A New Paradigm for Persistent Wide Area Surveillance

Lloyd L. Coulter, Douglas A. Stow, Yu Hsin Tsai, Christopher M. Chavis
Department of Geography
San Diego State University
San Diego, CA, USA
lcoulter@projects.sdsu.edu

Richard W. McCready
NEOS Ltd.
Prescott, AZ, USA
neos500@gmail.com
Christopher D. Lippitt
Grant W. Fraley
TerraPan Labs, LLC.
La Mesa, CA, USA
lippitt@terrapanlabs.com
fraley@terrapanlabs.com

Abstract—A novel and patent pending approach representing a new paradigm for persistent wide area surveillance is presented. As part of the Department of Homeland Security (DHS) National Center for Border Security and Immigration (BORDERS), San Diego State University (SDSU) researchers have developed a method for accurate and automated detection of people and vehicles moving through remote border regions or other uninhabited areas. Instead of imaging small areas at video frame rates (as with traditional surveillance), the approach uses a repeat pass, location-based image capture approach that trades time for space and enables repetitive imaging of large areas at lower repetition rates. Multiple targets may be detected and tracked over large areas, compared to video monitoring which focuses on small areas and often on individual targets previously detected using other means. The approach utilizes high frequency, repeat pass image collection (e.g., same imaging stations every 15 minutes) with frame array cameras to monitor large areas with a single aircraft and detect and locate objects moving through uninhabited landscapes. High frequency imaging from low-cost light aircraft is utilized to characterize the expected brightness response of each patch of ground corresponding to the ground resolution element of a pixel (3-inch ground sampling distance for this study), and an anomaly detection algorithm is used to detect subtle deviations from this expected response. Once anomalies (i.e., objects that have moved) are detected, small image chips (i.e., subsets) may be transmitted wirelessly to command and control stations so that the detection results may be visually verified in near real-time. The detection algorithm utilizes unique change detection thresholds per pixel, making the approach highly sensitive. Initial test results indicate that 98% of people and 100% of vehicles were correctly detected, with virtually no false detection (only 12 pixels within 19 images 21 megapixel in size). SDSU researchers, NEOS Ltd., and commercial partners are working to build a prototype system to further test and demonstrate this near real-time detection approach. This work is developed by the National Center for Border Security and Immigration: A Department of Homeland Security Science and Technology Center of Excellence.

Keywords- wide area surveillance, change detection, airborne, video, real-time, pattern-of-life, UAV, UAS, border security

I. 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 [1].

As part of the National Center for Border Security and Immigration, researchers with the Center for Earth Systems Analysis Research (CESAR) within the Department of Geography at SDSU have developed a novel approach for accurate and automated detection of people and vehicles moving through remote border regions or other uninhabited areas. This approach builds upon several years of experience with precise multitemporal image registration and detailed change detection. The people and vehicle detection approach utilizes time series imagery for characterizing expected scene/background response on a per-pixel basis, and then looks for subtle brightness changes that deviate from the expected response of each individual pixel. The general approach and initial results were first described in Coulter et al. (2012) [1]. The objective of this paper is to provide further insights into the characteristics and benefits of this time series change detection approach, and to discuss the next steps in the development and testing of the methodology.
II. BACKGROUND

A critical requirement for change detection is accurate co-registration of multitemporal images to be compared. The following section describes a specialized image collection and processing method developed by the authors in order to achieve accurate image co-registration, using simple and automated techniques. Following this section, a review of the general methods and results of [1] is provided.

A. Frame Center Matched Image Co-registration

Image registration involves the spatial alignment of multitemporal images, so that the location of ground features is consistent between the images. Without precise geometric registration, change artifacts can be introduced into change detection products [2], [3], [4], [5], [6], [7].

