KOLAM: A cross-platform architecture for scalable visualization and tracking in wide-area imagery

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ABSTRACT

KOLAM is an open, cross-platform, interoperable, scalable and extensible framework supporting a novel multi-scale spatiotemporal dual-cache data structure for *big data* visualization and visual analytics. This paper focuses on the use of KOLAM for target tracking in high-resolution, high throughput wide format video also known as wide-area motion imagery (WAMI). It was originally developed for the interactive visualization of extremely large geospatial imagery of high spatial and spectral resolution. KOLAM is platform, operating system and (graphics) hardware independent, and supports embedded datasets scalable from hundreds of gigabytes to feasibly petabytes in size on clusters, workstations, desktops and mobile computers. In addition to rapid roam, zoom and hyper-jump spatial operations, a large number of simultaneously viewable embedded pyramid layers (also referred to as multiscale or sparse imagery), interactive colormap and histogram enhancement, spherical projection and terrain maps are supported. The KOLAM software architecture was extended to support airborne wide-area motion imagery by organizing spatiotemporal tiles in very large format video frames using a temporal cache of tiled pyramid cached data structures. The current version supports WAMI animation, fast intelligent inspection, trajectory visualization and target tracking (digital tagging); the latter by interfacing with external automatic tracking software. One of the critical needs for working with WAMI is a supervised tracking and visualization tool that allows analysts to digitally tag multiple targets, quickly review and correct tracking results and apply geospatial visual analytic tools on the generated trajectories. *One-click* manual tracking combined with multiple automated tracking algorithms are available to assist the analyst and increase human effectiveness.

Keywords: wide-area motion imagery, WAMI, digital tagging, assisted tracking, trajectory visualization, trajectory data mining, spatiotemporal cache, multiresolution tiled pyramid imagery

1. INTRODUCTION

Exploratory visualization and analytics tools are powerful methods to support multiple data-streams and navigate through very large datasets. Such tools offer ways to mitigate the *data deluge*[1] being faced by users and analysts and are useful for providing insight into complex patterns in scientific, biomedical, geospatial, satellite, and surveillance applications. In the intelligence, surveillance and reconnaissance (ISR) community the massive data problem is popularly paraphrased as "Swimming in sensors, drowning in data"[2] to convey the increasing urgency of this problem with respect to processing the flood of airborne video from defense surveillance assets. KOLAM (K-tiles for Optimized muLtiresolution Access with coMpression)[3,4] is a scalable and extensible framework for high-resolution, high throughput image data visualization with applications in a variety of image analysis domains including WAMI.[5] It is platform and operating system independent and supports embedded datasets scalable from hundreds of gigabytes to potentially petabytes in size on architectures ranging from clusters to netbooks. KOLAM uses a scalable data structure and dual cache management strategies to support large datasets along with an extensive set of image processing and analysis features. Robust animation and novel tracking interfaces are available to enable smooth animation of WAMI sequences and support *one-click* per frame tracking of objects. KOLAM is capable of interfacing with different tracking algorithms and visualizing the resulting trajectories that may be composed of multiple segments. Figure 1 shows the coupling between the visualization environment and the open architecture supporting a collection of tracking algorithms. A feature-rich tracking interface enables

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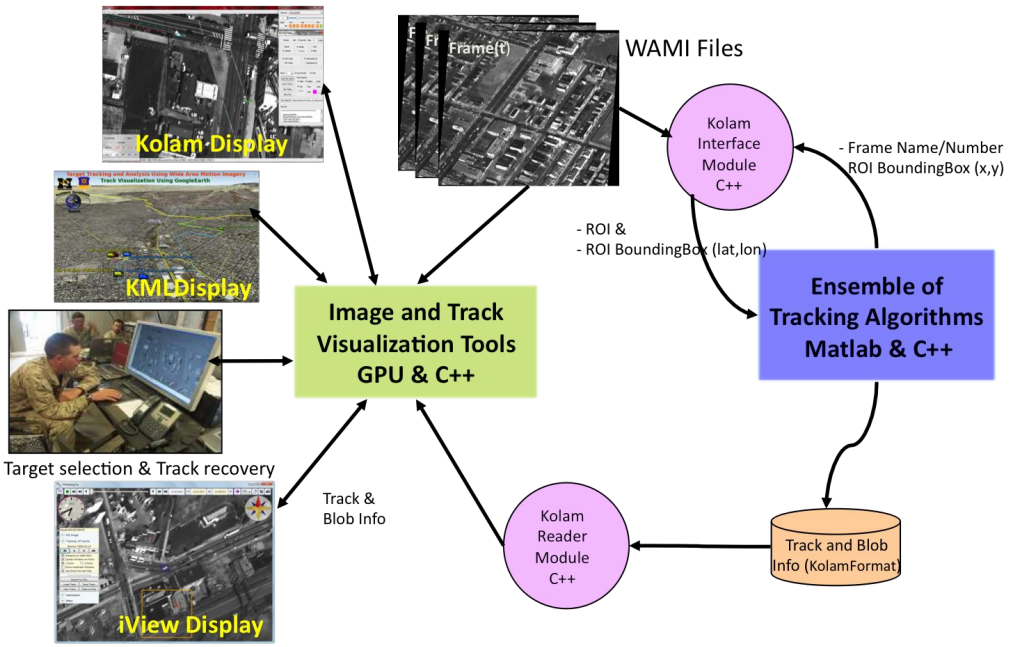


Figure 1. KOLAM is part of an open environment for visualization and target tracking supporting interfacing to several tracking algorithms and exchanging track files with multiple visualization tools.

simultaneous visualization of multiple tracks, context-sensitive track operations, track archival and retrieval, moving object ground truth generation, track editing and annotation.

In this paper we focus on the application of KOLAM to the visualization and analysis of WAMI datasets which are extremely large gigapixel-sized video frames with high spatial resolution and low frame rates of typically one to ten frames per second. WAMI sensors typically consist of an airborne camera array with electro-optical, infrared or multispectral sensors being used to acquire a wide spatial field of view in persistent observation mode as illustrated pictorially in Figure 2. There are a number of defense and commercial applications for WAMI ranging from surveillance and law enforcement to crop or infrastructure monitoring and emergency response. The rays in Figure 2 indicate the ground projection of tall structures that generate significant parallax induced motion proportional to the height of the building. Occluded rays are indicated by a black ground plane trajectory and such obscurations between the platform and the ground need to be anticipated in tracking systems. There are a number of challenges associated with acquiring and processing WAMI as detailed in recent publications.[4–17] In addition to large data volumes, vision processing and exploitation challenges, other dissemination related challenges in working with WAMI datasets include real-time downlink capability of full or partial video streams, shared on-board and ground-based processing to optimize data to decision, network-based video distribution of multiple regions of interest, managing thousands of targets and tracks, trajectory mining for patterns of life, etc. The need for user-driven models in the analysis of WAMI data to address difficult or unsolved problems in WAMI exploitation include: automated content-based search tools, a synergistic visual analytics tool for analysis, human-computer interaction that is capable of capturing user domain knowledge to improve productivity and search tools applied to multitarget tracking results. We describe the components of the KOLAM architecture and environment for accessing and visualizing WAMI.

