Time-Sensitive Remote Sensing Systems for Post-Hazard Damage Assessment

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Abstract

Remote sensing can provide useful information in post-disaster assessments, depending on the type of hazard and when in the emergency response and recovery stage, the particular types of information are required. Three general types of post-disaster assessment can be defined, for which remote sensing may contribute to data gathering and information delivery: (1) large-area reconnaissance, situational awareness, and/or mapping of damage extent and severity (i.e., what communities suffered the most impact), (2) impact to family stability in terms of homes and businesses damaged or destroyed, and (3) impact to critical infrastructure such as roads, energy grids (electrical, gas and water), and public facilities.

This chapter provides a comprehensive perspective on the rationale and end-to-end design of time-sensitive remote sensing systems (TSRSS) that are able to provide timely information on magnitude and extent of damage immediately following hazard events in support of emergency management decision-making. An emphasis is placed on airborne platforms because of their greater flexibility and lower altitude of operation, which enables finer spatial resolution sensing

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and greater control over imaging characteristics, as well as improved temporal tasking.

Remote sensing and related technologies associated with small aircraft, consumer grade digital cameras, and image processing procedures have matured substantially over the past decade and have been integrated into prototype TSRSS that are ready for operational and cost effective implementation for post-hazard damage assessment. Although some technology development in the area of image analysis still remains to be accomplished, the main limitations to implementation are institutional in nature (e.g., funding, technology coordination and acceptance, and government regulations). These limitations are worth overcoming so that TSRSS are implemented to save lives, aid in recovery, rehabilitation and remediation, and reduce clean-up costs associated with disasters.

Keywords

Hazards · Emergency response · Airborne remote sensing · Repeat station imaging · Change detection · Time sensitive

1 Introduction

Remote sensing (RS) imagery derived from airborne (suborbital) digital and earth observation satellite (orbital) systems (Visser and Darwood 2004) provide valuable sources of information about the location and severity of damage following major disasters (Stryker and Jones 2009). Disasters or hazards of a more geographically-extensive nature where remote sensing is particularly relevant include hurricanes, tornados, earthquakes, tsunamis, wildfires, floods, and terrorist events (Hodgson and Davis 1998). RS imagery has been underutilized and with limited effectiveness for these damage assessment tasks, largely because of a lack of technology integration, pre-event planning, and suitable data/information delivery systems. When effectively implemented, RS imagery can provide information on the degree, extent, and nature of damage to built and natural features which can be used to readily estimate the amount, distribution, and types of relief required.

Remote sensing can play multiple roles in post-disaster assessments, depending on the type of hazard and when in the various stages of emergency response and recovery particular types of information are required (Cutter 2003; Joyce et al. 2009). Three general types of post-disaster assessment can be defined, for which remote sensing may contribute to data gathering and information delivery: (1) large-area reconnaissance, situational awareness, and/or mapping of damage extent and severity (i.e., what communities suffered the most impact), (2) impact to family stability in terms of homes and businesses damaged or destroyed, and (3) impact to critical infrastructure such as roads, electrical grid, and public facilities. Another potential role of remote sensing is estimation of debris volumes for subsequent removal;

however minimal research and development activities have been conducted to evaluate, let alone operationalize such an implementation of remote sensing.

The goal of this chapter is to provide a comprehensive perspective on the rationale and end-to-end design of time-sensitive remote sensing systems (TSRSS) that are able to provide timely information on extent of damage and volume of debris immediately following hazard events in support of decision making by emergency managers. The objective is to describe the considerations and specifications for the components of the TSRSS in a manner that bridges the more theoretical treatment of TSRSS found in Chap. 1 with the more technical and applied material covered in Chap. 3. An emphasis is placed on airborne platforms because of their greater flexibility and lower altitude of operation, which enables finer spatial resolution sensing and greater control over imaging characteristics and timely acquisitions.

