a hazard for the wildlife in the area.
			Rain, Fog, Moisture	- Heavy rain conditions can cause hazards for the UAVs. Rain, which is a normal phenomenon in most of Norway, can cause hazards for the UAVs, for example, it can lead to sensor malfunction, and also it can disrupt the image quality, in case of heavy rain the possibility of navigation difficulties and loss of control is present.
			Disruptions of vision due to direct sun exposure	- During the midnight sun period especially in northern Norway, direct sunlight can disrupt the vision of both operators and the camera of the UAV. This can lead to both low quality imaging, and in worst scenarios, it can lead to accidents due to lack of vision.
	Operators related hazards	*Inadequate knowledge or skills (where applicable) in:*	*Regulations and requirements of the authority* *Terms or language used(e.g., incomplete, unclear, written in language unfamiliar to operator)* *Operation of the drone and operating instructions*	- Human operators' error: In this case the human operator's error will be related to UAV pilots' skills in controlling the UAV, especially since in the UAV-based inspection, the UAV is flying close to some parts of the bridge, small mistakes combined with a little of wind can lead to collision.
		Emotional Aspects	*Unanticipated physiology limitations* *Chronic, known physiology problems* *Exceedance of cognitive capacity* *Effects of emotional state*	- Emotion affects human performance through influencing individuals' judgment and behavior.Many physiological and psychological factors, such as drowsiness, fatigue, distraction, stress, and even confidence, can affect operators' task performance. External factors may also affect task performance in more implicit ways specifically, through affecting operators' emotion and cognition. For instance, task complexity might be main determinant of operators' confidence, which has certain effects on the final task performance (Cai & Lin, 2011; Gielo-Perczak & Karwowski, 2003).
	UAV related hazards	*Sensors related hazards*	*Inherent technical flaws (i.e., design or production)*	- Result from a failure in design or manufacturing which has a random effects inherent to process or usage condition
			GPS malfunctions	- GPS malfunction is a common error in UAVs operations, in particular in under bridge inspection processes the loss of GPS signal in these areas is a common error.
			Collision avoidance malfunction	- Due to the nature of the inspection process, the UAV needs to fly close to the bridge structure, and although the collision avoidance systems have a small margin of error, there is the possibility of malfunction that can lead to collision. This hazard is talking about the algorithms and systems embedded in the UAV for collision avoidance. In case of malfunction in any of these algorithms or systems, UAV can have problems in navigation, and this can lead to accidents.
			UAV is unable to collect information about the quality of internal materials	- UAVs cannot be used to gather data on the internal material quality by visual sensing techniques alone.
			Infrared sensor malfunctions	- Infrared sensor malfunction is another hazard, which is common. This hazard can lead to problems in collision avoidance systems.
			Visual camera malfunction	- For UAV-assisted bridge inspection, the visual camera mounted on the UAV needs to be operational and available at all times, in case of any malfunctions in this part of the UAV the mission cannot be completed. This hazard can lead to mission failure, due to inability of taking pictures and video. Further, if it paired up with other sensors malfunction it can lead to UAV colliding with the bridge structure or personnel.

(*continued*)

Table 1. Continued.