2. RELATED WORK ON BIG DATA VISUALIZATION

Gigapixel-sized images have become much more prevalent over the past decade in a variety of domains including medicine, space, satellite and defense. Consequently, the development of tools for gigapixel-sized image visualization has been an active area of research. Figure 3 shows the ability to visualize large temporal satellite imagery in KOLAM in a fashion similar to and building on the legacy of visualization techniques pioneered in the NASA Interactive Image SpreadSheet (IISS) approach[19–22] combined with scalable out-of-core methods.

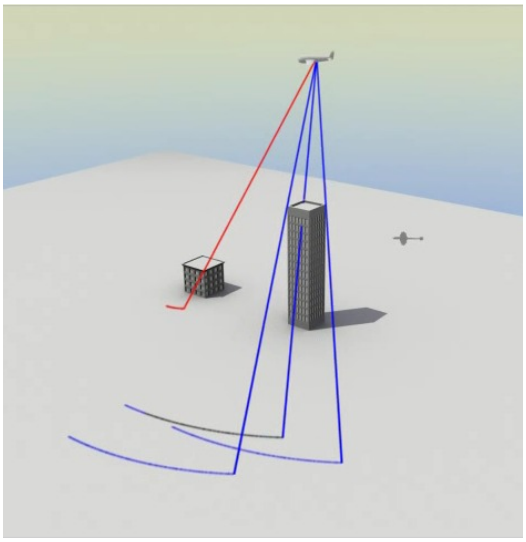


Figure 2. An airborne camera array system is used to acquire WAMI imagery in persistent mode. The rays indicate the ground projection of tall structures that generate significant parallax induced motion proportional to the height of the building. Occluded rays, indicated by coloring the trajectory on the ground black, and other geometric obscurations are a challenge for tracking systems. See color version of figure.

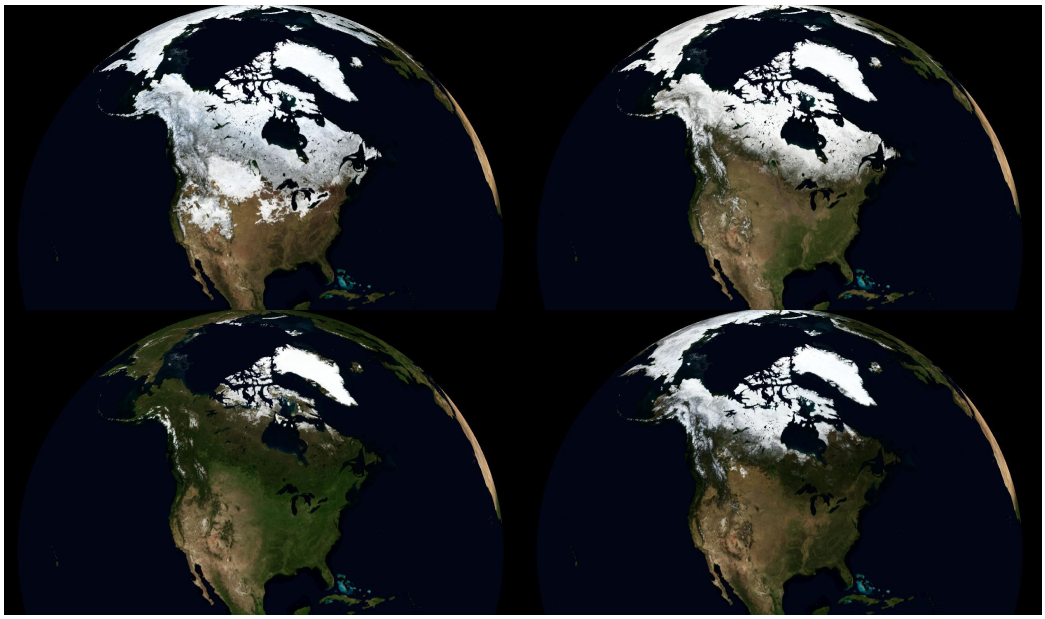


Figure 3. High resolution NASA EOS MODIS BlueMarble[18] global mosaic time sequence showing a sample four months of seasonal changes. Each image is 86,400 × 43,200 pixels in size, three channel RGB, and 500m pixel spatial resolution.

One key aspect of gigapixel visualization is display technology – single, multiple or tiled (wall-sized) displays and balancing data movement, rendering, computation and caching without sacrificing interactivity using a collection of (multicore) processors, storage devices, network services, and display capabilities. Recent examples using a single display for creating, processing and displaying ultra-high resolution images with high dynamic range and wide angle fields-of-view is work by Kopf *et al.*[23] and Summa *et al.*[24] Methods for systematically annotating and rendering both auditory and visual annotations in gigapixel imagery is described in.[25] Additionally, work has been done towards rapid post-processing of gigapixel imagery utilizing an efficient parallel programming methodology.[26] Based on the ability of the human visual system to rapidly identify patterns and discern differences, especially when the targeted data is extremely large, extensive research has been performed

regarding the visualization of high-resolution imagery on tiled displays.[27–38] Architectures such as SAGE[29,33,38] and DIGI-Vis;[37] and applications such as JuxtaView[30] and Giga-Stack[36] seamlessly display a number of visualization applications over the entire tiled display. The primary goal of such systems is to support application heterogeneity and scalability by decoupling the graphics rendering and display processes from each other, and by utilizing high-bandwidth lambda networks to bridge them. Such ultra large-scale visualization initiatives are currently being used with infrastructures such as the OptiPlanet Collaboratory.[31,35] This persistent, distributed visualization cyberinfrastructure connects a series of OptIPortals,[34,35] which are tiled displays that comprise the visual interfaces to OptIPuters.[27,34] These large scale visualization and analysis systems seek to create a synergistic combination between dense displays, high-speed networking, remote storage containing extremely large scientific datasets, distributed processing, data mining and visualization.[32] KOLAM supports a range of display technologies from single mobile displays to large hundred megapixel tiled wall-sized displays with sufficient computing resources to hide latencies and ensure seamless interactivity for the user. In this paper we focus primarily on the general architecture, visualization and object tracking features in KOLAM.