The proposed systems are based on theoretical, technical and applied aspects of: (1) time-sensitive remote sensing, (2) end-to-end airborne imaging systems, (3) precision image registration, (4) image change detection, (5) softcopy photogrammetry and light detection and ranging (LiDAR) for digital surface modeling, and (6) image and map delivery systems. All of these components of remote sensing are pertinent to effective damage assessments and are addressed in this chapter.

2 Information Requirements

Any remote sensing-based decision support system should be, first and foremost, responsive to users' information requirements (Phinn 1998). Information requirements of emergency response organizations need to be specified, in order to develop a TSRSS that provides appropriate information in a sufficiently reliable and timely fashion. National level emergency response organizations, e.g., the U.S. Department of Homeland Security (DHS), Federal Emergency Management Agency (FEMA), and regional and local emergency operations centers should be included as members of research teams to identify specific information requirements such as timeliness, accuracy and precision of damage assessments, cost constraints, and in-house technical capabilities. Their participation throughout any research involving the incorporation of advanced technologies to improve existing procedures is critical to successful implementation into operations.

Particularly important input from emergency response agencies is a determination of the types of hazards that have a reasonable probability of inflicting damage to a given jurisdictional area, as well as the types of built and natural features for which damage assessments are to be conducted. Damage and debris characteristics can be different for different types of hazards, as influenced by the nature of the disturbance associated with each type of hazard (e.g., water inundation for floods, high wind speeds for tropical storms, or ground shaking for earthquakes). For each hazard, the types of built features that may be damaged and the characteristics of damage will differ. Other important guidance from emergency managers is whether information on damage is desired for all built features or some subset, such as critical infrastructure. Critical infrastructural features could include for instance, major transportation features, power generating facilities and transmission equipment, medical facilities, or any feature that if severely damaged, could result in massive secondary damage (e.g., fire and flooding). Determining which infrastructural features are truly critical, where they are located, and how damage would likely be manifested, in preparation for a potential disaster, can help guide the development and implementation of an effective TSRSS for post-disaster assessment.

3 Remote Sensing Roles, Strategies and Options

The most timely and arguably the most important information required for disaster response is associated with critical infrastructure, which affects emergency response communications and transportation, and the ability to provide timely medical care and to minimize secondary hazards (e.g., fires stemming from earthquake damage). Critical infrastructure features tend to be more localized, so site-specific damage information is needed in a very timely manner. However, access to critical infrastructure on the ground may be limited by road and bridge closures, so flexible airborne remote sensing data collection may provide the only source of information within a few hours of a major hazardous event.

Assessing the full extent and degree of damage, particularly to residential and other areas where rescues, evacuations, or triage need to occur becomes the focus, once critical infrastructure has been assessed. The spatial coverage requirements are more challenging than for assessing damage to critical infrastructure, though spatial resolution requirements are less stringent for this phase of post-damage assessment. Thus, both aircraft and satellite systems provide viable solutions to performing wide-area reconnaissance and mapping activities (Tralli et al. 2005), as long as the satellite acquisition opportunity is within the window of opportunity for the data to be valuable.

Different strategies and options exist for implementing remote sensing approaches to damage assessment. For example, a strategy for mapping the distribution and type of damage is to analyze only post-event imagery, while another is to compare post-event and extant imagery through the process commonly referred to as change detection. An advantage of the change detection approach is that damage is manifested as a land surface change that is more readily detectable than a single static view of damaged features that may be amorphous or may not have characteristic image signatures. A disadvantage is that the change detection process requires access to relatively recent pre-event imagery for areas with average land use change due to population growth and both dates of imagery must be precisely registered (co-aligned) to minimize false detections. Replicating sensors and view geometries is the most effective means for achieving precise image registration, as elaborated in Chap. 3 in the image pre-processing section (Coulter et al. 2003; Stow et al. 2003).

As is demonstrated by Lippitt et al. (2014), a TSRSS for post-hazard damage assessment must be carefully planned and constructed as an end-to-end system in a manner that attempts to minimize time to information delivery while meeting information accuracy and reliability requirements. Components of such an end-to-end system include: (1) planning of RS data capture, (2) RS data capture, (3) RS image transfer to processing facility, (4) geometric and radiometric processing, (5) image analysis and information extraction, and (6) data and information delivery to user. Associated with each component is a lapse of time and the total time for the system to generate the required information must be less than the maximum time for information to have utility in disaster response operations.