	Potential hazard			Description
		Insufficient energy level	*Display battery depleted*	- All the batteries need to be fully charged otherwise it might cause serious problems
			Remote control battery depleted	
			Drone battery depleted	
	Communication related hazards	*Signal disruption because of frequency interference*	*In the communication channel between remote controller and drone*	- The wireless link between the ground control and, the UAV may be jammed or blocked by intentional/unintentional use of transmitting devices that are operating on the same frequency band, which can lead to loss of signal and the UAV pilot will not be able to control the UAV.
			In the communication channel between remote drone and display	
		Signal disruption caused by physical impenetrable obstacle	*In the communication channel between remote controller and drone*	
			In the communication channel between remote drone and display	
		Ineffective communication between UAS operator and display	*Limited visibility of display (e.g., glare, angle of view, reflections of environment)*	
			Indistinct information on the display (e.g., size of fonts and symbols, colours)	
	External factors	*Collision with Obstacle*	*passing ships/boats from under the bridge*	- A significant number of bridges in Norway connect two islands, which makes it essential for ships/boats to pass beneath the bridge, this can cause hazards of collision between ships/boat and UAVs during under-bridge inspections. With the ships/boats passing beneath the bridge, there is the possibility of UAV falling down and hit the ships/boats. The other case could be debris falling off due to the near collision or collision of the UAV with bridge structure, which can lead to hazards for both the personnel on the boat and the boat itself especially in under bridge inspection scenarios.
		Building		- There is a possibility of external objects collision such as birds attacking or colliding with the UAV, especially in the summer with the vast number of seagulls roaming in the skies of Norway. Seagulls are aggressive in nature; they might attack or collide with the UAV.
		Man-Made Structure		
		Natural Obstacle		
		Animals (birds attack)		
			Collision with Person(s)	
			Collision with Ground Vehicle	
			Collision with Train	
			Collision with Water	
			Crash in Landing Area	
			System recovery failure	
			Ground control hazards	
Indirect group actors			*Insurance companies*	- Insurance companies have an indirect contact with the process in terms of insuring the UAV itself; and, the UAV's possible damages to the surrounding environment
			Regulatory agencies	- The agencies, such as United States Federal Aviation Administration (FAA) and, the civil aviation authority of Norway that will regulate the flying of UAVs in Norway's airspace
			3rd party	– 3rd party intentional or unintentional involvement, anyone that uses the bridge in anyway, such as drivers, pedestrians, bikers, etc., and anyone that is interested in the bridge in anyway

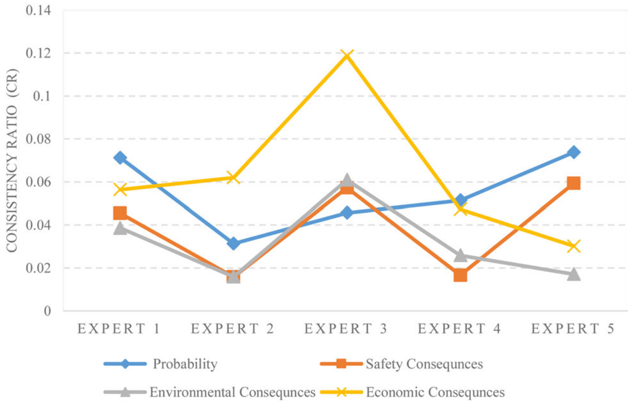

Figure 5. CR values of the five experts related to the risk criteria.

3.4.1. Identify hierarchy construction and defining criteria

The objectives already in the first step is identified which is conducting a PHA for UAV-assisted bridge inspection systems and also the hierarchy and criteria in proposed methodology are already constructed.

3.4.2. Pair-wise comparison matrix for each category

After all criteria identified and categorized pairwise comparison matrix can be established by putting them in row and columns. Table 2 is the pairwise comparison matrix of environmental related hazrards which is scaled by an expert.

3.4.3. Scaling pairwise comparison matrix

In this study, fundamental AHP comparison scales from 1 to 9 for all criteria is used (see Supplementary Material *Appendix II, Appendix III and Appendix IV*). Table 3 is an example of pairwise comparison matrix and its scales for potential hazards in environmental related category for the probability criteria. In general, comparison matrix is a symmetric matrix, which means that having scale of one pairwise compared criteria the other one is reverse of the given scale.

Based on the results from Table 2 for one expert low temperature is 3 times more probable to affect the UAV operation than ice and snow. Further, for the same expert, low temperature is however 5 times more probable to affect the UAV operation than darkness as well as 9 times more probable to affect the UAV operation than disruptions of vision due to direct sun exposure.

3.4.4. Calculating the consistency ratio (CR)

In this study, for calculating consistency ratio, firstly pairwise comparison matrix is normalized, thereafter its eigenvalue (λ) is calculated as follows:

$$\lambda = Average\left[\frac{[OS].[A_{rnm}]}{A_{rnm}}\right] \qquad (12)$$

where:

- A_{rnm} is the average of one row of normalized matrix,
- $[OS]$ is the same row of the scales of the original matrix,
- $[A_{rnm}]$ is column of the average of the rows of normalized matrix.

Based on Equation (12) eigenvalue (λ) for the normalized pairwise comparison matrix is estimated as 7.3999. In the same principle, based on Equation (3), the CI is estimated equal to 0.0666, and, the CR based on Equation (2) is estimated to be 0.0505. From these analyses, it can be deduced that the CR is less than 10% henceforth, the judgments from this particular expert are accepted for the probability criteria (see the Supplementary Material for a detailed analysis). Furthermore, to compare the quality and consistency of experts, the CR values are estimated for the five experts that are involved in this study and the result is depicted in Figure 5.