A patent pending approach for collecting and spatially co-registering multitemporal airborne imagery with high precision is described in [8], [9], [10], [11], and [12]. The approach referred to as frame center (FC) matching is based upon matching imaging stations in terms of horizontal position and altitude between multitemporal image acquisitions (Figure 1). When image frames are captured from exactly the same imaging station in the sky between multitemporal acquisitions, there is no parallax between images and they are expected to exhibit the same terrain related geometric distortions. Further, the relative spatial position of features within the images is consistent between image frames. Therefore, precise co-registration may be achieved when images from matched imaging stations are co-registered on a frame-by-frame basis. Matching image stations repeatedly over time 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 predetermined imaging station [8]. Since scene-related image distortions are identical (or nearly identical given possible slight errors in position matching), only sensor-related distortions such as those introduced by differences in aircraft roll and pitch are expected to be present between images. However, these are systematic distortions and can be accounted for when FC matched images aligned using 2nd order polynomial warping [8].

Using the techniques described in Coulter et al. (2003) [8] and Stow et al. (2003) [9], the authors have consistently achieved spatial co-registration within 2 pixels between multitemporal image sets, irrespective of spatial resolution or topographic variability of imaged scenes [10], [11], and [13]. These image sets ranged from 1 m spatial resolution to 0.08 m spatial resolution. For imagery with a spatial resolution of 0.08 m (3-inches), images may be expected to co-register with an accuracy of 6-inches (0.15 m). Even with misregistration on the order of four pixels with 0.08 cm spatial resolution (1 ft or 0.3 m), detailed changes may be detected. Figure 2 illustrates the level of image co-registration achieved between two images with 0.08 m spatial resolution simply by matching the imaging station, identifying matching points between multitemporal images, and applying 2nd order polynomial warping as part of the image registration process. The accuracy of co-registration in terms of root mean square error between these image frames is 1.3 pixels (0.1 meters).

The simplified image registration process of matching imaging station, matching a limited number of points (e.g., 10-20) between images, and warping image frames to match corresponding FC matched image frames with 2nd order polynomial warping enables automated and accurate image co-registration for near real-time change detection. Methods for automated image co-registration are described in [13].

B. People and Vehicle Detection

In [1], the authors describe a patent pending methodological framework for near real time monitoring of border areas with active and frequent illegal immigration and/or smuggling. The methodology is designed 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 aircraft systems (UAS) for repeat imaging over short time periods (e.g., 15 minutes) depending on the border response zone (i.e. urban, rural, and remote). Image-based change detection is performed in near real-time to detect changes associated with people and vehicles moving within the border region. There are five basic steps for near real-time change detection: (1) collect high frequency multitemporal imagery from matched imaging stations; (2) spatially co-register the multitemporal images on a frame-by-frame basis using automated techniques; (3) perform automated change detection to identify features of interest that are newly apparent or have moved locations; (4) collect geographic

Department of Homeland Security, Science and Technology,
National Center for Border Security and Immigration

Figure 1. Position of frame center and non-frame center matched images relative to a registration base image. Source: Coulter et al., 2003 [8].
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 [1]. This approach to near real-time change detection allows agents to see images of detected changes on their computer screens as they are detected, and to instantly identify the locations of these features of interest on a map. Further, images with detected changes can be compared to previous images to further understand the type and nature of detected changes.

Figure 2. Image co-registration example using frame center matched images processed on a frame-by-frame basis. The 0.8 m spatial resolution images from a multiple family residential area under construction are precisely aligned. The Time-2 image is displayed with lighter tone. Source: Coulter et al. (2012) [13].
When images are collected frequently (e.g., every 15 minutes for multiple days) and precisely co-registered with only 1-2 pixel co-registration error, a time series is built up that may be exploited to understand the expected brightness and local texture characteristics of each pixel in a scene at any particular time of day. For example, in order to understand what a scene is expected to look like at 12:15 today, images acquired at 12:00, 12:15, and 12:30 for the last week (21 images) may be analyzed to determine the expected response of each pixel. A new image collected at 12:15 today may be compared to the expected response to determine if the response of any pixel is anomalous, indicating that something changed or moved at that location. The key to the approach is that (under conditions of relatively consistent illumination) most pixels will have a narrow range of expected brightness, and minor deviations from this range (unique to each pixel) may be exploited to detect subtle changes. In areas where trees or bushes blow in the wind, a pixel may vary in appearance between vegetation, shade, and illuminated soil; in this case, the expected range of brightness will increase and decrease the sensitivity of detection but will not yield false detections. Similarly, shadows moving over the course of the reference time period increase the brightness variability, decreasing sensitivity of movement detection.

