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CURRENT METHODS AND FUTURE ADVANCES FOR RAPID, REMOTE-SENSING-BASED WIND DAMAGE ASSESSMENT

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ABSTRACT

Remote-sensing information provides an effective basis for the rapid assessment of wind damage. The development of remote-sensing based assessments has received notable attention over the past decade, although automated algorithms have not yet achieved the speed, objectivity, and reliability desired for practical implementation in time-critical damage assessments. The current standard practice for making swift, objective, and widespread assessments of wind damage currently consists of rapid visual interpretation of first-available imagery. Techniques for rapidly accomplishing widespread damage assessments by visual inspection have been implemented in recent major tornado outbreaks in Birmingham-Tuscaloosa, Alabama and Joplin, Missouri (2011). Quickly emerging technologies, such as unmanned aerial vehicles (UAVs) and laser scanners, are helping to improve both the speed and the accuracy of damage assessments, in particular for rapid and target-specific data collection at very high spatial resolutions. Applications of these emerging technologies following recent severe tornadoes at Pilger, Nebraska (2014) and Pampa, Texas (2015) have demonstrated their role in helping to refine strategies for making rapid semi-automated damage assessments. Algorithms for comparing before-and-after remote sensing imagery are also of great interest for the future development of automated damage detection. Current development activities are centered on high-resolution before-and-after aerial images of recent tornado damage.

Keywords: tornado; wind damage assessment; remote sensing; UAV; LiDAR; laser scanning

1. BACKGROUND

The rapid assessment of damage severity in natural disasters (including tornadoes and hurricanes) is of critical importance for decision-making regarding emergency response and relief efforts. Remote-sensing data provide a highly efficient basis for rapidly making rapid assessments of wind damage across a wide area, giving critical decision support for the efficient allocation of disaster relief resources. Imagery containing pertinent damage data covering large areas can be acquired rapidly following wind storms, and wind damage to buildings is particularly well-suited to detection from overhead imaging platforms (Womble 2005).

The modern era of remote-sensing technologies for the assessment of structural damages from earthquake and wind effects began with the launch of the first modern high-resolution (1 m) commercial satellite in 1999. By 2004, commercial satellite resolutions had improved to the 60-cm level in time for DigitalGlobe's QuickBird satellite to capture the first high-resolution multi-spectral (blue, green, red, near-infrared) satellite imagery of major windstorm damage following Hurricane Charley. This satellite imagery formed the basis of pioneering studies (Womble 2005, et al. 2007ab), as well as subsequent studies (e.g., Brown et al. 2012) for the use of remote-sensing technologies in wind damage assessment. Capabilities for satellite imaging were again bolstered with the launch of DigitalGlobe's WorldView-2 satellite in 2009, adding the capability of acquiring 46-cm imagery with 8 spectral bands.

The ability to preserve wind damage scenes coupled with the ability to make photogrammetric measurements was transformed in 2005 by the widespread acquisitions of pre- and post-storm aerial imagery for Hurricane Katrina by Pictometry, Inc., using a fleet of small aircraft. These images provide vertical and 4-directional oblique view angles with 15-cm spatial resolutions and 3 spectral bands (blue, green, red). Aerial imaging platforms have the potential of providing data more quickly than earth-orbiting satellite platforms, as they are not subject to the limitations of imaging time windows and revisit times which may coincide with cloud cover. Aerial platforms also have the ability to acquire multiple view angles of the same areas.

Following Hurricane Katrina in 2005, a pioneering and comprehensive analysis of remote-sensing technologies for application to wind and flood damage assessment (Womble et al. 2006) evaluated the utility of 21 different satellite and aerial remote-sensing platforms (ranging in spatial resolution from 5 km to 30 cm) for gauging the impact of wind damage at various spatial levels and identified a formal Tiered Remote-Sensing Reconnaissance System (Fig. 1). Remote-sensing imagery available in 2006 enabled assessment of wind damage at levels ranging from the *regional* level (Tier 1: satellite imaging with resolutions greater than 1 m) to the *neighborhood* level (Tier 2: commercial satellite and aerial imaging) to the *per-building* level (Tier 3: sub-meter aerial imaging).