3. LARGE DATA ORGANIZATION FOR WAMI

In order to efficiently manage the display of large time-varying imagery, each image is partitioned or tiled into subimages or image blocks of the larger dataset using a quad-tree like regular tiling[3,39] that is now widely used in visualization systems for images and meshes.[25,26,36,37,40–46] These tiles allow random access to spatially coherent regions of the image and thus allow for on-demand access to those parts of the image needed for display as well as application-level management of memory. While tiling the image at a single resolution allows for efficient access to the full resolution dataset, viewing the image in its entirety would require reading all tiles from disk. In order to provide interactive zooming of the image across scale, multiresolution tiling is used. Multidimensional tiles or bricks can be used to organize large volumes and higher dimensional datasets similar to our description for 2D images.

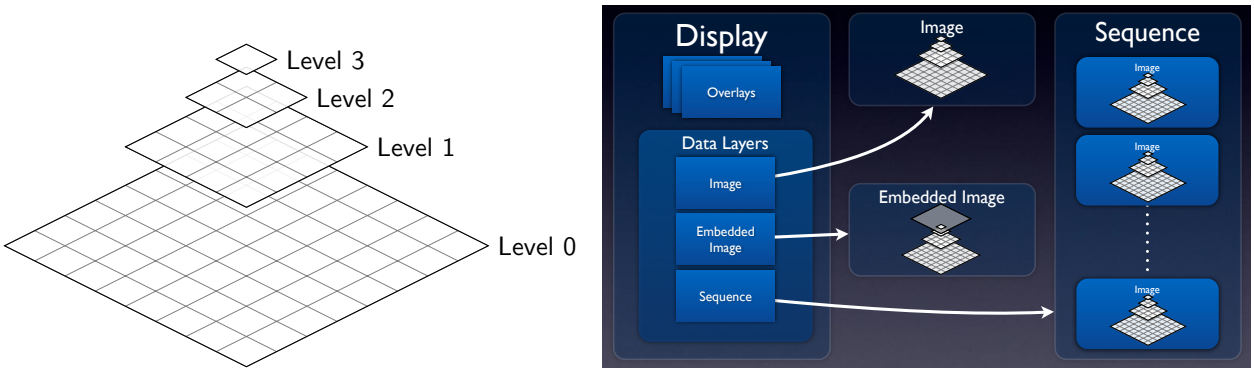
3.1 Pyramidal Data Format for Motion Imagery

A multiresolution pyramid is created by scaling the image in half along each dimension like a quad-tree until a minimum size (*i.e.* single tile) is reached. Following successive scaling, each resolution is divided into fixed-sized tiles. For our system, we've chosen fixed-resolution (compressed) tiles across all resolutions of the image. This tiled multiresolution data organization creates a pyramidal structure for each frame in motion imagery as shown in Figure 4. Each scaling results in an image that is one-fourth the preceding level of the pyramid with the finest resolution at the lowest level of the pyramid. Although the total size of the pyramid is one-third larger than the original wide-area image,[3] compressing individual tiles (lossy or lossless) across levels substantially reduces the total file size. In addition to the scale-and-tile approach described here, an alternative approach is to use a tile-and-scale organization as in JPEG2000[47–49] or a hybrid scheme.[3] KOLAM has support for multiple tiled pyramid image organization formats that continues to be extended.

Tiles can be individually compressed and a number of compression algorithms are currently supported including ZLIB, BZIP2, RLE, JPEG and JPEG2000. Compressing the individual tiles provides two advantages: alleviating the secondary-storage overhead of maintaining multiple resolutions, and improving I/O throughput from secondary-storage by requiring fewer bytes to be read than the raw uncompressed data. Lossless or high quality lossy formats are preferred because further analysis and processing such as automatic tracking will be performed on faint, low-contrast, and small targets.

3.2 Pyramidal Disk File Format for Motion Imagery

The on-disk pyramid (**.pyr**) format of our multiresolution pyramid files contains a header identifying the file and the image's underlying structure including depth, dimensions, tile dimensions, and tile count (Figure 5(b)). Following this metadata is a dictionary mapping each image tile to its byte offset in the file. Compressed tile data is located immediately following the header and tile dictionary. Organization of the tiles and specifics of the metadata are shown in Figure 5. The tiles in KOLAM pyramid files is organized and stored in sequential scan-line order from finest to coarsest resolutions as shown in Figure 5(a), with the highest original resolution numbered as level zero (Figure 4). The tile dictionary contains just the byte offsets for each tile contained in



(a) (b)

Figure 4. (a) KOLAM's multiresolution compressed-tiled pyramid data structure represented visually as a set of tiled rescaled images. (b) Class hierarchy for different types of pyramid files that can be displayed in each KOLAM data layer including single images, embedded images (also known as sparse or multiscale images), and a time sequence of pyramid files (*i.e.* wide-area motion imagery).

the pyramid. The number of resolutions contained in the file as well as the compressed size of each tile is not explicitly stored. The size of each tile is calculated as the difference of adjacent tile offsets from the tile dictionary. Likewise the number of resolutions contained in the file is derived from image size and tile size. The tile offsets are stored as *64-bit unsigned integers*[3] enabling more than 10^{19} addressable bytes; this addressable range is per file (i.e. per embedded layer, per time step, or multi-pyramid mosaic, etc.). So in theory there is no limit to the size of the image that can be handled by KOLAM since extraordinarily large images can be visualized as a tiling of pyramids.

In addition to organizing tiles in scan-line order a space-filling curve order, such as z-curve (also known as Morton curve), Gray-coded, Hilbert, or Peano curves can be used to preserve data locality as shown in Figure 5(c). Equivalent names for image pixel reorganization include z-order, Morton order or Lebesgue-order.[24,50,51] The mapping between raster position and space-filling curve order can usually be computed very efficiently using bit operations. The z-scan order or z-curve can be converted to and from raster coordinates, very simply, by interleaving the dilated bit representations of the standard row and column indices. The z-tree and related tilings are very effective for spatial data where nearby tiles are highly correlated and more likely to be accessed, visualized and processed together.[45,50] More sophisticated ordering of spatial and temporal tiles of time varying WAMI using space filling curves can potentially speed up out-of-core algorithms to a significant degree.

4. KOLAM MULTITHREADED SYNCHRONIZATION ARCHITECTURE

The reorganization of images into tiled multiresolution pyramids provides on-demand loading of partial regions and scaled views of the whole dataset. Loading the image piecewise as determined by the user's interaction, effectively amortizes the expense of transferring the entire dataset from secondary storage to primary and video memory. While the total amortized cost may exceed that of loading the original image, it is this on-demand view-dependent loading that provides an interactive experience for the user. Additionally, the total amortized cost for a given session will still provide savings as the user rarely views every tile contained in the dataset.

