NEAR REAL-TIME CHANGE DETECTION FOR BORDER MONITORING

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ABSTRACT

Advances in aerial platforms, imaging sensors, image processing/computing, and geo-positioning systems make near real-time detection and tracking of moving objects on the ground more practical and cost effective. We present a methodological framework for near real-time monitoring of border areas with active and frequent illegal immigration and/or smuggling. The goal is to assist law enforcement in locating and monitoring people and/or vehicles traversing the border region. The approach utilizes low cost platforms such as light aircraft (LA) or unmanned aerial vehicles (UAV) for repeat imaging over short time periods of minutes to hours depending on the border response zone (i.e. urban, rural, and remote). Specialized image collection and processing techniques are employed for automated detection of changes potentially associated with security threats along the U.S. border. This type of near real-time change detection with subsequent pattern/trend analysis is expected to also be applicable to other applications such as live stock management, biological surveys, disaster management, etc.

KEYWORDS: change detection, automated, real-time, sensor orientation, airborne, UAV, border security

INTRODUCTION

The U.S. Customs and Border Protection (CBP) agency is responsible for securing the borders of the United States, and the Border Patrol specifically is responsible for patrolling the 10,000 kilometers of Mexican and Canadian international borders. Their general mission is to detect and prevent illegal entry of people and/or goods into the United States. The Border Patrol also performs a humanitarian mission, by rescuing people lost in remote locations and exposed to harsh environmental conditions. Since the terrorist attacks of September 11, 2001, the focus of the Border Patrol has expanded to include detection, apprehension and/or deterrence of terrorists and terrorist weapons. It is not practical, however, to closely monitor the tens of thousands of square kilometers of open land within close proximity of the border using agents and ground-based sensors alone. Airborne remote sensing offers the potential to monitor expansive areas within the border region, and identify activity of people/vehicles that has not been detected by agents patrolling the border or by ground-based sensors.

As part of the National Center for Border Security and Immigration (NC-BSI or BORDERS), San Diego State University (SDSU) is developing low cost remote sensing techniques that can aid the Border Patrol in their mission. The vision of this project is to have light aircraft (LA) and/or unmanned aerial vehicles (UAV) patrolling active border regions, collecting repeat-pass imagery over periods of minutes, identifying changes in the imagery that are associated with the movement of people and/or vehicles through the border region, and providing that information in a timely manner to agents on the ground. Agents may then utilize the information to locate individuals of interest.

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Advances in microprocessors and communication technology have enabled advances in automated image processing and retrieval such that semi-automated monitoring of transient and dynamic phenomena is now possible using remote sensing (e.g., Herwitz et al., 2003; Stryker and Jones, 2009, Davies et al., 2006; Ip et al., 2006). The delivery of timely information from remote sensing sources requires consideration of all components of a remote sensing system: (1) a platform capable of carrying an appropriate sensor to the scene of interest with sufficient expediency to measure and characterize the phenomena of interest, (2) correction of radiometric and geometric distortions to a degree sufficient to enable the detection of the phenomena of interest, (3) processing or interpretation to characterize or measure that phenomena, and (4) transmission of those data or information to the person or system capable of acting on it, all in an amount of time sufficient to respond to that phenomenon. While the identification of appropriate sensors and platforms is critical to any remote sensing problem, the appropriate and timely processing of image data retrieved from those sensors represents the primary challenge to deploying remote sensing technologies to address time-sensitive information requirements (Joyce et al., 2009).

Near real-time change detection for border monitoring may be performed by collecting repeat-pass imagery over periods of minutes to hours using an aircraft flying a defined (e.g., racetrack) flight pattern. There are five basic steps for near real-time change detection: (1) collect multitemporal imagery using specific techniques that enable precise spatial co-registration of multitemporal images; (2) spatially co-register the multitemporal mages; (3) perform change detection to identify features of interest that are newly apparent or have moved locations; (4) collect geographic coordinate information about the features of interest; and (5) transmit the locations of change features of interest (as well as any relevant attributes) to command and control stations on the ground.

Multitemporal Image Collection

Regular imaging for long durations and across moderate to large extents (e.g., 100 km^2) is only practical with low cost imaging systems. Therefore, we are testing LA and UAV platforms for this purpose. We anticipate that the UAV will ultimately be the only platform conducting this work in an operational manner.

Achieving precise spatial co-registration of high resolution multitemporal imagery in near real-time using automated procedures is not trivial. However, we use specific image collection and processing techniques that minimize terrain related distortion between image sets and enable relatively simple image processing techniques to achieve precise spatial co-registration.

