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Structural Health Monitoring and Management with Unmanned Aerial Vehicles

Review and Potentials

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Structural Health Monitoring and Management with Unmanned Aerial Vehicles: Review and Potentials

February, 2021

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Preface

Unmanned Aerial Vehicles (UAVs) have been used for monitoring construction and operation of civil infrastructure as well as industrial facilities and power plants. Their operational simplicity along with time-and-cost-related benefits have already rendered them attractive for structural surveying. Nevertheless, the field of UAV research currently lacks a targeted employment of UAVs for the structural health monitoring and management. Therefore, this report provides a comprehensive state-of-the-art review of research work and industrial applications focusing on the employment of UAVs for inspection, monitoring and maintenance oriented towards facilitating an efficient structural health management. The latest developments in UAV and sensing technologies are also discussed while technological and methodological potentials as well as future challenges are identified in order to promote an efficient UAV-based infrastructure information and integrity management.

Copenhagen, February 2021

Medha Kapoor, Evangelos Katsanos, Lazaros Nalpantidis, Jan Winkler and Sebastian Thöns

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Contents

1. Introduction

Structures and infrastructures including the existing building stock, road networks and bridges, energy plants and the associated power grids, ports, marine and offshore facilities, water and waste-water treatment systems as well as flood-reduction structures and telecommunication networks are of high relevance for the progress, welfare and sustainable development of humanity. Modern societies are highly dependent on the constant and safe operation of these structures since any possible destruction or service disruption may trigger serious harm to the population and its prosperity (De Bruijne & Van Eeten, 2007). Nonetheless, structures and infrastructure systems are subject, during their design life-time, to adverse conditions associated with exposure to natural hazards (i.e., earthquake, flooding and landslides, tsunamis and climate change effects), man-made threats (i.e., human malfunctions and errors, operational flaws, malicious and terroristic activities) as well as several age-dependent structural performance degrading mechanisms (e.g. corrosion, stiffness-strength deterioration and scouring) (European Commission Directorate-General Justice Freedom and Security, 2009). These harmful sources may severely undermine the structural reliability and integrity of the systems and amplify the risk of failing to reach target performance objectives, associated with either serviceability or collapse prevention criteria. In terms of monetary burdens, the worldwide replacement campaigns of the aging infrastructure systems were recently estimated to exceed the cost of US$57 trillion by the year 2030 (McKinsey Global Institute, 2013) while infrastructure structural and operational deficiencies are expected to spur loss in US gross domestic product in the order of US$3.9 trillion until 2025 (American Society of Civil Engineers (ASCE), 2011). Therefore, systematic measuring, inspection and monitoring schemes as well as consistent maintenance strategies are essential to develop a holistic framework for the monitoring and eventually, efficient integrity management of the structure and infrastructure systems.

To address the aforementioned challenges that existing structures experience during their lifetime, intensive academic and industrial attention is being dedicated over the last 40 years to advance Structural Health Monitoring (SHM). The latter constitutes the demanding engineering field that accommodates diagnosis of the state of the various constituent materials, structural members and eventually the entire structural system. Numerous methods have already been introduced to scrutinize the monitoring and inspection of structures and infrastructure systems irrespective of their size, geometry, materials used, complexity and significance (Brownjohn, 2007). Scientific effort has also been committed to appropriately interpret the outcome of the SHM applications to engineering terms and quantifiable indices. To this end, sophisticated algorithms have been developed to utilize the monitored structural performance, identify the mechanical and dynamic properties and detect any damages or deficiencies that the structures may experience. Nonetheless, the use of contemporary SHM methods, which are mostly related to human-driven inspections or based on the installation of large instrumentation and sensor grids on structural systems, can frequently lead to increased time and monetary burdens. Additionally, the risk for life and limb further undermines the overall benefit from SHM campaigns.

On the other hand, the engagement of modern technologies and mainly of current robotic advancements can essentially shorten the limitations of the existing SHM methods and optimize their performance by fulfilling accuracy, time, and cost-related requirements. In particular, the Unmanned Aerial Vehicles (UAVs or the so-called drones), gaining currently an abundance of academic and industrial interest, can be appropriately leveraged to reach demanding SHM objectives while waiving restrictions usually imposed by the conventional measuring, inspection as well as monitoring methods. The UAVs, being equipped with advanced equipment and sensors including high-resolution cameras and image stabilization systems, can efficiently harvest and integrate data into preliminary design workflows, survey construction sites, monitor and document work-in-progress as well as inspect and monitor the condition and health of structures located in hard-to-access areas.

Along these lines, the current report provides a thorough state-of-the-art review of published research work concerning the employment of UAVs as a facilitator for the overarching purposes of structural health monitoring. In more detail, the authors aim at presenting a comprehensive survey of literature-proposed methods along with a detailed synthesis of applications scrutinizing the use of UAVs for the development of digital twins, the measurement of structural displacement and deformation, the detection and quantification of damages as well as the adaptation of structural system performance. Additionally, the report is further enriched by references regarding UAVs per se and the related robotic advancements, the pertinent sensors technology used for measuring and monitoring purposes as well the quantification of the benefit delivered by the SHM-UAV integration with the use of Value of Information (VoI) analysis. Lastly, this study emphasizes on potential technological impact of the UAV's engagement on the information and integrity management of infrastructures for both societal and industrial benefits, respectively.

2. Overview of the state-of-the-art literature review

To fulfill the objective of the compilation of a detailed literature review of published research work on the employment of UAVs for SHM purposes, a thorough review of more than 110 scientific articles (e.g., journal papers, conference articles as well as technical reports) was conducted. Elsevier SCOPUS database of peer-reviewed literature and the Web of Science were accessed to search for relevant papers while the digital library of the Techncial University of Denmark and the Google scholar database significantly facilitated the review. Keywords including, among others, “UAV”, “structural health monitoring”, “damage detection”, “digital twin”, “system identification”, “feature extraction” enabled the compilation of quite a broad list of articles to be reviewed. Research articles published in the form of extended abstracts, review papers or patents as well as papers not written in the English language were excluded from this review study. Additionally, in the case of similar research work (articles) published by the same authors, the published journal article(s) or the most recent publication was selected.