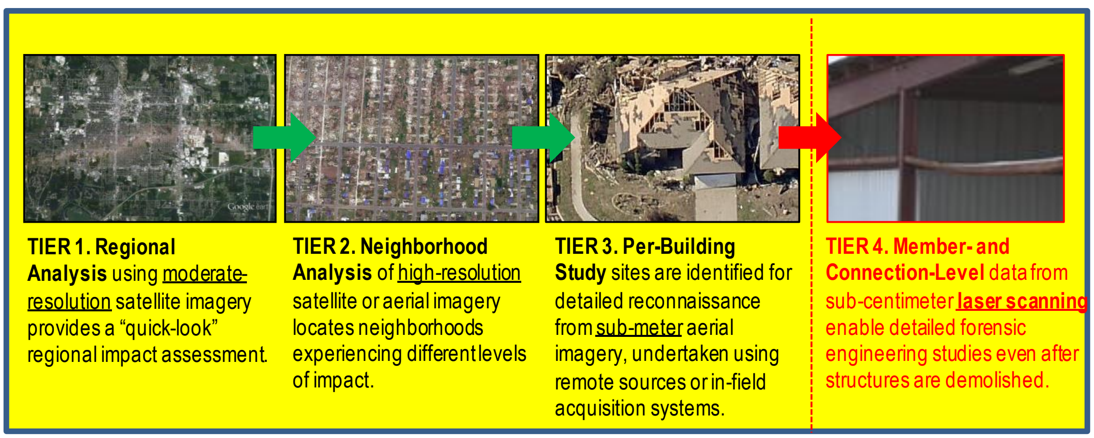

Fig. 1: Earlier tiered reconnaissance system has been expanded by the advent of laser scanning, which provides sub-centimetre resolution to give member-level damage data.

Significant advancements in automated damage assessment methodology have been recently accomplished (Radhika et al. 2015, Thomas et al. 2014, 2012), although algorithms have not yet achieved the speed, objectivity, and reliability desired for practical implementation in time-critical damage assessments. Research efforts continue to target the automation of damage detection using 2-D visual data as well as 3-D light detection and ranging (LiDAR) data (Kashani et al. 2015ab), showing significant promise for practical implementation in the future.

Until algorithms for automated damage assessments have reached maturity, practical applications for rapid hurricane damage assessments across large areas necessarily employ visual screening based on remote-sensing imagery (Womble et al. 2010, Atkins et al. 2014). Because of the current necessity of using rapid visual assessment of first-available data, recent research (Luo et al. 2014, Brown et al. 2012) has targeted the accuracy of visual assessments made with imagery of various spatial resolutions. The accuracy of such visual damage assessments also forms a fundamental part of the forthcoming ASCE Standard for Estimation of Wind Speeds in Tornadoes (LaDue 2014).

The recent widespread availability of unmanned aerial vehicle (UAV) technology has added a plausible new platform for rapid, target-specific data collection at very high spatial resolutions; this emerging technology is already helping to refine strategies for rapid semi-automated damage assessments, and two recent case studies are described below. Recent applications for both earthquake and tornado damage investigations have shown the enormous potential for rapid damage data collection using UAVs. As the availability of UAVs for both hobby and commercial purposes has grown exponentially, governmental rules regarding the application of this technology for both hobby and commercial purposes are presently in a rapid state of development (Witcher, 2015).

The advent of laser-scanning technology is also momentous for the overall application of remote-sensing imaging to wind damage assessment by transitioning the most-detailed capacity of such analysis from the per-building level to the *per-member* level (Fig. 1). This enables highly-detailed forensic analysis of wind-induced structural failures, even after structures have been demolished or repaired**.**

2. RAPID VISUAL DAMAGE ASSESSMENTS

Despite the now-widespread availability of satellite and aerial imagery following major disasters, damage assessment using remote-sensing imagery is still heavily reliant on visual assessment (Ghosh et al. 2011; Thomas et al., 2014;), as robust damage assessment algorithms have been slow in development. ImageCat, Inc. (2011) working with New Light Technologies completed a rapid building damage assessment after two extremely destructive tornadoes struck communities in Alabama and Missouri in April and May 2011, respectively. This study, commissioned by the FEMA Recovery Directorate, was designed to evaluate the efficacy of remote-sensing technologies for rapid post-disaster damage assessment. This study focused on levels of damage that are discernible from remotely-sensed imagery and the speed at which these results could be delivered to personnel in the field.

