Application of UAVs for Bridge Inspection and Resilience Assessment

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The inability to effectively and systematically identify and measure the damage in bridges will lead to an acceleration and dangerous deterioration of the health state of these structures. To repair and replace the aging and crumbling bridge infrastructures, and prevent catastrophic bridge collapse, there is an urgent need to develop reliable, innovative, and efficient approaches to the resilience assessment and inspection of bridges. The purpose of this paper is to examine the application of the suitability of employing new technologies, such as Unmanned Ariel Vehicles (UAVs), which is commonly known as drones, for bridge inspection and resilience assessment. The paper proposed UAV-based bridge inspection and resilience assessment methodology. The proposed methodology helps for assessing the bridge operational state and, for investigating the application of UAVs for enhancing the resilience of the bridge.

Keywords: Bridge, drone, UAV, inspection, resilience

1. Introduction

Between 2005 and 2018, Europe and the Americas succumbed to a total of 50 bridge collapses due to deterioration related issues, such as fatigue fracture, aging of materials, which culminated in more than 100 fatalities and close to $20 billion in overall losses, during which more than a million people were somehow affected. This deterioration process significantly increases due to aging and structural depreciation, which can modify over time the structural performance and functionality of the bridge; and, consequently, the system resilience (Biondini & Frangopol, 2016). The other key issue that affects bridge performance is inefficient maintenance, which is usually aggravated by technical and economic limitations associated to inspections (Love, Lopez, & Edwards, 2013; Subramanian, 2008). Hence, the predominant issue in various countries is the repairing and replacing of the nation's aging and crumbling bridge infrastructure. For instance, the report by American Road and Transportation Builders Association (Ferguson, 2018) showed that more than 50,000 bridges across the U.S. are falling apart and, endangering road users. Further, according to the Norwegian Public Roads Administration (NPRA), most of the Norway's bridges are built in the 60's and 70's; and, they represent a risk of collapse due to aging.

Typically, the consequences due to catastrophic bridge collapses are twofold. Firstly, restrictions of the availability of these infrastructures may lead to intense traffic interferences on the surrounding road network resulting in negative effects on the road user, high economic follow-up costs, and negative environmental impacts (Heimbecher & Kaundinya, 2010). For instance, the I-35W Mississippi River bridge collapse, significantly impacted road-users and the Minnesota economy. The Minnesota Department of Transportation (2008) (Mn/DOT) study concluded that road-user costs due to the unavailability of the river crossing would total $400,000 per day. In addition to the road user cost study, further analysis by the Mn/DOT estimate that the economic impact – or loss to Minnesota's economy – at about $17 million in 2007 and $43 million in 2008. Secondly, the other problem, of course, is the tragic loss of lives that can follow catastrophic bridge collapses. In addition, the tragic loss of lives usually hurt the company public image, leading to unfavorable public opinion. For instance, the recent catastrophic collapse of Morandi Bridge, in the northwest Italian city of Genoa, in august 2018 with the death toll to 43 lead to grieving families blame the politicians and the authorities. Subsequently, the Genoa prosecutor has opened an investigation of the maintenance company. Further, the bridge collapse sparked immediate calls in Genoa and across Italy for big investment in repairing and replacing, the nation's aging and crumbling infrastructure.

To prevent and minimize the impact of bridge failure, the resilience of the infrastructure is very essential (Barabadi & Ayele, 2018; Kaloop, Hu, & Sayed, 2015). Moreover, a proactive maintenance is also a key factor in minimizing the probability of bridge collapses. Over the years, various bridge performance

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assessment (Liu, Frangopol, & Kim, 2009; Okasha & Frangopol, 2012), health monitoring (Okasha & Frangopol, 2012) and inspection tools (Phares, Rolander, Graybeal, & Washer, 2001) have been developed and implemented, to estimate the remaining service/ useful life of bridges.

