A Holistic Approach for Visualization of Transportation Infrastructure Assets Using UAV-CRP Technology

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Abstract. Modern data analysis and visualization make it possible for engineers and practitioners to holistically perceive the details of sites and the performance of transportation infrastructures. Advancements in the field of unmanned vehicles, complemented by the development of portable sensors, have paved the way for unmanned aerial platforms mounted with sensors, such as visible range, thermal, and hyper-spectral cameras for collecting infrastructure performance data. A research study was performed to monitor various transportation infrastructure sites, using unmanned aerial vehicles close-range photogrammetry (UAV-CRP). Images were geotagged, using data from a highly accurate real-time kinematic global navigation satellite system (GNSS) to develop orthomosaics, dense point clouds, and three-dimensional mapping products. An aerial data collection provides safe access to areas that are usually inaccessible, such as under bridges, steep and unstable slopes, and others, and can be leveraged by three-dimensional printing technology to obtain the accurate size and shape of the structural elements that are needed for repair and rehabilitation of the infrastructure. The holistic approach provided in this paper will facilitate the development of infrastructure visualization models that will provide vital understanding of the condition of the transportation infrastructure.

Keywords: Unmanned aerial vehicle · Infrastructure · Visualization · Monitoring · 3D printing

1 Introduction

Transportation and civil infrastructures need to be sustainable and resilient to solve the challenges posed by extreme weather events, increased traffic loading conditions, service life demands, and others. The vast network of transportation infrastructure is comprised of highways, railways, bridges, towers, and other structures that connect communities and transport people from one place to another [1]. This network is a key contributor to the nation's economy, as it provides access and mobility to both passengers and freight. The recent ASCE infrastructure report card graded the infrastructure of the United States (US) as "D+" [2]. The increased demand for and deterioration of infrastructure conditions underscore the need for conducting proactive monitoring and preventive maintenance that will contribute to the resiliency of the

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infrastructure assets [3]. The expensive and time-consuming nature of the present traditional infrastructure assessment methods provide a case for exploring new data collection methods [4, 5].

Data sensing platforms, hardware, and image-processing software addressing safety, efficiency, and data quality requirements for data collection applications have evolved over the years. Recently, unmanned aerial vehicle systems, commonly termed as UAVs, UASs, or simply drones, have emerged as potential data collection tools for transportation infrastructure inspection and monitoring. In this paper, the terms UAV, UAS, and drones are used interchangeably to represent unmanned aerial vehicle systems. The advancement of computer vision and compact sensors that facilitate aerial assessments of the condition of civil infrastructures from a safe operating distance [6] have contributed greatly to the unprecedented growth and emergence of the UAV as a data sensing platform.

Photogrammetry is the art and science of measuring distances, using more than a single image captured remotely. In close-range photogrammetry (CRP), images are collected within a range of 1000 ft. [7]. Unmanned aerial vehicles do not require pilots or cockpit systems and offer ideal low cost and lightweight platforms for conducting close range inspections. The technology, known as unmanned aerial vehicle-close range photogrammetry (UAV-CRP) technology [4], has the potential to reduce labor costs and emissions, and provide access to inaccessible areas for infrastructure monitoring. It also considerably reduces personnel’s exposure to dangerous environments by replacing manpower with technology for risky inspections.

The two types of UAV units frequently used are rotary wing and fixed wing. A fixed wing UAV has a single rigid wing across its body that allows it to fly longer distances at high speeds, similar to manned airplanes [8]. A rotary wing UAV uses lift from the continuous rotation of its blades and has the ability to take off and land vertically, similar to manned helicopters. Rotary UAVs provide mobility and flexibility in conducting localized inspections.

The data collected from the drones can be processed to obtain three-dimensional mapping products that allow navigation through the models for better visualization of the infrastructure condition. These characteristics of aerial mapping have contributed to its extensive use for infrastructure monitoring in the last decade. Most of the previous studies witnessed a significant reduction in monitoring costs, thereby reducing the life-cycle maintenance costs of the infrastructure. The Federal Aviation Administration (FAA) predicts that by 2020, annual sales of commercial UAS (non-model aircraft) in the US will reach 2.7 million dollars [9].