An efficient multiresolution temporally registered tile access mechanism is essential to provide smooth interactivity for any user-driven view into the WAMI data volume. Determining the visibility of *spatial-temporal tiles*, load balancing I/O throughput, decompression, and memory management are key parameters to optimize to deliver tight interactive display updates. A *spatial-temporal dual-caching* mechanism is proposed to efficiently handle time sequences of large wide-area imagery organized as a collection of tiled pyramid files on disk.

4.1 Multithreaded Cache Access and Management

A tile is the smallest data element in the cache management system. As the user interactively pans, zooms, and animates the view on to the data, tiles are loaded on-demand in order to provide that view. When the

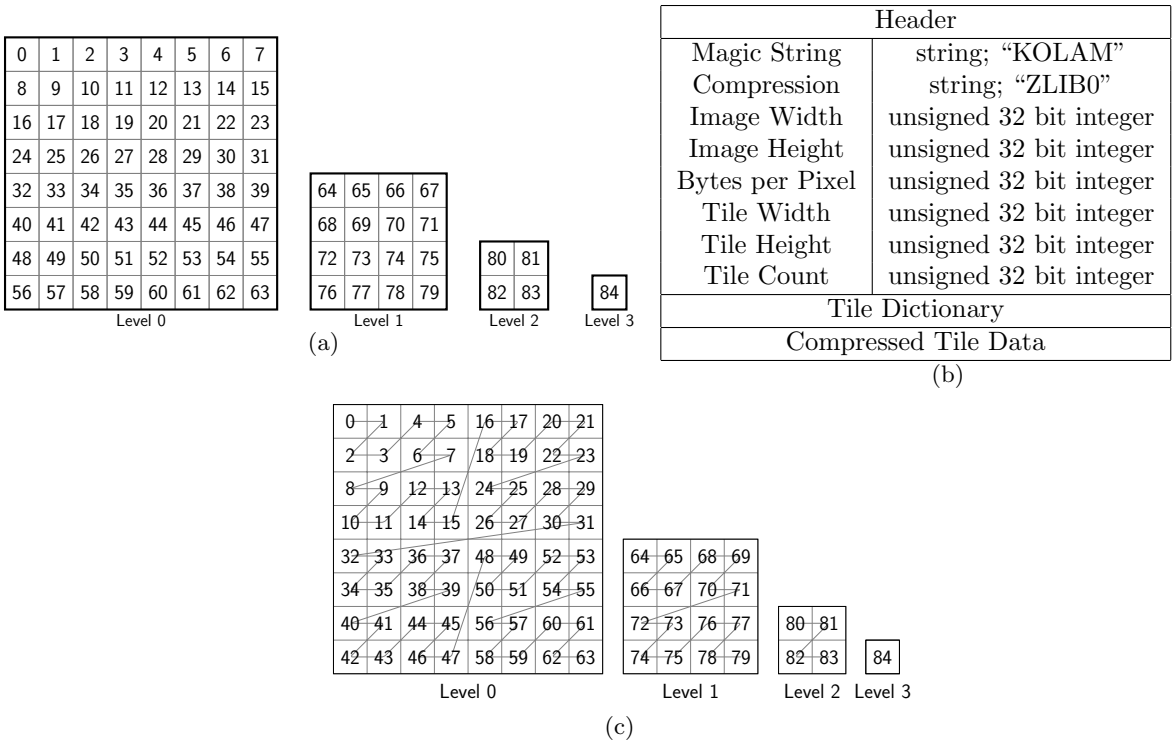


Figure 5. (a) Pyramid tile organization in raster scan-line order for a four-level hierarchy starting with 8×8 tiles. (b) Metadata structure of the KOLAM pyramid image file format header for storing all tiles across all resolutions within a *single image file*. (c) Pyramid tile organization in z-scan or Morton scan ordering for the same four-level hierarchy that improves spatial locality.

cache management subsystem in KOLAM determines that an unavailable tile is needed in order to fulfill any user-requested view, a tile access cache-request is generated and queued. This request is handled asynchronously by a separate thread to prevent any I/O blocking from interrupting the interactivity of the user interface and display event loop. To achieve this asynchronous behavior, two types of threads are used: one display thread for user interaction and display, and multiple read threads to fulfill tile requests from disk. The number of threads is variable and can be tuned for different systems. Thread cooperation behaviors are shown in Figure 6.

The display thread, Figure 6(b), is responsible for user interaction, determining which tiles are necessary to provide the current view of the data, and drawing the view as tiles become available (with or without display buffering). The display thread transforms the current view requirement to a set of tile requests. Mapping the current view to the underlying data is dependent on spatial position, scaling, and current time. The view is tracked in a global coordinate system with respect to the finest resolution of the pyramid and sequence order of the time-varying data. Uniquely identifying a tile in the system requires that each tile be first associated with its temporal index (mapped from time to a file), and then spatially within the pyramid structure.

When tiles associated with the current view are resident in cache and the system load is light, KOLAM will predict what will be needed in the near future based on current user behavior and generate requests for this data in advance. Preloading data is necessary to fulfill the user's expectation of interactivity; failure to fill the view within tens of milliseconds may cause portions of the view to remain blank or out-of-date. Prefetching occurs both temporally with respect to the time sequence, and also spatially by pre-loading tiles surrounding the current view. Spatial prefetching attempts to predict tiles that will soon be required to fill the display for the current time index. Scheduling tiles to be loaded immediately adjacent to the current view, but not yet resident, allows the system to anticipate future view requirements and ensure that needed data is available in the cache in a timely fashion. Temporal prefetching determines which frames of the sequence will be needed (and when) in order to ensure that the associated pyramids are available in the (temporal) frame buffer, and to issue requests

