Potential Structural Health Monitoring Tools to Mitigate Corruption in the Construction Industry Associated with Rapid Urbanization

Yongchao Yang, Alessandro Cattaneo, David Mascareñas

Significant investments have been made in infrastructure health monitoring research over the course of the last two decades. In the United States and Western Europe this research has primarily been motivated by the need to monitor the state of aging infrastructure. One issue with this philosophy is that it completely ignores the infrastructure health monitoring challenges associated with the developing world where the majority of urbanization is expected to occur over the next 35 years. The UN projects that 2.5 billion additional people will live in cities by 2050, and 90% of the increase will occur in Asia and Africa. 37% of this growth is expected to occur in India, China and Nigeria. The infrastructure development challenges in these countries are significantly different than those encountered in the United States and Western Europe. For one, these countries suffer from high levels of corruption. The result is that cities in these regions can contain tens of thousands of illegally and poorly constructed buildings erected by unscrupulous contractors. In many cases contractors have used substandard construction practices such as not adequately washing aggregate before placing it in concrete, or substituting bamboo for rebar in concrete, or filling concrete with refuse in place of aggregate. Structures often collapse during construction, shortly after being in service, or in the face of severe weather and natural disasters. In other cases significant loss of life has occurred when unscrupulous business owners have compelled employees to perform work in structures known to be unsafe and being used for unintended activities. This was the case with the 8 story Rana Plaza garment-factory collapse in Bangladesh in 2013.

The work has generally followed the paradigm of instrumenting a structure with a wireless sensor network, collecting data from the structure and then applying statistical classification techniques to infer the presence and characteristics of damage in the structure. The wireless sensor network-based paradigm of infrastructure health monitoring for instance, has many challenges including supplying energy to sensor nodes, communication bandwidth, and the high-costs associated with installation. These problems are only going to be exacerbated when proposing infrastructure management solutions for the developing world. Furthermore, it is doubtful the energy challenge associated with long-term deployment of these measurement systems will be solved by new battery technology or energy harvesting on the timescale associated with rapid urbanization. If the infrastructure health monitoring community is going to have a global impact we need to invest in research that facilitates monitoring and construction verification in an agile, low-cost fashion that goes beyond the individual structure scale to the city-scale. This work will present a number of novel, cross-disciplinary approaches to the infrastructure health monitoring problem we are currently exploring, including imager-based techniques for structural assessment on the city scale, taking aerial robotic structural inspection beyond imaging, remotely-readable tamper-evident seals, and haptic interfaces for infrastructure monitoring. The goal of this work is introduce the sustainable development community to the research done by the structural health monitoring community that may help reduce corruption encountered during development activities.
1. Introduction

The goal of this work is to provide a summary of emerging structural health monitoring technologies that could potentially be used to mitigate corruption in the construction industry across the developing world. Examples of construction industry corruption-related problems that may be possible to address include challenges associated with verifying the quality of new construction in a manner that is difficult to influence via bribery. In cities experiencing rapid urbanization, multi-story buildings are occasionally erected in an ad-hoc manner. A construction crew will arrive at a site they do not necessarily own or have legal access to, and then quickly erect a building, while living on the construction site itself during the construction process. These buildings are erected without regard for building codes. The result is that the buildings are often built with substandard materials and building practices. In some cases an existing building may be illegally modified so it can be reused for purposes that exceed its intended design capabilities. A good example of this is the installation of generators at Rana plaza to convert it from retail store use to a garment factory. The installation of these generators added unintended weight to the structure, and also introduced dynamic loads.

By introducing structural health monitoring technology to the sustainable development community we hope to start a conversation that leads towards the development of technologies that can help combat corruption in the construction industry. These technologies could potentially be used to verify the quality of construction, detect and characterize illegal/unsafe construction, and prevent substandard materials from being used in construction.

2. Image/video based city-scale infrastructure health monitoring

2.1. Video based vibration measurement and dynamic analysis

Rapid urbanization propels fast construction of infrastructure, which might be at high risk of failure (especially under natural and man-made hazards) due to the substandard construction quality in the developing countries. Monitoring their operational performance therefore becomes critical. One of the most established approaches for condition assessment of structures is to through monitoring and evaluating their dynamic properties, which are essentially characterized by their modal parameters. This is based on the widely accepted premise that change of the structure, which may be due to damage or modification, will cause the variation of the modal parameters [1]. Current modal analysis of structures generally depends on physical wired or wireless sensors. However, physical instrumentation of a set of accelerometers on the structure is an expensive and time and labor consuming process [2]. In addition, if a wireless sensor network is used, there are challenges associated with their available bandwidth and energy supply. Non-contact or remote sensing techniques are potential to address some of these issues [3]. Among others, laser vibrometer systems have been successfully applied to experimental modal analysis. However, they are relatively expensive and time-consuming for the testing process. It is most desirable to seek a low-cost, efficient, and reliable approach for dynamic analysis and condition assessment of infrastructure in the city-scale.