Three Areas of Interest (AOI) were identified for the study – Tuscaloosa and Birmingham in Alabama, and Joplin in Missouri. The methodology employed consisted of a three-step process: 1) data access and setup, 2) damage analysis using manual interpretation techniques, and 3) validation of damage results using an independent expert review process. In addition, the study produced a detailed description of the damage protocol used for assessing tornado damage at a "per-building" level. In the development of this description, FEMA's Tornado Damage scale was used along with the Enhanced Fujita (EF) Scale (TTU 2006, McDonald et al 2009) and a remote-sensing-based damage scale (Womble 2005, et al 2007a). This particular development was considered ground-breaking in that observable information from aerial surveys is merged with expert engineering knowledge on the behavior of buildings in extreme winds to arrive at an integrated, remote-sensing-based damage scale.

Major observations and lessons learned from this study include the following:

- This study showed that Tuscaloosa and Birmingham had roughly the same number of damaged buildings (around 4,000 buildings in all damage classes for each AOI) while the Joplin AOI had over 8,000 damaged buildings - roughly equal to the combined total of Tuscaloosa and Birmingham.

- Although there were multiple data sources available to the project team, the NOAA aerial imagery was essential in providing timely and useful data for all damage assessments.

- Pre-event imagery was extremely important in assessing post-event damage levels. It was essential to understand the geometry of the structure in the pre-event image in order to assign a final damage level - this determination became a challenge when very high-resolution aerial imagery (pre-event) was unavailable.

- Development of a damage protocol at a per-building level using FEMA's observed damage classifications, input from FEMA's field inspection team, and descriptions from other engineering-based damage scales (e.g., EF-Scale) were essential to produce and deliver a consistent damage assessment product.

- In addition to the building damage database, a key product from the damage analysis was a distribution of damaged buildings by occupancy (e.g., residential or commercial). This information was important in supporting the housing assistance program and in identifying the owners of damaged buildings. This latter task was accomplished by linking tax assessor's parcel information to the locations of damaged buildings.

- A remote-sensing-based damage methodology has its limitations and is not expected to provide 100% agreement with ground surveys of building damage, i.e., damage to some building surfaces (walls, windows, and doors) cannot be directly observed from nadir (vertical) remote-sensing imagery. However, the methodology provides nearly 100% accuracy for detection of structures that have been completely destroyed ("catastrophic damage") given that very high-resolution pre-event imagery (25 cm or better) is available for baseline comparison.

Fig. 2 shows the distribution of damaged buildings in the Joplin tornado. For Joplin, a total of 8,440 buildings were identified as having some level of damage according to the FEMA damage classes. Finally, in order to improve the overall damage assessment operations using remotely-sensed data, a set of recommendations for responding to future events was identified in the study. These included availability of high-resolution vertical and oblique aerial data before and after any event, creation of pre-event planning databases (such as parcel boundaries with occupancy, structural type, etc. information), establishing methods to quantify accuracy and confidence levels of the damage assessment, and expanding the knowledge of damage assessment for tornadoes to other hazards.

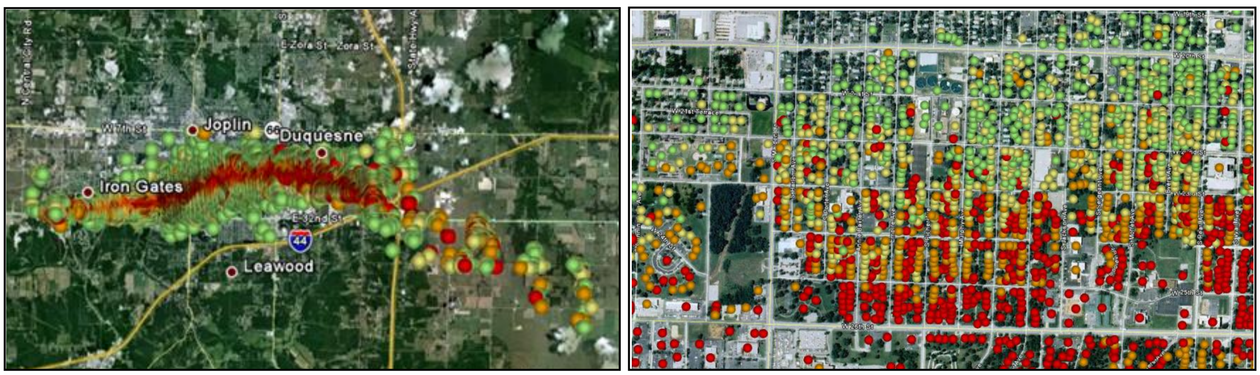

Fig. 2: Regional (left) and neighbourhood-level (right) views of damaged buildings in the Joplin AOI.

