Toyon Research Corp.
Dim Target Tracking Capabilities Statement

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1.0 TOYON DIM TARGET DETECTION AND TRACKING CAPABILITIES

Toyon has developed numerous dim target detection and tracking capabilities over more than a decade of research and development. Here we provide the details of two approaches and their relevance to the SINTRA program. The first is our track-before-detect (TrBD) algorithm chain that leverages a near-optimal estimation framework to integrate information over multiple images to provide high probability of detection on dim targets with a very low false alarm rate. This method has been implemented as a software application, known as Dim Target Extraction and Conjoint Tracking (DTECT), which processes high framerate sensor data in real-time and has been proven on numerous dim target detection and tracking use cases. The second is an approach currently being designed with the support of AFRL and Space Systems Command (SSC) specifically for onboard processing using FPGA-based architectures. This approach leverages recent advances in machine learning to achieve similar performance using a single frame for detection.

For each of these approaches, the required sensor characteristics are fairly minimal for satellite-based target tracking missions. The DTECT application has been successful in processing line-scanned, push-broom, and global shutter imagery. The basic requirement is that an image be sufficiently large enough for scene information to be leveraged in frame registration and background estimation. There is also the assumption that multiple frames with a high percentage of overlapping scene content are available for processing. For example, if a sensor in LEO is collecting image frames at nadir with only a 10% overlap between two sequential images, then the utility of TrBD would be completely lost as information cannot be reliably integrated over multiple frames. Notably, there is *NO* requirement that the scene remain stationary from frame-to-frame as is often the case for existing SBIRS GEO processing. In fact, Toyon’s algorithms were designed for lower altitude moving platforms, so frame-to-frame scene motion is accounted for within our algorithms.

2.0 TRACK-BEFORE-DETECT

In classical tracking methods, a thresholding operation is performed on the detection metric (e.g., filtered clutter-suppressed imagery) to generate target detections, or exceedances, that are subsequently processed by data association and state estimation algorithms. Thresholding, however, causes partial loss of information and target tracking based on this approach may be completely infeasible in complex clutter environments. For example, if the detection threshold is set low enough to detect very dim targets, the number of false alarms on clutter may result in either poor track estimation performance, or prohibit real-time operation as the number of data association hypotheses explodes. In TrBD, information from individual frames is integrated over time until the number and locations of targets can be accurately estimated. The effective increase in target SNR that is obtained via TrBD is proportional to the square root of the number of frames processed. Toyon has verified in past work that our real-time TrBD algorithm is able to achieve effective SNR improvements essentially equivalent to these theoretical limits.

Toyon's TrBD algorithm processes image data (typically post clutter suppression) and performs joint detection and tracking in the sense that tracks are generated without first formulating detections per-image. The algorithm integrates information from target intensities over time, enabling successful detection and tracking at lower signal-to-noise ratios (SNRs) than would otherwise be possible with a standard detect-then-track architecture. In addition, for high-frame-rate imagery (HFRI), the TrBD algorithm can perform joint target classification and tracking. This means that reported tracks are believed to correspond to targets that the algorithm locates based on approximate *a priori* knowledge of the targets' temporal signal characteristics. For example, knowledge of a target's approximate power spectral density (PSD) can be exploited under these conditions.

For standard frame rate imagery (SFRI), the information used to discriminate between targets and non-targets (e.g. clutter, stars, etc.) is target motion and target-to-background contrast. Clutter suppression is performed by comparing motion-compensated images collected over multiple frames. No specific assumptions are made regarding the target intensity being constant or time-varying. Thus, the algorithm is able to automatically detect and track a wide variety of target types, including maneuvering targets as well as multiple targets within the scene. The algorithm is able to track both bright targets and dim targets simultaneously by merit of integrating information in the TrBD framework. The latency associated with declaration of a confirmed target track is typically less than the latency inherent in other algorithms that perform detect-then-track and do not exploit all available information due to the binary nature of exceedance generation by thresholding.

3.0 DTECT SOFTWARE APPLICATION

Toyon's dim target detection, TrBD technology, has been implemented in a software application called DTECT. Our baseline application includes end-to-end processing of raw data streams to enable a complete dim target detection and tracking capability. This includes data pre-processing, spatial-temporal background estimation and removal, residual clutter processing, and automated target detection and tracking. DTECT is written as a highly modularized application which allows sub-capabilities to be quickly reformatted as independent applications for image processing. An example is Toyon's Clutter and Leakage Estimation And Removal (CLEAR) application, which performs all of the front-end data processing along with clutter estimation and removal to produce a clutter-suppressed version of the scene. The CLEAR application has been utilized as a standalone application on several existing programs involving satellite-based image processing.