This keynote paper presents UAV-CRP technologies and describes how they can be used to assess, monitor, and manage the condition of transportation infrastructures. The paper is divided into several sections, with the first section covering a review of the existing literature on various topics, including FAA guidelines, flight planning, UAV payload characteristics, and previous UAV studies performed in the infrastructure monitoring area. The second section covers the methodology used in this research for conducting different types of infrastructure monitoring. The third section provides details of the data collection activities performed at different transportation infrastructure sites, and the fourth section discusses the innovative visualization of the infrastructure assets, with the help of downscaled 3D printed models. The last section summarizes the key findings.

2 Literature Review

UAVs were first developed in the United States during the early 19th century, when they were used for long-term reconnaissance videos to assist with target designations and attacks in war. Since then, among other benefits, they have proven to be immensely helpful in eliminating pilot risks [10]. Following pioneering research and development in military area applications by researchers and various agencies worldwide, the last decade has experienced rapid growth and increased demand for UAVs, because of their capabilities and potential applications in numerous civilian missions that have many societal benefits [11]. However, the application of UAVs in non-combat missions has faced challenges due to the legal and technical constraints that prevailed with regard to the safety of flying in non-segregated spaces and other policies related to flying operations [11].

2.1 Flight Operation Guidelines

The aerial data collected in this study followed the flight operation guidelines set by the FAA and TxDOT. A review of both of the guidelines is provided in the following sections.

Federal Aviation Administration (FAA) Guidelines. In 2016, the FAA released new guidelines that are still effective for the safe operation of small unmanned aerial vehicle systems in the United States [12]. They are instrumental in safely conducting commercial operations using UAV platforms. Some of the highlights of the FAA part 107 rules for flying small drones (less than 55 lbs.) are provided below.

(1) All UAVs must be registered, with the registration number attached to the aircraft before field operations are performed.
(2) Pilots must have FAA certification to operate a single UAV commercially.
(3) Airspace charts are provided to check whether the site location falls within class G airspace. If it does not, a waiver needs to be obtained from FAA. The FAA sectional chart also details other potential hazards, such as intense glider activity, military exercise areas, and many others where pilots need to exercise caution.
(4) The aircraft must remain within a visual line of sight (LOS), and can only fly during the daytime, less than 400 feet above ground level.
(5) The drone should always the yield right-of-way to a manned aircraft, and fly at or below 100 mph.
(6) The FAA must be notified, within 10 days, of any aerial operation that results in serious injury, loss of consciousness, or property damage of at least $500.
(7) The pilot must not fly over people or moving vehicles not associated with the aerial operations.

TxDOT Flight Operation Manual (FOM). A recently completed Texas Department of Transportation (TxDOT) funded research study at the University of Texas Arlington (UTA) focused on the review and validation of an Unmanned Aircraft System (UAS) Flight Operations and User's Manual (FOM) developed by TxDOT. The FOM includes topics on flight crew requirements, the safety management system (SMS), flight planning rules, project risk assessment (PRA), traffic control plans, submission of forms, health and safety plans, emergency procedures, the downed aircraft recovery plan (DARP), and accident-reporting protocols. The guidelines provided in the FOM assist the UAS crew in executing safe ground operations and aerial tasks related to data collection pertaining to TxDOT assets. Most of the guidelines are similar to those prescribed by the FAA, and many of the topics were updated to target local state needs. For example, the minimum qualifying hours' requirement for a remote pilot in command (RPIC) and the visual observer (VO) are based on local regulations. The FOM also includes general flight planning rules, with visuals, and describes the files and information that need to be submitted, The standard flight plan format is provided in the annexures [13].

