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## DESIGN AND IMPLEMENTATION OF AN INTEGRATED OPERATIONS AND PRESERVATION PERFORMANCE MONITORING SYSTEM FOR ASSET MANAGEMENT OF MAJOR BRIDGES

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### ABSTRACT

A cross-disciplinary group of researchers at Drexel University, spanning several generations, disciplines and departments, has taken a holistic approach to infrastructure research and education. Specifically, the Drexel research team is exploring the development of a comprehensive maintenance and management plan for movable bridges. This includes the transformation of state of the art inspection protocols that leverage expert knowledge, past events and existing standards, manuals and recommendations. Drexel researchers are also investigating Non-Destructive Evaluation (NDE) strategies and their potential implementation on robotic platforms for automated assessment and evaluation of infrastructures to augment the inspection process. Thanks to the foresight of a regional infrastructure owner in the Greater Philadelphia Area, the described initiatives are allowing the rigorous implementation of technology on real, complex systems. Furthermore, many of these research efforts will be integrated into existing courses at Drexel University where students will be exposed to real life living infrastructures.

**KEYWORDS:** *Bridge maintenance and management, Non-Destructive Evaluation.*

### INTRODUCTION

Civil engineering has long suffered a lag in the adoption of technology and innovation with respect to other engineering fields. The causes are multiple; perhaps the most critical root cause is the lack of knowledge regarding how actual constructed systems perform. These systems need to be designed, constructed, operated and managed – over their centuries-long lifecycles. Constructed systems that are embedded in rock, soil and/or water are subjected to a great variety of operational and structural demands at multiple time and geometric scales – corrosion, deformations, and damage at the micro-macroscopic levels are characteristic examples.

Societal concerns motivated a significant investment into infrastructure and bridge technology research, development and demonstrations by federal and state governments in the US and abroad in the last few decades. There is a need for objective and mechanistic approaches to bridge evaluation, maintenance, and repair. Although there are many aspiring technology providers, there have been a few applications providing insight, knowledge and actionable recommendations to the satisfaction of a bridge owner. Fujino at the 6th ISMII Conference articulated this fact forcefully.

A cross-disciplinary group of researchers at Drexel University, spanning several generations, disciplines and departments, has taken a holistic approach to infrastructure research and education. They are leveraging real operating landmark infrastructures in the Greater Philadelphia Area as field laboratories to observe and learn before they explore and introduce state of the art technology for

asset management. This multifaceted effort begins by recognizing that these assets need to be treated as Complex, Large-Scale, Interconnected, Open Socio-Technical (CLIOS) Systems [1]. The knowledge and interests of all the major organizational and institutional elements (bridge owners, users-stakeholders, decision makers, etc.) of the system, and their interactions with the physical system (bridges, roads and other infrastructure elements within their influence area), need to be incorporated in asset management as multiple objectives with constraints. Drexel researchers have first examined and defined the subsystems/parts of the studied assets, and are now investigating the system to include all the critical elements needed for its indefinite preservation. Some of the key elements of this system, a major toll-infrastructure, are a Maintenance and Management (MM) system, an Inspection and Information Management (IIM) system, a Capital Planning and Management system (CPM), a Security system, a Central Information Repository system (CIR) and a Performance and Health Monitoring system (PHMS). Drexel researchers, in collaboration with the infrastructure owners and industry partners, are currently working on the IIM, the CIR and the PHMS modules.

One of the present goals is to explore the development of a comprehensive maintenance and management plan for movable bridges. This includes the transformation of state of the art inspection protocols that leverage expert knowledge, past events and existing standards, manuals and recommendations.

Simultaneously, the Drexel research team is beginning to create a software platform to integrate the massive amount of text, images and information collected from multiple data streams into one searchable, flexible, and expandable database. This is an urgently needed foundation for an efficient bridge management system.