3. NEW PLATFORMS – UNMANNED AERIAL VEHICLES

Among the newest accessible platforms for the remote sensing of wind damage are unmanned aerial vehicles (UAV) with payloads of digital and/or still cameras. UAVs offer a number of distinct advantages for the rapid acquisition of high-resolution damage information for windstorms and other hazards over large areas including mountainous terrains and urban centers (Moss et al. 2015, Bose et al. 2016). UAVs are available in a variety of grades and user levels– ranging from the amateur/hobby level (costing less than one-hundred USD) to the commercial (near-survey-grade) level (costing tens of thousands of USD). Early use of UAVs in earthquake-damaged areas abroad (Bose et al. 2016, Wood et al. 2015, Brando et al. 2015), has proven the utility of UAVs for damage data collection. UAVs are ideally suited for rapidly capturing wind damage data, as they offer the advantage of overhead imaging, which has shown to be particularly well-suited for detection and assessment of damage due to wind action (Womble et al. 2007a), and therefore offer viewing angles generally superior to those available to ground-based investigations. UAVs also offer the advantage of manual or automatic control. Operators can pilot the UAV in real time and observe conditions of structures at extremely close range to the object or areas of interest – from positions and view angles not otherwise available due to accessibility or safety concerns (Murphy 2015). UAVs also are well-suited for following linear tornado paths as they can be controlled manually in real-time for exploratory investigations of specific damage sites or pre-programmed to follow specific autonomous flight plans.

Compared to satellite-imaging systems, UAVs are less-limited by atmospheric conditions (e.g., cloud cover and haze) and revisit times and can therefore collect data more rapidly provided that investigators are able to quickly travel to the damage site. UAVs can also provide much finer spatial resolution for detailed damage assessments. Given the proper circumstances, UAV systems can often provide first-available and highly-detailed damage information, although legal issues, requirements for filing and gaining approval for flight plans, and the necessity of operator travel to a damage site can hinder the timeliness of UAV-based acquisitions. Commercial use of UAVs in the US is presently limited to airspace over public areas and private property owned by the operator or the operator's client; however, the view angles and ranges provided by such imaging systems are generally sufficient to capture the necessary data for most urban areas even in accord with such restrictions. Ever-increasing government restrictions on the legal operation of UAVs provide some of the primary hindrances to the most-efficient use of UAVs for such data acquisitions, e.g., requirements for pilot certification of commercial UAVs, restrictions on flight altitudes and line-of-sight conditions. UAV systems are not able to acquire data in high-wind conditions, and short battery life can also provide obstacles for extended uses.

4. NEW PLATFORMS – LASER SCANNING

Laser light detection and ranging (LiDAR) scanning technology has quickly matured and proven extremely useful for the rapid collection of 3D scene-condition information both from mobile and stationary platforms. Mobile LiDAR systems can be mounted on aircraft for acquisition of neighborhood-level condition information and can also be mounted on moving vehicles for rapid terrestrial imaging from a platform height in excess of 10 ft. At the present time, such systems are costly and are therefore limited in their availability.

Stationary 3D laser scanners (similar in price to commercial near-survey-grade UAVs) provide the ability to rapidly obtain detailed and accurate measurements of structures from a distance, enabling measurement of member sizes and deformations that would not otherwise be possible due to access, time, and safety issues. Many systems offer the added benefit of a full-color camera that enables the draping of images over the 3D point cloud for enhanced reality capture and visual identification. Such laser scanners have recently been employed for condition assessment of selected structures following a limited number of major earthquakes and tornadoes.