2.2 Previous Infrastructure Monitoring Studies Using UAVs

Doherty et al. presented the applications of UAVs performed in transportation-related areas at the Wallenberg Laboratory for Information Technology and Autonomous Systems (WITAS) in Linkoping University (LiU), Sweden. Due to the multidisciplinary nature of the aerial vehicle project, different departments in LiU collaborated on the research, gathering traffic and road information on fully autonomous UAVs. They used a vertical takeoff and landing system (VTOL), mounted with either digital or infrared cameras, to collect traffic patterns involving overtaking and U-turns [14]. Rathinam et al. conducted fixed wing UAV-based monitoring of linear structures such as roads, pipelines, bridges, and canals. Linear structures were detected by visual recognition techniques controlled by a closed loop algorithm [15].

Irizarry et al. used a small-scale drone equipped with a video camera that captured images and rendered real-time videos at construction sites. They found that a high-resolution camera, vocal interaction, and autonomous navigation were some of the ideal features of a drone system that were useful for safety inspections at construction sites [16]. Pereira and Pereira demonstrated embedded image processing systems for automatic crack recognition, using UAVs. They focused on identifying the different types of mortar cracks on facades, using aerial inspection. Segmentation by edge detection and particulate filter are the two crack-identifying algorithms discussed in their study, in which crack images were used to calibrate the crack-identifying algorithms and were tested with simulated mortar cracks on façades [17].

Marinelli et al. presented work on identifying the horizontal alignment from the road data images collected from mobile terrestrial and aerial remote sensing platforms. The images were subjected to edge extraction and feature recognition in Matlab to identify the horizontal alignment [18]. Puppala et al. used UAV platforms to identify pavement heaving caused by high sulphate soils. They were able to obtain the longitudinal elevation profiles along the wheel paths to spot any unusual elevation difference along the pavement surface [19]. Congress et al. conducted a comprehensive calibration analysis of drones and camera accessories to understand their compatibility for obtaining accurate data. They also demonstrated field data collection procedures for collecting images, and processed those images to generate accurate dense point cloud models, digital elevation models (DEM), and contours [20].

2.3 US Departments of Transportation Agencies' (US DOTs') Works

In March 2018, the American Association of State Highway and Transportation Officials (AASHTO) conducted a survey of various state departments of transportation (DOTs) in the United States to gather information about their usage of unmanned aerial vehicle systems. The response was unprecedented, as 35 out of 44 DOT respondents have approved using UAS for wide range of applications [21]. The survey reported that twenty DOTs have incorporated UAVs into various daily applications, and fifteen DOTs have been performing research on setting up standards, protocols and safety precautions to be adopted during aerial data collection methods [21].

The University of Washington collaborated with the US Department of Transportation (US DOT) in exploring the ability of UAVs to identify avalanche conditions, especially over slopes near state highways that are located on mountainous terrains. In an effort to reopen the avalanche-prone road section, the Washington State Department of Transportation (WSDOT) opted for the low-cost alternative of using UAVs during an initial trial and identified the avalanche-prone trigger zones and snow chutes. They also identified the limitations of using a fixed wing aircraft requiring a 100-foot long flat road surface to land in an urban area. In their second test, WSDOT used an R-Max, a rotary wing UAV, to follow preprogrammed waypoints to conduct a survey of terrain conditions along a road prone to avalanche events [22]. According to a special report on drones in Asphalt, the magazine of the Asphalt Institute, the University of Vermont partnered with the Vermont road agency and used a UAV to monitor the rivers adjacent to roadways. This study focused on preventing the pavements from flooding and other moisture-related pavement failures [23].

McGuire et al. addressed different ways in which the Kansas Department of Transportation (KDOT) could benefit from using UAS for different applications [24]. For the first time in the United States, KDOT partnered with AirMap, Inc. to ensure safer skies by integrating the unmanned aerial traffic into the national airspace through unmanned traffic management (UTM). UTM implements airport notification and awareness systems for UAS operators [25]. In 2017, the North Carolina Department of Transportation (NCDOT) and North Carolina Highway Patrol conducted a joint study to compare traditional and UAS methods for collecting crash-scene data. They realized a saving of 1.5 h by using three drones, compared to the traditional data collection methods adopted by the highway patrol Collision Reconstruction Unit, and estimated that using a drone to collect the crash-scene data on a busy highway would result in savings of approximately $9,300 [21]. The North Dakota Department of Transportation (NDDOT) is one of the 10 selectees of UAS-IPP program, and was assigned the task of evaluating the night time and beyond-line-of-sight operations of UAS in airspaces ranging from rural to urban areas [26].