In broad sense, the conventional bridge performance assessment and inspection procedures relied on data collected from the onsite visit as well as the visual inspection for severe and observable damages. Further, most of the recent research activities, related with bridge damage detection and performance assessment, are in particular have been focusing on damage diagnostics and concrete-type structures. These activities involves identification of cracks on mostly flat structures and under highly controlled conditions (e.g., adequate lighting, reduced noise due to texturing and weathered concrete surfaces). Moreover, most of these studies are based on an assumption that the cracks are characterized as dark, spatially narrow and elongated objects that have high contrast with the background (Jahanshahi, Masri, Padgett, & Sukhatme, 2013). However, in the case of steel bridges, for instance, cracks in steel elements are very difficult to identify and quantify due to their location, difficult accessibility, and small area of influence in their initial states. That means that by employing the traditional inspection tools, it is demanding to detect most of these factors solely based on human vision, such as the state of foundations under water level, fracture or cracks in main beams without easy access from the surface, among others (Jahanshahi et al., 2013). In other terms, the current bridge damage detection procedures, produces inspection and monitoring tools, which are non-resilient and, are not capable to capture the timely 'near' real-time system resilience. Moreover, the inability to effectively and systematically identify and measure the damage in bridges will lead to an acceleration and dangerous deterioration of the health state of these structures.

Hence, to repair and replace the nations aging and crumbling infrastructure, and prevent catastrophic bridge collapses, there is an urgent need to develop reliable, innovative, and efficient approaches to the resilience assessment and inspection of bridges. The purpose of this paper is thus to examine the application of the suitability of employing new technologies, such as Unmanned Ariel Vehicles (UAVs) which is commonly known as drones, for bridge inspection and resilience assessment. In general, the UAVs are equipped with a wide range of technologies such as an integrated camera with aerial zoom function, video, infrared (IR) sensor, and in some cases with radiometric-capable IR camera solution. The key benefits of using drones for bridge inspection is for performing inspection in hard to reach locations and parts of any complex bridge. The other benefits is the reduction of risks associated with current bridge inspection methods, which include – but are not limited to – rope systems and special inspection vehicles. Further, the paper explores the use of drones for automatic damage identification and data collection. The paper also proposed UAV-based bridge inspection and resilience assessment methodology. The proposed methodology helps to assess the bridge operational state and to investigate the application of UAVs for contingency plan, for enhancing the resilience of the bridge. The rest of the paper is organized as follows: Section II discusses the rules and regulations while using UAVs. Section III presents the proposed drone-based bridge inspection and resilience assessment methodology. Section IV provides an illustrative case study. Section V provides the concluding remarks.

2. European and US Drone Regulations – A Birds Eye View

An unmanned aerial vehicle (UAV), also commonly known as a drone is defined by the Norwegian Civil Aviation of Authority (2019) as an aircraft without a pilot aboard. In general, UAVs are a component of Unmanned Aircraft System (UAS); which describes the entire system, consisting of a ground station and the aircraft as well as all the other components that is needed for operating the system, such as equipment for launch, communication, and automatic landings etc. (Norwegian Civil Aviation of Authority, 2019). The UAV can be controlled either autonomously; or with the use of remote control by a human operator. The Autonomous UAS are systems where the aircraft flies according to pre-programmed course of action and makes its «own» automatic decisions based on the pre-plan. It is not possible for a pilot to make corrections during the flight when the system is operated autonomously. On the flipside, Remotely Piloted Aircraft System (RPAS) are systems, which describes that there is at all times a person in control of the remotely piloted aircraft. As per the Norwegian CAA, currently, the Civilian UAS operation are limited to «Remotely Piloted» system, which means that there should be a pilot on the ground who can take over control of the aircraft at all times.

As the use of UAV technology booms, countries are struggling to cope up with laws related with the safe use of drones. A number of European countries and, some states in US have established drone laws; however, many others countries do not. In addition, the existing rules and regulations do not consider the ever-changing UAV landscape over the last couple of years (Coach, 2018). The European Union (EU) have a fragmented regulatory framework. Even if, the EU region follows the safety rules, the drone's rules, regulation, and several key safeguards varies across the region. For instance, the Norwegian CAA categorized the use of UAV into two: for commercial usage and for leisure. If one uses drones for the purpose of leisure, there are five key rules one has to follow, see for e.g. (CAA, 2018). On the other hand, if one uses drone for research and commercial purposes, the CAA have implemented somehow a restricted rule.