3.1 Pre-acquisition Planning

Pre-event planning of remote sensing data acquisition is important if timely and reliable information is to be generated, yet it is rare for such planning to be conducted, since most types of disasters are unpredictable, infrequent and episodic. In fact, a plan for the entire image capture, processing and delivery procedures should be prepared for disaster prone areas and particularly for critical infrastructural features (Lippitt et al. 2014). Flood, tornado, and particularly hurricane disasters are somewhat predictable through storm forecasts. For these more predictable events and their likely areal extents of damage, it is feasible to determine the coverage of satellite imaging assets hours to several days in advance of a likely disaster (Hodgson et al. 2010) and/or plan for effective airborne imagery acquisitions. Since it can be difficult to predict the location of likely damage and conduct pre-event planning for other types of hazardous events, preemptive planning should be conducted for areas such as major earthquake fault zones, hurricane prone regions, and wildland-urban interface zones subject to wildfires.

Whether or not image acquisition is conducted prior to or after a disaster event has occurred, some form of pre-acquisition planning is required, particularly for airborne imagery. Of all choices and considerations pertaining to planning RS image acquisition for damage and debris assessment, the most critical is the choice of platform and sensor. Determining the performance domains and specifications for airborne and satellite platforms and imaging and elevation measuring sensors should be based on information requirements derived from user surveys. The primary trade-off is normally between spatial resolution and extent of coverage, such that the lower the altitude of imaging, the finer the spatial resolution and the more limited the extent of coverage per frame or swath. Though greater operational flexibility exists for airborne systems, satellite sensing systems do not have to be mobilized and may be the first asset available for capturing post-event imagery. However, most post-disaster assessments require fine spatial resolution imagery that can only be provided today by commercial satellite sensing systems (e.g., GeoEye and WorldView) that have fairly limited spatial and temporal coverage and irregular viewing geometries over time. Given these factors and trade-offs, airborne imaging systems are likely to be the primary RSS of choice for most post-disaster damage assessments.

Once the choice of airborne platform and sensor has been made, the next pre-acquisition planning decisions pertain to altitude of operation (to achieve a desired spatial resolution). The flight altitude above ground level will also determine the extent of coverage per frame (for framing systems) or swath width (for line array or scanning systems). Based on the coverage characteristics and requirements for stereo or variable view perspectives that determine along-track overlap percentages, flight lines and imaging station locations can be established based on flight planning software tools. Variable view perspective (i.e., nadir and oblique viewing) can be obtained from vertical imagery captured with substantial overlap or by using multiple camera systems with nadir and off-nadir pointing sensors. The advantage of oblique or off-nadir view perspective is the ability to detect structural failure that may be difficult to observe from nadir-viewing perspectives.

There are many other factors to consider when acquiring airborne imagery, each of which affect the final image quality and utility. These include: camera orientation, speed of the aircraft (affects image blur and overall area covered), time of day (affects illumination and shadowing), flight line orientation (affects bi-directional reflectance across images), camera/lens specifications (affects viewing geometry and area covered), and supporting systems, e.g., global positioning system (GPS), inertial measurement units (IMU), gyro-stabilized mount, that affect the ability to accurately capture and geo-reference imagery. Each of these factors affects single date and repeat-pass imaging. Camera orientation pertains to whether nadir, oblique or dual-perspective image data are to be captured. Normally either color or infrared imagery would be captured, given the high spatial resolution nature of the information requirements and the likely manual image interpretation or hybrid approach where semi-automated routines are followed by manual image analysis and editing.