The Texas Department of Transportation (TxDOT) supported a research study conducted at UTA, which researched the applications of unmanned aerial vehicles for monitoring transportation infrastructures. A comprehensive flight operation manual (FOM) was developed by TxDOT and was validated by field studies. After successfully conducting inspection tasks on pavements, bridges, rail tracks, and stockpiles, a follow-up implementation project was performed to further validate the UAS FOM in field operations. The following sections cover the research and methodologies performed on UAV-based infrastructure monitoring studies.

3 Holistic Approach to Infrastructure Monitoring Using UAVs

The methodology adopted in the research study performed at UTA offers a comprehensive guide for conducting aerial inspections, using UAVs for monitoring various transportation infrastructure condition tasks. The holistic approach explains the selection of drones for various inspection tasks. The monitoring tasks are classified into two types, based on the nature of the data collection and the processing of the data collected in the field. Qualitative inspection involves the collection of high-quality images and videos that assist in predominantly visual inspections. Quantitative inspection involves building three-dimensional models from photogrammetry studies and measurements that can be used to make engineering decisions regarding rehabilitation strategies.

3.1 Drone Selection

The five major factors taken into consideration when selecting a drone for infrastructure monitoring are shown in Fig. 1. One of the factors is payload, which includes different sensors and other drone accessories necessary during the flight. Payload characteristics vary depending upon the type of inspection, and the payload and type of inspection play key roles in selecting the appropriate drone. Some inspections require a drone that accommodates a top gimbal or additional sensor. The availability of safety features, such as collision avoidance sensors and return-to-home features are of great value during close-range infrastructure inspections. A global navigation satellite system (GNSS) controls the quality of data collected by the drone. The flight time per battery set limits the extent of inspection, hence drones with a long battery life are selected for inspecting large areas.

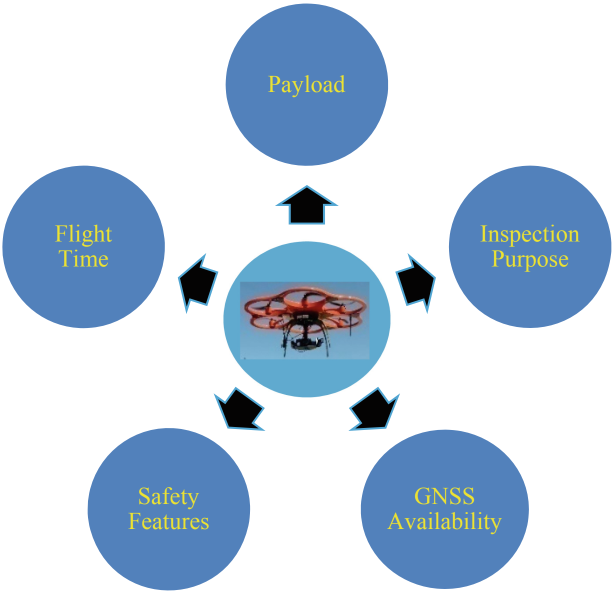


Fig. 1. Factors affecting drone selection for various infrastructure monitoring tasks.

3.2 UAV Procedure Steps

Most of the steps involved in qualitative and quantitative inspections of transportation geotechnics infrastructure assets are the same as those shown in Fig. 2. They are classified as preflight, mission flight, and postflight tasks. Preflight tasks involve checking the airspace of the site location and obtaining the appropriate FAA waiver for sites with airspace other than Class-G. Obtaining mission objectives and the preliminary site investigation details assist with mission planning.