Figure 1 below shows a high-level block diagram of the processing flow for the DTECT application. Practically speaking, Toyon has several different algorithms that can be brought to bear for each of the processing blocks. For example, when processing SBIRS OPIR data, we typically use a principle component-based algorithm for clutter estimation and rejection. However, when processing remote sensing data collected from an aerial platform, we typically employ alternative clutter suppression algorithms that are designed for challenges such as parallax. These algorithms include both Toyon's Typical Apparent Change Model (TACM) and Modeling and Prediction of Scenes (MAPS) algorithms. TACM is a computationally efficient algorithm based on statistical background modeling of the expected differences in images. This method is a major deviation from both simple frame differencing and standard statistical background modeling. TACM is therefore well-suited for onboard processing where methods using the principle components and/or MAPS approach are traditionally better suited for ground-based processing.

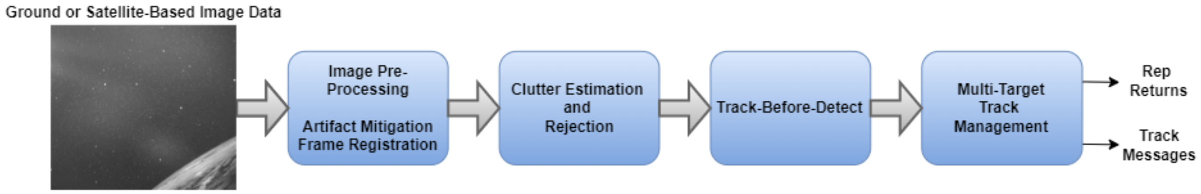

Figure 1: High-level block diagram of Toyon's DTECT processing chain

The DTECT application is currently implemented in C++. It performs real-time operation for many remote sensing applications, however, it is also employed to process higher framerate data where additional speedup is required to achieve real-time capabilities. To this end, the algorithms have been implemented and optimized to take advantage of Graphics Processing Unit (GPU) acceleration. This enables a processing speed of greater than 30 frames per second (fps), for 1024x1024-pixel imagery, on standard video formats with a single GPU desktop computer. The specific throughput performance is largely dependent on several factors including the computing hardware specifications, the data size being processed, the metadata accuracy and scene specifics. Currently this requires use of an NVIDIA GPU to leverage the CUDA API functionality. However, implementations have been transitioned to other GPU architectures via OpenCl.

DTECT can be run in various configurations for input and output type. Currently, Toyon has implemented streaming interfaces using zookeeper and kafka that allow messages to be passed using standard proto definitions. For certain specific missions, DTECT ingests ILOS messages (in either the HEMI or SAGE format) and produces detections as either an exceedance, rep-return or track. However, we also have our own internal track class that allows the reformatting into other output types. We have experience with many standard tracking definitions (e.g. MISB) and have many existing interfaces for producing and ingesting those data streams. DTECT can also operate directly on standard image formats, such as sequences of .png formatted imagery.

Toyon's DTECT application has been demonstrated on real-world SBIRS data on numerous contracts. This includes the Power Walker program under SMC BAA 16-086 led by Lockheed Martin, and on an MDA sponsored Phase II STTR program where it has been integrated at the Enterprise Sensors Laboratory (ESL). In its current version DTECT is TRL 6-7.

4.0 ONBOARD DIM TARGET DETECTION AND TRACKING

For processing onboard an aerial or satellite platform, detection algorithms must physically reside within the available onboard processing resources. These processing architectures depend on the platform design, the environmental conditions in which it will operate, and its intended lifespan. The design of spacecraft computing hardware architectures typically requires the use of radiation-hardened components, excellent power management, and sufficient component redundancies. This has historically limited the use of more modern computer architectures/components, such as GPUs, and also limits the size of available memory. On the other hand, the data available to the onboard detection processing scheme is not limited by the size of the communication link to the ground. Solutions must balance the tradeoffs between false detections and missed detections while adhering to strict processing resources, latency timelines and bandwidth considerations. The solution space for detection processing on the onboard architecture will be much different than that for the ground station.