Platforms and Imaging Sensors. Traditional remote sensing platforms (i.e., satellites or fixed wing aircraft) and sensor technologies (e.g., large format digital sensors, film based aerial mapping cameras, and line scanners) require significant hardware and human resources to operate. The phenomena of interest when monitoring the border are typically persons, vehicles, informal infrastructure, and or changes in vegetation condition due to the movement of persons or vehicles. Detection and classification of these targets using remote sensing requires imagery of relatively high spatial (i.e., 0.1-0.5 m) and temporal resolution (Strahler et al., 1986; Woodcock and Strahler, 1987). Real-time, continuous airborne monitoring of moderate to large areas of interest necessitates the deployment of multiple systems, each simultaneously covering some segment of the border.

Manned LA and small to medium sized UAV (Figures 1 and 2) represent viable data acquisition alternatives to traditional, large manned aircraft at significantly reduced relative cost (Laliberte et al., 2010). UAVs permit extended flight times (>12 hours) and coverage without putting human assets at risk. Their current operation, however, in the National Airspace System remains restricted under the present Federal Aviation Administration (FAA) regulatory environment. LA have fewer operating restrictions than UAV, but generally offer limited flight times compared with UAV due to the inclusion of human pilots. In the near term (e.g., 5-10 years), LA represent a viable alternative. However, the extended duration, automated repeatability, and relatively small resource footprint of UAVs will eventually make them the platform of choice for remote sensing based monitoring of the United States border.

Both LA and UAV platforms are ideally suited for the deployment of a variety of relatively low cost imaging sensor technologies. Costs of frame-based digital optical sensors have dramatically dropped in recent years thanks to the broad availability of digital camera technologies. The relatively limited array size, however, of commercially available digital optical sensors (e.g., 8-24 million pixels) when compared to large format digital optical sensors, means they monitor less ground area per unit time at a given resolution, necessitating the deployment of a greater number of sensors to maintain a given temporal resolution. Deployment of un-cooled thermo-optical sensors has also been demonstrated on both LA and UAV platforms. These thermal sensors may enable detection of people and/or vehicles at night. LA and UAV platforms (as shown in Figures 1 and 2) can easily be equipped with a broad range of sensors to meet different mission requirements.

Figure 1. NEOS Ltd. GT500 “Mosquito” light aircraft.

Image Collection using Matched Frame Centers. The Department of Geography at SDSU developed methods for acquiring and processing imagery so that near pixel-level spatial co-registration between high spatial resolution (0.15 m or 0.5 ft) multitemporal image sets may be attained (Coulter et al., 2003; Stow et al., 2003). This is a remarkable technical achievement considering the fine image spatial resolution and highly variable terrain relief of the study areas used for testing the image registration techniques. With these techniques, very detailed land cover changes may be detected (Coulter and Stow, 2005; Coulter and Stow, 2008; Stow et al., 2008; Coulter and Stow, 2009).

Image acquisition procedures that enable precise spatial co-registration between multitemporal image frames are described in Coulter et al. (2003). The approach referred to as frame center (FC) matching is based upon matching camera stations in terms of horizontal position and altitude between multitemporal image acquisitions (Figure 3).

Figure 2. Remotely piloted UAV imaging platform owned and operated by San Diego State University.

Matching image stations is most effectively accomplished through the use of global positioning systems (GPS) to aid the pilot in maintaining the desired track and altitude, and automatically trigger image capture at the same camera station previously visited during the first multitemporal pass. Four specific tools required for operational frame center matching using GPS data are:

1. Global positioning systems for logging and digitally archiving flight line and frame center coordinates for each image acquisition.
2. Flight planning software integrated with digital coordinates of flight line and frame coordinates from previous image dates.
3. In-flight, heads-up display enabling pilot to maintain flight line course and altitude (based on GPS coordinates).
4. Automatic triggering of image frames (based on digitally archived coordinates and in-flight GPS).

When image frames are captured from exactly the same camera station between multitemporal acquisitions, there is no parallax between the images, and they may be expected to exhibit the same terrain related geometric distortions (assuming that differences in camera attitude are negligible). Further, the relative spatial position of features within the images is consistent between image sets and the individual image frames may be precisely co-registered using simple warping functions.