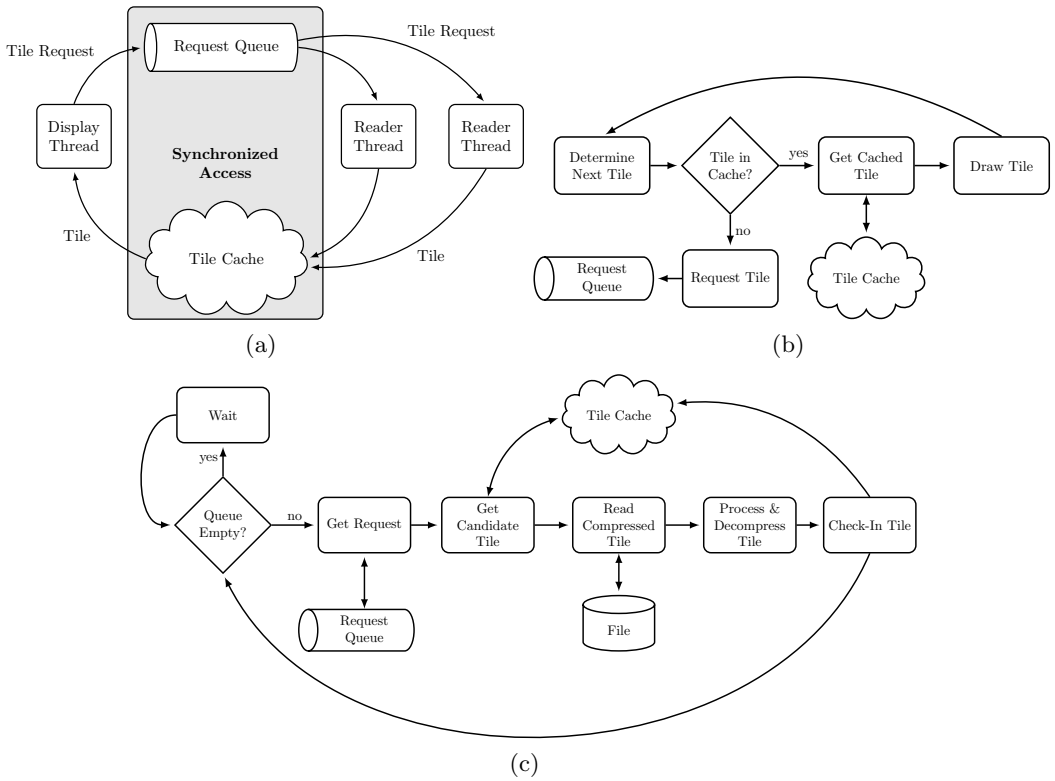


Figure 6. (a) Multithreaded synchronization of display and reader (worker) threads in KOLAM. (b) Display thread interactions with Request Queue and Tile Cache. (c) Reader thread interactions with Request Queue and Tile Cache.

for tiles that will be needed in the next time step.

Under heavy system load, the demands of the view may exceed the ability of threads to deliver data. Compromises must be made to provide a seamless experience for the user. Spatially, rather than allow blank regions or out-of-date data to be displayed, a consistent view can be presented by progressively loading coarser tiles when tiles at the current resolution are not yet available. Temporally, rather than playing back the animation too slowly, the system should attempt to fulfill the user's expectations of interactivity by dropping frames. These compromises affect only the display component of KOLAM and not the tracking subsystems which has predictable access patterns and utilizes the full spatiotemporal resolution data.

Reader threads (Figure 6(c)) provide asynchronous delivery of tiles to the spatial-temporal tile cache. Initially a reader thread is in a wait state. The thread waits on a POSIX condition until there are tile requests in the queue. When the request queue is no longer empty, reader threads are awakened to retrieve requests from the queue and service those requests. When the thread has completed the task of delivering a tile to the tile cache, it either continues with the next request in the queue or returns to the wait state if the request queue is empty.

Reader threads are responsible for fulfilling the three phases of a tile request: reading, decompressing, and caching the tile in primary memory. The first phase of fulfilling a tile request is to find memory within the cache to hold the result of the request. A centralized cache contains the collection of all tiles currently resident and provides storage for new tiles if the cache has not reached its predetermined maximum size. If the cache is currently full, a candidate tile for replacement (removal) is chosen and checked out of the cache. Checking out a tile transfers ownership of the tile's memory to the thread and ensures that the tile scheduled for deletion is unavailable to other threads. The replacement tile can no longer be accessed by the display thread nor is it available to other reader threads until it is again checked back into the tile cache.

Once cache memory for a tile has been determined, the read phase begins. A requested tile is mapped from its spatial-temporal index first to a file in the sequence, and then to a byte offset and size within the file using the

tile dictionary. Using this size and offset, a read system call is issued to the file to transfer the data from disk to memory. This system call is intentionally a synchronous call which will block the current thread of execution–but not other threads–until such time as the operating system can honor the request. The result of this read is a compressed tile which is saved into a thread-specific local buffer.

Once the compressed tile is available, the thread is then responsible for decompressing the tile. The tile is decompressed from the thread read buffer into cache memory. The result of this decompression is a display-ready tile located in the central tile cache. Following successful loading and decompression of a tile, the cache is notified of the presence of this new tile. The check-in of this tile serves two purposes: transferring ownership of the tile's memory back to the system for reuse and notifying the display thread that new data is ready for display.

4.2 Thread Synchronization and Load Balancing

Synchronization of threads is necessary when accessing two structures: the request queue and the spatial cache. This synchronization process shown in Figure 6(a) ensures that access to these protected structures is serialized amongst multiple competing threads. Sychronization is provided using POSIX mutex variables and conditions.

Coordination of tasks amongst the threads is provided by a workpile concurrency model. Tasks (in this case tile requests) are placed in a first-in-first-out request queue by the display thread. Threads retrieve requests from this queue in order to fetch tiles for delivery into the spatial-temporal tile cache. As previously described KOLAM uses synchronous blocking reads when fetching compressed tile data. The purpose of blocking reads is to achieve load balancing between I/O and processing. Blocking reads provide a yield point for the executing read threads. When a read from disk is requested to the operating system, the thread will block yielding execution to other threads until that transfer from disk is available. While one thread is blocking on the read system call, other threads can utilize the CPU for processing and decompression. This workpile model is well suited for the nature of KOLAM's I/O and CPU intensive demand patterns for the visualization of large tiled motion imagery.

4.3 *Spatial-Temporal Dual-Caching* Tile Organization

Motion imagery requires coherent caching both spatially and temporally. To determine temporal caching of tiles as the view varies in time requires knowledge of the next frame in time which may not be immediately adjacent in the sequence. As an investigative tool, simple sequential linear playback of the data may be insufficient for the demands of the user. The playback sequence of frames may occur in a cyclic pattern as opposed to just clamped from the beginning to the end of the sequence. Looping and rocking playback are examples of this cyclical pattern. The user should also be able to play the animation both forwards and in reverse at a specified frame rate. Additionally, the user may wish to stride through the data in order to visualize long sequences more quickly by setting the step size.