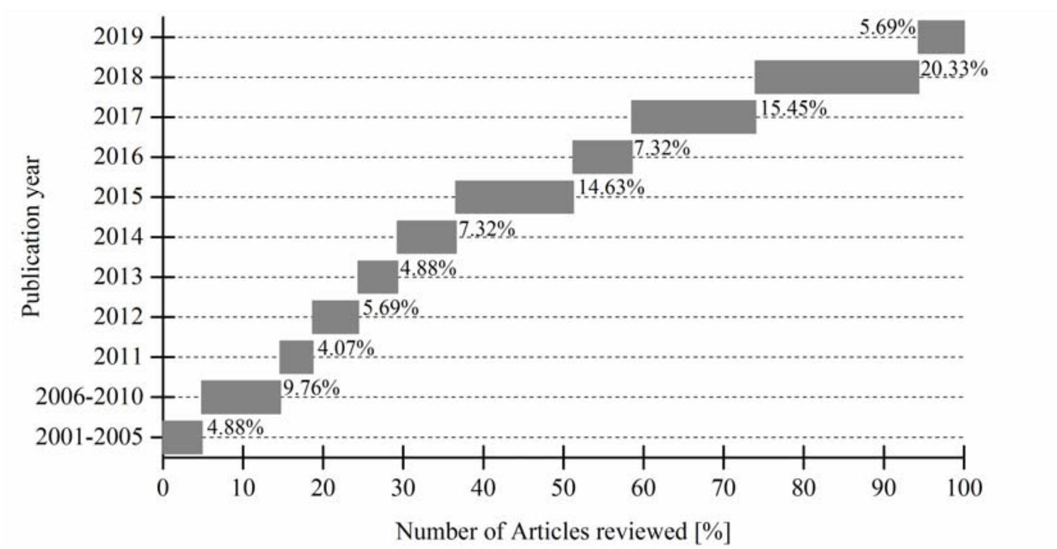

Figure 1. Categorisation of all reviewed literature according to year of publication

According to the chronological categorization of the articles considered (Fig. 1), an increasing interest in research and application activities for the UAV-driven SHM can be identified during the last few years. Especially, almost half of the pertinent articles reviewed have been published since 2016. Further, the statistical evaluation of the aggregated data, as shown in Fig. 2, enabled categorizing and presenting the UAV-SHM relevant papers on the basis of their ultimate goal. Hence, after a short overview of the current advancements in UAVs per se and the sensing technology (§3), a thorough discusion is provided accounting for papers focusing on the digital twin development (§4.1), displacement and deformation measurement (§4.2), damage detection and quantification (§4.3), structural system performance adaptation (§4.4) as well as benefit and value quantification (§4.5). Special attention was also attributed to emphasize the demands that are currently associated with the SHM strategies as well as the methodological and technological potentials that the synergy between UAVs and SHM may release (§5). Finally, the conclusory part (§6) of this study enables gaining an overall insight into the current state-of-the-art status and provides a series of challenges that needs to be addressed by ongoing and future research activities in order to safeguard the successful integration between UAVs and SHM.

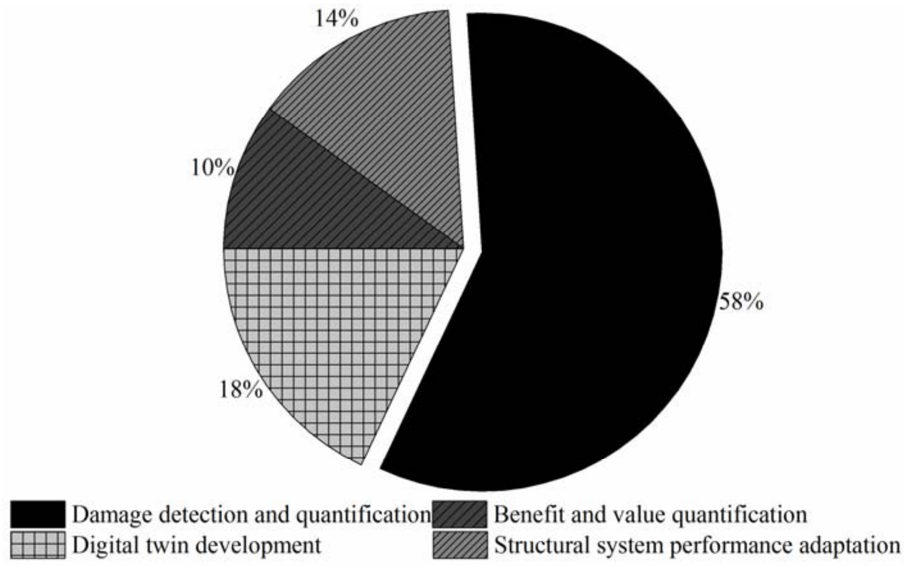

Figure 2. Categorisation of reviewed literature on integrated UAV and SHM research and application

3. Unmanned aerial vehicles and sensor technologies

As technology advances, the potential of using UAVs for SHM purposes increases. Among all advancements, the technologies underlying UAVs per se as well as the sensor technologies are of paramount importance for capturing the behaviour of structures and infrastructure systems.

3.1 Unmanned aerial vehicles technology

UAVs have attracted significant interest in recent years. In the past, the development of UAV systems and related platforms was primarily motivated by military goals and applications, whereas lately more civilian uses are also considered (Hassanalian and Abdelkefi, 2017). UAVs are essentially flying robots capable either of executing tasks or supporting humans in undertaking them. As a result, a factor that can differentiate UAVs is the level of autonomy (or the lack of it) that they exhibit during their operation. According to this point of view, one could identify a continuum of possibilities ranging from manually operated (tele-operated) systems, to machine assisted teleoperation, high-level commanded and finally to fully autonomous ones. Alternatively, UAVs are commonly categorized on the basis of their morphology as rotary-wing (also known as rotorcrafts) or fixed-wing UAVs while hybrid or bio-inspired solutions also exist, as discussed by Floreano and Wood (2015). Fixed wing UAVs can cover long distances as their speed and efficiency are generally very high. On the other hand, rotorcrafts are related to less endurance but enable hovering and moving freely in six degrees of freedom. UAVs could be also categorized according to their size, endurance and flight capabilities resulting in the following categories (Watts, Ambrosia, & Hinkley, 2012): Micro Air Vehicles (MAVs), Nano Air Vehicles (NAVs), Vertical Take-Off & Landing (VTOL), Low Altitude – Short Endurance (LASE), LASE Close, Low Altitude - Long Endurance (LALE), Medium Altitude - Long Endurance (MALE) and High Altitude - Long Endurance (HALE).