Prevatt et al. (2011, 2013) describe an effective and comprehensive strategy employed for field-investigation studies of damage resulting from the severe (EF-5) tornado outbreaks of 2011 in Tuscaloosa, AL and Joplin, MO. As is common for such major natural disasters, it was not possible for investigators to collect detailed information for each structure within the available timeframe. Investigators implemented a sampling strategy with a 3-tier approach leveraging data acquisition speeds with various levels of detail, utilizing highly-detailed laser-scanning data for engineered buildings where damage and failure mechanisms were of particular interest and where direct measurements of member sizes and deformations were not physically or practically possible. In a comprehensive study of damage from the 2011 Tuscaloosa, AL tornado, researchers from the University of Alabama-Tuscaloosa employed a 3D laser scanner to rapidly capture post-storm condition data for several different important types of features, including residential buildings, institutional buildings, terrain features, and trees (Graettinger et al. 2012). In each case, the laser scanner was able to obtain measurements that could not otherwise be obtained due to accessibility constraints and time limitations; however these data sets were limited to ground-level -based surveys.

Devastating damage from the 2011 Joplin, MO, tornado forced evacuation and eventual demolition of the St. John's Regional Medical Center. This structure was impractical for close inspection due to its size and prohibitions on access. The inspection team utilized ground-based laser scanning to rapidly obtain high-precision geometric data for subsequent detailed forensic studies (Prevatt et al., 2013). The resulting 3D model enabled determination of elevations, distances, lengths, and deformations which could not otherwise be rapidly or directly measured.

5. PILGER TORNADO CASE STUDY

A severe weather system produced more than 100 tornadoes in the Great Plains of the US on June 16-19, 2014. The system produced five EF-4 tornadoes, four of them in northeast Nebraska. Approximately 90 miles northwest of Omaha, two EF4 tornadoes were located in close proximity of the village of Pilger. One of these EF4 tornadoes transected the village, resulting in two fatalities. This tornado had a path of approximately 29.6 km (18.4 mi) and estimated wind speeds up to 300 km/h (189 mi/hr), as determined by the National Weather Service. This resulted in wide spread damage throughout the community where 75% of the village sustained damage from broken windows and localized roof damage to complete structural collapse or superstructure separation from the foundation. The debris field was noted to be larger than 0.8 km (0.5 mi) wide.

Structural damage was observed at various locations throughout the village. One building on the east side of the village sustaining considerable damage was the Wisner-Pilger Middle School (Fig. 3). Observed damages included airborne missile impacts from the detached nearby grain siloes, wind-pressure-induced window and door failures, roof-uplift as a result of anchor failures, unreinforced masonry collapse, and extensive nonstructural failures of windows, partition walls, and mechanical-electrical-plumbing equipment.

To characterize the damage to the school's exterior, LiDAR and a tethered UAV with an onboard camera were deployed to create detailed point clouds, which are digital representations of objects with vertices in three-dimensional space. (LiDAR scanning directly produces a point cloud, while the UAV images require further processing via a computer vision technique, Structure-from-Motion (SfM), to reconstruct the scene as a point cloud. Using point clouds, geometry and textural details are captured that can permit non-destructive evaluation of potential damage (Olsen et al. 2012)). For this building, 11 exterior LiDAR scans and numerous UAV passes were conducted to acquire more than 800 images for the SfM algorithm. Fig. 3 illustrates the resultant point cloud of the Wisner-Pilger Middle School that is useful for future analysis and assessment.

Fig. 3: Damaged Wisner-Pilger Middle School: ground-survey image (left) and point-cloud imagery (right).

- Remote sensing platforms allow for low-cost and low-risk damage assessment. In the aftermath of natural disasters, significant debris may cause tripping and fall hazards, while precarious structural components and the possibility of structural collapse compromise the safety of inspectors, volunteers, and residents.
- The aerial SfM platform (a visible camera mounted on an unmanned aerial system) permits the visual inspection of difficult-to-reach areas, such as the inaccessible roof of this school building. For this study, the performance of two different roof systems was assessed. The light-gauge truss roof section experienced a 50% failure rate compared to a failure rate for rolled-steel W-section roof supports of only 6%.
- Remote-sensing LiDAR and UAV SfM platforms permit more-objective detailed structural damage assessments from point clouds. The level of detail of the assessed damage varies as a function of distance to the structure; however, for the Wisner-Pilger Middle School this is at the sub-centimeter level.