Dual-caching is used to accommodate a sequence of files for animation. The first form of caching is at the temporal file level to organize temporal information and the second form of caching is at the spatial level which is discussed subsequently. Each frame in a sequence exists as a separate file. The cost of opening and parsing the file's header and generating the associated tile lookup tables requires that the results of this process be cached for fast access to the tile data. Additionally, because the length of a sequence can be very long, the entire sequence of file pointers and associated pyramid data structures cannot all remain resident due to limited resources–both with respect to memory and also the maximum number of open file handles imposed by the operating system. To manage this two-tiered caching, a separate file buffer is maintained. This buffer is kept full based on playback of time and the animation parameters set by the user. As the display updates time, this file buffer is kept up-to-date. When one frame of the sequence is removed from this buffer, a future frame is loaded from disk. At the time of this loading, no tile requests are actually issued, the file is only opened and parsed to build the necessary structures for accessing the tiles. As a file is paged out of the animation buffer, the tiles associated with that file are marked for recycling. This recycling marks those tiles in the cache as immediately available for reuse by future tile requests.

It is important to note that the order of images in the resident file buffer may not be sequential or in increasing order. Rather the buffer will reflect the parameters used for playback of the animation. For example, the user may have chosen to loop a subset of the entire animation for playback with a negative stride. The cyclic nature

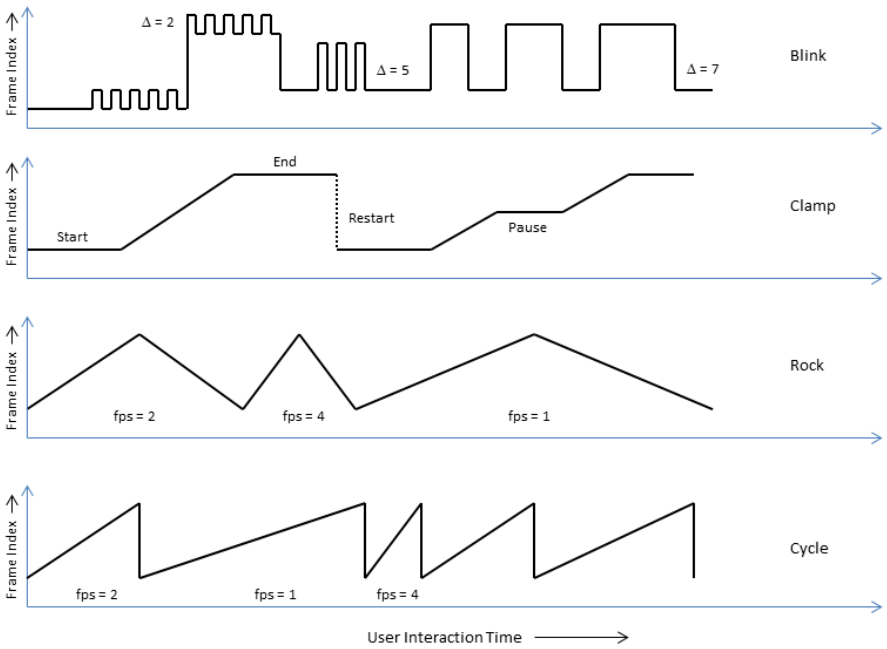


Figure 7. Sample ordering of frame sequences as a function of user interaction time showing four different user selected playback modes (top to bottom) including blinking between two closely or widely separated frames at different speeds, play through the loop once (clamp) with and without an intermediate pause, rocking back and forth at different frame rates, and continuous looping at different rates. Scrubbing through the sequence and random frame access are not shown.

of playback (loop and rock) and the need to skip frames (stride or frame dropping) in the sequence creates a non-linear sequence of frames needed for playback. In order to properly preload and buffer frames of the sequence, the system must be able to properly predict those frames which will be drawn in the future. Toward this goal, the sequence of past and future frames is modeled as a function of time. For any given time, the system must be able to query what frame would be drawn at that time. By monitoring latencies to fulfill a view, the system can choose to load only the sequence of frames which can be successfully retrieved from disk.

This ability to determine only what will actually be available for display as opposed to what would be next without the unavoidable latencies allows the system to manage its limited resources more effectively. Accurately predicting which frame to load based on playback speed and load time, the system can fill the caches without wasting precious resources on frames that will be skipped.

The various modes of playback can be modeled using clamped, sawtooth, and triangle functions as shown in Figure 7. These models are used both for preloading data as well as maintaining a temporally coherent file cache. During the preloading phase, the system examines the frame cache and requests tiles for the current view at the next time. The next time is simply the span determined by the frame rate when the system is not under full load and can reliably fulfill all data requests. When the system is under a full load, the next time is the average current latency of successfully filling the view as determined by the display.

We now elaborate on the second form of caching at the spatial tile level. Tiles in the cache are referenced to their associated temporal frame in the animation sequence. A number of approaches can be considered for the tile replacement or *tile paging* strategy including random, minimum, First In First Out (FIFO), Not Recently Used (NRU), Least Recently Used (LRU) and our proposed *spatial multiresolution distance-based* (SMD) tile replacement or *SMD tile paging*. Similar to the classic operating system level paging strategy,[52] the LRU *tile paging* or replacement strategy chooses the oldest tile contained in the spatial tile cache to be swapped out for a new incoming tile. This approach is effective in that as the user zooms and pans the image, recently drawn tiles are likely to be needed again in the near future. The approach predicts that the least recently accessed tile will be the best candidate for removal from the tile cache.

While the LRU approach is effective, and has been implemented in KOLAM, it ignores additional spatial information that can be used to improve upon the LRU tile replacement algorithm. Although the user can make large disconnected jumps from one view to another in the image, this is not the typical way in which users visualize and navigate large motion imagery. Rather, users tend to pan around the image and zoom in and out in order to inspect the data. The nature of this user interaction suggests that paging based on a tile's distance from the current view rather than age of tiles would be more effective. Our preferred *SMD tile paging* strategy utilizes this spatial coherency to more efficiently manage the paging of the tile cache. Our approach is to keep all the tiles closest to the current view, and choose as replacement tiles those that are the furthest way in terms of spatial distance. A simple L_1 or Manhattan distance metric is used to update the distance of each tile in cache with respect to the current view. The result of this distance-based caching is a clustering of resident tiles nearest to the current view. When a new tile is requested and the cache is full, then the tile with the greatest distance value is chosen for replacement.

5. KOLAM INTERFACE FOR VISUALIZATION AND TRACKING

KOLAM allows users to exploratively interact with and manipulate a time sequence of very large imagery in pyramid format or (same-sized) image files in common image formats including TIFF, PNG and JPEG. In addition to image visual analytics, KOLAM also supports the interactive visualization of extremely large, spatially and spectrally varying geospatial imagery rendered as a 3D globe. KOLAM uses the Qt application programming interface and GUI framework to provide interactive tracking and management of trajectories for WAMI datasets, as well as the ability to interface with and invoke external tracking algorithms. The remainder of this section describes interface elements pertaining to the visualization of information layers in KOLAM, followed by a description of the interface front-end and corresponding implementations for the animation and tracking subsystems.