An important factor in guiding pre-acquisition planning is whether or not a change detection approach to damage assessment is to be conducted. If such an approach is to be implemented then the most reliable change analyses are based on multi-temporal airborne digital frame imagery collected through a patent pending strategy called repeat station imaging (RSI). Repeat station imaging involves returning the same (or similar) sensor to the same imaging stations (defined by specific horizontal and vertical positions) over time, replicating view geometry, and geometrically processing images on a frame-by-frame basis to maintain the benefits of replicated view geometry (Fig. 1). The RSI approach is further described in Chap. 3. This means that flight-line and image capture station locations (x-y-z position of where each image was captured) and information on the sensor type for pre-event acquisitions must be available or can be reliably estimated. The matched station approach is particularly useful for assessment of damage to critical infrastructural features, where even subtle damages to built features (e.g., cracks and slumping) may be important to detect. For areas prone to disasters, it may be prudent to collect and have available metadata (e.g., flight altitudes and image station locations) for the most recent and/or most suitable archived airborne image data sets.

For wide-area reconnaissance and situational awareness of damage extent and severity (i.e., urban areas and built features not associated with critical infrastructure), the key is to efficiently obtain extensive imagery coverage with a spatial resolution

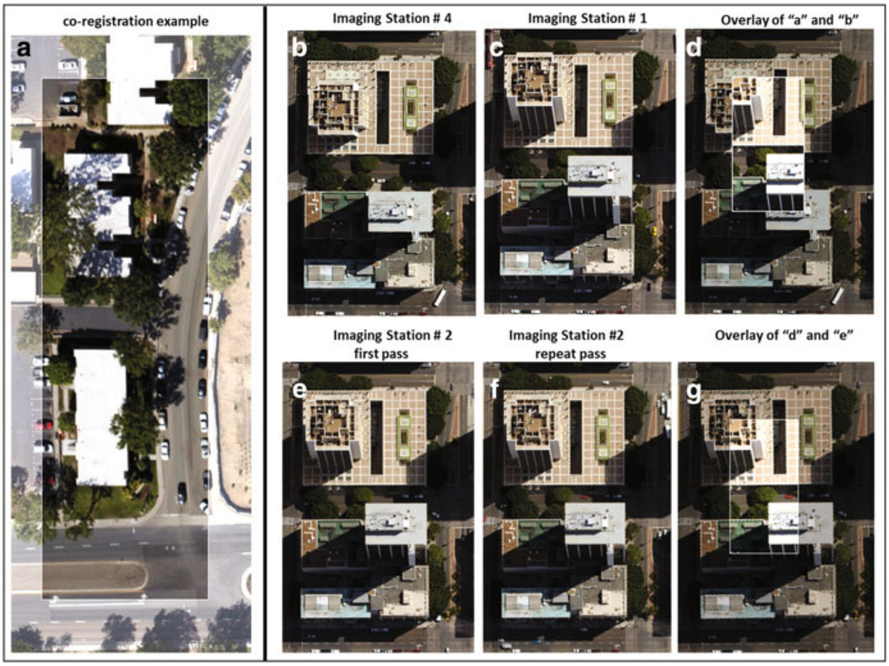

Fig. 1 **a** Time-2 image chip is displayed atop a lighter toned (i.e., washed-out) Time-1 image. The quality of the spatial co-registration between the 8 cm (3 in.) spatial resolution image sets is evident. A vehicle turning the corner is only present in the smaller image chip, and is not present in the larger chip. View angle differences between non-station matched images **b** & **c** are apparent, while view angle replication between station matched images **e** & **f** is demonstrated. Station matched images align precisely when co-registered **g**, compared to non-station matched images **d** which do not align well and are not appropriate for detailed change detection

and view geometry that are sufficient for determining the nature and extent of damage. Any knowledge of the spatial extent of hazard (e.g., from maps of flood extent or ground shaking magnitude) should be used to determine the area of image acquisition. Flight lines are then determined so as to optimize coverage for the desired areal extent.

Flight planning for image-based debris volume estimation can be conducted in a similar manner as for wide-area reconnaissance for damage assessment. A higher degree of along-track overlap in frames is likely since stereoscopic coverage is necessary for determining building/debris volumes. It may be that the same imagery would be used for both reconnaissance and debris volume estimation, such that the image capture requirements of the latter would dictate most of the flight planning specifications. The key consideration for whether this dual purpose usage of RS imagery is effective is the timing of acquisition, such that reconnaissance information can be derived in a sufficiently timely manner to enable rescue and evacuation efforts, while capturing a sufficiently stable debris field (i.e., the hazardous agent has subsided).