As an alternative, video cameras are ubiquitous, low-cost, and non-contact sensors that offer very high spatial resolution and reasonable temporal resolution sensing capability. By tracking
the motion encoded in the videos, it is feasible to develop video based dynamic measurement and vibration analysis technique that are suitable for condition assessment of infrastructure. Interest in these techniques has been inspired by recent breakthroughs in Eulerian video magnification [Hao-Yu Wu].

This section presents our work toward developing a cost-effective and easy-to-deploy method of remote operational modal analysis using the video camera as the sole means of data collection (Figure 1) and advanced computer vision algorithms in an automated manner requiring minimal user input. The video measurement of the structure is first processed by the optical flow method to extract the structural displacements (Figure 2(a)). They are then used as inputs into an automated operational modal analysis method to extract the modal coordinates (Figure 2(c)), thus obtaining the frequency and mode shapes of the structure (Figure 3). The results of laboratory experiments on a 3-story structure show that the video based modal analysis method are comparably accurate with those using traditional wired accelerometers (Table 1).

The developed video based modal analysis technique has the potential to efficiently monitor and evaluate the time-variant structural dynamic properties due to structural modification. An experiment was conducted where the pristine structure was modified by adding mass, eliminating a column, and adding a column (Figure 4). The video based method was able to rapidly detect the frequency change of the modified structures (Table 2), which could serve as informative signs of the illegal structural modification due to construction corruption.

This presented method may prove useful for structures experiencing damage or modification. In the developing countries, construction regulations are often ignored, which may lead to modal properties that do not match the expected dynamic output of the structure. Also, many infrastructure failures occur during construction when the structure is severely loaded and/or modified. The extreme loading of construction equipment may be enough to alter modal properties such that this method could detect the changes.

![Figure 1. The experimental setup of the video based modal analysis method.](image)
Figure 2. (a) The velocity of the three story structure estimated by the optical flow algorithm from the video measurements and (b) their Fourier transform. (c) The modal coordinates extracted by an automated modal identification method and (d) their Fourier transform.

Table 1. Identified modal parameters from the video measurements compared to from accelerometers

<table>
<thead>
<tr>
<th>Mode</th>
<th>Accelerometer</th>
<th>Video</th>
<th>Difference</th>
<th>Modal assurance criteria (MAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.26</td>
<td>6.34</td>
<td>1.33%</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>17.81</td>
<td>17.83</td>
<td>0.11%</td>
<td>0.92</td>
</tr>
<tr>
<td>3</td>
<td>25.81</td>
<td>25.89</td>
<td>0.31%</td>
<td>0.95</td>
</tr>
</tbody>
</table>
Figure 3. The identified mode shapes of the structure from the video measurements. (From the left to right are mode 1, mode 2, and mode 3, respectively. Videos are available for better visualization.)

Figure 4. (a) The pristine structure (27.56 kg). (b) The structure with added mass (2.24 kg) on the top floor. (c) The structure with a missing column on the left of the second floor. (d) The structure with double columns on the left of the second floor.

Table 2. Frequencies of the modified structures identified by the video based modal analysis method.

<table>
<thead>
<tr>
<th></th>
<th>Mode 1</th>
<th></th>
<th>Mode 2</th>
<th></th>
<th>Mode 3</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. (Hz)</td>
<td>Change</td>
<td>Freq. (Hz)</td>
<td>Change</td>
<td>Freq. (Hz)</td>
<td>Change</td>
</tr>
<tr>
<td>Pristine</td>
<td>6.34</td>
<td>-</td>
<td>17.96</td>
<td>-</td>
<td>25.89</td>
<td>-</td>
</tr>
<tr>
<td>Added mass</td>
<td>5.81</td>
<td>8.36%</td>
<td>17.04</td>
<td>5.12%</td>
<td>25.49</td>
<td>1.54%</td>
</tr>
<tr>
<td>(2.24 kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missing column</td>
<td>5.94</td>
<td>6.31%</td>
<td>17.44</td>
<td>2.90%</td>
<td>24.04</td>
<td>7.15%</td>
</tr>
<tr>
<td>Double columns</td>
<td>7.00</td>
<td>10.41%</td>
<td>18.49</td>
<td>2.95%</td>
<td>35.27</td>
<td>36.23%</td>
</tr>
</tbody>
</table>
2.2. Automated computer vision based damage detection scheme

In addition to providing a low-cost and rapid-to-deploy remote sensing solution for global structural dynamic measurement and analysis, video cameras can also serve as an alternative tool to facilitate local structural assessment. If mounted at appropriate positions, video cameras can continuously image (“film”) critical structural components such as bridge joints and anchored stay cables. In the case of the illegally and poorly constructed infrastructure which is subject to high risk of collapse and failure, video based structural health monitoring system with automated computer vision technique has potential to provide early warning and timely feedback of the structural condition, thus potentially having immense impact of life safety and economic benefit. It is also possible that this technology could be used to verify that construction of infrastructure has been executed in an appropriate manner with the specified building materials.