3.2 Sensor technologies

In comparison to a conventional helicopter concept, the multi-rotor UAV systems are associated with a very simple mechanism and a highly effective design in terms of different payload concepts. Therefore, the multi-engine, electro-driven platforms can be equipped with various inspection sensors and be adapted according to the individual application. Sensors on-board a UAV can be divided in proprioceptive and exteroceptive ones. Proprioceptive sensors describe the state of the UAV per se and typically include, among others, gyroscopes, compasses and Global Positioning System (GPS) localization modules. On the other hand, the exteroceptive sensors are the critical ones to facilitate the SHM purposes since they are used for gathering information about the environment around the UAV and may include vision sensors, 3D sensors, distance sensors or more specialized ones in accordance with the application scenario. Especially, the well-established 2D imaging has been becoming more and more affordable while, lately, advancements have taken place regarding 3D sensing technologies. Those technologies allow for perceiving the environment in 3D revealing, thus, numerous details about the state of the object (i.e., structure) under surveillance. Commonly, the 3D sensors are characterized by several important characteristics such as their Field of View (FoV, i.e., the angular area perceivable by the sensor), the spatial resolution, the minimum and maximum operation range as well as the depth accuracy, the depth resolution and the operation frame rate. The physical constraints of a sensor, including their dimensions, weight and power consumption, the cost and its ability to operate under vibrations, constitute additional features that are of high importance for the user and the application scenario.

To operate UAVs in outdoor environment, three main technologies, namely the stereo vision, Time of Flight (ToF) cameras and Light Detection And Ranging (LIDAR) technology, are essential to facilitate SHM purposes. On the other hand, a fourth type of interesting 3D sensing technology, infrared structured light, is not suitable for outdoor robotics. More specifically, the stereo vision is based on comparison between two images depicting the same scene but captured from a slightly different location (Nalpantidis, Sirakoulis, & Gasteratos, 2008). Common features between the two (or multiple) views are identified and matched by applying stereo vision algorithms, which dictate that the relative observed displacement of each feature is inversely proportional to its depth. Surveying systems equipped with stereo vision have multiple advantages since they can retrieve 3D information combining also colour information without any moving part. A significantly high resolution can also be achieved due to the available camera technology while the data is captured almost instantaneously by both cameras. Furthermore, a great variety of FoVs can be reached using suitable lenses. Finally, the stereo vision technology is less vulnerable to environment obscurants, e.g. fog, haze, rain, snow, dust, compared with active solutions, such as the ToF cameras and LIDARs. The latter renders stereo vision to be rather appropriate for outdoor applications. On the other hand, the stereo vision systems are suffering from increased computational demand and the associated depth accuracy degrades with the distance following a quadratic trend.

The ToF camera technology is based on the comparison between the phase of emitted and received signals (Schuon, Theobalt, Davis, & Thrun, 2008). Those systems are characterized as active ones since they emit their own signals while the conventional stereo vision systems are considered as passive. Regarding the advantages of ToF cameras, one measurement per pixel is provided and they are capable of simultaneous data capturing from all pixels. Furthermore, no moving parts are associated with those systems and their error grows linearly with distance. To the contrary, commercially available systems are currently associated with low resolution and limited range that render them mostly suitable for indoor environment applications. The operation principle of the ToF cameras often requires data capturing over a period of time; thus, the results are significantly affected by the motion of the carrying platform and of the target. Last but not the least, the active nature of this technology increases its susceptibility to environment obscurants.

LIDAR devices use laser beams and perform phase-based measurements, comparing emitted and received signals (Schwarz, 2010). Nowadays, commercially available devices rely on one or multiple laser beams steered mechanically to cover 1D or 2D target areas. Solid state LIDARs without moving elements are currently under development but no commercially available solution exists. The main advantages of LIDARs are their long ranges combined with remarkable accuracy even at these long ranges. Moreover, the error associated with the LIDAR technology grows only moderately with distance. On the other hand, the disadvantages include the high cost and power consumption of the LIDAR-based systems. The latter are less immune to shocks and vibrations during operation since the vast majority of the currently available solutions involve moving parts. LIDAR operation requires time due to the sequential capturing of data by steering one (or a few) laser beams to cover a larger area. The output of the LIDAR systems is also influenced by the egomotion of the carrying platform and the target. Finally, the environmental obscurants can also affect the LIDAR, being an active device akin to the ToF cameras.

4. State-of-the-art of integrated UAV and SHM research and application

During the last four decades, the field of Structural Health Monitoring has been subjected to tremendous development. Numerous SHM techniques have been introduced aiming at objectives related to the reliable damage detection and assessment of the existing capacity of a structural system. Moreover, the system identification[1], embraced by SHM techniques, has also been pursued in order to extract the dynamic properties and other mechanical properties of a structure features while critical parameters of various loading sources have also been detected (Brownjohn, 2007; Sohn, Farrar, Hemez, & Czarnecki, 2002; Worden, Farrar, Manson, & Park, 2007). Lately, one of the foci of the relevant research activities has been on the uncertainty treatment. For instance, advanced probabilistic approaches have been introduced to accommodate damage detection by leveraging statistical testing approaches (Bernal, 2014; Cha & Buyukozturk, 2015; Döhler, Marin, Bernal, & Mevel, 2013; Q. Huang, Gardoni, & Hurlebaus, 2012; Sun & Betti, 2015).

Beyond the specific SHM approaches, the pertinent technologies and intended objectives, the ultimate goal of SHM is commonly perceived as damage prognosis, associated with tremendous life-safety and economic benefits (Farrar & Worden, 2013; Sohn et al., 2004). However, such SHM approaches that integrate the quantification and prediction of the structural system's safety with monetary criteria and cost-benefit analysis principles have been marginally developed (Faber & Thöns, 2013; Pozzi & Der Kiureghian, 2011). Actually, it is only in the last few years that the quantification of the Value of SHM Information has significantly progressed throughout civil engineering (Memarzadeh & Pozzi, 2016; Straub, 2014; Thöns, 2018).

In the following sections of this chapter, the integration of UAVs with SHM techniques is thoroughly discussed. The latter is achieved through the description of relevant studies and industrial applications that focus on UAV-facilitated SHM tasks related to digital twin development, displacements measurement, damage detection as well as system identification and structural system performance adaptation. Especially, the currently reviewed articles demonstrate UAV-based SHM techniques ranging from semi-automated image-based inspection to advanced and fully automated methods associated with machine learning, Digital Image Correlation (DIC) and modal analysis. Furthermore, the expected benefit and value assessment of UAV-based SHM are highlighted by demonstrating industrial applications combined with the quantification of the Value of SHM Information.

4.1 Digital twin development

A digital replica of any structure and/or infrastructure system is currently denoted its digital twin that allows for assessing the structural behaviour and, eventually, its health condition. The fundamental rationale behind the digital twin of a structure has been refined over decades; however, recent advances in digitization and big data have accelerated the development and application of digital twins in several engineering-related fields including, among others, SHM campaigns, maintenance strategies as well as the holistic structural integrity management of assets (Macchi, Roda, Negri, & Fumagalli, 2018). Therefore, the digital twins currently facilitate the decision-makers and the relevant stakeholders in defining the most optimal inspection, monitoring and maintenance strategy that fulfils both safety and cost-related criteria. For example, the condition of a bridge may have changed several times during its

[1] The use of the term "system identification" denotes herein the estimation of the modal properties (e.g., Eigen-frequencies, mode shapes and damping ratios) of any structure by undertaking various analysis techniques including, among others, the Operational and Experimental Modal Analysis (Brincker & Ventura, 2015).

service life. Thus, the prediction model (i.e., digital twin) must be constantly modified and updated with monitoring data to reflect the actual conditions of the structure. The latter enables the enhancement of its operational performance and allowing for planning and conducting life-cycle management with lesser uncertainties.

