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Satellite image collection modeling for large area hazard emergency response

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ABSTRACT

Timely collection of critical hazard information is the key to intelligent and effective hazard emergency response decisions. Satellite remote sensing imagery provides an effective way to collect critical information. Natural hazards, however, often have large impact areas – larger than a single satellite scene. Additionally, the hazard impact area may be discontinuous, particularly in flooding or tornado hazard events. In this paper, a spatial optimization model is proposed to solve the large area satellite image acquisition planning problem in the context of hazard emergency response. In the model, a large hazard impact area is represented as multiple polygons and image collection priorities for different portion of impact area are addressed. The optimization problem is solved with an exact algorithm. Application results demonstrate that the proposed method can address the satellite image acquisition planning problem. A spatial decision support system supporting the optimization model was developed. Several examples of image acquisition problems are used to demonstrate the complexity of the problem and derive optimized solutions.

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1. Introduction

For hazard emergency response, the most critical information during the three days immediately following a hazard event are the accurate and timely intelligence about the extent, scope and impact of the event (FEMA, 1999). Based on such information, hazard managers and decision makers can make intelligent and effective response decisions. However, timely acquisition of such information is often prevented and hindered from conventional methods (e.g. ground surveys) because of the scope of the hazard (e.g. large areas) and transportation challenges (e.g., unusable roads and bridges). Instead, remote sensing may provide an effective means (especially for large area hazard response) to collect timely critical information of the impact area in support of effective decision-making during the response phase.

Considerable research has been conducted on the application of remote sensing imagery during the mitigation, warning and recovery phases of the hazard cycle (Tralli et al., 2005; Ostir et al., 2003; Jensen and Hodgson, 2006; Chen et al., 2012; Dong and Shan, 2013; Martinis et al., 2015). However, relatively little research has focused on the use of remote sensing during the hazard response phase, particularly on the image acquisition challenge. For the application of remote sensing during the response phase, the first issue is the coordination and planning of image acquisition (Hutton and Melihen, 2006; Hodgson et al., 2010). Coordinating and planning a solution for image acquisition is not a simple problem. There are a number of potential remote sensing imagery sources from different satellite sensors that could be available during a hazard event. Some of the available imagery may be more helpful based on sensor type, spatial resolution, spectral bands, collection times, etc. Moreover, many hazard events impact an area much larger than a single satellite imaging swath, requiring multiple collection paths from the same satellite-sensor or the use of multiple satellite sensors. This combination of factors makes the image acquisition planning a challenging problem. Hodgson and Kar (2008) modeled the potential swath coverage of nadir and off-nadir pointable remote sensing satellite-sensor systems. Based on their model, determining which satellite-sensor can collect images covering a hazard point location (e.g., latitude and longitude) is possible. Liu and Hodgson (2013) developed a satellite image acquisition planning model. They defined the hazard impact area as a single polygon where the priority of collection was constant across the polygonal area. Using a multi-criteria decision model, they incorporated satellite image acquisition requirements (e.g., spatial resolution, spectral bands, and fully spatial coverage)

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and created an optimum modeling solution for covering the polygon. However, their model did not address varying priorities within a polygonal impact area or multiple polygons (e.g., common in tornado events). For example, infrastructure and residential areas may be considered as higher priority areas than a forested area during the emergency response phase because of the goal to save lives and provide food/water/shelter to local populations. During a hazard event, numerous state and federal agencies have their particular domain areas and thus, possibly different geographic priority areas.

In this research, we extend the satellite image acquisition modeling problem to a complex situation with multiple polygons and consider the varying priority differences in the hazard impact area. A spatial optimization model for large area satellite image acquisition planning was developed and applied in context of the hazard emergency response phase. In this model, different portions of the impact area are represented as separate polygons with different weights reflecting priorities. The acquisition planning optimization problem was transferred to a set covering problem with multiple constraints. An exact algorithm was developed and demonstrated using a hurricane hazard impact area along the coasts of Mississippi and Louisiana. An online spatial decision support system (SDSS) was used to implement the optimization model for satellite image acquisition planning.

2. Background

Remote sensing has increasingly been used for researching hazards and other related practical applications. Intelligence revealed from remote sensing imagery can provide valuable information to hazard managers throughout the life cycle of the hazard event. Over the past 40 years, considerable research has been conducted on the use of remote sensing for the warning, recovery and mitigation stages. However, relatively little research has focused on the use of remote sensing during the hazard emergency response stage.

