Enabling Resilient Urban Infrastructure with Photogrammetry-Based Structural Assessment

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Infrastructure is an important factor for achieving economic growth. The World Economic Forum estimates that an economic return between 5%-25% is achieved for every dollar spent on infrastructure [1]. One of the most important global challenges we are facing today is the issue of building and maintaining sustainable and resilient civil infrastructure. This problem is so acute that it has been specifically called out in 2 of the United Nation's 17 sustainable development goals [2]. Oxford Economics projects that between 2014 and 2025, ~$78 trillion dollars will be spent globally on infrastructure [3], so these investments must be made prudently.

The nature of the global infrastructure challenge takes on two distinct faces. In the developed world, (*e.g.* United States and Western Europe), maintaining, monitoring, repairing, refurbishing and replacing aging infrastructure is the primary challenge [4]. A large percentage of the civil infrastructure in these regions is currently operating beyond its design lifetime. The situation is so dire that that American Society of Civil Engineers estimates that an investment of 3.6 trillion dollars is required to meet the infrastructure gap in the US by 2020 [4]. Funds do not exist to replace even a modest fraction of all the civil infrastructure beyond it design lifetime so instead governments often adopt policies of monitoring, repairing, and refurbishing civil infrastructure in order to keep it online.

Alternatively, the developing world is currently experience a large surge in urban infrastructure development. The draw for people to move to cities include job prospects, cultural events, and social development [5]. In 1930, 30% of the world's population lived in urban centers, as of 2014 the number had risen to 54%. The United Nations projects that by 2050, 60% of the world's population will live in urban centers [6], and 90% of the increase will occur in Asia and Africa. 37% of this growth is expected to occur in India, China and Nigeria [6]. Unfortunately, an examination of the 2015 Corruption Perception Index [7] reveals that nearly all of the top 50 countries with the highest perception of public sector corruption are located in either Africa or Asia. This is an observation of concern for the infrastructure community because according to the Organization for Economic Co-operation and Development (OECD) Foreign Bribery Report, the largest percentage of the companies sanctioned for foreign bribery come from sectors of the economy that are directly related to infrastructure development. These sectors are led by extraction (*e.g.* oil, gas, mining) (19%), construction (15%), transportation/storage (15%), and information/communication (10%) [8]. This data suggests that addressing problems associated with corruption in the infrastructure sector will be vital for protecting the large investments that will be made in infrastructure worldwide in the coming decades, particularly in the developing world.

Consider some of the most recent infrastructure disasters in the developing world. The earthquake in China's Sichuan Province in 2008 triggered the collapse of ~7,000 classrooms [9] while neighboring buildings were unscathed. After the event Ma Zongjin, chairman of the official committee tasked with studying this incident noted that rushed construction practices resulted in poorly built schools [9]. The collapse of the illegally modified Rana Plaza garment factory that left more than 1100 people dead in 2013 [10]. More recently, the 2016 earthquake in Taiwan triggered the collapse of the 17 story Wei Guan Golden Dragon Apartment complex. Poor construction practices are suspected to have been used in the construction of this tower partially because the surrounding buildings survived the earthquake unscathed. In addition, it was found that empty cans were found within the concrete making up the building [11]. It should also be pointed out that in the developing world it is not uncommon for structures to be built in a completely illegal manner [12]. Multistory buildings are routinely built without any form of building permit and unsafe modifications to structures are not unusual [13]. In many cases members of the population do not have the financial resources to live in any other conditions leaving the government with limited enforcement options. These examples suggest that the problems surrounding infrastructure in the developing world are mostly focused around verifying the construction has been completed in a sound manner, and that illegal structural modifications are not jeopardizing the safety of the public.

Aris Papadopoulos, CEO of Titan America (US Subsidiary of Greece's Titan Cement Group), and head of the Private Sector Advisory Group for the United Nations International Strategy on Disaster Reduction (UNISDR) made the following observation, "In the next 20 or 30 years, we are going to spend more money on urbanization worldwide than we have spent in our entire history. If our investment isn't resilient the first time around, we're going to have to do it over [14]." An examination of the infrastructure problems facing both the developed and developing world suggests that one capability that would be of great help to both sectors would be cost-effective tools that allow for the high-resolution assessment of structural integrity. This observation is validated by an Indian state government resolution calling for the use of remote sensing technologies to detect the presence of illegal structures [12].

The structural health monitoring research community has been considering structural integrity assessment challenges for the last 20 years. Unfortunately, many hurdles remain before structural health monitoring can be considered a viable technology to address these urgent challenges. However there is now great reason for hope. In the spring of 2013 Structural Health Monitoring researcher David Mascareñas came across a YouTube video on Eulerian motion magnification [15] from MIT. David, immediately recognized that this technique suggested that there was more information in normal video relevant to structural dynamics application than anyone had realized previously. In the summer of 2013 David had his PhD student, Nathan Sharp, do some initial experiments trying to quantitatively extract mode shapes from video using the Eulerian video magnification techniques. The student only had one week to work on the project but the results he did get were promising enough to suggest to David that this line of research should be considered further. Over the next two years David wrote proposals to fund the work but these were unsuccessful. In January of 2014 Justin Chen of MIT presented his work at the International Modal Analysis Conference on using the motion magnification techniques to extract mode shapes from video [16]. David was at Justin's presentation and his beliefs in the potential of the video was further validated. In the summer of 2015 David Mascarenas, Yongchao Yang, and Garrett Kenyon mentored some Los Alamos summer students on the use of hierarchical deep learning to try and blindly extract the spatio-temporal patterns associated with high-resolution mode shapes directly from video. Yongchao made the observation that the process for extracting the mode shapes could be sped up greatly if techniques used for the blind source separation problem were used in place of hierarchical deep learning [17]. This insight came from Yongchao's prior experience in output-only structural ID. The key observation was that the systems of equations used to describe structural dynamics in modal coordinates exactly match the model used in the blind source separation problem. This insight allowed us to extract natural frequencies, high-resolution mode shapes, and damping ratios very quickly from video in a completely automated manner, which opened up a whole new world of possibilities in structural dynamics. We realized that high-resolution mode shapes could be used to detect very small damage in structures using a global video measurement. As of 2016 damage detection had been limited by low spatial sensor density [18] resulting from the use of expensive accelerometers. However, our technique essentially used every single pixel located on the structure as a sensor, resulting in an extremely low-cost, highly-dense sensor array on the structure with minimal setup costs. We could simply identify the mode shapes of the structure and then estimate the fractal dimension of the mode shapes to identify locations where small kinks in the mode shape curves indicated the presence of damage. Using these techniques we have been able to detect damage as small as a 3% loss in stiffness [19]- nearly and order of magnitude better than the current state of the art, and with an extremely low-cost measurement systems that requires no calibration.