From the CR results (Figure 5) it can be deduced that Expert 3 is less consistent in his judgments since its consistency ratio is higher than 10% in economic consequence criteria and has overall higher inconsistency. Interestingly, based on expert assessment criteria, Expert 3 is assigned a lower overall weight (k_{nw_i}) compared to other experts.

3.4.5. Calculating pivot ratio and global weight

As mentioned in Section 2.4.5 the pivot ratio is used to link different categories weight together and estimate the global weights for each potential hazard. Figure 6 presented the estimated global normalized weights as accumulating value of both the probabilities and consequences. The consequences, in the accumulated values, include the safety, economic and environmental consequences of the identified potential hazards for UAV-assisted bridge inspection. As discussed above, for estimating the probability and consequences of potential hazards, Equations (10) and (11) are employed, respectively. Further, for estimating the risk Equation (13) is employed.

Based on the results (Figure 6) it can be inferred that low temperature has significantly higher global weights for the probability. To be more specific, for the low temperature its:

- *Global probability weight is estimated to be 0.15434;*
- *Global safety consequence weight estimated to be 0.02024;*
- *Global economy consequence weight estimated to be 0.01192;*
- *Global environmental consequence weight estimated to be 0.02256.*

To estimate the overall normalized weight of the low temperature, each of the above weights will be multiplied and the resulted weight estimated to be 0.20906. It means that the global normalized weight of the low temperature is more than 4.2 times higher than the global normalized weight of limited visibility hazard, for instance. Furthermore, based on the result, Figure 6, it can be concluded that among the most probable potential hazards for UAV-assisted bridge inspection in cold environment operating systems, the following environmental-related hazards

Table 2. Pairwise comparison matrix and its scales for probability citeria.

Environment related hazards	Low temperatures	Ice and Snow accretion	Darkness	High Winds and Vortex ring state	Noise	Rain, Fog, Moisture	Disruptions of vision due to direct sun exposure
Low temperatures	1	3	5	3	7	3	9
Ice and Snow accretion	0.333333333	1	3	3	5	3	7
Darkness	0.2	0.333333333	1	3	3	1	5
High Winds and Vortex ring state	0.333333333	0.333333333	0.333333333	1	3	0.333333333	3
Noise	0.142857143	0.2	0.333333333	0.333333333	1	0.333333333	1
Rain, Fog and Moisture	0.333333333	0.333333333	1	3	3	1	3
Disruptions of vision due to direct sun exposure	0.111111111	0.142857143	0.2	0.333333333	1	0.333333333	1