5.1 Visualization of Multiple Layers of Analytic Information

KOLAM can simultaneously display and combine multiple layers of raster or vector information interactively to produce composite analytic visualizations using a layer selection interface. A layer is a high level visual representation of a dataset that encapsulates both the image information and relevant metadata.[39] It is possible to simultaneously visualize multiple layers, and each layer may have one each of several types of viewers and navigators associated with it. The user can interactively move a given layer up or down the layer-stack to control its visibility and blending with regard to other visible layers. The regions of a given layer that are occluded depends on its position in the overall layer-stack; this feature allows for rapid control of the visibility and overall spatial composition of layers. Additionally, alpha blending enables exploratory visualization by combining different layers. The user can interactively switch between applying a global navigation transformation to affect all visible layers of information or apply a local transformation to align each layer image. This is useful for performing interactive mosaicing and georegistration of large composite imagery.

5.2 Visualizing Motion Imagery

KOLAM provides a highly compact user interface via the KOLAM-Loop tool that comprehensively addresses user needs when playing back WAMI and other image sequences. KOLAM supports playback of a given sequence, in any direction, with or without looping, and with immediate frame rate adjustment. The user can choose to step through the sequence one frame at a time (with a skip/stride factor), *scrub* through the sequence or jump to an arbitrary frame. The user can also construct collections of related time-varying data and switch between them. This enables comparison and collation of related motion imagery sequences that may be spread over multiple datasets.

5.3 Tracking and Trajectory Visualization Subsystems

The tracking subsystem in KOLAM is specifically designed to accommodate the visual analytic needs of tracking objects of interest in both WAMI datasets as well as more general video sequences. The KOLAM-Tracker tool accomplishes this by providing manual ground-truth (target) annotation, simultaneous tracking of multiple

(a) (b)

(c)

Figure 8. Visualization of multiple tracked objects and their trajectories in KOLAM using different vector primitives. (a) Vehicle trajectories generated by manual ground truthing over several hundred frames are shown in different colors for ten cars and drawn in unstabilized coordinates, (b) stabilized trajectories for the same cars over the same frames, and (c) ground-truth polygons marked for tracked objects. The first row shows results for a PSS WAMI dataset collected over Charlotte, NC racetrack and the second shows ground-truth for a multi sensor video dataset (Army Research Lab FPSS[53]).

objects, editing of trajectories, and assisted tracking. Sample multi-colored trajectories showing tracking results for two different data sets are shown in Figure 8.

Trajectory Drawing Using Overlays Techniques for the annotation of gigapixel-sized imagery have been recently described by Luan et al.[25] The Annotation or Overlay system in KOLAM provides the different vector generation and drawing elements necessary for tracking, object selection and trajectory visualization. Object selection, typically by using bounding boxes, for interactive track initialization occurs in the overlay drawing planes. The annotation architecture supports the simultaneous display of multiple overlay vector annotations associated with the underlying imagery in the data layers as shown in Figure 4(b). KOLAM event management of user interactions separates the flow of input requests into *Annotation Layer* or *Data Layer* event streams.

***KOLAM-Tracker* Tracking Interface** The tracking interface in KOLAM constitutes a versatile GUI front-end for target tracking by interfacing with multiple automatic tracking algorithms using the proposed open architecture environment. The interface supports manual ground-truth generation (target annotation), track editing, and assisted tracking that combines manual corrections with automated tracking. The various elements of the GUI permit the configuration of object tracking parameters and appearance of trajectories. KOLAM-Tracker object tracking properties include creating object IDs for targets, selecting a tracking algorithm namely LOFT[10] or the single-object tracker based on an adaptive cloud of dense SURF descriptors,[7] and switching between automatic algorithm invocation and manual ground truth generation tracking modes. The manner in which trajectories are drawn is determined by a set of track-specific properties. Chief among these are choosing whether to display locally unregistered, registered or both types of trajectories; and altering the visibility, color and thickness of the trajectories. Other properties include dynamic display centering on the current target, deleting trajectory data on a per-object basis, and saving to or loading from a trajectory data archive.

5.4 Tracking Modes in KOLAM

The KOLAM-Tracker tool supports three modes of operation including manual tracking, fully automatic tracking and a mixed mode of assisted tracking. The interactions between KOLAM and the automatic tracking algorithms are illustrated in the flow diagram shown in Figure 9. The various tracker and tracking properties that are set using the interface prior to initiating tracking are encapsulated in a *trackedObject* container class, instances of which are created for every distinct target.

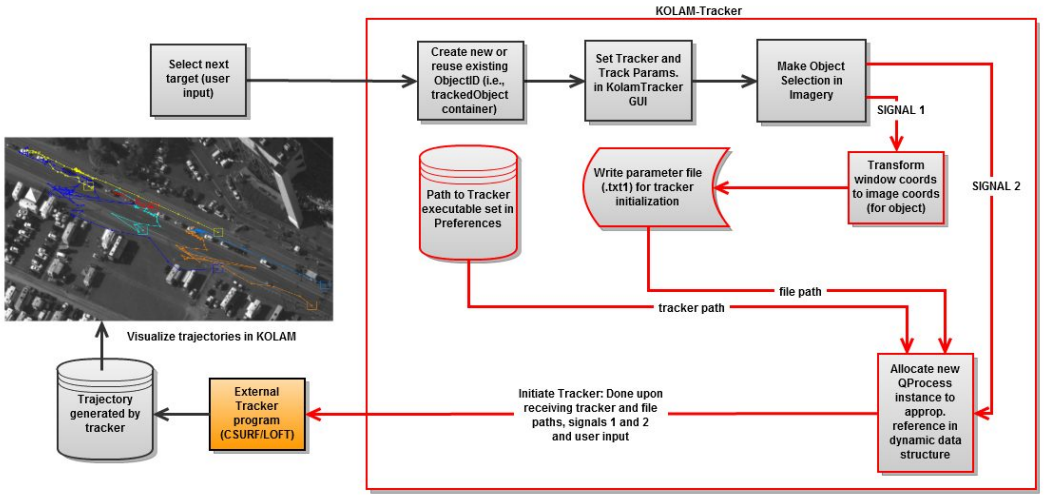


Figure 9. Automatic tracking mode in KOLAM-Tracker. Interaction steps and flow of processing involved in invoking an external tracker program for object tracking and trajectory visualization in KOLAM. The black-outlined boxes stand for user interactions with KOLAM-Tracker, and the red-outlined ones denote steps in the KOLAM-Tracker algorithm execution.