Finally, Non-Destructive Evaluation strategies are being investigated and their potential implementation on robotic platforms for automated assessment and evaluation of infrastructures to augment the inspection process. Thanks to the foresight of the infrastructure owner, the described initiatives are allowing the effective implementation of technology on real complex systems. Many of these research efforts will be integrated into existing courses at Drexel University where students will be exposed to real life living infrastructures.

## 1 ASSET MANAGEMENT

Asset management is a concept that provides the framework towards a more efficient model of managing infrastructure networks and their components. A recent National Cooperative Highway Research Program (NCHRP) report defines transportation asset management as “a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their life cycles. It focuses on the business and engineering practice for resource allocation and utilization, with the objective of better decision making based on quality information and well-defined objectives” [2]. A few simple questions are proposed to help understand what the current level of management of an agency. Many agencies should be able to answer these questions accurately and in a timely fashion. These questions are:

- What is the current state of the assets?
- What is the current level of service that the assets are providing?
- What are the critical assets?
- What strategies are in place to minimize the life cycle cost?
- What is the long-term funding plan?

An agency faces many challenges when trying to adopt a new way of thinking about management. In most cases agencies are political entities. This means that the decisions made are not always aligned with the long term preservation plan. Such decisions tend to be short sighted, by the need to save money while neglecting the complete life-cycle of the project.

Aging landmark structures have the benefit of being designed during a period of master designers, when the structures were not intended for a limited 50 year life span. An indefinite life cycle is only achievable with proper maintenance and care. The level of care and desired

performance of the structure must be part of a comprehensive asset management plan. Preventive maintenance is a large contributing factor to reducing the life-cycle cost of a bridge by prolonging its useful service life. Managers who take a proactive approach in the preservation of their inventory can see huge rewards from adopting this approach [3]. However, these rewards are often hidden by the reduction of bridge components that need major rehabilitation or frequent repairs [4].

An aged structure can present unique problems. The original shape and the use of built up members often do not permit easy access for inspection. It is often very costly to retro-fit access walkways and ladders needed for a safe and thorough inspection of the bridge. Furthermore, after an inspection, elements that exhibit excessive wear are identified for repair or replacement. On the aged structure many of these parts are not standard or have become obsolete. If the management does not have a replacement plan, it can be very costly to find and source these parts.

On movable bridges these problems are exacerbated since these structures are made up of unique parts and mechanical configurations that require a high level of expertise for proper preservation. If mechanical systems are not taken care of, deterioration can lead to the systems to self-destruction due to misalignments and vibrations. Agencies tend to retain a few experts, engineers and practitioners that are fundamental in keeping the structure in a state of good repair, but this also poses a unique risk to the agency. These experts are the sole carriers of invaluable resources and information that will be lost with their retirement. It is crucial that an agency takes steps to transfer this institutional knowledge to junior members, by documenting the processes that have been developed over decades of operations.

The adoption of a comprehensive asset management plan should be developed by a multidisciplinary team comprised of both technical and policy experts. This team needs to agree upon the long term goals for the agency. There are requirements from all levels of government from federal, state, and local regulations that must be met. These come in the form of inspection requirements, bidding processes, environmental protection, etc. To help facilitate the meeting of these requirements it is customary to define metrics to help track the performance of the agency.

Data collection is a large part in an asset management plan. Good data can provide valuable information about the current conditions of an inventory. It also helps to identify which elements are in distress and the new elemental level data requires hazards to be associated to a particular element rather than simply a smart flag applied to an entire structure. An agency should align its data collection process with its long term goals. Establishing quality data collection standards can help to avoid error and quickly bring meaningful information to the decision process. The scope and depth of the collection process has an effect on how an inventory is managed. The more data that is collected, the more time and effort is required to ensure that the information that is gathered is accurate, but the benefits can be seen in more effective planning and allocation of resources. Depending on the scope such data collection can include element level conditions, major and minor events, resources required per activity, maintenance activities quality and frequencies, and performance and health monitoring sensing data, amongst many others.