In general, the Norwegian CAA have categorized the remotely piloted aircraft system organization (RO) into three: RO1, RO2 and RO3. In the case of RO1, which covers drones with maximum take of weight (MTOW) less than 2.5 kg, one has to send a declaration to CAA that states that he/she will operate in compliance with regulations. The key regulations for RO1 are (CAA, 2018):

- RO1 category is for drones with weights less than 2.5 kg and/or have a maximum speed of 60 Knot, which is approximately around 111 km/h or 31 m/s.
- All activities should be carried out within the visual line of sight (VLOS).
- The pilot can only fly the drone during the daytime within secure distances.
- The pilot should be at least 16 years of age to fly the drone.

In addition, an RO1 operator has to follow all general rules and regulation in Chapter 3 and the operative requirements in Chapter 7 of the Regulation by the Norwegian CAA. In addition, there are rules/limitations in Chapter 4 of how operation in RO1 is to be carried out. Further, regarding the security system, the Norwegian CAA states that the UAV must have system, which automatically sets it on the ground if the operator loses control of the aircraft. For instance, for fixed wing UAV, the aircraft have to have an additional system, which ensures that the UAV can land if an emergency occurs. On the flipside, in the case of Categories RO2 (with MTOW between 2.5 – 25 kg) and RO3 (with MTOW more than 25 kg), in addition to sending a declaration one has to pass the Norwegian CAA theory exam for drone pilot license.

On the other hand, prior to 2016, the US Federal Aviation Administration (FAA) have had several restrictions regarding the application of drones for the commercial purposes (Lovelace & Zink, 2015). One of the key restriction is that the need for FAA Section 333 Exemption and a Certificate of Authorization (COA) for commercial UAV operations. However, in 2016, the FAA have implemented a Small Unmanned Aircraft Regulations (Part 107), which alleviates the restrictions for drones weighing less than 55 pounds (approximately 25 kg).

3. Proposed UAV-based Bridge Inspection and Resilience Assessment Methodology

The proposed UAV-based bridge inspection and resilience assessment methodology comprises of three parts: *i*) bridge data collection and onsite risk assessment; *ii*) selecting an appropriate drone and performing UAV-based inspection; and *iii*) carrying out resilience assessment. The main objective of the first part is identifying, assessing, and utilizing the data regarding the health status of the bridge; and, to carry out the onsite risk assessment. On the other hand, the focus of the second part is to investigate the appropriate drone for a particular purpose and, perform the drone-based inspection. The third part focuses on evaluating the resilience of the bridge.

3.1 *Part I – Bridge Data Collection and Onsite Risk Assessment*

Figure 1 depicts the specific steps, which should be followed for collecting the necessary data as well as assessing the onsite risks associated with the application of drones for bridge inspection.

3.1.1 *Part I – Step 1: Bridge Data Collection*

Now a days, comprehensive data collection and digital documentation are becoming key to transport sector productivity & competitiveness. With current technologies, collecting both internal and external data of any infrastructure are becoming less demanding. However, without effective data collection, this ever-bigger amount of data can become overwhelming. Further, inadequate or poorly designed and performing data collecting and sharing platforms leads to major financial and social challenges, which governments and businesses need to address (Ayele, Barabadi, & Markeset, 2013; Dobbs, Pohl, & Lin, 2013). Hence, in this step, one has to identify, assess, and utilize the bridge data, which is critically essential for its core activities. Some of these essential data are:

- *Historical maintenance and repair data*: Collecting these data helps identifying a component or part of the bridge, which might have a higher risk of failure. In addition, the historical data can supplement the drone-based inspection process in such a way that to accurately identify the components with known defect (s).

- *Bridge remaining service life (RSL):* The remaining RSL is the time remaining for a bridge or its component to perform its functional capabilities before failure (Okoh, Roy, Mehnen, & Redding, 2014). In general, the RSL of existing bridges depends on the past, present as well as forecasted traffic loads. In order to estimate, the bridge RSL it is important to collect the load and vehicle data. This can be done by employing structural monitoring systems, which consists stain gauges, displacement transducers, and thermal sensors (von der Haar, Marx, & Hansen, 2012).
- *Load limit of the bridge:* The local authorities, generally, regulate load limit of bridges. The safe load carrying capacity of the bridge can be obtained by carrying out bridge load test. Such types of tests will help to identify the relationships between safe load carrying capacity of the bridge and its service condition.
- *Type of bridge component:* Bridge component are designed to fit the specific case scenario such as highway, railway, pedestrian and so on. Here the data related to the performance or service condition of the key component of the bridge should be collected. Some of the key components comprises of the bridge pile, girder, deck beam, abutment, etc.