In Fall 2011, San Diego State University and NEOS Ltd. personnel worked with the San Diego sector of the Border Patrol to test the methodology described above [1]. Repeat pass imagery with 0.08 m (3-inch) spatial resolution was acquired at three sites near Jacumba, CA. The sites are characterized as desert (site 1), grassland (site 2), and chaparral scrub vegetation (site 3). Figure 3 illustrates the diversity of land cover types within each study site. Imagery was collected on September 29, 2011 using a Flight Design CTSW, 2006 model light aircraft and a 21 megapixel Canon EOS 5D Mark II camera. RAW format color (RGB) images recorded on the Bayer array were later converted to 3-band TIFF image files. A Track’Air EZtrack navigation and camera triggering system was used to accurately navigate pre-planned flight lines and to automatically trigger the camera at the exact same predetermined imaging stations (same horizontal and vertical image station each time, within approximately10 m). Several passes were made down the individual flight lines, collecting repeat-pass imagery approximately every 4 to 5 minutes. For site 1, nine passes were made over a 40 minute period (9:00-9:40 AM). For sites 2 and 3, thirteen passes were completed over a 55 minute period (10:15-11:10 AM). For site 1, the aircraft flew a race-track pattern and collected imagery with the west/southwest heading each time. Sites 2 and 3 were adjacent to each other, and site 2 was imaged with an east/northeast heading and site 3 was imaged with a west/southwest heading as part of the same race-track pattern, as would be performed operationally.

During the image collections, SDSU and Border Patrol personnel and vehicles moved regularly so as not to be in the same locations on successive imaging passes. For most instances, people moved between each imaging pass. Participants were instructed to move vehicles every ten minutes. However, given the high frequency of imaging passes vehicles were in the same positions for 2-3 imaging passes in several instances.

To simplify processing of the color aerial images, only the red waveband was utilized since it provides good discrimination between scene features such as vegetation, shadow, and soil background [14]. First, red-waveband images for each individual site were spatially co-registered on a frame-by-frame basis using the methods described above. Since our automated co-registration approach was still under development, this was accomplished by manually selecting 9-13 matching points between images and co-registering all images to the same reference image. Image warping was accomplished using second-order polynomials and bilinear interpolation. No georeferencing or terrain correction was performed.

Following spatial co-registration, the images for each individual site were radiometrically normalized using a mean-standard deviation normalization technique [15]. This approach normalized all images radiometrically and accounted for minor variations in illumination, as well as differences in image brightness resulting from varying aperture settings. The camera was set for shutter priority, and aperture subsequently varied between photos due to slight aircraft rotation and resulting variations in scene extent.

To detect moving/changing objects at each of the three sites, 1) the full time series of images at each site was used to determine the average brightness (mean) and expected variability (standard deviation) at each pixel, 2) standardized (Z-score) thresholds were interactively determined for brightness increase, brightness decrease, and 3x3 texture increase, and 3) individual image digital number (DN) values were compared to the threshold values to identify change pixels that fell outside of the expected range. As described in [1], a measure was used to allow for up to two pixels misregistration error, and a 3x3 focal majority was used to remove isolated change pixels representing noise.

Using this patent pending approach, threshold settings were unique per pixel, allowing varying sensitivity depending upon the scene background at individual pixels. Further, only three standard deviation values were specified to establish these varying/pixel-specific thresholds, so adjusting and fine tuning thresholds to change the sensitivity required for detection is simplified.

The change detection procedure described above was applied to 19 total images, including five from site 1, seven from site 2, and seven from site 3. The images utilized were from the middle part of the imaging sequence, so that any variations in shadow, etc. would be accounted for by the wider temporal range of the full time series.