In this respect, the utilization of UAVs for the development of a detailed 3D model of a structure or infrastructure system has been elaborated upon by several researchers and relevant recommendations for automated UAV-based inspections, image acquisition, 3D model reconstruction and the subsequent image analysis algorithms for decision support have been discussed (Kersten, Rodehorst, Hallermann, Debus, & Morgenthal, 2018; Morgenthal et al., 2019). For example, Khaloo, Lattanzi, Cunningham, Dell'Andrea, and Riley (2018) performed a UAV-based inspection on a bridge in Alaska via the generation of a dense 3D point cloud by using captured images and a hierarchical dense Structure-from-Motion (SfM) algorithm. The performance of the aforementioned inspection framework resulted in generating a 3D model of the bridge with a higher image resolution compared to the use of laser scanning for creating 3D structural models. Moreover, S. Chen, Laefer, Mangina, Zolanvari, and Byrne (2019) assessed comparatively the UAV-based 3D model reconstruction with the use of the Terrestrial Laser Scanning (TLS) method accounting mainly for cost and time related perspectives. The researchers concluded that the UAV-based model reconstruction needs further enhancement since it resulted in higher noise level in the 3D point cloud, lower geometry accuracy and longer post-processing time than the TLS method. Hallermann et al. (2014) also employed a UAV for 3D reconstruction of a retaining wall structure with positioning and depth accuracy of ±1.3 mm and ±10mm, respectively. Following the development of the 3D model, several authors have focused on automating feature extraction. For example, Akbar, Qidwai, and Jahanshahi (2018) investigated an automated approach to determine the points of interest for feature extraction. The latter enables the detection of structural changes by comparing the current and previous views of the structural site. Fernandez Galarreta, Kerle, and Gerke (2015) also studied the extraction of damage features using object-based image analysis software on a 3D cloud generated with UAV imagery and the generation of building damage scores based on the assessment results.

The fusion of optical imagery with thermal imagery in the developed 3D structural models can lead to a better identification of the surface anomalies. In this regard, Y. Huang, Chiang, Hsu, and Cheng (2018) proposed the integration between photogrammetry and thermography to generate 3D models of wind turbines by using segmented thermal images. They observed that the optical imagery acquired therein could facilitate determining possible displacements of the wind turbine tower while the thermal imagery could be used to identify surface defects. Eschmann and Wundsam (2017) also emphasized on the use of UAVs for inspection and SHM of a bridge infrastructure. Especially, they employed visual cameras or thermal images for structural state detection while LIDAR technology was used for scanning of object contours that, in turn, allowed for inspection and trajectory control. Based on the inspection data, ultra-high resolution reconstructions were built as two-dimensional (2D) projections, which were then post-processed in a full three-dimensional (3D) building model. These models were, finally, integrated into a web-based geographic information system platform, which provided georeferenced implementation and visualization of the inspection.

Apart from feature extraction, an application of the developed 3D model in structural analysis through Finite Element (FE) modelling has been investigated. The 3D photogrammetric reconstruction for FE model analysis and crack pattern mapping was described in an article by Mongelli et al. (2017). Roselli et al. (2018) produced a detailed FE model of a contemporary bridge structure based on a 3D reconstruction that was developed by UAV-based image acquisition. An accuracy of 1.3 mm was achieved and the refined model, being calibrated on the basis of the modal frequencies extracted from vibration measurements, facilitated the assessment of the seismic safety of the structure. Potenza, Castelli, Gattulli, and Ottaviano (2017) also employed a similar framework to construct a FE model of a steel bridge while image-processing techniques were further adopted therein to evaluate the extent of the corrosion. The FE model was directly updated by modelling the corrosion-affected area with a loss of mass and stiffness. Additionally, geometric characterization of a historic building was studied by Sánchez-Aparicio, Riveiro, González-Aguilera, and Ramos (2014) by launching a combined data acquisition approach with UAVs and stationary laser scanning systems that facilitate the geometric characterization of the structure. More specifically, the UAV-SfM photogrammetric approach was used by the authors to build a 3D model of the structure that was, then, imported to a FE modelling package, in which a global dynamic analysis was performed for further calibration of the numerical model.

4.2 Displacement and deformation measurement

The differences between UAV-based structure imagery obtained over time intervals can be applied towards the quantification of deformation and displacement. Ellenberg et al. (2015) quantified the accuracy of displacement measurements by using a commercially available UAV with a marker identification algorithm based on the Digital Image Correlation technique. Considering indoor experiments, the displacement measurements were found to be associated with an accuracy of ± 2 mm and ±3.5 mm when the UAV was in static configuration and hovering, respectively. Displacement measurements of steel and rubber bearings using a UAV in a laboratory test setup was also reported by Ellenberg et al. (2016). Further, Reagan et al. (2017) investigated the feasibility of using UAVs along with the DIC technique for measuring deflections of bridges. The authors used 3D DIC technology, which enabled extracting full-field displacement and geometry profiles of the measured surface. The integrated system, widely evaluated through comprehensive laboratory tests as well as by monitoring in-service concrete bridges, showed that the 3D-DIC UAV system could reach measurements in the order of 10^{-5} m.

An innovative approach for quantitative strain measurement was proposed by Ong, Chiu, Kuen, and Kodikara (2017). The authors used a UAV for 3D scanning of a membrane structure and generating an FE model. After applying a known deformation to the membrane, they updated the 3D model (and consequently the FE one) with imagery from the deformed membrane. The FE model could, then, be analysed to estimate the strains and, subsequently, the stresses in the deformed membrane. A benefit of using UAVs was that the entire membrane could be measured while, on the contrary, the conventional methods would allow for measuring of a rather limited number of points.

The accuracy of displacement measurements from conventional aerial photogrammetry and close-range photogrammetry was compared with measurements for a large-scale solar plant obtained by using UAV with a non-metric digital camera (Matsuoka et al., 2012). They investigated the root mean squares of error in eight measurements using the two techniques and concluded that a high accuracy was achievable if the orientation and measurement was performed using close range photogrammetric techniques.