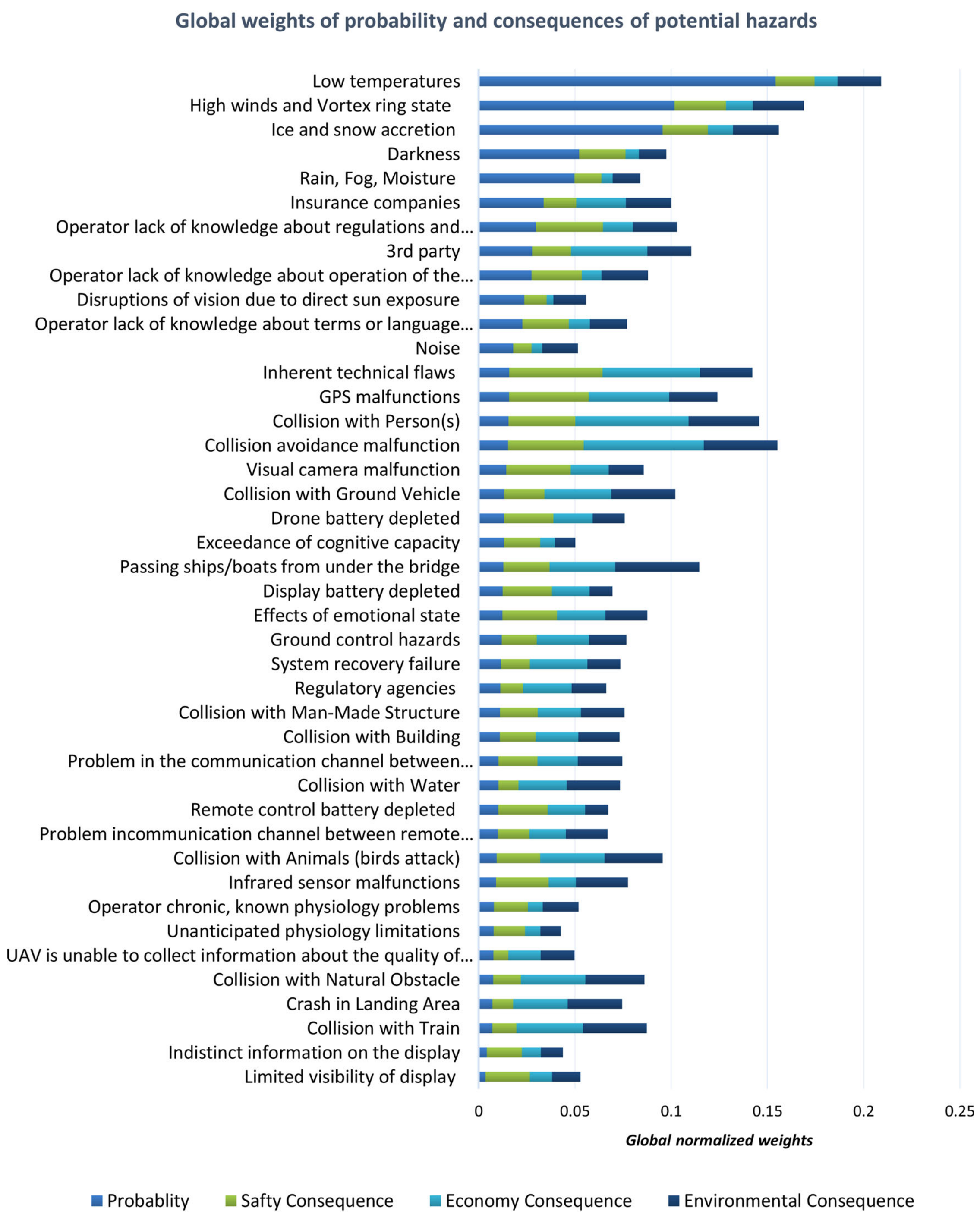

Figure 6. Global weights of probability and consequences of potential hazards.