For the first time these techniques suggest a path forward for city scale-monitoring of civil infrastructure at low cost. These techniques can be combined with thermal imagers to try and gain a significantly better understanding of how temperature loading affects large-scale infrastructure such as bridges which is known to be important but not well understood. We also imagine using the models derived from the measurements to help inform structural modification and repair plans of infrastructure. We hope that one day we may even be able to use these techniques to infer how dead loads redistribute themselves in a structure as a structure degrades and verify the quality of new construction. By identifying an intimate coupling between structural dynamics and computer vision there is great potential to address urgent infrastructure monitoring needs worldwide.

References:

[1] World Economic Forum, "Strategic Infrastructure: Steps to Prioritize and Deliver Infrastructure Effectively and Efficiently," 2012.

[2] United Nations, "United Nations Sustainable development goals.," [Online]. Available: http://www.un.org/sustainabledevelopment/sustainable-development-goals/. [Accessed 15 06 2016].

[3] Oxford Economics, "Critical Project and Infrastructure Spending: Outlooks to 2025," Price Waterhouse Cooper, 2014.

[4] American Society of Civil Engineers, "2013 Report card of Infrastructure Health," [Online]. Available: http://www.infrastructurereportcard.org/executive-summary/. [Accessed 15 06 2016].

[5] United Nations, "Sustainable development goals, Goal 11: Make cities inclusive, safe, resilient and sustainable," [Online]. Available: Goal 11: Make cities inclusive, safe, resilient and sustainable. [Accessed 2 06 2016].

[6] United Nations: Department of Economic and Social Affairs, "World Urbanization Prospects," 2014.

[7] Transparency International, "Corruption Perceptions Index 2015," 2015. [Online]. Available: http://www.transparency.org/cpi2015. [Accessed 12 June 2016].

[8] Organisation for Economic Co-operation and Development (OECD), "OECD Foreign Bribery Report: An Analysis of the Crme of Bribery of Foreign Public Officials," OECD Publishing, 2014.

[9] E. Wong, "China Admits Building Flaws in Quake," *New York TImes,* 4 September 2008.

[10] Reuters; AFP; AP; dpa, "Thousands mourn collapse victims of Rana Plaza garment factory one year on," *DW,* 24 April 2014.

[11] J. Kaiman, "Shoddy construction suspected in Taiwan Earthquake Collapse," *Los Angeles TImes,* 10 February 2016.

[12] A. Deshpande and M. Menon, "Illegal structures abound in Thane," *The Hindu,* 7 April 2013.

[13] D. David Bergman and D. Nelson, "Bangladesh building collapse: Dhaka buildings not given final safety clearance," *The Telegraph,* 7 May 2013.

[14] Price Waterhouse Cooper, "Rebuilding for Resilience: fortifying infrastructure to withstand disaster," September 2013. [Online]. Available: https://www.pwc.com/gx/en/psrc/publications/assets/pwc-rebuilding-for-resilience-fortifying-infrastructure-to-withstand-disaster.pdf. [Accessed 12 June 2016].

[15] H.-Y. Wu, M. Rubinstein, E. Shih, J. Guttag, F. Durand and W. T. Freeman, "Eulerian Video Magnification," 23 May 2012. [Online]. Available: https://www.youtube.com/watch?v=ONZcjs1Pjmk&feature=youtu.be.

[16] J. G. Chen, N. Wadhwa, Y.-J. Cha, F. Durand and a. O. B. William T. Freeman, "Structural Modal Identification Through High Speed Camera Video: Motion Magnification," in *IMAC XXXII,* , Orlando, Florida, , Feb. 3 - 6, 2014.

[17] Y. Yang, C. Dorn, T. Mancini, Z. Talken, G. Kenyon, C. Farrar and D. Mascarenas, "Blind identification of high spatial resolution vibration modes from video measurements with video motion magnification," *Mechanical Systems and Signal Processing,* p. Under Review, 2016.

[18] P. Qiao and W. Fan, "Vibration-based damage Identification Methods: A Review and Comparative Study," *Structural Health Monitoring,* April 20, 2010.

[19] Y. Yang., C. Dorn, T. Mancini, Z. Talken, J. Theiler, G. Kenyon, C. Farrar and D. Mascareñas, "Reference-free Detection of Minute, Non-visible, Damage Using Full-field Mode Shapes Output-only Identified from Video of Operational Structures(Submitted)," *Journal of Sound and Vibrations,* 2016.