Displacement measurement through contact inspection undertaken by a UAV was lately demonstrated by Sanchez-cuevas, Ramon-soria, Arrue, Ollero, and Heredia (2019), who used a lightweight multirotor, being capable of flying to close proximity of a surface and sticking to it in order to perform contact inspection. The system was demonstrated in the estimation of displacement of a bridge. A reflector prism was mounted on the UAV while a laser tracking system on the ground followed the position of the reflector prism, which, when in contact with the bridge's surface gave the geometry of the deflected bridge beams. The UAV got into contact with the bridge five times for a period of five seconds each time and the measurements of the contact points were used to estimate the displacement of the bridge.

4.3 Damage detection and quantification

The earliest studies of UAVs employment for damage or defect detection have been based on the use of single or double rotor aircraft. Along these lines, Metni and Hamel (2007) presented a novel control law based on computer vision for autonomous flight with orientation limits in order to keep the object (target) in the camera's field of view. Moreover, Eschmann et al. (2012) advanced the scanning of buildings by utilizing a rotary wing aircraft equipped with a high-resolution digital camera. The acquired imagery was stitched together to obtain a complete 2D image of the building surveyed with such a resolution that, eventually, allowed for the detection of cracking in the millimetre range. UAVs equipped with high definition photo and video cameras were also employed by Hallermann and Morgenthal (2013) to facilitate visual inspection of a reinforced concrete chimney in a power plant and a tower of a historical building. Within the framework of post flight analysis, the imagery was collected and then analysed with the use of an automatic crack localization and detection.

Bridge structures have been the testbed to investigate the efficacy of UAVs for visual damage inspection. For example, Lovelace and Zink (2015) conducted a bridge inspection project for the Minnesota (US) Department of Transportation, within which UAVs were used for damage inspection of four bridges with varying types and size. Monitoring data was collected in the form of still imagery, videos, infrared images as well as site maps and 3D models. The authors corroborated the use of UAVs as a cost-effective inspection platform capable of obtaining details and information that, otherwise, may be obtained through expensive and time-consuming methods. Cai et al. (2011) also emphasized on the bridge visual inspection by a prototype quadrotor UAV while the feasibility related to crack detection and crack width measurement was tested by appropriately designed indoor experiments. Additionally, defects such as rust stains, concrete spalling and cracking were identified by Gillins, Gillins, and Parrish (2016), who used a multi-copter UAV to capture imagery during an inspection on a large plate girder bridge in Oregon, US. Similarly, Otero (2015) conducted a proof of concept study concerning the use of UAVs for visual inspection of traffic infrastructure, wherein the risk and safety aspects related to the operation of UAVs in the proximity of humans and traffic were also addressed. Image data, obtained by the use of UAV, was also employed by Duque, Seo, and Wacker (2018) to quantify structural damage. They confirmed, through applications on a timber arch bridge, that the measurements obtained using the UAV had accuracies within 3.5%, 7.9%, and 14.9% for measurements of crack length, thickness and rust stain area, respectively, when compared with the traditional measurement methods. Additionally, the application of UAVs in remote sensing for quantitative post-disaster structure damage mapping of buildings through the analysis of UAV acquired imagery was explored by Sdongos et al. (2014) while Zakeri, Nejad, and Fahimifar (2016) used a quad-copter based digital imaging system to collect pavement surface data over a distressed area. The images were then analysed to detect and classify the cracks as well as provide reliable information about cracking distress. Morgenthal and Hallermann (2014) emphasized on UAVs-obtained imagery data and the associated bias and/or error introduced by several factors such as the lighting conditions and additional environmental effects, the distance between the UAV and the object to be surveyed as well as the motion of the UAV. In particular, the effect of wind speed fluctuations on the quality of recorded images was thoroughly studied therein while methods were also proposed to assess the quality of damage detection. The challenges faced in UAV-driven damage detection due to wind gusts and other flight stability issues were also studied by Dorafshan, Thomas, and Maguire (2018). They undertook inspections on steel bridges and observed that the use of UAVs, which rely heavily on GPS for navigation, disfavoured the reliable detection of fatigue cracks. On the other hand, the UAV platform's performance was found to be comparable to human inspectors within the framework of an outdoor surveying test on a bridge structure. Problems have been found to be associated with use of GPS for autonomous UAV flight in certain critical locations such as underneath a bridge or in indoor environments. Especially, during an image acquisition campaign under a bridge structure, the autonomous flight of a UAV equipped with a top-facing camera was found to be affected due to deficient GPS function (C.-H. Yang, Wen, Chen, & Kang, 2015). To resolve this problem, Kang and Cha (2018) proposed the use of an ultrasonic beacon system instead of the conventional GPS. The former led to 96.6% accuracy in concrete crack detection using the video data. Finally, a list of recommendations for UAV-based monitoring systems including more reliable positioning, turbulence resistivity, clearance measurement capability as well as the use of 360-degree gimbal, on-board light source and optical zoom camera settings was provided by Dorafshan et al. (2018).

Automated crack and defect detection techniques based on e.g., advanced image analysis algorithms from computer vision theories have recently been the focus of several researchers when dealing with large volumes of imaging data acquired on large-scale structures (Ellenberg et al., 2016; J. Kim, Kim, Park, & Nam, 2015; Sankarasrinivasan, Balasubramanian, Karthik, Chandrasekar, & Gupta, 2015; Yeum & Dyke, 2015). For example, H. Kim et al. (2017) introduced an image processing strategy for accurate extraction of the crack width while minimizing error in length estimation. The proposed strategy, when applied on images of a concrete wall acquired by a UAV, successfully measured cracks thicker than 0.1 mm with the maximum length estimation error of 7.3%. Moreover, the effect of the hovering motion of the aircraft on the accuracy of the image-based crack width identification was investigated by Zhong, Peng, Yan, Shen, and Zhai (2018). Especially, they used an octocopter for the aerial survey and the image processing toolbox, provided by MATLAB (The MathWorks Inc., 2018), was used for the relevant image analysis. Less than 5% of relative error was found therein between the airborne image and the static one, respectively. Additionally, convolutional neural networks have been used by B. Kim and Cho (2018) to further refine the automated detection for crack morphology on concrete surface under an on-site environment. The proposed method succeeded in detecting cracks from a real time video with a precision of 88% and a recall of 81% while, concerning the still images, the precision and recall were found to be 92.35% and 89.28%, respectively. Several researchers have also investigated the automated crack detection algorithms based on machine-learning techniques (Dorafshan, Thomas, Coopmans, & Maguire, 2018; Kang & Cha, 2018; I. H. Kim, Jeon, Baek, Hong, & Jung, 2018; Lei, Wang, Xu, & Song, 2018; L. Yang et al., 2017). The detection rate with such techniques was found to be dependent on the development of comprehensive training datasets (Z. Chen & Tang, 2017).