Finally, an often overlooked but critical aspect of pre-event planning is the mechanism and form in which remote sensing derived data and information products will be distributed to decision makers (Lippitt et al. 2014). Established responsibilities and protocols are required to ensure an efficient and coordinated response by first responders in various branches and levels of government (Alexander 2002). When coupled with the gravity of their charge to save lives and property, this structure requires that first responders know what information will come when, from whom it will come, and how to integrate that information into their response planning and coordination *before* the hazard occurs.

Collectively, pre-event planning represents the single most overlooked aspect of remote sensing for disaster response. Remote sensing based information collection following hazard events has typically been *ad hoc*, with collection, processing, and dissemination conducted by various private and public parties with minimal coordination. The end result of which is that a very small fraction of the information collected from remote sensing sources is typically exploited during the response phase of the disaster cycle.

3.2 Data Acquisition

Most decisions regarding image data acquisition should be made in pre-acquisition planning stages of the RSS implementation, preferably in advance of an actual disaster event. However, specific conditions during the post-hazard time frame will often require adjustments regarding timing and system configuration when actually acquiring airborne imagery. Factors such as weather (particularly cloud cover), airport runway, and air traffic conditions may necessitate deviation from pre-acquisition imaging plans, such as adjustments to flight plans and camera exposure settings.

While the choice of platform and sensor is made in pre-acquisition planning stages and some considerations pertaining to these TSRSS components were mentioned above, it is worth elaborating on some of the airborne platform and sensor system considerations that could prove to be useful in post-hazard image acquisitions. Unpiloted aircraft systems (UAS) and piloted light sport aircraft (LSA) are mobile, flexible and economical platforms that have great potential for supporting rapid damage assessment of critical infrastructural features (Ambrosia et al. 2003; Laliberte et al. 2010). These platforms can take-off and land in short distances and on a variety of surfaces, fly underneath most cloud cover, and most can be purchased and operated for very low cost when compared to traditional manned platforms. Their limitations are instability in turbulent atmospheric conditions, limited payload capacity and currently in the US, substantial regulatory limits on their operations. Small, high-wing aircraft (e.g., Cessna 172/182) are utilized by the US Civil Air Patrol, a volunteer group of private pilots who are funded by the US Air Force to support post-disaster imaging operations in addition to other mission responsibilities. Of greater utility for wide-area reconnaissance imaging are higher performance aircraft that can rapidly cover large areas and change altitude, with minimal need for refueling. Such aircraft are more expensive to operate, but cover ground quickly, allowing for significantly reduced acquisition times and increased areal coverage (Lippitt et al. 2014).

Most airborne imaging for damage assessment is conducted with digital frame cameras, with some usage of digital line array sensors, while the use of metric film cameras and line scanner sensors is diminishing. The current trend with digital frame cameras is toward smaller, high-density arrays available (i.e., greater number of megapixels) at lower cost compared to large or medium format sensors, but still enabling high spatial resolution imaging and extensive areal coverage per frame. Another trend is more precise and lower cost global positioning and inertial measurement unit hardware, providing exterior orientation information for the location and view perspective of an airborne sensor. Similarly, cost reductions and performance enhancements of stabilized camera mounts help to ensure stable view perspectives.

The hardware component that has the potential to revolutionize time-sensitive remote sensing is the air-ground communications link. Such hardware enables images and/or image-derived maps (processed on-board) to be transmitted to a ground based command and control center for rapid product disseminate. These communication links tend to be prohibitively expensive and limited in range and frequency availability. Recent improvements in all of these characteristics offer great opportunity for remote sensing to contribute to the disaster response effort. An example of a relatively new development in airborne image transmission capability is the Real-time Airborne Management System (RAMS) developed by Pictometry, Inc. with support of the US Department of Homeland Security, Science and Technology Directorate specifically for post-disaster emergency response purposes.