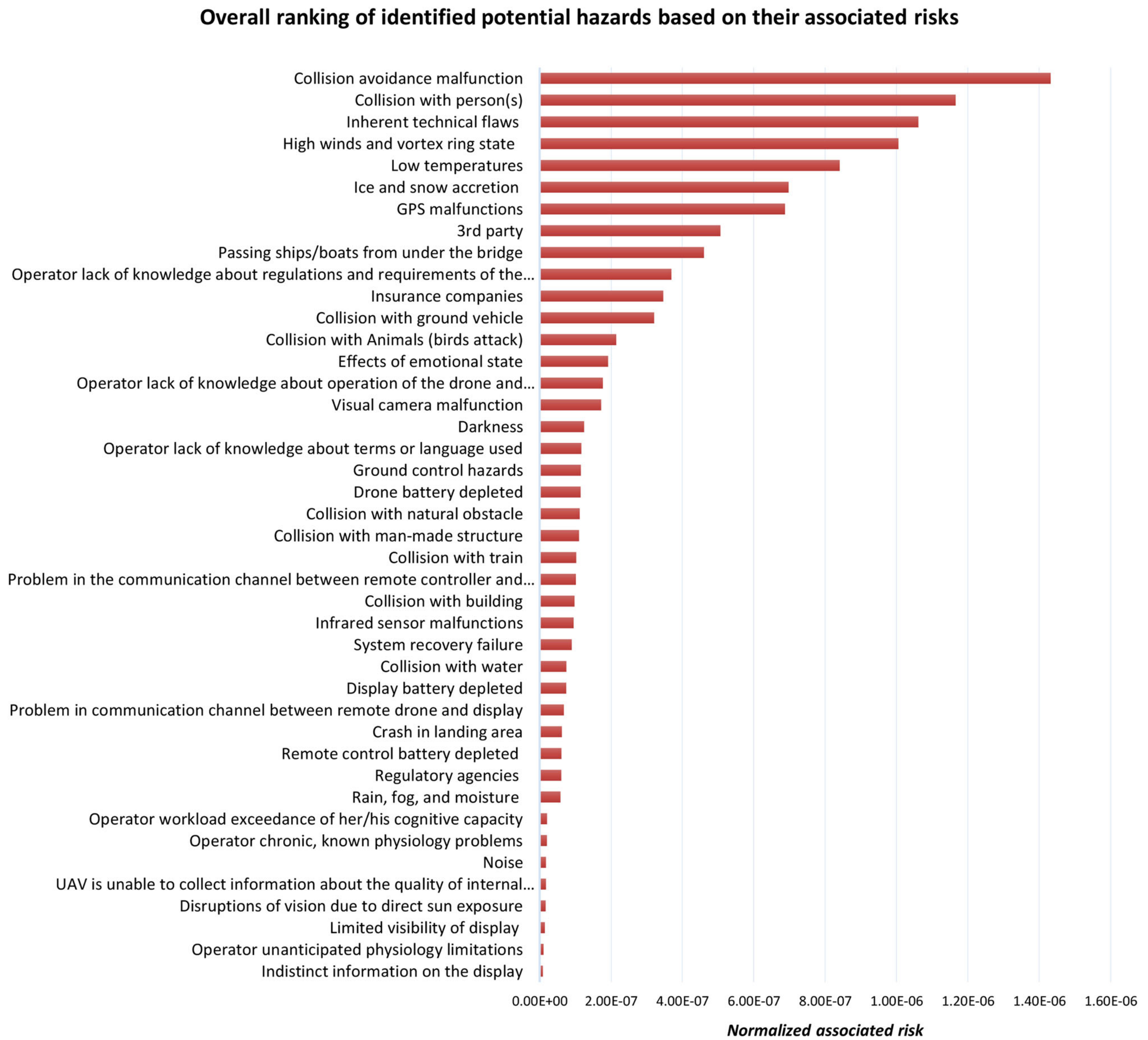

Figure 7. Overall ranking of identified potential hazards for UAV-assisted bridge inspection system in cold environment based on their associated risk.

Table 3. Normalized pairwise comparison matrix.

Environment related hazards	Low temperatures	Ice and Snow accretion	Darkness	High Winds and Vortex ring state	Noise	Rain, Fog, Moisture	Disruptions of vision due to direct sun exposure	Average weight
Low temperatures	0.407503234	0.561497326	0.460122699	0.219512195	0.304347	0.333333333	0.310344828	0.37095163
Ice and Snow accretion	0.135834411	0.187165775	0.27607362	0.219512195	0.217391	0.333333333	0.24137931	0.23009856
Darkness	0.081500647	0.062388592	0.09202454	0.219512195	0.130434	0.111111111	0.172413793	0.12419795
High Winds and Vortex ring state	0.135834411	0.062388592	0.030674847	0.073170732	0.130434	0.037037037	0.103448276	0.08185552
Noise	0.058214748	0.037433155	0.030674847	0.024390244	0.043478	0.037037037	0.034482759	0.03795872
Rain, Fog, Moisture	0.135834411	0.062388592	0.09202454	0.219512195	0.130447	0.111111111	0.103448276	0.12210770
Disruptions of vision due to direct sun exposure	0.045278137	0.026737968	0.018404908	0.024390244	0.043478	0.037037037	0.034482759	0.03282990

possess a high normalized probability weight i.e. they possess a high rate of occurrence and may lead to issues for UAV-operations:

- *Rank 1: Low temperature with an estimated normalized probability weight of 0.15434,*
- *Rank 2: High wind with an estimated normalized probability weight of 0.10184,*
- *Rank 3: Ice and snow with an estimated normalized probability weight of 0.09554, and*
- *Rank 4: darkness with an estimated normalized probability weight of with 0.05225*

Table 4. Plan of actions for safeguarding and mitigating the risk for UAV-assisted bridge inspection.