Recently, Khaloo and Lattanzi (2019) presented an algorithm to automatically identify and evaluate structural defects in 3D models of extensive infrastructure systems by analytically comparing the 3D models of both the damaged and undamaged system. By testing the developed algorithm on a dam in Maryland, US, it was demonstrated that minor cracks, section loss etc. could be identified and measured with millimetre level accuracy. With regard to automated detection, the pre-processing of images to correct motion blurring may be applied along with additional measures such as noise reduction and image enhancement in order to make the crack details more clear and complete (Aldea & Le Hégarat-Mascle, 2015; Peng & Liu, 2018).

Despite the advancements being associated with the UAV-facilitated damage detection, constraints regarding, for example, the battery life of the UAV can reduce the overall efficiency of such a surveying and monitoring system. Along these lines, Bolourian and Hammad (2019) proposed a path planning method of a LIDAR scanner equipped UAV for bridge inspection with the objective of minimizing time-of-flight and also achieving an acceptable visibility. The method was implemented with a software generated model of a three-span bridge and the results demonstrated the method's capacity in considering potential defect locations based on structural analysis and providing an optimal path for the UAV to perform image acquisition. Algorithms for automated path-planning and collision avoidance for UAV-based inspections have also been proposed by Freimuth and König (2018) in the context of building inspections and by Schäfer, Picchi, Engelhardt, and Abel (2016) with a focus on inspection of wind turbines.

Other UAV-driven methods for defect detection, which exclude the sole use of optical imagery, are related to a wall-sticking UAV equipped with electro-magnetic hold mount elements. The latter allows for sticking a ultrasonic flaw detection sensor probe (Mattar, 2018) for thickness measurements in metal structures susceptible to corrosion. The method presented therein was applied on a crude oil storage tank and was found to be associated with an accuracy up to ±0.005 inch. Likewise, Qidwai, Ijiaz, and Akbar (2017) introduced a hybrid method for structural inspection, in which a UAV scans the structure for defects and then, communicates their location to a probe deployment robot for performing a closer inspection with a magnetic flux leakage probe on the target area. Similarly, studies have also been directed towards the development of manoeuvres and prototypes for contact-based inspections (Mehanovic, Bass, Courteau, Rancourt, & Lussier Desbiens, 2017; Myeong & Myung, 2019).

An integrated approach considering remote sensing technologies that include aerial and satellite visual as well as thermal image data, UAVs, spectroscopy and ground penetrating radar was proposed by Themistocleous, Neocleous, Pilakoutas and Hadjimitsis (2014) in order to elaborate the monitoring and damage assessment of road networks. Similar multi-spectral approaches were also demonstrated by Brooks et al. (2015) for condition assessment of bridges as well as inspection of confined spaces, e.g. culverts and pump stations, and by Khan et al. (2015) to detect surface defects in bridge decks and provide comprehensive records of their locations. Additionally, Blaney and Gupta (2018) investigated a sounding technique using a UAV equipped with microphones and an impactor hammerhead for subsurface concrete defect detection. The results of this study showed that the UAV-based measurements on a concrete slab were as accurate as the reference measurements made with the traditional (manned) method using a hammer and microphone.

Furthermore, an approach for supplementing optical imagery with thermographic data was presented by Ellenberg, Kontsos, Moon, and Bartoli (2016) in order to detect subsurface delamination defects. To this end, a novel post-processing algorithm was used to facilitate such multi-spectral imagery. To assess the performance of the method presented therein, a bridge deck mock-up with pre-manufactured defects was tested and, especially, for small delamination (30-40%), larger detection errors (in size estimates) were found compared to actual measurements and location data. However, the method was rather successful in detecting shallow delaminated areas, which are the most common in bridge decks. UAV-based infrared thermography for detection of subsurface delamination was also explored by Omar and Nehdi (2017) to survey two in-service concrete bridge decks while similar detection technique was applied by Galleguillos et al. (2015) for aerial inspection of two in-service wind turbines.

4.4 Structural system performance adaptation

This section covers the engagement of UAVs for system identification, data collection and integration with wireless sensors while the performance of adaptive tasks to fulfil structural integrity management purposes is also highlighted herein. It is to be noted that the term structural system performance adaptation refers to the updating of the structural performance via: (i) the system identification and consequent extraction of mechanical and/or modal properties to predict the structural response with increased accuracy, and ii) the performance of adaptive (e.g., repair) actions.

The efficiency of UAV-based approaches for system identification is highly dependent on accurate and repeatable displacement measurements. Yoon, Hoskere, Park, and Spencer (2017) presented a method for system identification using relative displacement signals obtained directly from UAV-obtained videography. The study utilized cross correlation functions to compensate for the effect of the UAV’s egomotion in the displacement signals. An experimental investigation on a scaled model of a six-story shear-building highlighted the method’s potential to identify the natural frequencies of the structure with a maximum error of 1% and modal shapes with over 99% consistency when compared to the reference identification results obtained using the conventional sensor system (accelerometers). Following the aforementioned study, Yoon, Shin, and Spencer (2018) proposed a technique to measure the actual absolute displacements by using relative displacements obtained with the UAV-obtained video of the structural response. An experimental setup where the traffic loading on an actual pinned-connected truss bridge was simulated in the laboratory while a motion simulator was used to validate the proposed technique. The absolute displacements were measured with a root-mean-square error of 2.14 mm. Catt, Fick, Hoskins, Praski, and Baqersad (2019) also presented the development and testing of a prototype mobile DIC platform, being capable of recording accurate and repeatable displacement measurements while airborne. The aim of the study was to highlight the use of the drone for the vibration-based SHM of wind turbines. Similarly, Na and Baek (2017) introduced a vibration-based non-destructive evaluation method for SHM, within which the damage was detected via the temporary attachment of a Piezoelectric Transducer (PZT) device on the target structure by the use of a UAV. The authors, through laboratory experiments, assessed the applicability of the method by repeatedly attaching, detaching and re-attaching the PZT device with a drone on a test specimen. However, the drone reattachment was found to affect the impedance signature measured by the device that, in turn, could potentially undermine the accuracy of the measurement.