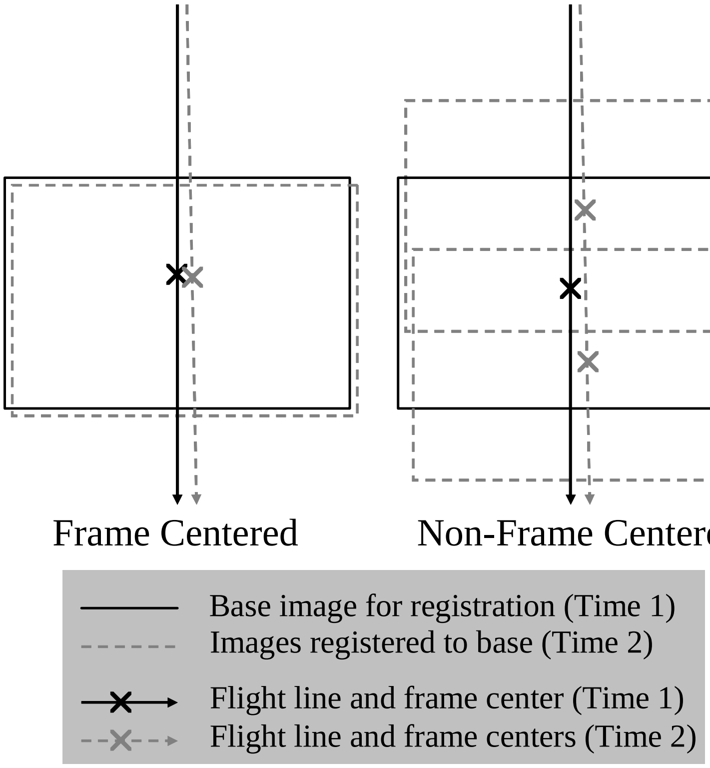

Figure 3. Position of frame center and non-frame center matched images relative to a registration base image. Source: Coulter et al., 2003.

Support Sensors. In recent years, digital sensor technologies have advanced to a degree that enables acquisition of remote sensing data from a range of platforms using readily available off-the-shelf technologies. Consumer-grade cameras, digital gyros, global positioning system receivers, and long-range radio technologies have all seen drastic reductions in price and substantial increases in functionality. In combination, these technologies promote autonomous flight and monitoring of sensor orientation enabling direct projection of acquired imagery at significantly reduced cost when compared to traditionally equipped aerial mapping systems. Power consumption, size, and precision errors have been substantially reduced and the trend seems poised to continue, suggesting that investment in the operation of small UAV systems based on these technologies will lead to substantial cost savings in both the medium and long term.

Multitemporal Image Preprocessing

Atmospheric correction, geometric correction and geo-registration, collectively called ‘preprocessing’, is a computationally intensive portion of the processing sequence. Atmospheric correction has been avoided in most time-sensitive remote sensing (TSRS) applications to date, due to the computational rigor and ancillary data requirements of most atmospheric correction models (Song et al., 2001). Geometric correction requirements are no different for TSRS applications, and have subsequently been well documented (see Toutin, 2004). For TSRS applications with strict temporal constraints, most authors have limited geometric correction to sensor calibration level corrections (e.g., Esquerdo et al., 2006). If TSRS had a preprocessing mantra, it would be “less is more.”

Throughout the TSRS literature, researchers employ the minimal levels of processing necessary to extract the desired information, in a similar vein to the views expressed by Song et al. (2001).

Radiometric Co-registration. To limit ancillary data requirements, radiometric correction in time-sensitive applications is typically relative. Histogram matching or empirical line calibration between image data represent techniques that can be automated and provide relative radiometric co-alignment sufficient to detect subtle changes in brightness. More often, radiometric calibration is omitted from the image processing sequence under the assumption that illumination and sensor properties are static between acquisitions collected over very short time periods.

Geometric Co-registration using Frame Center Matched Images. Image acquisition using the FC matching approach described above yields image frame pairs with similar ground coverage, which exhibit nearly identical spatial distortions since they are captured from the same viewing point. Achieving precise multitemporal spatial co-registration requires that the FC matched image sets be spatially co-registered on a frame-by-frame basis (Coulter et al., 2003; Coulter and Stow, 2008). This may be accomplished using image tie points and simple warping techniques. Automated tie point matching techniques such as spatially invariant feature transformation (SIFT) with random sample consensus (RANSAC) may be used to automatically identify tie points between FC image pairs (Lowe, 2004; Fischler and Bolles, 1981.). Second-order polynomial warping algorithms are appropriate to handle any residual geometric distortions resulting from differences in aircraft pitch, roll, and yaw (or crab) between FC matched image pairs (Coulter et al., 2003). During spatial co-registration one frame (subject) is be matched to the other (reference), and resampling is performed to transform the grid of the subject image. Bilinear interpolation is an appropriate resampling option as it offers efficient processing, while avoiding geometric distortions that result from methods such as nearest neighbor interpolation (Parker et al., 1983).