The field tasks during mission flights include equipment inspection, site reconnaissance, informing the nearest air traffic control (ATC) towers (when necessary), setting up signage (where necessary), and flight plan preparation. Quantitative inspection requires the additional task of placing ground points before collecting the data. Often, qualitative inspections are conducted for manual flights, and quantitative inspections are conducted for automated flights.

Post-flight operations include data retrieval procedures and debriefing of the data collection tasks. The retrieved data can be georeferenced, using high precision RTK data, and a quick quality check of the collected imagery can be performed at the field before packing all the equipment. Analysis of the data depends upon its type. For qualitative inspections, the videos collected can be processed to obtain the frames at the desired frequency, and the EXIF data can be processed to overlay the location coordinates on still images. For quantitative inspections, the geotagged image data can be used to process the image alignment, point cloud generation, rendering of mesh & texture, and ortho-rectification. A fully navigable digital elevation model (DEM), in addition to dense point cloud, mesh, and orthomosaics are some of the 3D mapping products that can be obtained. These data outputs are further analyzed to enable sound engineering judgements and 3D printing, as discussed in the sections below.

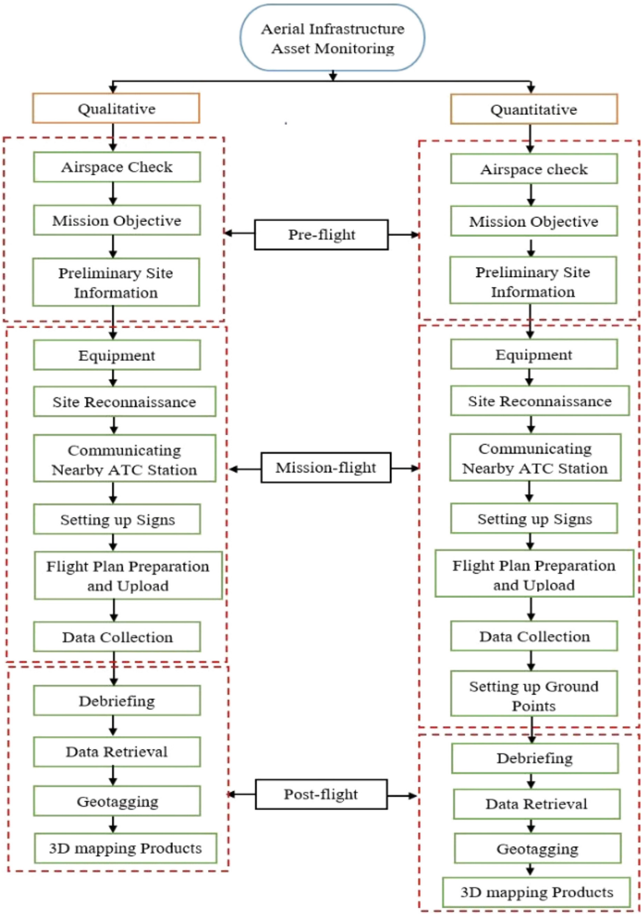


Fig. 2. Steps involved in qualitative and quantitative inspection of infrastructure assets.

4 Infrastructure Data Monitoring, Analysis and Visualization

Civil infrastructure assets can be subjected to both qualitative and quantitative inspections, depending upon the task objectives. Most of the objectives of the inspections are related to engineering performance, including distress patterns and quantification, and fall under the category of geoengineering. The majority of the data provided in this study was collected using a hexacopter, on which a camera with either a top or bottom mount can be installed for inspections.

4.1 Qualitative Inspections

Qualitative inspections of transportation infrastructure assets include the monitoring of pavements, bridges, communication towers, buildings, and other structures either during construction, post construction, or after a natural or manmade disaster events. Video inspections of these assets cover the entire infrastructure and identify critical areas that can be overlooked in traditional visual inspections in the field.