For collecting information over large areas immediately after a hazard event, remote sensing approaches have substantial advantages over other methods (e.g., *in situ* observations, field data collection). There are some successful applications of remote sensing for hazard emergency response. For example, Laben (2002) introduced the use of remote sensing data and GIS for emergency management at the Pacific Disaster Center. Huyck and Adams (2002, 2004) described the contribution of airborne and satellite imagery to emergency response efforts following the World Trade Center attack. San-Miguel-Ayanz et al. (2005) applied remote sensing systems to detect active fires for fire emergency management. Flanders et al. (2006) introduced the application of remote sensing in oil spill detection and response. Hutton and Melihen (2006) discussed the use of remote sensing for emergency response and noted that preparation/planning is the only way to maximize the security and effectiveness of available information assets and is the first step toward short emergency response phase. Hodgson et al. (2010, 2013) summarized the use of remote sensing and GIS data/information in the emergency response and recovery stage of the hazard cycle. They discussed the social/institutional and logistical issues in the integration of geographical information technologies for the emergency response phase based on a nationwide survey of state-level hazard offices' spatial data needs and use of geospatial technology. By introducing the evolutionary use of remote sensing data/information in three major hurricanes (i.e. Hurricane Andrew 1992, Hurricane Floyd 1999 and Hurricane Katrina 2005), they proposed five research aspects related to the use of remote sensing data/information in the response phase of the hazard cycle and take "Coordination and planning of image acquisition" as the first key issue (Hodgson et al., 2013). To be most useful, planning of image acquisitions is most important before a hazard event occurs. This requires planning in advance to determine which satellite sensors can provide imagery to cover all or part of a potential hazard impact area, and what combination of multiple images need to be acquired to cover the hazard impact area. Once the hazard event happens, imagery can then be acquired immediately from related imagery venders.

Relatively little research has focused on the problem of collecting imagery from multiple satellite sensors to quickly and completely cover the impact area. Ideally, a decision maker could use a generic tool/system to draw a point or polygon on the map and quickly determine which satellite sensors can collect imagery covering the point/polygon during a specified data collection window. Hodgson and Kar (2008) modeled the potential swath coverage of nadir and off-nadir pointable remote sensing satellite-sensor systems based on spherical trigonometry and a satellite orbital propagation model. Instead of searching archived images, this model innovatively provides a generic approach for modeling future satellite-sensor collection opportunities that can cover the hazard location. Liu and Hodgson (2013) studied the polygon-based satellite image acquisition planning and proposed the concept of spatial optimization for innovatively image acquisition planning. However, their research represented the hazard impact as a single polygon and did not address the different priorities within the impact area. In this research, we extend the simple homogenous polygonal problem to a more complex case where the hazard impact area is represented as multiple polygons. We examined the multi-polygon large area satellite image acquisition planning and optimization; each polygon can have unique priority when make the image acquisition plan.

In the next section, the methodology is discussed in detail including the formation of the optimization problem and algorithmic solution. This section is followed by the application results under different scenarios. The article is concluded with a brief discussion.

3. Methodology

3.1. Satellite image requirements identification

Weather forecast technologies and models are becoming more advanced and accurate in monitoring weather related hazards. For example, when a hurricane forms, more reliable estimates of the path of the hurricane, the landing location and time, and the potential impact area along the hurricane path are possible. With this kind of information, hazard management departments/agencies can take effective ways to prepare for the emergency response, such as making evacuation and data acquisition plans. For satellite image planning, the hazard-related remote sensing tasking and acquisition process begins with the identification of an information requirement that can only be satisfied through the application of remote sensing (FEMA, 1999). The identification of satellite image requirements relies on the specification of spatial resolution and spectral bands. For different emergency response information needs, there may be different spatial resolution and spectral bands requirements. FEMA and DHS, under the Remote Sensing Coordinating Committee, have previously defined these information needs as essential elements of information (EEIs) and attempted to match the requirements with spatial resolution and spectral bands. These EEIs are categories assist in the acquisition of critical, geospatial information that allows government agencies to assess and respond to hazards (i.e. hurricanes and floods). Hodgson and Jensen (2010) subsequently conducted a survey on remote sensing experts to identify the satellite image requirements for different

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