Asset management is a flexible framework that can be facilitated with tools, strategies, and personnel to align an agency with its long term goals. Institutional knowledge should be seen as a limited resource which should be captured and documented for the next generation of bridge workers. For aged structures and particularly movable structures, the proper care and preventative maintenance must be established to continue to provide an acceptable level of performance.

Drexel University has a unique opportunity to be directly exposed to the challenges of managing and preserving for an indefinite amount of time a cluster of movable landmark structures thanks to the partnership between the university, industry and a local bridge owner. This paper covers only a limited set of experiences Drexel researchers have been exposed to. This study shows how technology is being explored to enhance infrastructure management. For instance, the paper shows how the exponentially increasing mass of data necessary to manage aging structures could be effectively retrieved and efficiently shared with all the stakeholders involved in the maintenance

process. Furthermore, the deployment of emerging technology for the non-destructive inspection of the infrastructure is discussed.

## 2 ELECTRONIC ARCHIVE (E-ARCHIVE)

An integral part of the bridge management is represented by the Central Information Repository (CIR). This component is critical in providing the needed, accurate information that allows the proper decision making process. An ideal CIR should be formed by a Bridge Information Model (BrIM), a three dimensional model that can include multi-faceted information of the bridge easily accessible by the many users involved in the maintenance of the structure. This module allows access to information. Such information is stored in an electronic archive (E-archive) that, for a century old landmark structure, includes technical original design blueprints, modern Cad drawings, text documents, high resolution photos, inspection reports, etc. Unless a rigorous archiving protocol is defined and properly applied by the entire personnel involved with the bridge, the entropy associated with the data progressively increases to the point of no return.

Drexel researchers are currently developing a document retrieval and searching algorithm that is similar in many aspects to popular search algorithms used in many different industries. A screen shot of a recently developed Graphical User Interface of such software is shown in Figure 1.

The algorithm searches key words within all the documents included within a complex, unstructured archive. The keyword and predefined synonyms are sought inside each individual files (pdf, word, emails, cad) as well as in the metadata associated with the files (including images). The user can restrict the search by selecting date range, looking only within the title or the file name, limiting the search to a specific file type, or excluding files with words that are unwanted.