The automated tracking mode refers to the tracking of objects solely through the invocation of a selected (external) tracker algorithm such as LOFT. Once the user sets the KOLAM-Tracker GUI parameters, the first step involves selecting a target to track in WAMI starting from a given frame (forward or backward in time). If the user makes an error in drawing the box around the object of interest, the box can be redrawn more accurately multiple times. Each object selected for tracking is internally maintained in KOLAM in a dynamic linked list data structure of references to Qt QProcess instances. This list with process instance information is used to start and optionally stop the external (MATLAB- or Octave-based) auto-tracking program execution applied to multiple objects in a distributed processing fashion. Each auto-tracker invocation is initialized as a forked process on Unix-based systems or as an independent child-process on Windows-based systems, which ensures that KOLAM functionality is neither blocked, left in a wait state, nor unpredictably interrupted by the external auto-tracker program. The computationally intensive tracking code executes in the background without impeding KOLAM interactivity. The output of the tracker for each object is saved to disk and incrementally updated in an internal data structure for interactive off-line review of the tracking results. The results of a given tracking session may be archived in a user-specified location to preserve session-specific target information and trajectories.

In the manual tracking mode the user tracks objects by hand marking the location of the target in each frame. These points can be visualized as a connected trajectory (vector plot in the overlay plane) as in the automated tracking mode. KOLAM currently supports marking of objects using points, bounding boxes or polygons. The fastest and easiest means of manual tracking involves using the *auto-advance* option to automatically step to the next frame as soon as the user marks the location of the object. In this mode of operation, an expert user can quickly generate long ground-truth trajectories. The auto-advance feature in combination with frame advance aims to provide flexibility in quickly jumping to the frames where the target is moving (more rapidly) and skip frames when the target is stationary for example; the skipped frames are connected via a constant velocity trajectory. To update an incorrect target location on the current frame, *auto-advance* should be disabled.

Tracking performed in either the automatic or manual modes may include erroneous target locations. Tracking errors can be repaired using the track editing facility which operates on the overlay drawing planes. This feature of the tracker GUI, while not a tracking mode per say, is capable of modifying output generated by any of the tracking modes. The current implementation is based on a set of atomic editing operations including move, add, delete, and join. Moving a primitive (*e.g.* target location represented as a node) involves translating the selected vector data on a given frame to the desired location under user control and adjusting the trajectory appropriately. The add operation is used to create track segments in portions of the WAMI sequence where no previous track data exists (extending a trajectory at the ends). This enables inserting a primitive before the beginning of a track, after the end of a track, filling in gaps in an existing trajectory, or creating a track segment in-between two (or more) existing tracks in order to create a single, longer stitched track. Deleting a primitive involves removing the vector data associated with an object on a given frame and either splitting the track into two segments or interpolating the object location between the previous and next available target positions along the trajectory. Joining two separate trajectory segments involves selecting both tracks and applying the join operation to link the tracks. In all cases, the on-screen trajectory drawing is immediately updated to reflect changes made by the user. KOLAM uses only a few keystrokes to implement these core track editing operations.

Assisted tracking is perhaps the mode with the most interesting set of real-world applications. Current automatic tracking algorithms are not trustworthy enough in dense urban environments with many movers, while fully manual tracking is time consuming and error prone. Assisted tracking augments an automatic tracker with manual intervention for rapid and accurate trajectory generation, especially when tracking involves many similar targets maneuvering through multiple occlusions and shadows in complex environments and flows. The assisted tracking mode is a composite of automatic and manual tracking modes to enable users to quickly switch between the two modes dynamically and perform corrective track editing operations efficiently. It needs to be carefully designed to maximize human effectiveness. In the assisted tracking mode the user is able to stop the automatic tracker as necessary, manually correct trajectory errors, or add target location information in a difficult to track region, then switch back to the auto-tracker mode in a seamless fashion. The sequence of operations in assisted tracking includes use of the automatic tracking process (as shown in Figure 9), combined with manual tracking and track editing procedures (not shown) which are performed by the user in an iterative

Figure 10. Simultaneous visualization of tracker algorithm execution and trajectory visualization in KOLAM. There are three instances of the tracking algorithm running to track three objects. The two inlaid (MATLAB) windows shown on the left are the realtime (heads-up or cursor-on-target) displays generated by the automatic tracking algorithms. The main window shows both stabilized and unstabilized computed trajectories for the three objects.

fashion until the supervised tracking task is completed. In supervised tracking and video indexing, the user learns to anticipate the most common failure modes of the automatic tracker, thereby significantly increasing the productivity of the analyst. Preventative intervention by the user aims at avoiding long invalid track segments from being generated by the automatic tracker running unsupervised that then need to be manually inspected and corrected. Analysts may potentially favor the assisted tracking mode since it ensures high accuracy without the necessity to manually track multiple targets in very long sequences.

5.5 Tracking and Trajectory Visualization Applications

The utility of KOLAM for exploratory visualization and analysis of both static and time-varying imagery of different sizes, types and formats demonstrates the usefulness of the system for applications requiring accurate multiple target tracking that can scale to a large number of objects. The loose coupling between KOLAM and the external automatic tracking algorithm processes enables immediate display of the computed trajectory up to that point in time as shown in Figure 10. For WAMI imagery KOLAM's ability to interactively animate gigapixel-sized images as well as perform automatic or manual tracking and trajectory visualization and analysis translates into applications in both the civilian and defense sectors. On the civilian side, the tracking, visualization, and annotation capabilities may be utilized by law enforcement for forensic analysis, for urban planning and traffic patterns, video summarization for long duration surveillance and emergency response.[5] In the defense context KOLAM can be used for improved situational awareness, persistent observation of targets, reconnaissance, force protection, rapid targeting and response.

6. SUMMARY AND CONCLUSIONS

KOLAM is demonstrated to be a scalable and flexible tool for exploratory analysis of WAMI datasets that provides dense spatiotemporal coverage of wide field-of-view urban regions and can be used for object detection and tracking. The current KOLAM environment supports an efficient tiled memory representation of very large image timeseries using a spatial and temporal dual-caching mechanism. The multithreaded synchronization architecture ensures that tile access and tile display processes work smoothly with each other and can be readily scaled with the availability of additional processing cores and memory. KOLAM has been designed to facilitate user interaction with large format video in general and supervised exploitation of WAMI sequences. KOLAM is able to improve human effectiveness measured in terms of productivity for accurately tracking multiple targets and reviewing and validating the results of tracking especially in the assisted tracking mode. Future improvements

include support for IR and multispectral WAMI, a knowledge base for managing thousands of trajectories from automated and interactive event detection, developing techniques to visualize statistical trajectory flow information, distinguishing between normal and abnormal patterns of activity, and processing event-based queries using semantic models. A new use of KOLAM would support visual analytics and visual synopsis to provide useful tools for summarization and management of large data volumes from WAMI sensors.

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