Bridges. Bridges consist of superstructure and substructure elements that need to be monitored regularly to maintain their optimal working condition and maximize their lifespan. Superstructure elements are comprised of bridge decks, approach slabs, railings, and joints. Substructure elements are comprised of beams, soffits, bearings, wing walls, abutments, piles and caps, and others. The under-bridge inspections help in understanding the condition of different bridge elements that are inaccessible or hard-to-reach during currently used traditional inspection methods. The condition of permanent metal deck forms, bearings, and pier caps, shown in Fig. 3, provides information that will be needed for future rehabilitation assessments.

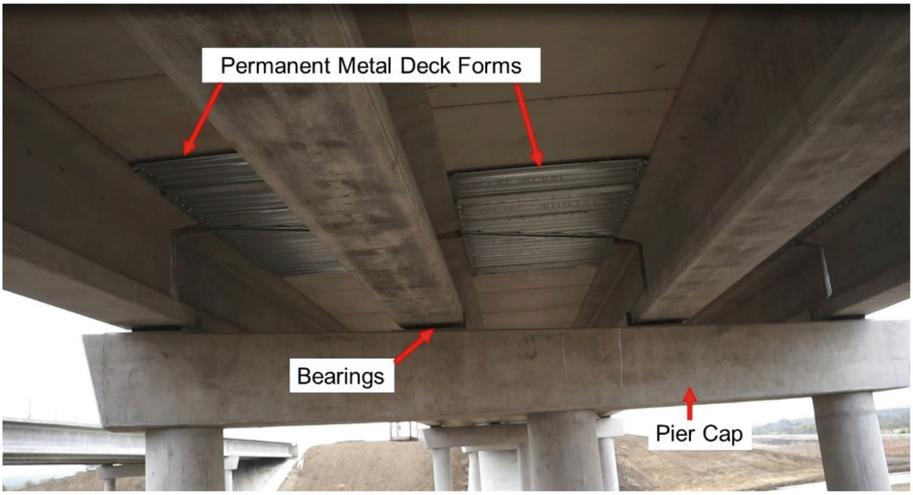


Fig. 3. Under-bridge inspection of a concrete bridge.

Pavements. Disasters are occurring more frequently than in the past, creating the need for tools and equipment that are useful in various disaster management operations. UAVs have the capability of monitoring places that cannot be easily accessed by humans, especially during the time of disasters. Hurricane Harvey struck the state of Texas, USA, in 2017 and inflicted huge damage [27]. Floods inundated the coastal areas, and most of the pavement networks were inundated. Aerial monitoring of pavements during emergencies quickly identifies the damaged sections of roads and assesses the amount of debris piled on the streets, as shown in Fig. 4, enabling decisions as to whether it is feasible for the roads to be open for traffic.

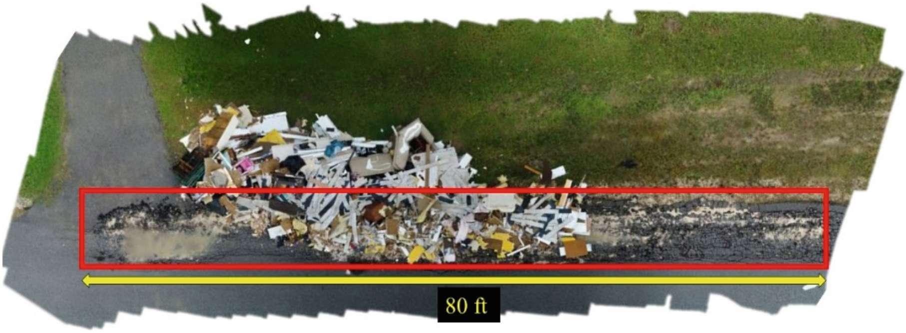


Fig. 4. Identifying cracked region of the pavement after Hurricane Harvey.