Results from the people and vehicle detection testing are presented and discussed in detail in [1]. People and vehicles that moved between imaging passes were detected with high accuracy, with almost no false detection. Detection accuracy for people and vehicles that moved between imaging passes was 98% (63 of 64) and 100% (11 of 11), respectively. Twelve pixels of false detection were identified out of nineteen
Figure 3. Desert (site 1), grassland (site 2), and chaparral (site 3) study sites near Jacumba, CA. Yellow rectangles indicate planned extent of image area per site, approximately 400 m by 300 m each. Source: Coulter et al. (2012) [1].
images 21 megapixels in size each, which were associated with power pole and power line shadows that moved as the sun changed position over the 40 minute imaging period from 9:00-9:40 AM on September 29, 2011. Figures 4 and 5 show detection results for two images acquired on September 29, 2011 at sites 1 and 3.

People and vehicles that stayed in the same position for two or more of the nine (site 1) or 13 (sites 2 & 3) images in the temporal sequence became part of the background (or expected variability) and were not detected. These people/vehicles were not included in the accuracy assessment because in an operational scenario these people/vehicles would have had to stay in one position for one or more days, which is not very likely to occur. Further, the one person that was missed actually stood at a location where there was a vehicle shadow, which made the expected variability high at that location which (in the absence of the vehicle shadow) normally had bright soil. If the vehicle had not been present, the person would have likely been detected.

III. CHARACTERISTICS AND BENEFITS OF THE CHANGE DETECTION APPROACH

The image collection and change detection procedures used by [1] open up a wide range of possible image analyses and applications. These include slow frame rate video and automated detection of moving/changing objects using a range of sensor/platform combinations and imagery collected with wide range of temporal frequency (e.g. several frames per second to one frame every several minutes, hours, days, etc.).

A. Slow Frame Rate Wide Area Imaging

The approach utilized in [1] for people and vehicle detection is referred to as the Wide Area Time Series Change Indicator (WATSCIN), and is comprised of two primary innovations: 1) repeat-pass imagery collection with precise co-registration and 2) a specialized change detection algorithm referred to as automated temporal thresholding (ATT). The repeat pass imaging approach exploits the ability to automate co-registration of airborne frame images using the FC matching technique, and has many interesting and useful characteristics. The approach substantially extends the area that may be monitored by a single airborne system by trading time for space, and imaging large areas frequently, but not continuously. This is in contrast with existing wide area surveillance systems which attempt to continuously image an area within the sensors field of view at rates of 2-30 frames per second.

Another aspect of this imaging approach is that when an aircraft flies a racetrack pattern repetitively imaging from multiple (e.g., 100) imaging stations in the sky, and multitemporal frame images from each imaging station are automatically co-registered and precisely aligned (creating unique sequences of multitemporal images for each imaging station), effectively slow frame rate video is captured. Thus, with 100 imaging stations there are effectively 100 video cameras fixed mounted in the sky imaging at a slow frame rate (i.e., one frame every 15 minutes). Further, these images with high temporal resolution and wide area coverage may be assembled in different sequences, depending upon the purpose. For example, the images may be assembled in chronological order, creating slow frame rate video in the order in which the images were collected, or they may be assembled into sequences or sets from a particular time of day (e.g., 12:00, 12:15, and 12:30) to understand the expected brightness/texture characteristics for a given area at that time of day. For the former case, where image sequences are assembled based on chronological order, the precisely aligned image sets from individual imaging stations may also be mosaicked with other sets from different imaging stations to create a mosaic of slow frame rate video for a single large area. This patent pending approach may be useful for understanding the progression of events such as natural disasters. An analogy to this would be the slow frame rate video that was captured from a hillside looking at Mount St. Helens when it erupted in 1980, only in this case the wide area, slow frame rate video would be from an airborne perspective and likely less frequent.

B. Near Real-time Automated Moving Object Detection

Rather than continuously tracking selected features of interest within a scene that were previously identified by a human analyst (as many current wide area imaging systems such as the Constant Hawk, Kestrel, Gorgon Stare, and ARGUS are designed to do), the WATSCIN ATT algorithm is designed to automatically detect previously undetected moving and/ or changing objects. The WATSCIN system acts as a sentry alerting agents that there is new activity in a previously inactive area, rather than providing a continuous video feed for intelligence purposes. Also, the ATT algorithm can be used with time series images collected with varying frequency. In fact, the algorithm may be appropriate for 30 frame per second video, assuming that the video images are stabilized and co-registered well. As a side note, if the ATT algorithm is used with continuous video imaging systems using time series images selected for a frequency of approximately every second, it is possible to save the movement tracks and use that information for pattern-of-life (POL) analysis. Pattern-of-life analysis involves gathering information on activities of subjects of interest over periods of days and weeks [16].