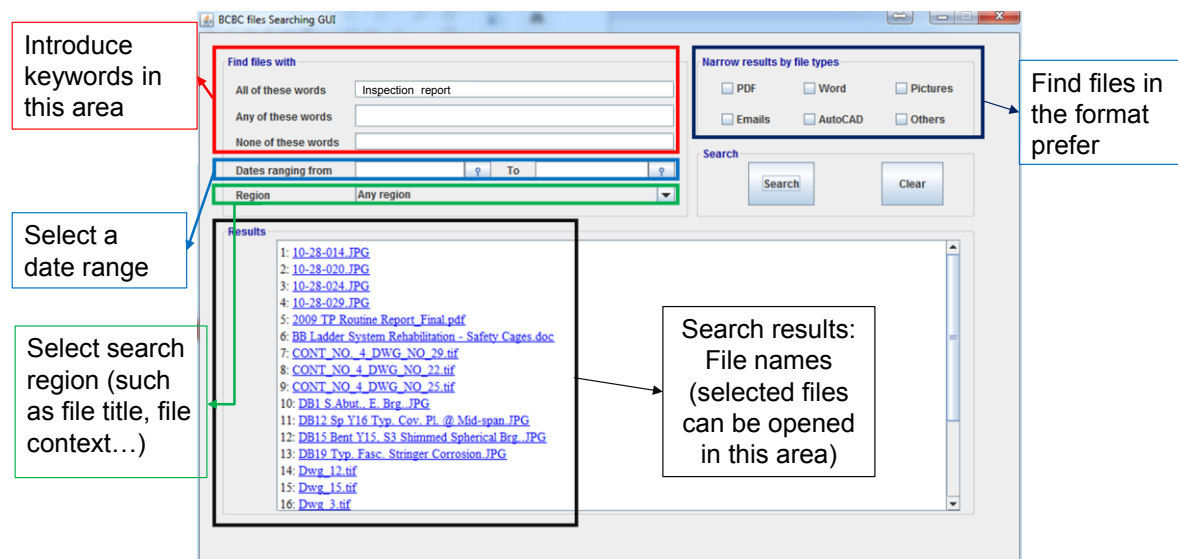


Figure 1: E-Archive - Search Interface

The preliminary interface shown in Figure 1 is currently being enhanced including features that are common in commercial search engines. Auto completion of the searched keywords, highlighting of the search items, and sorting according to predefined queries are a few of the necessary functionalities that will be added to the searching algorithm to effectively enhance the bridge maintenance. In the process of developing such a tool, feedback from professionals involved daily in the preservation of the structure is essential. A successful E-archive has to be designed to be included in emerging devices that will be soon available to bridge engineers, inspectors, and personnel. For instance, google glasses are now being distributed to an increasingly broad group of users. This powerful portable computing device could leverage a properly implemented searching

algorithm allowing a bridge inspector in the process of inspecting a girder located 100 feet from the ground to visualize an old inspection report.

### 3 NEXT GENERATION INSPECTION TOOLS

The partnership between Drexel University, local industry and bridge owners has offered the chance to implement selected non-destructive inspection methodologies on a long span bridge located in the Greater Philadelphia area.

A group of researchers performed a set of tests to:

- Evaluate the potential of Infrared Thermography for the assessment of the condition of the complex bridge decks;
- Guide the selection of regions of interest for the coring of the bridge deck based on the inspection results provided by Infrared scanning;
- Provide recommendations about the future Non-Destructive-Evaluation of the bridge deck through the use of infrared as well as other techniques such as Impact Echo.

In this document the protocol used during testing is described.

Coring locations have been selected based on Infrared Scanning to discover potential delaminations not visible at the surface through high resolution visual cameras. Infrared has also proven to enhance the visualization of asphalt cracks induced by the distress often associated to defects in the deck.

The goal of the test was to assess the condition of the deck using Infrared Thermography (IR). The test was conducted according to American Society for Testing and Materials (ASTM D4788-03) “Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography”. The bridge was inspected at the beginning of the summer from 1030am to 2pm.

The weather conditions were not ideal for IR inspection. ASTM D4788-03 suggests that the deck should be dry for at least 24 hours prior testing. Given the uncertain weather conditions experienced in the region during the month of June and given scheduling issues, the test was performed 15-16 hours after a significant rainfall. 0.32in of rain were reported in the region on June 24th. Wind speed remained within 10mph for the duration of the entire test. ASTM standards recommend maximum wind speeds not exceeding 30mph.

Partially sunny conditions were experienced during the deck evaluation. The tests used an imaging infrared (IR) scanner and standard video RGB cameras mounted on a vehicle to detect delamination and debonded regions on the bridge deck (Figure 2). The RGB camera 1 was mounted near the IR camera but, given its larger field of view, it recorded images covering the entire lane.