Hazards	Safeguards and risk mitigation
Low temperatures	Pre heating the battery Using thermal coating Personal Protective Equipment's
Ice and Snow accretion	EESS (Electro explosive separation system), a pulsing current of electricity will clear the ice build-ups. Pre heating the blades and fuselage of the UAV with a heating device.
Darkness	Use of infrared cameras. GPS navigation. Use of a mounted lighting device.
High Winds and Vortex ring state	GPS navigation can help with correcting the path if the wind is dragging the UAV off the path. Use of Personal protective equipment (PPE)
Noise	Employ a case-specific noise reduction procedure
Rain, Fog, Moisture	Accurate weather forecasting and planning the inspection in sunny days Halt the UAV-assisted inspection in case of heavy rain
Disruptions of vision due to direct sun exposure	Planning the inspection in the way that minimize direct exposure to sun for instance the UAV flight pass diagonal to sun light exposure
Operator lack of knowledge about regulations and requirements of the authority	Training , workshops and courses for the workforce to increase their knowledge about rules and regulations
Terms or language used(e.g., incomplete, unclear, written in language unfamiliar to operator)	Use work procedure guidelines in different languages
Operation of the drone and operating instructions	Training , Workshops and Courses
Operator unanticipated physiology limitations *Operator chronic, known physiology problems* *Workload of operator exceeds his/her cognitive capacity* *Operator effects of emotional state*	A physical and physiological health follow up program for workforces to reduce the physical and psychological burden
Inherent technical flaws (i.e., design or production)	Communicating with supplier about inherent technical failures
GPS malfunctions	In the case of a GPS problem, it is very important for the operator to know how to use traditional methods of fixing a vessel's position. These can include *(John Southam, 20/06/2018)*: ● Plot the position: Take ranges and bearings from land marks or navigational features. ● Increase frequency: Plot positions at intervals so that the vessel will not run into any risk. ● Parallel indexing ● Echo sounder: This can confirm that the ship has plotted position. ● Beam bearings: Beam bearings can visually confirm when to change course. ● Change of course: The vessel's position should be plotted right before and right after the course change, in order to confirm that the ship is in the correct position.
Collision avoidance malfunction	Relying on vision-based navigation Advanced algorithms for collision avoidance
UAV is unable to collect information about the quality of internal materials	Coupling UAV-assisted inspection with some regular NDE techniques for better results
Infrared sensor malfunctions	Testing the sensors before the flight in the case during the flight there is problem redundant equipment if possible can be used
Visual camera malfunction	Since the mission is failed in case of camera malfunction the only safeguard here is to save the UAV by using GPS navigation to fly it back to base.
Display battery depleted *Remote control battery depleted* *Drone battery depleted*	Redundant equipment such as batteries if possible can be used
Malfunctions in the communication channel between remote controller and drone *Malfunctions in the communication channel between remote drone and display* *Malfunctions in the communication channel between remote controller and drone* *Malfunctions in the communication channel between remote drone and display* *Limited visibility of display (e.g., glare, angle of view, reflections of environment)* *Indistinct information on the display (e.g., size of fonts and symbols, colours)*	Informing and clearing the operation site of any 3rd party users of the same frequency band equipment's. Redundant equipment such as second ground station if possible can be used
passing ships/boats from under the bridge *Collision with Building* *Collision with Man-Made Structure* *Collision with Natural Obstacle* *Collision with Animals (birds attack)* *Collision with Person(s)* *Collision with Ground Vehicle* *Collision with Train* *Collision with Water* *Crash in Landing Area* *System recovery failure* *Ground control hazards*	Closing the under-bridge passing during under-bridge inspection process. Communicating with UAV hardware and software supplier to develop advanced algorithms for collision avoidance.
Insurance companies	Communicating with Insurance companies to facilitate problems regarding insurance
Regulatory agencies	Communicating with authorities to facilitate problems regarding rules and regulations
3rd parties	Communicating with authorities to facilitate related issues

3.5. Stage 5: risk assessment

Due to the lack of information in UAVs operation in a cold operating environment, in this study, the subjective (knowledge-based, judgmental) probability perspective for risk description is used. Once the probability ($P_{ue}(ue)$) and consequences ($C_{ue}(ue)$) of potential hazards are estimated then the risk profile can be described as:

$$Risk = P_{ue}(ue) * C_{ue}(ue) \tag{13}$$

where:

- $P_{ue}(ue)$ is the aggregated expert judgment probability weight of an unwanted event,
- $C_{ue}(ue)$ is the aggregated expert judgment consequences weight of an unwanted event.

Figure 7 illustrates the overall ranking of the identified potential hazards based on their associated risk which is estimated based on Equation (13). From the result, it can be deduced that the cold operating related hazards such as low temperature and ice and snow are listed on the top of the risk rank i.e. hazards with high risks. For instance, the estimated risk of low temperature is about 10 times more comparing to risk due to a lack of knowledge about terms or language. The highest estimated risk is the risk due to collision avoidance malfunction, with a risk value of 1.43157E-06, see Supplementary Material Appendix V for more details.