3.1.2 *Part I – Step 2: Bridge Onsite Risk Assessment*

To evaluate the peculiar operational risks associated with bridge inspection process, in particular hazards associated with drone-based inspection it is important to map the risks related to the planned activities and the susceptible areas. Bridge inspection is a demanding process and, involves safety hazards and risks for the civil engineers/inspectors, equipment operators, divers, construction workers, and others while they are involved in road or bridge inspection and repair. The US Occupational Safety & Health Administration (2019) have compiled the common hazards associated with the conventional roadway and bridge inspection and repair:

- Falls from the heights or through openings,
- Structural instability,
- Contact with downed lines and live electrical equipment and other utilities (such as gas, water),
- Work on, over, or near water,
- Improper ladder or scaffolding use, etc.

However, the key benefit of UAV-based bridge inspection is the reduction of the risks associated with conventional bridge inspection methods, which are mentioned above. In this stage, one has to investigate the appropriateness of employing drones for specific types of bridges since not every bridge inspection is ‘‘drone appropriate’’. Bridge inspection projects, which can be suitable for drone use, include those that (Bridge Masters, 2016):

- Requires expensive and hard-to-set-up equipment to inspect a small section of a bridge. This means that the cost of inspection is significantly high comparing with the very limited use and pay off,
- Bridges with a an unusually high level of risk and catastrophic consequence,
- Bridges that might lead to intense traffic interferences and have a significant impact on traffic.

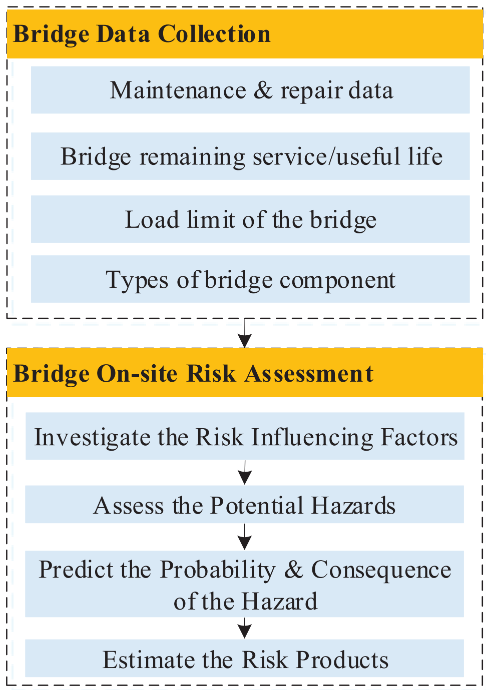

Figure 1. Part I of the Proposed UAV-Based Bridge Inspection and Resilience Assessment Methodology

3.2 *Part II – Select Appropriate Drone and Perform UAV-based Bridge Inspection*

The second part comprises steps for investigating the suitable UAVs for bridge inspection purpose as well as steps for performing UAV-based inspection (Figure 2).

3.2.1 *Part II – Step 1: Select Appropriate UAV for Bridge Inspection*

In this stage, the selection of an appropriate drone for bridge inspection should be carried out. The following considerations needed to be corroborated when selecting the most suitable inspection drone:

- *Drone Model:* Typically, drone-pilot is only as good as the equipment they use. That means that there is no amount of skills, which can overcome poor camera quality or an unstable drone. For bridge inspection, a hexacopter and preferably an octocopter are suitable since they have a high factor of safety should a rotor or three fail. However, the quadcopter is not appropriate, since the factor of safety is minimum comparing with the other types of drones.
- *Maximum Takeoff Weight (MTOW):* MTOW is the maximum weight authorized for an aircraft while taking-off. While selecting suitable UAV, one has to take into consideration the MTOW of the UAV. This is to minimize the consequence of an incident, which involves a UAV. For instance, the consequence of an incident with a 2.5kg drone is exponentially less than with a 25kg drone.
- *Flight time:* UAVs have a wide-range of flying time. An average commercial drone have an average flight time of between 10 and 30 minutes. However, there are some exceptions, such as Vanilla Aircraft's VA001 36-ft wingspan, diesel-powered drone, has managed a flight lasting 121.4 hours during October 2017. Hence, for bridge inspection, one has to select a drone with a relatively longer flying time in order to limit the interruptions during inspection due to the need for additional batteries.
- *Image Quality and Camera Resolution:* In bridge inspection, high quality images are essential rather than video. Hence, the selected UAV has to have a camera with aerial zoom function, for capturing high detail images in hard to reach locations and parts of any complex bridge. This will significantly reduces the unenviable task of reviewing a video. Further, it can also be beneficial to integrate omnidirectional camera on the top of drone for inspecting the underneath of the bridge. The other key requirement is the video resolution. For bridge inspection, the video should be high-resolution in order to visually observe bridge damage details.