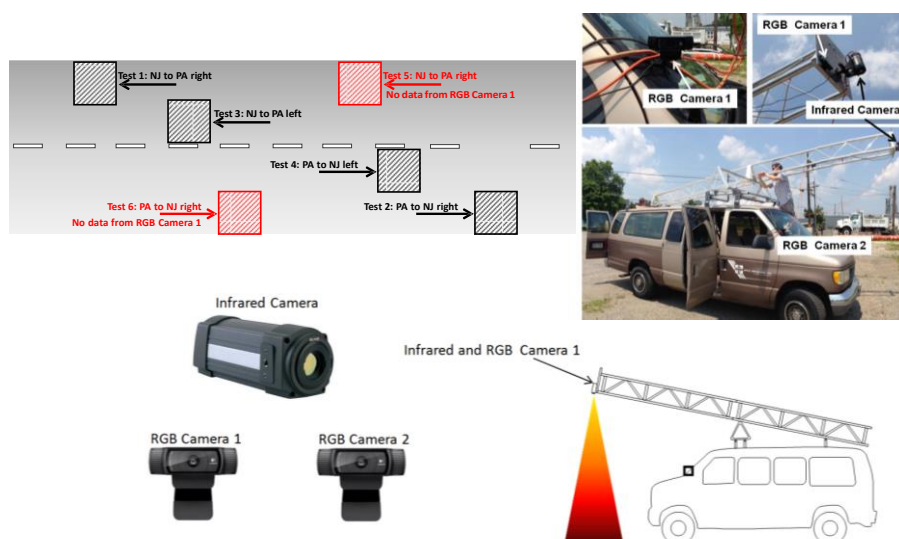


Figure 2: IR and RGB Sensors location used for deck inspection.



### 3.1 IR Delamination Detection

Infrared images collected on the bridge deck show hot regions on cooler backgrounds at delaminations if the test is performed during daytime. Conversely, during night time testing, the delaminations will appear as cooler areas on a warmer background. The conventional video images (RGB images) were used to interpret infrared images separating patches or surface defects that may result in hot areas and not representing delaminations. Furthermore, elements from the superstructure can generate shadows on the bridge deck resulting on cold spots. This can make data interpretation relatively difficult.

### 3.2 Observations

The IR method provides a quick method to assess the overall conditions of the bridge deck. However, the following set of recommendations should be considered:

- Perform the test multiple times to verify that hot/cold spots are not a consequence of experimental variability or environmental conditions;
- Repeat the test 3-6 hours after sunset when shades from complex superstructure elements will not affect the thermal images. Furthermore, regions with high temperatures observed during the day should become cold spot overnight, providing a confirmation of delamination;
- Perform the test at least 24 hours after rain events since water and humidity might decrease the thermal gradients necessary to observe delaminations;
- Use infrared at low speeds and confirm with other NDE such as Impact Echo approach before coring is executed.