Tower Structures. Communication towers play a key role in facilitating the daily tasks of transportation agencies. Aerial inspections of these towers result in time and cost savings and provide safety for the inspectors. A photo of a qualitative tower inspection is provided in Fig. 5. Rust, missing parts, improper alignment, and other features can be easily identified and fixed. Overlaying the aerial images with location coordinates helps in estimating the elevations of the elements located on the tower, as shown in Fig. 5. The location coordinates include latitude, longitude, and the elevation of the image captured above the mean sea level. This helps in effectively managing and maintaining an asset inventory of towers.

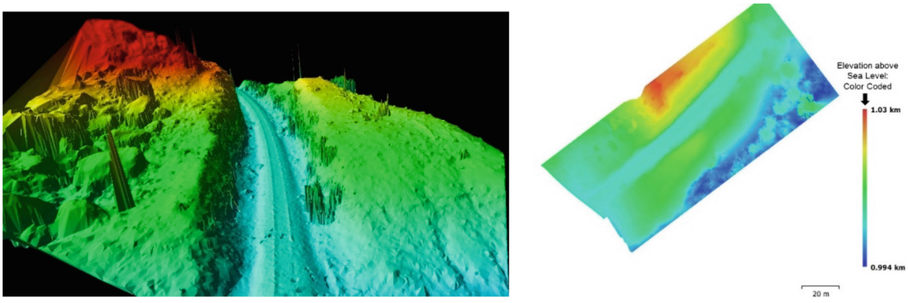
Fig. 5. Tower inspection with location coordinates overlaid on the image.

4.2 Quantitative Inspections

Quantitative inspections provide three-dimensional (3-D) mapping products that help in understanding the condition of the infrastructure and making engineering decisions based on measurements made from the aerial data. In this study, the concept is further extended to provide an innovative way of showcasing the infrastructure condition by 3D printing the 3D models.

Rail Corridor. The collected data can be analyzed using structure from motion (SfM) or stereo mapping. The data collected as part of this study was processed using SfM techniques. The triangulated irregular network (TIN) model and the DEM of the rock cut in Fig. 6 reveal information that is difficult to safely collect using traditional methods within a timeframe similar to that of the aerial platforms. It took 30 min to collect the data of whole rock-cut site, with multiple flight altitudes and camera inclinations to capture the rock walls.

Slope stability information was calculated at three locations on the rock slope. The slopes (presented as tangent of slope angles) connect each of the three points on the sloped region with the point located on the toe of the rock slope are measured as 3.3, 2.0, and 1.7, respectively for a section. This slope information along with the material properties of the rock can be inputted into slope analysis software and used to predict the stability of the slopes. This approach helps in safely providing data of inaccessible areas like steep rock slopes, and also saves money and time.



(a) (b)

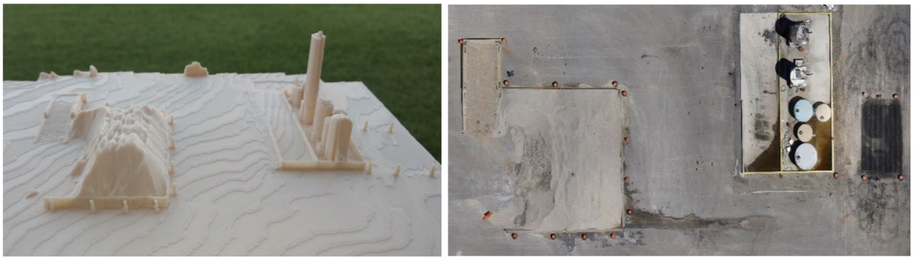
Fig. 6. 3D Mapping products of rock cut: (a) Triangulated irregular network (TIN) model (b) Digital elevation model (DEM).

3D Printing of Models. Infrastructure data collected by the UAV platforms is used to provide in-depth understanding about the condition of the assets. Previous studies explored 3-dimensional visualizations of infrastructure assets, using aerially-collected data [28]. In this study, 3D printed models were generated in addition to the navigable 3D mapping products. Some of the infrastructure data that was 3D printed is shown in Figs. 7, 8, and 9. The 3D printed model of the rail track passing through the rock cut discussed in Fig. 6 is shown in Fig. 7. The 3D printed model and the digital 3D model of the rock cut can be observed in Figs. 7a and b, respectively. The engineers and decision makers were able to get a real field view through the 3D printed models, helped in understanding field conditions that may need proactive maintenance strategies.