We have proposed the development of an automated computer vision system (“dynamic imaging”) (Figure 5) that could continuously image of the structure and perform video processing for damage detection by exploiting the fundamental data structure of the high-rate multiple images (video stream) [3]. The key component of the computer vision system with autonomous damage detection capability is an algorithm that is able to decompose the multiple frames into a superposition of a low-rank background component and a sparse innovation (dynamic) component. The low-rank component contains the irrelevant temporally correlated background of the multiple frames, whereas the sparse innovation component indicates the damage-induced information. Laboratory experiments were conducted on concrete structures and as part of the results, Figure 6 shows the success of the established approach of decomposing the original structural video into a background component and sparse component for indicating the damage evolution.

Figure 5. The dynamic imaging paradigm for damage detection. A structure is continuously imaged. Each image of the structure is thought of (and blindly decomposed into) as a superposition of a background (pristine) component and a sparse innovative component (if any damage).
3. **Vibro-haptic human-machine interface for SHM**

Although an automated computer vision system is most desirable for early warning and timely detection of infrastructure damage or modification due to construction corruption, in many cases expert judgment is superior to automated structural damage or modification classification. This is especially true when sudden damage occurs, such as the Rana Plaza garment-factory collapse in Bangladesh in 2013, in which case human judgment could easily signify the advent of potential structural failure [J. Yardley].

This section introduces a new paradigm to facilitate the warning and detection of infrastructure damage. We propose interfacing the human nervous system to the distributed sensor network located on the structure and developing new techniques to enable human-machine cooperation [4]. Results from the field of sensor substitution suggest this should be possible. Sensor substitution is a process by which a human can partially regain the use of a lost sense using a different sense as a surrogate. The plasticity of the human brain allows the human to interpret the stimuli to the alternative sense as coming from the original sense that was lost. Recent advances in smart structures and haptic technology have enabled a wide range of new human-machine interfaces to facilitate sensory substitution. Examples of these interfaces include force feedback for robotic applications, refreshable Braille displays, and prosthesis devices. Thus far, haptic devices have mainly been limited to physical applications. It is possible that haptic devices may allow humans a new interface to interact with abstract entities such as the data from a wireless sensor network, the topography of a high dimensional cost function, or the structural health of a wind farm. This section presents a vibro-haptic human-machine interface for SHM.
A glove equipped with vibratory motors was used as a haptic interface to communicate structural integrity with a human subject (Figure 7(a)). In order to verify that the vibro-tactile interface has potential to benefit the structural health monitoring community, a preliminary human subject experiment was conducted and a simple three-story structure is chosen as a test platform (Figure 7(b)). An experimental protocol was finalized by the team and subsequently approved by the Los Alamos National Laboratory Human Subjects Research Review Board (HSRRB). As a first step in testing a human’s ability to detect damage with the vibro-tactile interface, a training procedure was developed. The results for a study conducted with seven human subjects are displayed in Figure [8]. This preliminary study shows that a human can differentiate building health states by adapting to this new “sense”.

Such a vibro-tactile feedback system and a symbiotic relationship between a human and machine could complement an automated structural health monitoring system, improving the accuracy and reliability of identification and classification of damage.
4. A multirotor-based approach for tap-testing difficult-to-access structures

While automated computer vision system associated with a human machine interface system shows tremendous promise for condition assessment and damage detection of urban infrastructure, the implementation of such a system in the city scale may not be realized in the imminent future. The prevailing structural assessment approach remains traditional human visual inspection. One of the major challenges and costs associated with human-based visual inspections is that structures are often difficult to access. They may be located high above waterways, thus requiring that an expensive crane or barge be rented to provide the inspectors a platform from which to conduct their inspection. In some cases inspectors may even need to rappel down the side of a structure in order to gain access, thus introducing additional safety concerns.