3.2.2 *Part II – Step 2: Perform UAV-based Inspection*

After identifying the suitable UAV and carry out onsite risk assessment, one has to perform the systematic inspection of bridges. The following steps are recommended:

- *Collect UAV (drone) Image:* The key purpose of employing drones for collecting images and assessing the bridge operational state is its suitability to collect a huge array of data within a short period of time. Hence, the aim of this stage is collecting and examining the quality of array of data collected by drone-mounted sensors.
- *Carrying out Drone Image Segmentation:* The next stage is to carrying out drone image segmentation. In principle, during drone flight, a number of images should be taken at regular intervals to make sure that images overlap. This should be done in order to measure the objects presents in the drone image. Thereafter, one can employ image stitching by using the relevant metadata, which is necessary for the inspection data analysis and identifying the defects. In this step, one have to stitches images of the same bridge components from different angels, together by comparing, matching and measuring angles between components within each image. In order to facilitate the stitching process, images can be geo-referenced. This will make it easier for attaching the location information to the specific drone image.
- *Damage Detection, Localization and Classification:* For facilitating the detection of damage, one can employ vibration-monitoring sensors coupling with the drone images is beneficial for damage detection, localization as well as classification. Hence, at this stage, a reasonable effort has to be made to investigate the fracture mechanics and, to model the propagation of cracks under various loads by analyzing the vibration signals and drone-based digital images. Several studies have demonstrated that vibration-monitoring sensors, which can be cement-based, are predominately well suited for structural health monitoring of bridges due to their numerous possible field applications, ease of use, and long-term stability (Downey et al., 2017). Moreover, using the a novel image processing approach such as Convolutional Neural Networks (ConvNet, or CNN) coupled with multiple sensor signals (vibration) data offer unique opportunity for identifying and quantifying cracks in steel elements. ConvNet or CNN– is one of the most commonly used deep neural networks for analyzing visual imagery. Further, this is a unique opportunity for monitoring steel bridges, since cracks in steel elements are very difficult to identify and quantify due to their location, difficult accessibility and small area of influence in their initial states.

- *Damage Quantification and Prognosis:* Here various image processing and sensor data analysis approaches can be employed for damage quantification and prognosis. One of the latest approach for quantifying damage is to employ ConvNet, or CNN integrate it with multiple vibration-monitoring sensor signals data. This approach can also be employed for estimating the remaining useful life of the bridge. The other key aspect of this stage is employing dynamic damage prognosis for formulating the growth of the crack as well as predict its incremental crack growth, see e.g. He, Lu, and Liu (2011) and Yu and Zhu (2016).

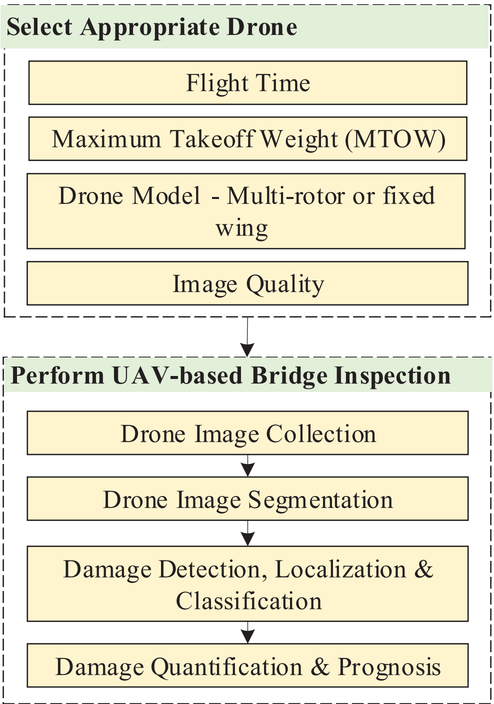

Fig. 2. Part II of the Proposed UAV-Based Bridge Inspection and Resilience Assessment Methodology