Research effort has been recently dedicated on the utilisation of UAVs’ mobility for collecting data from wireless sensors, mounted already on a structure, and communicating it to a ground station for further processing. For example, J. Chen, Chen, and Beard (2018) focused on the development of an aerial-to-ground wireless sensing network (AG-WSN) to facilitate integrated remote sensing and monitoring with both UAVs and wireless sensors. The WSN provides monitoring data in terms of vibration recordings that can be used for system identification. However, changes in modal properties induced by slight damages may not be readily identified by using only vibration recordings. Hence, the supplementary engagement of visual data, obtained with the use of optical systems mounted on a UAV, can enhance the system identification and, eventually, lead to detecting slight damages or other time-dependent degradation phenomena such as corrosion-induced cracking. The integrated approach further benefits from the imagery data communicated during run-time via the UAV. Additionally, such a system is associated with increased energy efficiency since the UAV can activate and interrogate the sensor on an as-need basis. Likewise, Musiani, Lin, and Rosing, (2007) introduced an AG-WSN system, in which the sensor network acquired the data and processed it locally after being radio-triggered by a UAV. A prototype hybrid SHM system has also been proposed by Todd et al. (2007) consisting of a UAV and embedded stationary wireless sensors, the latter being powered and interrogated wirelessly via the UAV. Recently, Zhou et al. (2016) developed a UAV platform with an integrated robotic gripper that is used to: (a) install wireless sensors on a structures, (b) drop a heavy weight introducing, in such a way, impact loads for vibration analysis and eventually, (c) interrogate the sensors to collect vibration data. The latter, obtained by using a simply supported beam within the framework of the aforementioned study, led to quite accurate identification of the modal properties.

The benefits, being already associated with the use of UAVs for surveying, inspecting and monitoring of structural systems, have lately triggered the research and industrial interest in investigating the potential to involve UAVs in adaptive tasks such as autonomous repair of structures. Especially, the idea of mounting a 3D printer on a UAV that would enable repairing of small cracks has already been discussed by Jackson, Wojcik, and Miodownik (2018). Additionally, a research project, undertaken by the University of Leeds, UK, explores the potential of integrating UAV-driven inspection with 3D asphalt printers as a means to undertake road maintenance activities and pothole repair tasks (Smith, 2018). A white paper (Richardson et al., 2017) highlights the potential of engaging UAVs in autonomous bridge repair tasks accounting for optimal path-planning principles based on 3D models of the infrastructure. In more detail, the UAVs are envisaged therein to perch on the bridge structure and undertake contact measurements. The latter can enable determining the condition of the structure and performing, when necessary, preventative maintenance tasks directly by depositing material or undertaking small repair tasks.

4.5 Benefit and value quantification

As highlighted before, the UAV-based SHM methods offer several advantages over the traditional SHM techniques including reduced risk of accidents, lesser logistics and working time, reduced closures for traffic and the possibility of leveraging Non-Destructive Testing (NDT) techniques for damage detection (Metni & Hamel, 2007). Lately, S. Chen et al., (2019) investigated the cost and time efficiency of UAV-SfM method for 3D model development compared to the use of Terrestrial Laser Scanning (TLS) for the same purpose. The UAV-based method was found to be associated with 1/3rd of the TLS-related cost while using 3% of the time taken by the TLS to acquire the data. Similarly, Weng and Enbar (2015) also emphasized on the higher time and cost efficiency of the UAV-driven inspections compared to the human-related ones in case of solar photovoltaic panels. By undertaking a purely conceptual analysis for gas pipelines monitoring, Hausamann, Zirnig, Schreier, and Strobl (2005) compared systems consisting of optical or infrared (IR) based remote sensing and commented on the applicability of small and medium sized UAV equipped with optical or IR cameras for the inspection of gas pipelines.

In the wind energy industry, UAVs are already employed as a robust and cost-efficient facilitator for inspection purposes (Navigant Research, 2015). Currently, UAV-based inspections may include up to 10 or 12 turbines in a daily basis while reviewing each blade can last for few minutes. On the other hand, according to the current industrial practice, the conventional human-driven inspection rate corresponds to two to five turbines per day. Additionally, the UAV-based aerial survey combined with online image processing software was found by Galleguillos et al. (2015) to be time efficient for detecting relevant structural indications of wind turbine blades since a short period of inspection time (i.e., 15-20 min per blade) accommodated rapid decision making. Similarly, L. Wang and Zhang (2017) scrutinized the crack detection for wind turbines blades by using image analysis techniques on wind farm imagery data harvested by a UAV. More specifically, a thorough detection of cracks and their location was made feasible by applying the proposed technique in a Chinese wind farm.

Further exploitation of the benefits associated with the UAVs can leverage their use from the structural health monitoring to the structural integrity management (SIM) and the relevant actions and decisions related, for example, to the extension of service life as well as repair and strengthening of structural systems. To facilitate, though, both the SHM and SIM purposes, the systematic quantification of the value of UAV-obtained information needs to be undertaken. To this end, the rather robust framework of the Value of Information (VoI) analysis coupled with Bayesian decision analysis methods can be employed to predict the potential benefit gain from the application of these advanced techniques. In this regard, the quantification of the value of structural health information obtained by UAV-based SHM systems was recently undertaken by Kapoor and Thöns (2018) in the context of structural integrity management of wind turbines. Particularly, a pair of UAV-based SHM methods was considered accounting for remote sensing methods and contact-based measurements. A conventional SHM method, being related to the instrumentation of a modern wind turbine with a permanent grid of sensors, was also considered and the structural health information from these three methods was modelled accounting for the type, costs and precision perspectives. The comparative assessment highlighted that the value of structural health information associated with the contact-based UAV method for the monitoring of wind turbines structures was found to be 5% higher in comparison to the conventional SHM system.

5. Outlook: requirements and potentials

Despite the growing gap in building new infrastructure, it should be emphasized that the worldwide stock of existing infrastructure is worth about US$ 50 trillion, being of a similar order as the global stock market capitalization (US$ 72 trillion, World Federation of Exchanges) and the global GDP (US$ 82 trillion, The World Bank Data Bank, 2017). The global civil engineering infrastructure ages and the challenge of keeping and enhancing serviceability grows; thus the need for information integration for safety and cost efficient structural integrity as well as serviceability management strategies becomes even more vital. The existing infrastructure stock offers a tremendous opportunity to narrow the infrastructure gap if governments are capable and willing to optimize the operations and maintenance of their infrastructure assets (Wong & Almedia, 2014). The ongoing cost of maintaining the world's physical infrastructure is extremely high. For bridges alone, it is estimated that about US$ 70 billion is spent annually on repairing bridge structures that have deteriorated under loads and environmental conditions to the stage where expensive reactive maintenance is required.

A principal difficulty with adding several traditional monitoring systems is that they may produce vast quantities of data and may be labour intensive. Gathering information requires structural health monitoring and inspection on a grand scale and, for it to be useful, it must be accurate, inexpensive and straightforward to interpret and avoid interfering with the functionality of the structures. Therefore, there is a need to introduce recent innovations in digital technologies, such as remote sensing, advanced analytics, autonomous operations, integrated scheduling and robotics devices to improve current inspection and monitoring strategies and optimize performance and efficiency of maintenance programs. In this perspective, technological and methodological potentials for structural health monitoring and management with UAVs are shortly outlined in the following section.