3.6. Stage 6: follow up and risk mitigation plan

Table 4 presenting the various plan of actions for safeguarding and mitigating the risk, based on the identified potential hazards for UAV-assisted bridge inspection.

4. Conclusions

UAV deployment in bridge inspection could potentially save time and money. However, it also has various shortcomings. In this study, a practical methodology for preliminary hazard analysis for UAV-assisted bridge inspection is proposed. The proposed PHA identifies and quantifies the risk of the hazards related to operational, technical, and environmental aspects, which are due to the effects of cold and harsh environments. The proposed PHA recognizes the impact of potential hazards on the performance of UAVs and UAV-pilots and creative quantitative interpretation of the hazard factors of identifiable problems.

The findings from the case study are as follows:

- The proposed PHA is beneficial as it provides a simple proof of concept that assist the decision-makers to be able to recognize, how cold weather affects the UAV systems and human performance and consequently adjusts management and operational tools and approaches while planning UAV-assisted bridge inspection.
- From the case study results, it inferred that UAV-assisted bridge inspections are significantly affected by several environmental-related hazards such as high winds and vortex ring state with 1.00501E-06 associated risk, low temperature with 8.40E-07 associated risk, and ice and snow with 6.97352E-07 associated risk.
- The risk of high winds and vortex ring state is about 10 times more comparing to the problem in the communication channel between remote controller and drone; however, the risk is about 20 times more comparing to the risk of depleted remote-control battery.
- Further, the case study demonstrates that the risk of collision avoidance malfunction is one of the predominant risks for UAV-assisted bridge inspection; and it is about 8 times more compared with the risk of visual camera malfunction.
- Indistinct information on the display of remote-control maintains the lowest associated risk, which is due to the lowest probability weight, with 0.0043 probability, and lowest total consequences weight, with 2.04E-06.

Authors' intent is not to provide generalized advice on whether UAV-assisted bridge inspection should replace the conventional inspection or not, since these prescriptions will be particular to and heterogeneous to types of bridges and accompanied UAVs rules and regulations. Rather, the intent is to highlight the fact that even if UAV-assisted bridge inspection has a huge potential in the years to come, the associated hazard has to be investigated thoroughly. This will assist the decision-maker to identify the most cost-effective and efficient bridge inspection procedures with a minimum level of HSE-C (health, safety, and environment, and cost) risk. A lack of data, for different risk of events, was an issue during the illustrative case study analysis, due to the lack of experience in the cold operating environment.

Thus, the results should not be taken at face value; they should be interpreted in light of the current state of knowledge about operating experience in the cold operating environment. Moreover, the resulting risk values from the illustrative case study analysis should be updated as new data/evidence becomes available, preferably in the form of field (hard) data reflecting the actual operational experience in the cold operating environment and therefore gradually supplanting the opinions elicited from experts. All these elements, however, do not invalidate the results from the illustrative case study analysis.

Nomenclature

UAS	Unmanned aircraft system
UAV	Unmanned aerial vehicles
NCAA	Norwegian Civil Aviation Authority
RPAS	Remotely Piloted Aircraft System
RO	Remotely piloted aircraft system organization
MTOW	Maximum take of weight
VLOS	Visual line of sight
UBIT	Under-bridge-inspection-truck
FAA	Federal aviation administration
$C_{ue}(ue)$	The aggregated expert judgment consequences weight of an unwanted event

$P_{ue}(ue)$	The aggregated expert judgment probability of an unwanted event
$Sc_{ue}(ue)$	The aggregated expert judgment safety consequence of an unwanted event
$Ecc_{ue}(ue)$	The aggregated expert judgment economic consequence of an unwanted event
$Eevc_{ue}(ue)$	The aggregated expert judgment environmental consequence of an unwanted event
knw_k	The average weight of criteria k for expert i.
knw_i	The total weight for expert i.
$[OS]$	The row of original pairwise comparison matrix
$[A_{rnm}]$	The average column of normalized matrix
A_{rnm}	The same row average of normalized matrix
Pvr_{ij}	The pivot ratio of criteria k between categories i and j
Ca_i	The average weight of representative criteria in category i
Ca_j	The average weight of representative criteria in category j
Wc_k	The total weight of criteria k
AWc_k	The average weight of criteria k in category i
Gr_k	The global weight of criteria k

Disclosure statement

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