(a) (b)

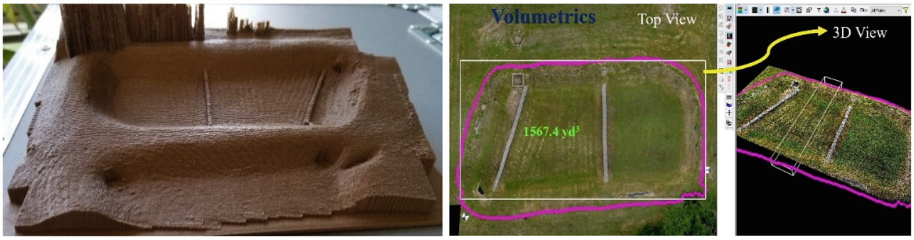
Fig. 7. Rail track passing through a rock cut: (a) 3D printed model (b) 3D photogrammetric model.

Stockpile Volumetrics. Another important application is using UAV data for volumetric assessments. Volumetric information pertaining to the construction material stockpiles and the detention pond sites was extracted and calculated from the aerial data collected from UAV surveys. Figures 8a and b show the 3D printed model and the top view of the stockpiles, respectively. The two stockpiles were delineated, depending upon the texture, and the volume of material in each stockpile was calculated as 614.9 m^3 (804.3 yd^3) of fine sand material and 41.3 m^3 (54.5 yd^3) of coarse sand material. The silos can also be seen in the both the top and the 3D printed views shown in Fig. 8. The 3D printed model and the digital 3D model of a detention pond can be observed in Figs. 9a and b, respectively. Aerial imagery data of the detention pond was also collected and processed to obtain the detention volume of 1198 m^3 (1567 yd^3), as shown in Fig. 9.



(a) (b)

Fig. 8. Construction material stockpile and silos: (a) 3D printed model (b) Top view in orthomosaic.



(a) (b)

Fig. 9. Detention pond: (a) 3D printed model, and (b) 3D Photogrammetric model.

The 3D printed model gives engineers and decision makers a field perspective about the condition of infrastructure assets. In the future, this technology can be further used to print the prefabricated structural elements of an infrastructure, using additive manufacturing, in order to replace a distressed element of the infrastructure asset. One potential application is the design and printing of precast concrete slabs or pavement sections, which can be used to replace distressed pavement sections. Such approach is not far from reality and can be anticipated in the near future.

5 Summary and Conclusions

The holistic approach to infrastructure monitoring and visualization presented in this paper provides comprehensive guidelines on the selection of drones, preparation for field tasks, data collection, and analysis for monitoring the health of infrastructures.

Information provided on drone selection addresses various factors that are key for qualitative and quantitative inspections, such as payload, type of inspection, GNSS, safety features, and flight time. Data collection tasks performed in this research study resulted in quickly identifying the condition of the infrastructure and were especially helpful in accessing the hard-to-reach areas such as under-bridges in a safe manner. Navigable mapping products and the 3D printed models can be produced by analyzing the UAV-CRP data, which will be helpful in understanding the infrastructure health condition.

Additive manufacturing, using 3D printing technology via UAV collected data, can further leverage the shapes and sizes of the structural elements of infrastructure, and help in rectifying/replacing the damaged elements with 3D printed elements, using equal or higher quality material. Challenges that are commonly experienced during aerial data collection in the field are described in the following.

- Weather conditions, such as precipitation, wind gusts, and light conditions affect the aerial data collection procedures.
- The FAA has to approve waivers for sites that fall under airspace other than Class-G; hence, the data collection tasks are delayed.
- A standard unmanned aircraft system traffic management (UTM) system is needed to manage the drone traffic, as UAVs do not possess see-and-avoid capabilities.

- Drones need experienced pilots because they fly under bridge decks without GPS assistance.

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