6. PAMPA TORNADO CASE STUDY

On November 16-17, 2015, a rare and intense late-season tornado outbreak produced at least 17 confirmed tornadoes stretching across portions of Texas, Oklahoma, and Kansas. The most intense of these tornadoes severely damaged a group of engineered structures at the Halliburton Oilfield Services facility at Pampa, TX (Fig. 4). The National Weather Service rated the intensity of this tornado as EF3 (estimated wind speed of up to 250 km/hr or 158 mi/hr), based on damage to the buildings at this facility. This facility contained multiple types of engineered structures for which structural resistances can be estimated, thereby enabling the estimation of tornado wind speeds. The tornado also overturned engineered center-pivot irrigation systems in nearby agricultural fields (Fig. 5).

Fig. 4: Tornado damage to Halliburton facility, Pampa, TX.

Due to safety and security liability concerns, facility owners made immediate plans to demolish the damaged buildings and prohibited access to the site; investigators were therefore not able to make direct measurements of structural member sizes and deformations to assist with resistance calculations. Investigators were, however, able to acquire laser scan data from the property line. As structural steel members of the pre-engineered metal buildings were visible, measurements of the member sizes could be utilized in structural analysis models to validate or correct the wind speed estimates for damage to pre-engineered buildings in the current EF Scale. Laser scanning from the property line and UAV imaging (Fig. 6) provided effective solutions for rapidly and accurately preserving damage data for subsequent detailed forensic analysis. Although access to the nearby center-pivot irrigation systems was possible, measurements of the overall structure (approx. ¼ mile long) and deformations were again most readily accomplished by laser scanning and aerial imaging (Fig. 7).

Fig. 5: Center-pivot irrigation system toppled by tornado, Pampa, TX.

In the weeks following the tornado, a collaborative team of investigators from WTAMU, the University of Nebraska-Lincoln, and the Texas Tech University National Wind Institute and TTU School of Architecture conducted a multi-platform remote-sensing investigation of the Halliburton facility and surroundings to capture data for further analysis. The various remote-sensing platforms included UAV imaging, 3D laser (LiDAR) scanning, 3D photogrammetric modeling based on a suite of 2D digital images, third-party aerial 3D FoDAR modeling, and high-resolution satellite imaging. The multi-platform data collection has facilitated the comparison and evaluation of available remote-sensing platforms for their utility in rapidly capturing and preserving damage scenes via 3D models which will allow for future analysis of the storms.

7. PROGRESS TOWARD AUTOMATED DAMAGE ASSESSMENTS

In a pioneering exploration of remote sensing technologies for automated wind damage assessment, Womble (2005) identified remote-sensing signatures of wind damage for four most common building types: single-family residences, mobile homes, metal warehouses, and industrial buildings with built-up roofs. This study showed that wind damage has distinctly different remote-sensing characteristics depending on building type. For each type of building, progressive levels of wind damage were described from a remote-sensing perspective. Womble (2005) identified 4 distinct levels of damage for single-family residences discernable in 60-cm satellite images and consequently formulated separate damage descriptions for each of the building types, consistent with the methodology employed in the Enhanced Fujita Scale (McDonald et al. 2009). Subsequent researchers (Brown et al. 2012; Luo et al. 2014) have further refined these damage levels for single-family residences by subdividing these original damage levels into as many as 36 different levels.

Fig. 6: LiDAR point-cloud data (left) and UAV imagery of damaged Halliburton facility at Pampa, TX (right).