Some research has been done to address these concerns by using emerging multirotor technology to facilitate visual structural inspections. Multirotors have shown great potential for maintaining state awareness of structures and construction sites, but one issue is that visual inspection is often hampered by mud, corrosion, vegetation, and other debris on the structure. A proper visual inspection often requires that this debris be removed. This limits the effectiveness of current multi-rotor based visual inspection technology. Furthermore, it is not uncommon for structural inspectors to enhance the quality of their inspection by using a conventional hammer to tap-test the structure of interest. The inspector will simply strike the structure and listen for differences in acoustic response that might indicate the presence of damage in structure. In this work we begin exploring the utility of adding a remotely operated hammer to a multi-rotor vehicle that can be used to facilitate structural inspections [5]. The system features acoustic microphones and accelerometers that can be used to quantifiably document the results of the tap test (Figure 9 and 10).

Perhaps more importantly though, this paradigm involves transmitting the acoustic response directly a remote structural inspector through earphones. The remote structural inspector can then use their expert judgment to select locations to perform additional tap tests. Furthermore, the pneumatic hammer could also be used to remove debris and corrosion from the structure in order to enhance visual inspection. The results of experimental tests have begun to explore the effects of the hammer impulse on the acoustic response of a structure[5].
5. Tamper evident seal

Tamper evident seals are devices conceived to easily recognize unauthorized access to a protected article. A seal is not designed to offer physical security; instead, its mission consists of providing non-erasable traces as proof of penetration [Johnson]. Tamper evident seals are commonly used by the government and industry to reveal unauthorized access/usage has occurred. Tamper-evident seals could play a role in mitigating corruption in the construction industry by providing evidence that a package or container has been opened containing sensitive construction materials. For instance, these seals could be placed on shipping containers to provide evidence that someone has opened the container and perhaps swapped expensive construction materials for sub-standard, low-cost materials. Furthermore, tamper-evident seals must be verifiably unique. They must essentially have their own, “fingerprint,” which cannot be easily copied. For this reason tamper-evident seals could be used to ensure that a container filled with construction supplies are the actual supplies sent from a specific point of origin and have not been tampered with during transit.

The tamper evident seal presented in this work aims to offer advantages over conventional seals in terms of the required breach-inspection resources and the potential difficulty associated with their defeat. One major problem with conventional tamper-evident seals is that they require an inspector to physically interact with each seal. In many industrial and treaty-verification applications this is not practical because of the large number of tamper-evident seals in use. We have developed a tamper-evident seal that can be interrogated remotely in a manner similar to a Radio Frequency Identification (RFID) tag. By allowing remote interrogation the number of seals an inspector can interrogate can increase significantly. The remotely readable seal is enabled by combining the strengths of the signal processing technique known as compressive sampling (CS)4–7 and the tamper-sensitive electrical properties of a graphite oxide (GO) thin-film8–10 into a highly versatile and reconfigurable architecture controlled and supervised by a
microcontroller unit. The circuit manufactured on the GO film acts as a sensitive element to detect tampering and, simultaneously, implements a compressive sampling procedure. The reduced graphite oxide (RGO) circuitry is used to build a physical encryption key. CS equips the seal with a low-power means for self-authentication and self-state-of-health awareness. The device expressly takes advantage of the not bit sensitive encryption capability provided by CS, which is of paramount importance for ensuring correct operation of the seal. Moreover, the not bit sensitive encryption mechanism, featured by CS, enables the seal to accommodate perturbations to the GO physical encryption key when it is exposed to environmental changes (e.g., temperature and humidity modifications). Therefore, small variations in the parameters used to construct the encryption key should not prevent the seal from correctly detecting if tampering has occurred. The prototype tamper evident seal can be found in Figure 11.

6. Conclusions

This work has summarized a number of emerging Structural Health Monitoring technologies that may help address problems associated with corruption in the construction industry in the developing world. These technologies could potentially open the door to affordable, rapid, city-scale structural assessment monitoring for ensuring the safety of the public and verifying that construction work has been executed as claimed. Furthermore, these sensing technologies may also help enable the collection of evidence needed to prosecute person’s involved in construction industry corruption.

It is important to note that technology on its own will not be sufficient to prevent corruption. Any technologies developed to prevent corruption must also take into account the socio-economic factors that are creating an environment that allows corruption to exist. For this reason a multi-disciplinary approach must be adopted when developing technologies to combat corruption. Any solutions that are developed must take into account human-centered design issues. For this reason it may be beneficial to adopt a design-thinking methodology in order to identify
promising technologies that could combat corruption. The advantage of a design-thinking methodology in the corruption context is that it offers the hope of detecting early-on unintended consequences that might arise as a result of the deployment of an anti-corruption solution. As unintended consequences are detected early in the design cycle they can be addressed before large development investments have been made.

7. Acknowledgements

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