The WATSCIN approach utilized in [1] enables near real-time detection of previously undetected objects, with visual verification of the detection using high spatial resolution (e.g., 0.08 m or 3-inch) imagery. Near real-time detection will occur within seconds to minutes after the aircraft passes the area with a new/moving object (some minimal time will be required for on-board processing). When a new/moving object is detected, small image chips showing the previous image (when nothing was present), the current image (when something new is present), and an image indicating which pixels exhibited change may be wirelessly transmitted to a ground based command and control station. An agent may then view the images and determine if there is activity of interest or not at the site of the detected change. Further, the geographic coordinate providing the location of the detection may be wirelessly transmitted along with the image chips, so that the location may be displayed on a map. Figure 6 illustrates the display that an agent might view with new detections continuously feeding in as they occur.
C. Benefits of the WATSCIN Approach

The WATSCIN border monitoring system provides many benefits over or in addition to current tower mounted and airborne surveillance systems. Using 0.08 m (3-inch) spatial resolution imagery, small features on the order of 0.5 m² may be detected, and visually verified. Unlike tower systems, the WATSCIN approach provides the eye-in-the-sky vantage point, and also covers much more area. Unlike General Atomics’ Lynx synthetic aperture radar (SAR) system, objects do not have to be moving to be detected. This is the case because the approach is exploiting brightness and texture changes over time, instead of looking for near instantaneous motion. The product delivered by the WATSCIN system would also be user-friendly, requiring no specialized skills to interpret the change detection results or to adjust the sensitivity of the system, which could be controlled by three dials that increase or decrease the detection sensitivity associated with brightness increase, brightness decrease, and texture increase.

Another key benefit of the WATSCIN system is that high frequency repeat pass imagery may be downloaded from the aircraft at the end of each mission and utilized for immediate forensic analysis or stored for future analysis. Since images are always collected from matched imaging stations, future image sets may also be automatically and precisely co-registered using simple techniques and used for intermittent change detection. For example, imagery collected today and imagery collected next month may be compared in order to identify land cover changes associated with new/changing trail use and land cover changes potentially associated with tunneling activity (new buildings, spoil piles, soil changes, etc.). An example with new trail activity is shown in Figure 7.

The WATSCIN approach is expected to function well in a variety of environments. Desert environments are expected to be ideal when the WATSCIN approach is used with visible imagery, since atmospheric and associated weather conditions generally are relatively stable. With stable atmosphere/illumination conditions, the approach is also
expected to work well in environments with tall and varying tree cover. In these environments, current systems that rely on staring video from moving/circling platforms are affected by trees entering the field of view and obscuring the view of the target of interest. Since the WATSCIN approach uses repeat pass images collected from the same position in the sky, the viewing geometry is unchanged between successive images passes and nothing in the imaging geometry changes substantially to obstruct the area viewed. However, weather along the northern border changes often, so that is problematic. It is possible that the WATSCIN approach may function with panchromatic images from SAR sensors, but this remains to be tested. The benefits of SAR imaging include all weather and day/night imaging.

As was mentioned earlier, the detection sensitivity of the WATSCIN approach depends upon the range of variability that any given pixel has through the time series. When features such as branches blow in the wind or shadows move over the reference time period, the range of values in the time series for pixels corresponding to those feature goes up (e.g., branch, shade, or bright soil may be seen at different times). When this happens, detection sensitivity is reduced and fewer change features will be detected. Similarly, if atmospheric conditions vary between images utilized for the time series, then the range of values in the time series will increase and detection sensitivity will be reduced (mean-standard deviation normalization applied using local kernels or windows may correct for such atmospheric variability). However, it is important to note that the approach is robust against false detection, because new image brightness/texture values must exceed the range of all/most of the images utilized for the time series.