Automated Change Detection

Image-based change detection may be used to locate changes within a scene over time. TSRS detection applications have primarily used thresholding techniques; either simple (Galindo et al., 2003) or change thresholding (Visser and Dawood, 2004). Most threshold-based detection approaches employ subsequent filtering of false detections using ancillary data (e.g., Ferreira et al., 2007) or additional spatial and/or spectral information not originally used for the detection (e.g., Galindo et al., 2003). The computational efficiency of Boolean thresholding makes it an attractive option for TSRS applications (Joyce et al., 2009). The identification of change features between time-sequential registered images through Boolean thresholding of change values typically requires no or, at most, relative radiometric calibration between images dates under the assumption that change features exhibit greater change values than non-change features, even if images from time-1 and time-2 are not radiometrically aligned. SDSU is reviewing and testing several approaches to automatically detect changes associated with people and vehicles moving within the border region (Figure 4). These approaches exploit such things as change feature brightness, shadow pattern, size, and shape.

The subsequent classification of identified change features based on spectral or spatial properties is possible using automated techniques, but most require ancillary data (i.e., calibration data) or complex decision rules (e.g., object-based approaches). For border monitoring, human interpretation and classification of identified change features is expected to be more effective and provide improved contextual information. Therefore, image chips depicting time-1 and time-2 images as well as change features will be transmitted to command and control stations for review by agents.

Geolocating Detected Changes

Most TSRS applications do not require high positional accuracy of image data unless the information they produce is to be compared to ancillary data layers (Joyce et al., 2009). In a border monitoring context, positional accuracy need only be sufficient to respond to the detected phenomena. Given that the deployment of assets to an area requires time, the location of the phenomena of interest is typically only a starting point for response. Geo-registration by direct projection of image data based on sensor models, GPS data, and inertial measurement unit (IMU) data is the most expedient and most commonly employed registration technique in TSRS applications, despite providing limited registration accuracy (Toutin, 2004, Joyce et al., 2009). Such an approach to geo-registration may be used in near real-time to identify the locations of suspected illicit activity involving people/vehicles in the border region.