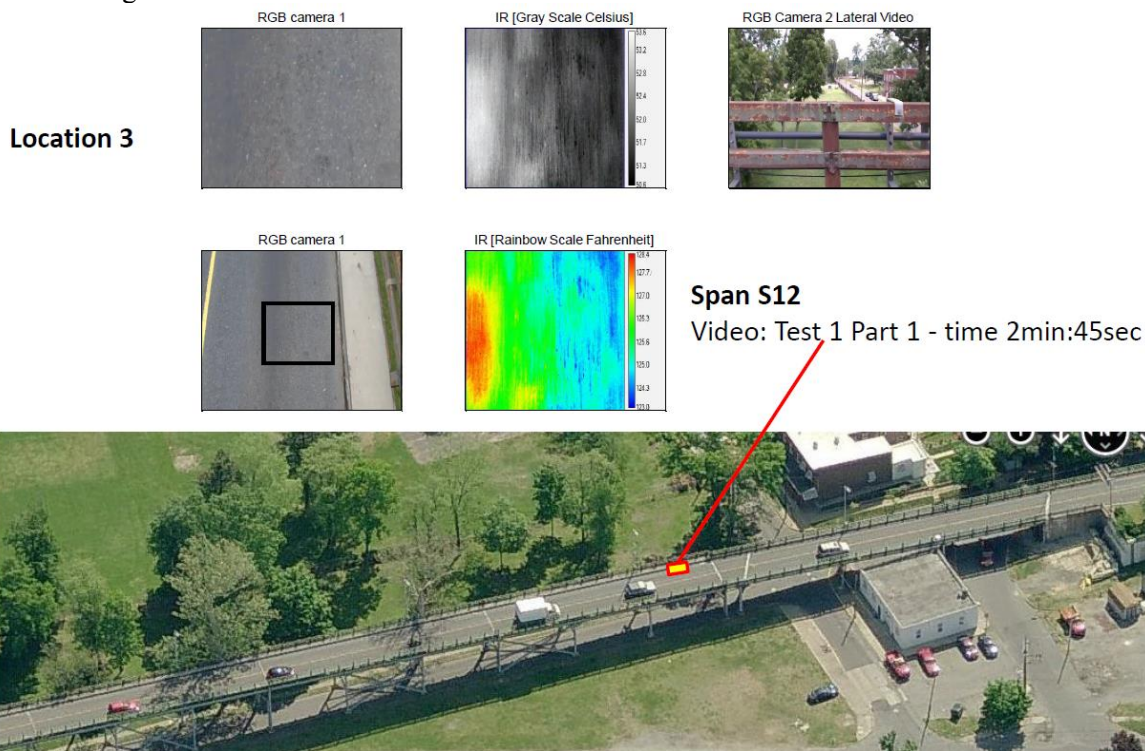


Figure 3: Region of interest with potential delamination according to IR scanning of bridge deck.

### 3.3 IR Results

A sample of the results obtained with the IR inspection are shown in the following. For each location the following information was provided:

- A RGB video matching the field of view (FOV) of the Infrared FOW;
- A RGB video of the entire region covered with the RGB camera 1;

- An Infrared image in grey scale and with temperature in Celsius;
- An Infrared image in rainbow scale and with temperature in Fahrenheit;
- An RGB video from a second RGB camera providing the location along the bridge of the region being scanned;
- A location of the regions with potential delaminations detected using IR shown on aerial image of the Bridge.

Figure 3 shows a region of interest with potential delamination.

### 3.4 Aerial Imaging of bridges with manned vehicles

The U.S. currently spends more than a billion dollars annually to inspect run-of-the-mill bridges and collect subjective, qualitative data that has proved unreliable and largely irrelevant [5]. Inspection also requires adequate access to remote locations, for e.g. snoopers, rope-access and other protective equipment, which might increase the associated personal safety risk and add costs. In this context, a paradigm-shifting monitoring strategy is envisioned, which is capable of not only preventing catastrophic failures, but also reliably flagging signs of early deterioration, and providing the type of quantitative data required to underpin life-cycle cost and performance models for asset management. In the near future, domestic applications of Unmanned Aerial Systems have the potential to transform the civil engineering industry. Use of unmanned vehicles is currently experiencing a tremendous growth primarily in military and homeland security applications. However, it is only a matter of time until UAS will be widely accepted as platforms for implementing monitoring and inspection procedures potentially impacting the inspection of civil infrastructures.

A proof of concept test was performed by the Drexel team leveraging a manned helicopter to acquire multispectral images (RGB and Infrared). This test resulted in a better understanding of what is required in such field measurements, as well as the associated challenges to overcome when flying a UAS. The helicopter used for inspection had a payload that consisted of high resolution visual and IR camera. The three major spans of the structure were scanned in less than 20 minutes flying at a minimum distance of 100-150 feet from the structure (Figure 4). Images were collected from the sides and from the top of the bridge. Representative selected images of the bridge, specifically samples of the RGB and infrared images obtained from the test, are shown in Figure 4-d. This test showed that even with experienced pilots, it can be difficult to keep a fixed distance from a structure using a helicopter. This type of test, however, could be easier with an UAS because of the constant feedback received from GPS. Specifically, a flight path could be planned before the flight and continuous GPS feedback could keep the drone within defined distance from the target structure. The speed to cover the path can also be predetermined allowing pictures collection at regular intervals along the structure.