To optimize the RSI image collection and subsequently improve the accuracy and efficiency of change detection processing, airborne data collection should be based on GPS (or other global navigation satellite system) triggering and flight line navigation systems. In the post-event image acquisition, x-y-z positions of flight lines and imaging stations, the digital frame camera, and exposure settings from a baseline collection need to be readily accessible and replicated to the extent possible. The approach enables view geometries and interior orientation properties of sensors to be replicated, which greatly simplifies and refines image-to-image co-registration. The biggest deterrents to implementing the RSI approach are (1) having access to the sensor originally used for baseline imaging and (2) the increasing availability of larger sensor array sizes at lower costs that make using the original sensor less attractive. Capturing images at nearly the same sun angle (or at least time of day) as the baseline image set is desirable, to minimize differences in shadows between image dates/times of acquisition. Scene features viewed from both nadir and off-nadir (i.e., oblique) perspectives may be required for definitive damage assessment. The RSI approach can be applied to either nadir or off-nadir view geometries.

3.3 Image Pre-processing

Image preprocessing considerations include geometric and radiometric corrections, and pre-analysis image enhancements. For geometric processing with single date imagery, it is important to ascertain the level of georeferencing accuracy that is required for a particular time-sensitive task. Unlike traditional image products that often require accurate positioning so that they may be used with GIS data (or used to create GIS data), initial damage assessment immediately following a disaster tend to require less stringent geometric accuracy requirements. This is because the need to have a basic understanding of the extent and severity of the damage in a time frame to make critical decisions is more valuable than a perfectly registered image map. The level of positional accuracy required will depend on the intended application of the data and will primarily be affected by the image collection and supporting sensor systems (e.g., GPS & IMU) when employing a direct georeferencing approach. Geometric correction approaches that rely on reference datasets, significant human intervention, or computationally intensive optimization routines are rarely employed in a hazard response context due the expediency of direct project approaches in comparison.

The accuracy of direct projection is insufficient to enable change detection. The RSI approach may be employed to achieve precise (pixel-level) spatial co-registration between multitemporal image sets using automated techniques (Stow et al. 2003; Coulter et al. 2003; Coulter et al. 2013; Wyawahare et al. 2009) and coupled with direct projection to approximately locate detected changes. The co-registration accuracy of a large number and wide variety of data sets collected using the RSI approach have been tested and consistently found to have a co-registration accuracy within 1–2 pixels even with images having spatial resolution as fine as 8 cm (Coulter et al. 2003; Coulter and Stow 2008; Stow et al. 2003). Registration routines based on automatic control point generation and second-order polynomial warping functions can be implemented "on board" (i.e., images processed on the aircraft, immediately after acquisition) (Coulter et al. 2013; Du et al 2008; Zitova and Flusser 2003), when an RSI approach is used for image acquisition. The georeferencing accuracy of the matched image sets depends upon either the accuracy of the pre-event imagery (assuming that it was georeferenced ahead of time) or the accuracy afforded by the GPS/IMU systems on-board the aircraft at the time of acquisition. Achieving pixel-level spatial alignment between post-disaster imagery and existing ortho-rectified image mosaic products (such as the National Agriculture Imaging Program imagery) is not practical in most cases due to variable terrain and building feature distortions that can't be corrected without ortho-rectifying the post-disaster images with high quality control data. However, flying at higher altitude in combination with a gyro-stabilized mount and long focal length lens can help to minimize geometric distortions caused by 3-D features.

Radiometric processing is useful for aligning digital number (DN) values between multitemporal image sets for reliable change detection. Automated global or local normalization techniques such as empirical line normalization and histogram matching routines can help to standardize image brightness values in like wavebands and therefore, reduce false positive change detections. For many time-sensitive remote sensing applications, however, radiometric preprocessing is minimized or omitted to reduce processing time. Identifying shadows and normalizing differences resulting from variations in shadow patterns between multitemporal image sets is also a critical

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