Toyon has been pursuing target detection and tracking algorithms enabling onboard processing for the last few years in support of next-generation OPIR satellite systems. To date, Toyon has produced well-performing approaches for both single frame and multi-frame dim target detection and tracking capabilities by using a combination of spatial-temporal processing, machine learning, and multi-target tracking methods. These have not outperformed state-of-the-art aforementioned TrBD methods for dim targets, but have far less computational requirements and are ideally suited for onboard FPGA implementation. These algorithms have been demonstrated at TRL 5+ to AFRL and SSC, and transitioned to the AFRL SPACER Lab for integration into their operational test system. This was achieved by utilizing Toyon's embedded systems' expertise and FPGA hardware in-the-loop testing and analysis.

5.0 DTECT EXAMPLE

Figure 2 shows simulated imagery and results from DTECT application processing. The simulated data included two very dim target signatures that were inserted within an actual satellite image. The target intensities were set so that the average signal-to-clutter ratio (SCR) was 1/1000 with an SNR = 4. Both targets were imperceptible in the raw imagery seen on the left. The target tracks generated by DTECT are shown in red in the center image, with the associated track covariance ellipses drawn around the estimated track states. The right-most image shows the estimated DTECT track state plotted against truth for both targets over the entire trajectory.

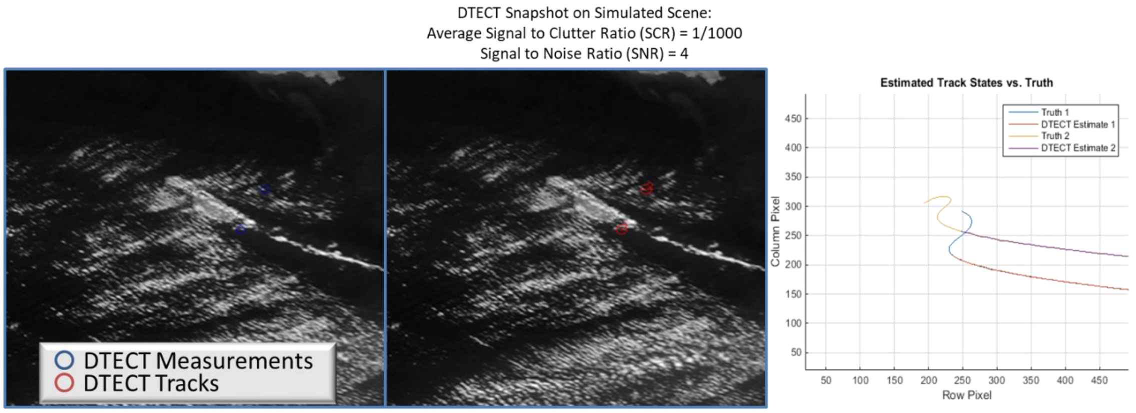
DTECT Snapshot on Simulated Scene:
Average Signal to Clutter Ratio (SCR) = 1/1000
Signal to Noise Ratio (SNR) = 4

Figure 2: DTECT clutter suppressed imagery with automated detection and tracking results

6.0 SIMULATION OF OPIR DATA

Over the past decade Toyon has developed numerous data simulation capabilities for various platforms and wavebands. For satellite-based data simulation, we are currently using the AFIT Sensor and Scene Emulation Tool (ASSET). ASSET is a medium-fidelity model that avoids computational cost of higher fidelity ray tracing methods yet retains sufficient radiometric accuracy to represent a wide range of sensors and scenes. It consists of two main components, the scene model (to include backgrounds and targets) and the sensor model. Scene generation is accomplished by using one or more input images as geographic texture maps defining surface reflectivity, emissivity and temperature of the earth background. Thermal emitted and solar-reflected spectral radiances from ground terrain are calculated for user-defined solar position. Temporally and spatially varying target signatures are created either internally, using stochastic kinematic models with user-defined kinematic and radiometric bounds, or externally and based on user-defined 3D trajectory and radiometric signatures. These targets are not just added to the scene, but injected, including background obscuration, atmospheric path radiance and atmospheric transmission loss. Dynamic clouds that change both in shape and position, as well as spanning a range of altitudes to allow for altitude-dependent target transmission and obscuration, may also be included using a global cloud texture map.

7.0 CYBERSECURITY

As part of our ongoing integration efforts on several programs Toyon is conducting cybersecurity scanning of the DTECT application as needed. This includes the use of Fortify and Sonarqube scans. Any perceived risks have been remediated with the required cybersecurity leads for all of our integration tasks thus far. This includes recent integrations at the TAP Lab, ESL, and FORGE Framework.