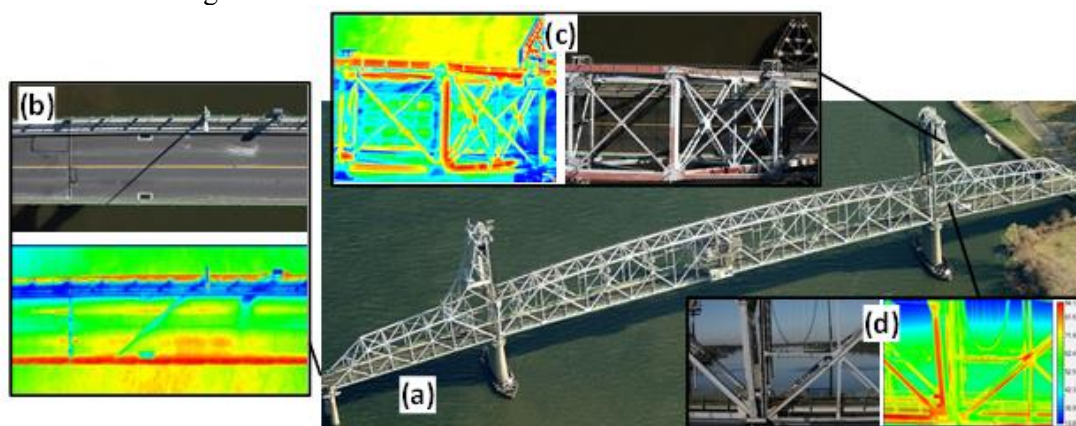


Figure 4: Multispectral (IR and RGB) aerial imaging of large infrastructure; (a) Bridge inspected; IR and high resolution images from (b, c) the top, and from (d) the side.



A second scenario considered during the helicopter flight tested the possibility to rapidly map the entire scanned bridge with high resolution images. Figure 5 (top) shows the entire bottom cord of the inspected bridge completely scanned with high resolution pictures that were stitched together. In the same figure (bottom), progressive zooms (marked with red boxes and arrows) on regions of interest show the detail that can be captured by high resolution imaging. Images with high resolution collected periodically, could be analyzed using computer vision algorithms that have the potential to automatically flag signs of deterioration without the need for personnel to closely inspect the structure.

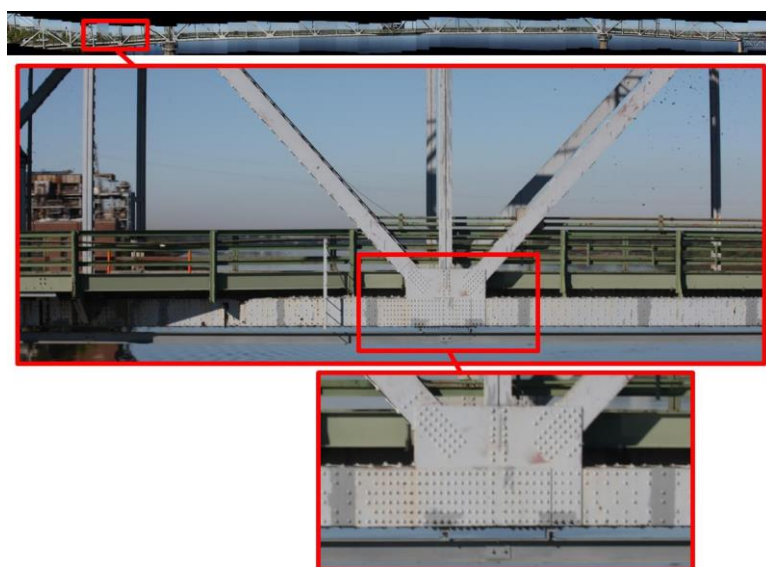


Figure 5: High resolution aerial imaging of the inspected Bridge collected by a manned helicopter to show potential for rapid damage assessment.

## CONCLUSION

This paper shows the research that is currently being performed at Drexel University that focus on the management of landmark aging assets in the Philadelphia region. The challenges of this research include recognizing the complexity of the assets to manage that could be represented completely only once their Complex, Large-Scale, Interconnected, Open Socio-Technical nature is understood. Drexel researchers are currently investigating different technology tools to help local bridge owners in the management of their infrastructure. The efforts include application of NDE methods for infrastructure assessment, aerial imaging for rapid bridge inspection, development of dedicated software for the automated search of documents in the existing unstructured archives associated to historic structures.

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