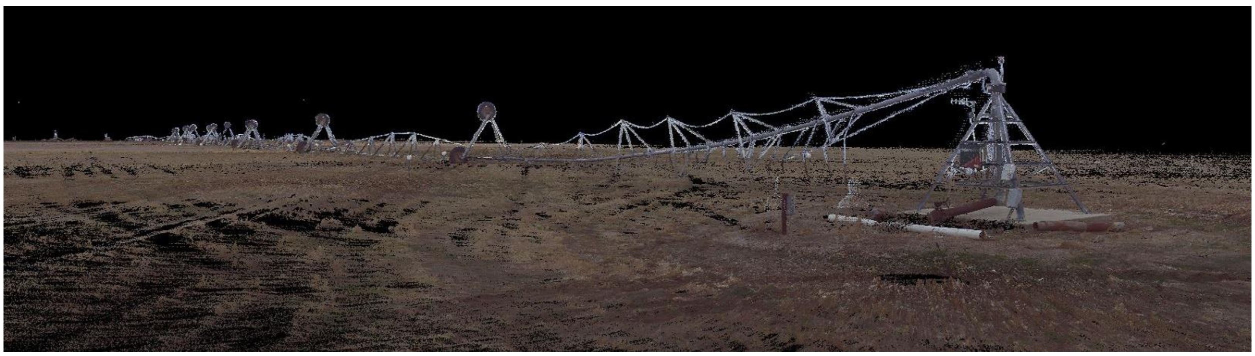

Fig. 7: LiDAR point-cloud data for overturned center-pivot irrigation system at Pampa, TX.

Thomas et al. (2014, 2012) made significant strides toward automation of remote-sensing wind damage assessment for simple building forms using 50-cm, 3-color vertical imagery of hurricane damage captured by NOAA airborne sensors in 2004 (Hurricane Ivan) and 2005 (Hurricane Dennis). Thomas' study identified a plausible framework for the development of automated damage classifications based on temporal changes in edge-based measures as well as color-based statistics, such as hue and saturation values. When applied to simple building forms (such as industrial buildings and metal warehouses), the proposed algorithms predicted damage with overall 80% accuracy for a 3-level damage scale and 72% accuracy for a 4- level damage scale. Thomas' study of simple-form buildings was further expanded (Thomas et al., 2014) with the inclusion of additional datasets including vertical images from additional windstorms, including Hurricane Katrina (2005), Hurricane Ike (2008), and the Joplin, MO tornado (2011), with spatial resolutions varying from 60 cm to 1 m. The expanded study demonstrated similarly good prediction accuracy for simple-form buildings.

Single-family residences form the largest category of buildings sustaining damage in major windstorms. Womble (2005, et al. 2007b) concluded that single-family residences present significantly more complicated geometric forms than other types of buildings, and that finer spatial resolutions (much finer than the 60-cm satellite images available in 2004) are necessary to accurately determine the levels of damage for such complex building forms. Presently, the 15-cm Pictometry images from more recent windstorms provide spatial resolutions 4 times finer than the satellite images available in 2004; these images form the basis for preliminary and continued investigation of automated damage-detection measures for the complicated geometric forms of single-family residences using automatic extraction techniques (Womble and Patriani 2015) as well as edge-identification and change measures.

8. FUTURE DEVELOPMENTS

Research into change-detection and classification techniques for the automated detection of wind damage remains an active pursuit among wind-engineering, natural hazards, and remote-sensing researchers.

In 2014, the American Society of Civil Engineers (in conjunction with the National Weather Service) formed a new Standards Committee for the Estimation of Wind Speeds in Tornadoes, of which the authors are members of the Remote Sensing Subcommittee. The forthcoming ASCE Standard for Estimation of Wind Speeds in Tornadoes will provide guidance for the estimation of tornado wind speeds using a variety of tools and techniques: including radar, in-situ measurements, forensic analysis, remote sensing, and treefall. The remote sensing section of the standard will initially address minimum requirements (e.g., spatial resolutions) for making visual assessment of tornado damage within certain levels of accuracy. Related research efforts are directed at quantifying minimum image requirements necessary for the assignment of various degrees of damage to specific damage indicators (e.g., residential buildings, manufactured housing, industrial buildings, metal warehouses, and light poles) within the Enhanced Fujita Scale used by the U.S. National Weather Service for the official ratings of tornado intensity. As associated research and development efforts are accomplished, the standard can eventually incorporate the automated use of remote-sensing for damage and wind speed estimation.

For the near-future, rapid visual screening provides an effective means for quickly disseminating damage data from remote-sensing imagery, although greater speeds and accuracies are certainly desired. Future research and development needs include the continued development of algorithms for automated classification of building damage based on changes in 2D pre- and post-storm imagery, changes in pre- and post-storm point-cloud LiDAR/SAR data, and combinations of 2D visual imagery and 3D visual imagery to fully utilize first-available data to achieve rapid and accurate assessments of damage.

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