5.1 Technological and methodological potentials

The identified technological and methodological potentials – in the view of the authors – constitute (1) the UAV-based digital image analysis, (2) the integration of structural health information and UAV technology, (3) the employment of UAVs for integrity management actions and (4) embracing the previous potentials: the UAV employment optimization for ensuring an efficient infrastructure information and integrity management.

5.1.1 Image Analysis

According to the authors' point of view, image analysis holds a high potential as a camera equipped UAV is straightforward to operate, readily available and provides analysable images by a variety of algorithms including neural networks and other artificial intelligence techniques. The latter constitutes a field of tremendous attention for research and applications yet to come. The DIC system accuracy is comparable to existing displacement measurement techniques and DIC is an easier way to measure displacement of multiple points at once. DIC was also proposed as a method to asses dynamic characteristics of suspension bridge hanger cables (S. W. Kim & Kim, 2013). In this study, a non-contact sensing method to estimate the tension of hanger cables by using digital image processing based on a portable digital camcorder was proposed. Moreover, DIC technique has been used to record the strain on a concrete girder during a full scale bridge failure test (Sas, Blanksvärd, Enochsson, Täljsten, & Elfgren, 2012) and for the measurement of the displacement field on a cracked concrete girder during a bridge loading test (Küntz, Jolin, Bastien, Perez, & Hild, 2006). In both cases, the method was able to detect a change in loading condition and locate cracks. Recent applications of DIC include fatigue testing of monostrands for bridge stay cables. Here, the vision-based system allowed for the measurement of the interwire movement (fretting fatigue) being the governing mechanism responsible for the fatigue life reduction in modern stay cable assemblies (Winkler, Fischer, & Georgakis, 2014;

Winkler, Georgakis, Fischer, Wood, & Ghannoum, 2015). DIC was also employed in structural monitoring to measure strain at fatigue-sensitive bridge detail with a view to avoiding the need for strengthening (Winkler & Hendy, 2017).

5.1.2 UAV and SHM integration

The current state-of-the art as well as the industrial usage of UAVs for obtaining structural health information is primarily concentrated on image-based applications. However, the integration of conventional structural health monitoring sensing technologies and analyses methods with a UAV platform (a few applications are outlined in section 4) holds, in the view of the authors, a considerable potential as such structural health information can readily be used and integrated in the existing portfolio of structural integrity models and management procedures.

5.1.3 UAV employment for integrity management actions

The high mobility and self-autonomy of the drones offer the potential for asset operators to view them as a resource for automating integrity management actions such as repair following damage detection. This opens up new possibilities for maintenance activities, especially in hard-to-access structures, thereby offering potential cost-cutting and also the opportunity for repair to be initiated before large scale degradation has occurred. A white paper providing the philosophy and the technological vision has been published (Richardson et al., 2017). The technological vision constitutes an autonomous and disruption-free integrity management performed by UAVs. There is a clear technological progress towards such a vision. However, it is concluded that an integration of robotic technology and infrastructure engineering is required to be substantially supported with research and applied research funding including extensive testing facilities. It is also noted that a wider deployment depends especially on the cost and safety efficiency of the technology.

5.1.4 UAV employment scenario optimization

UAV utilization hold a clear potential in providing value for the infrastructure information and integrity management. The value of UAV utilization depends on the information UAVs can provide and the integrity management actions they can – potentially – perform for ensuring the safety of infrastructures and proving functionality that ensures integrity management throughout the infrastructure service life.

Crucial for the exploitation of the potential high value of UAVs for the infrastructure information and integrity management is a systematic and integrated analysis of the infrastructure performance, management objectives as well as various UAV based employment scenarios. The analysis of these scenarios will yield the ability of UAVs to ensure the infrastructure safety and the projected costs and benefits for the UAV employment for information acquirement and potential performance of integrity management actions in comparison to scenarios without UAV usage (see a first step towards this aim in Kapoor & Thöns, 2018). With this scenario analysis setup, an optimization of the UAV employment is facilitated by the identification of the UAV employment strategies, which lead to the highest expected infrastructure functionality benefits and the least expected operational costs, while fulfilling the human safety requirements. The optimization ensures to meet the efficiency challenges for the management of infrastructures – as outlined above - and thus the competitiveness of the infrastructure information and integrity management and the UAV operation.

6. Summary and conclusions

The state-of-the-art review presented herein provides a thorough compilation and description of published research work and industrial applications relevant to the employment of the Unmanned Aerial Vehicle (UAV) as a facilitator for the overarching objectives of structural health monitoring and management. The urgent industrial and societal demands to survey, inspect, monitor, evaluate and eventually, manage the structural health and integrity of the existing structure and infrastructure stock are persistently forcing the research community to develop novel and intelligent systems for providing reliable and cost-efficient information. On the contrary, the existing, mostly human-driven inspection strategies and the conventional monitoring techniques, the latter being commonly related to the installation of large instrumentation grids, are frequently associated with excessive time and monetary burden. Moreover, the performance of those techniques is severely disfavoured in cases of hardly accessed structural components (e.g., long cables of modern bridges) or structures placed in a hostile environment (e.g., offshore platforms). Thus, the engagement of state-of-the-art robotic technologies and especially of UAVs is envisaged to introduce a rather revolutionary era to obtain structural health information for the efficient health management of structures counteracting several limitations of the existing methods.

A rigid conclusion derived by reviewing the pertinent and recently published literature is that the UAV-based SHM techniques were found to favour the challenging tasks of: (i) the development of the digital replica (twin) of either a structure or an infrastructure asset, (ii) the detection of damages and defects based on image analysis, and, potentially (iii) an active and well promising employment of UAVs to undertake adaptive tasks including autonomous repair actions in structures for already identified deficiencies. However, the UAV-facilitated SHM is in its infancy and hence, several early stage symptoms need to be treated meticulously. Otherwise, the overall benefit that can be delivered by such a novel synergy can be seriously undermined. Along these lines, a series of challenges is presented below, for which the engagement of ongoing and future research activities is essential.

- Advancements in image analysis, computer vision algorithms and data science-related disciplines including, among others, machine learning and data analysis techniques, should be highly prioritized by joint efforts of the research community and industrial partners.
- Higher levels of UAV autonomous operation by uninterrupted operation time (e.g., longer battery life), enhanced flight control, autonomous path planning and sensing data acquisition should be pursued as a part of optimised structural health information and integrity management strategies.

The optimisation of the UAV employment strategies to achieve the highest utility for the structures and infrastructures integrity management, is composed of expected infrastructure functionality benefits and operational costs, while accounting for human safety. Such an optimisation ensures fulfilling the efficiency challenges for the management of infrastructures and thus, the competitiveness of the infrastructure information and integrity management as well as the UAV operation.

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