3.2 *Part III – Perform Bridge Resilience Assessment*

Figure 3 depicts the recommended steps for carrying out the resilience assessment of a specific bridge. Resilience is defined herein as the function of robustness and rapidity. Robustness is defined as the ability of a bridge to resist the initial adverse effects of a disruptive event; while the rapidity is the rate or speed, at which a bridge is able to return to its primary intended function following the disruption.

The first stage of the resilience assessment is structural safety analysis of the bridge. The deterministic check for sufficient structural safety of existing structures is done by verifying the well-known inequality that the structural capacity exceeds the actions in any design situation, which is given as (Zwicky, 2005):

$$S_d \leq R_d \tag{1}$$

where:

- S_d is the design values of the action
- R_d is the design values of the resistance

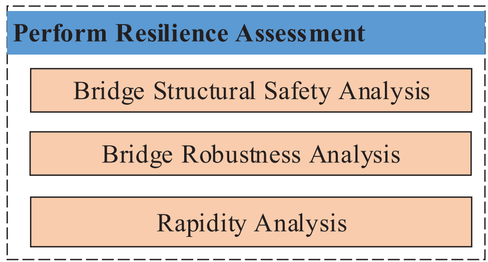

Fig. 3. Part III of the Proposed UAV-Based Bridge Inspection and Resilience Assessment Methodology

The next stage is carrying out the robustness analysis of the bridge. Tierney and Bruneau (2007) defined robustness as the ability of systems, system elements, and other units of analysis to withstand disaster forces without significant degradation or loss of performance. In general, robustness is associated with the ability of a bridge or primary load-carrying components perform as per its intended function. Further, robustness can be also associated with the redundancy. Redundancy is typically defined as the ability of the bridge system to sustain damage without collapse (Chavel & Yadlosky, 2011). In broad, redundancy can be categorized into three: internal redundancy, structural redundancy, and load path redundancy. Internal redundancy relates to the fact that the failure of one element of a member will not result in the failure of other elements of the members (Chavel & Yadlosky, 2011). Structural redundancy refers to the redundancy that exists because of the continuity within the framing element. Load path redundancy is related to the ability of the structure-carrying load following the loss of a single member (Chavel & Yadlosky, 2011).

The final stage of the resilience assessment is, performing rapidity analysis. Rapidity is defined as the capacity to restore functionality in a timely way, containing losses and avoiding disruptions (Tierney & Bruneau, 2007). To reduce the negative impact of component failure or bridge collapse, the rapidity of the system should be improved, which can be achieved by improving the robustness, redundancy, and resourcefulness aspect of the bridge.

4. Concluding Remarks

Bridges are key elements of the road infrastructures; and, they have proven to be very susceptible to deterioration and collapse because of ineffective, and, in some cases, inappropriate inspection techniques. One of the latest advancement in bridge inspection is employing UAVs for performing inspection in hard to reach locations and parts of any complex bridge. In this work, UAV-based inspection and resilience assessment methodology is proposed. The proposed methodology comprises:

i) Bridge data collection and onsite risk assessment;
ii) Selecting appropriate drone and performing UAV-based bridge inspection
iii) Performing bridge resilience assessment

Our conclusion is that the proposed inspection and resilience assessment methodology for bridges, based on the fusion of automated image processing, can significantly contribute to overcome the deficiencies of the current performance assessment, inspection and monitoring tools. Consequently, helps to repair and replace the aging crumbling bridge infrastructure and prevent catastrophic bridge collapse. Further, employing drones for inspection is beneficial for the reduction of risks and costs associated with current bridge inspection methods. Drone-mounted sensors can be used to collect large amounts of inspection data, which paves the way for increased digitization of bridge inspection and monitoring processes. In addition, an automated, digitized bridge inspection combined with drone images can detect bridge damage at a level likely to be impossible for a human inspector. It can also reduce much of the uncertainty and weaknesses associated with an inspector's personal assessment of the severity of structural damage.

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