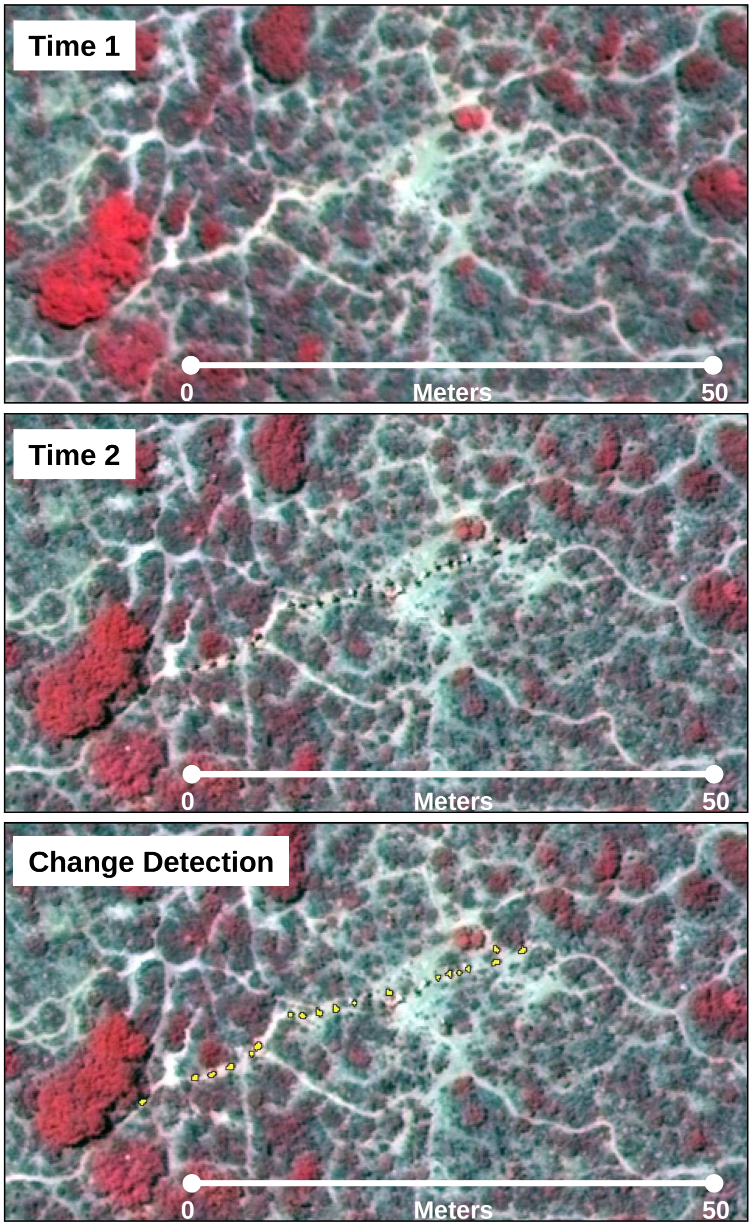

Figure 4. Image-based detection of potential illegal activity in the border region. A suspected group of undocumented immigrants and/or smugglers is detected using airborne digital CIR images and semi-automated image processing.

If image data are to be compared to ancillary data layers and positional accuracy beyond the accuracy of the GPS/IMU is required, the data must be registered using ground control features. For this, precise sensor models and automated ground control point identification systems based on grey level pattern recognition are employed to match subject images to reference images with minimal human intervention (e.g., Bentoutou et al., 2005; Joyce et al., 2009). Further, correction of terrain related distortions through image orthorectification may be required. Such approaches, however, increase computing time compared to the direct projection approach (Bentoutou et al., 2005).

Transmitting Change Information to Command and Control Stations

Wireless transmission of geographic coordinates of detected changes and small image chips containing the time-1, time-2, and change detection images (e.g., Figure 4) will enable Border Patrol agents to locate, identify, and track human activity occurring within the border region. Wireless data transmission, both through existing cellular networks and through independently operated systems, has advanced rapidly in recent years to permit the transmission of data in timescales sufficient for response to many phenomena. Data transmission rates between the sensor and receiving station are constrained by distance and line-of-site (LOS) (Visser and Dawood, 2004). In addition to distance and LOS, power availability and regulatory access to the radio spectrum present challenges to the operation of small UAV and LA. Transmission based on existing cellular broadband technology (i.e., 3G, 4G) alleviate both of these concerns, but currently cellular network distribution in the border regions is insufficient to allow connectivity in many areas. An independently operated wireless network using 802.11 wireless protocol based technology represents a more viable option to support wireless data transmission in more rural segments of the border region.

The 802.11 protocol wireless technology operates in the 2.4 GHz wireless spectrum, which is available for use in the public domain. Hardware and software to support 802.11 protocols are therefore readily available and supported. Without a waiver, 802.11 broadcast strength is limited to 1 watt by Federal Communications Commission (FCC) regulation, which limits omni-direction broadcast and receiving distances (Herwitz et al., 2003). Herwitz et al. (2003) demonstrate the use of omni-direction onboard antenna technology coupled with directional ground based antennas to transmit UAV acquired imagery distances of 24 km when operated at 1 watt broadcast strength. Wireless ethernet bridges employing direction antennas to both broadcast and receive permit data transmission at ranges up to 80 km. A system to support wireless data transmission from all border regions would therefore require the construction of a backbone system based on wireless ethernet bridges, coupled with more frequently distributed (16-24 km) omni-directional receiving stations. Such a system would support connectivity across all border regions simultaneously, permitting each border sector to access data feeds from any other border sector without relying on internet connectivity. Wireless connectivity established across border sectors could provide benefits beyond that of transmission of image data over long distances.

CONCLUSIONS

LA and UAV systems offer low cost, scientific imaging capability. Currently, LA have fewer flight restrictions with the National Airspace System than UAV and represent the most viable option in the near term. The trend, however, is an increase in UAV operations and dominance over the long term. The functionality of LA and UAV imaging systems continues to increase, as does the utility of these systems for information collection and extended duration flight. UAV systems such as the Predator-B already play a role in Border Security. Implementation of affordable, airborne imaging and near real-time change detection capability will provide valuable tools and information that support the mission of the Border Patrol and aid daily operations. Derived information products will further augment existing tools and sensor information streams.

The approach presented here is expected to be appropriate for a variety of applications that require persistent surveillance and detection of moving objects over time for enumeration purposes or rapid response. Potential applications include live stock management, biological surveys, and disaster management.

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