Figure 5. Image-based detection of people and vehicles moving within a portion of the U.S./Mexico border region. Staged people and vehicles are detected as they move through a chaparral area (site 3) near Jacumba, CA. Red indicates detection of movement, as people or vehicles were not at these locations during other imaging passes. All people and vehicles were detected, with no false detection (commission error). Source: Coulter et al. (2012) [1].
IV. DISCUSSION AND NEXT STEPS

To date, the WATSCIN approach has only been tested using ground-based imagery (oblique imagery from a roof top) and for the airborne imagery collection of the border region described above. SDSU, NEOS Ltd., and partner companies are interested in testing the approach using time series image sets from a range of geographic locations (including areas with tall trees), at varying times of day, with a range of sensors (e.g., thermal or SAR), and time series image sets collected over periods of several days. Further, the testing to date has not used automated systems and we seek to develop a prototype system that will demonstrate on-board, automated processing with detection results provided in near real-time.

Several steps should be taken to improve the functioning of the WATSCIN system and to improve/maintain high detection accuracy. The WATSCIN approach relies on accurate image co-registration, so that small patches of ground corresponding to individual image pixels may be analyzed through time. For the test documented in [1], frame center matching was based on uncorrected, pseudo-random code GPS data, resulting in position matching on the order of +/- 10 m. The use of survey grade GPS in combination with an autopilot (autopilot was also not used previously) will result in improved position matching, which is critical when trying to replicate terrain/feature distortions between multitemporal images. In addition, flying at higher altitudes will also remove distortion differences, given a constant error in position matching (e.g., 10 m). However, flying at higher altitudes likely will require the use of gyrostabilized mounts with inertial measurement units (IMU) so that aircraft movements don’t result in drastically different image footprints on the ground (i.e., multitemporal images maintain a common ground extent). Use of IMU will also enable corrections of aircraft rotations associated with yaw/crabbing so that image footprints are well matched.

Having a longer time series is expected to improve the scene/background characterization and result in improved sensitivity for detecting new/moving object within newly acquired images. The Canon 5D Mark II camera used by [1] utilized a Bayer array [17] which subsamples individual spectral wavebands and reduces image quality. Results are expected to improve when a high quality camera with complete
sampling per waveband is used. Modifications to the algorithm as well as incorporation of multispectral information may also improve results (only red waveband was used by [1]). Further, we tested the approach with a small format 21 megapixel camera, but medium format, large format, and even gigapixel sensors may be utilized to extend the swath of each image and therefore the extent of area that may be imaged during a fixed time period.

V. CONCLUSIONS

The characteristics and utility of patent pending technology for detailed change detection in the context of people and vehicle detection for border security are presented here. Using the frame center matching approach to image collection and coregistration, precise image alignment is consistently achieved between multitemporal frame images. The wide area time series change indicator, or WATSCIN, approach to change detection enables accurate detection of moving/changes within uninhabited landscapes, allowing light aircraft or unmanned aircraft systems to act as sentries alerting when there is new activity in a previously inactive area. The same automated moving object detection approach is expected to have applications with continuous video streams and for pattern-of-life analysis.

The extent of area that may be monitored by one system depends upon the type of camera(s) used (i.e., the number of megapixels/gigapixels), the image spatial resolution, the number of cameras, the velocity of the aircraft, and the frequency with which the system returns to each imaging station as the aircraft flies a racetrack flight pattern (visiting multiple imaging stations along the way). The extent of area to be monitored may be increased by increasing the size of the imaging array, increasing the number of systems performing monitoring, or adjusting other variables listed above.

Detection and tracking of moving objects across wide geographic areas may also be appropriate for such things as search and rescue of missing persons, wildlife tracking, and monitoring military resources or enemy movements on the battlefield. In addition, the sensitivity of the change detection approach may have applications for improvised explosive device (IED) detection. San Diego State University personnel, NOS Ltd., and other partner companies seek to build a prototype system for testing and demonstrating near real-time change detection. The low-cost system that is envisioned would utilize light aircraft and commercial-off-the-shelf (COTS) technology, providing a cost-effective solution for near real-time change detection. Such a system also has applications for rapid disaster assessment, and SDSU is currently developing automated change detection routines for post-earthquake assessment.

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