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Summary of Methods in Wide-Area Motion Imagery (WAMI)

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ABSTRACT

In the last decade, there have been numerous developments in wide-area motion imagery (WAMI) from the sensor design to data exploitation. In this paper, we summarize the published literature on WAMI results in an effort to organize the techniques, discuss the developments, and determine the state-of-the-art. Using the organization of developments, we see the variations in approaches and relations to the data sets available. The literature summary provides and anthology of many of the developers in the last decade and their associated techniques. In our use case, we showcase current methods and products that enable future WAMI exploitation developments.

Keywords: Wide-Area Motion Imagery, Wide-Area Surveillance, Registration, Detection, Tracking

1. INTRODUCTION

Persistent surveillance has been an important research topic ever since the developments of digital image processing that sought to combine video imagery from distributed sources. Numerous books and articles have been developed for such applications as security (e.g. perimeter surveillance), environmental analysis (e.g., monitoring flood damage), and emergency response (e.g., disaster relief). While a comprehensive literature review of advances in distributed imagery surveillance would be beyond any confined publication, we seek to overview the developments of methods and techniques used in ***Wide-Area Motion Imagery*** (WAMI), shown in Figure 1.

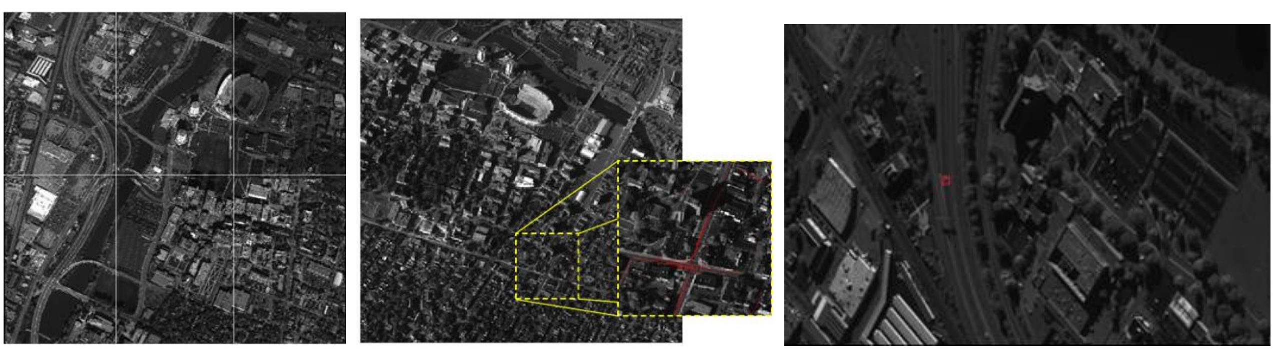

Figure 1: WAMI Data from the Columbus Large Imagery Format (CLIF) collection [1].

The motivation of the paper is to focus on advances in ***Wide-Area Persistent Surveillance*** (WAPS) and WAMI. ***Wide-area*** includes a geographical region larger than 50 square miles. Notionally, satellite imagery provides a large geographical area, but the challenges induced by satellite imagery include atmospheric transmission and pixel resolutions that limit surveillance resolutions to areas versus specific objects of interest. ***Persistence*** includes continual

Geospatial InfoFusion and Video Analytics IV; and Motion Imagery for ISR and Situational Awareness II,
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motoring of areas of interest. Satellite imagery could provide persistent surveillance, but is limited in that coverage consists of spot images versus constant monitoring. Furthermore, ***motion imagery*** includes visual imagery and video that does not include Synthetic Aperture Radar (SAR) imagery (typically done in spot model) in that resolutions are in the visual spectrum for object recognition. Finally, to further refine the historical developments, we are interested in ***motion analysis*** of moving targets. Using the above details to refine the organization of developments, we note the rich history in imagery surveillance[1], but focus on the aerial systems that motivated the developments in WAMI.

Key challenges for the WAMI include low frame rates, extended camera coverage, multiple targets, weak target texture, and environment occlusions. The generalized advantages purposed by WAMI sensors, which includes platform routing for persistent surveillance, including constant coverage from overhead imagery (5000-1000 ft), 3D processing for terrain analysis, and target tracking [2]. The literature review captures many of the leading developments which includes multi-year efforts. Continuous reporting has produced various approaches. When possible, we grouped the literature survey by the key approaches and sustained efforts of researchers. Thus, it is both a grouping of issues as well as a multi-year reporting by the same research groups.

The rest of the paper is as follows. Section 2 begins with a historical overview. Section 3 starts the literature analysis with an organization of the published papers. Section 4 presents sensor designs for surveillance, while Section 5 presents the WAMI exploitation methods and Section 6 is WAMI methods for extended coverage. Section 7 discuses other issues of situation awareness, standards, and viewers. Conclusions are drawn in Section 8 with future directions.

2. WAMI HISTORICAL DEVELOPMENTS

In focusing the contributions of this literature analysis, the historical development begins with the notional sensor design and then the techniques used to exploit the collected imagery. The motivation for WAMI designs can be organized around the technical, political, and social developments that fueled further developments. A precursor to many of today's WAMI systems was the SONOMA project at Lawrence Livermore National Laboratory (LLNL) which demonstrated the utility of WAMI by taking and analyzing a data set using two 11 Megapixel cameras and a high quality Inertial Navigation System (INS). A significant follow-on to this activity was the Angel Fire[2] program that added real-time 3D projection, distribution and viewing of the entire data set to capabilities similar to SONOMA. This effort was begun by U.S. Air Force and Los Alamos National Laboratory, but quickly grew into a team encompassing Kitware, Inc., the Air Force Institute of Technology (AFIT), and the Air Force Research Laboratory (AFRL). Key attributes include the sensor design, the exploitation systems, and the viewers, as shown in Figure 2.

Figure 2: WAMI Summary: Sensors, Image Exploitation, and Viewer [3].

Sensor developments emanating theses research groups included both military and civilian applications. One civilian application is traffic analysis, such as a helicopter surveying the city traffic at busy times of the day. The persistence is afforded by the starring mode of the cameras pointing to a similar spot on the ground. The surveillance systems enable traffic perspectives at intersections. The military and law enforcement have continued to develop WAMI systems such as ARGUS-IS, Gorgan Stare, and Transparent Sky's systems. Live WAMI data has been recorded with 68 square mile coverage to detect moving objects such as vehicles and people. These WAMI systems are capable of operating in real-

1 http://en.wikipedia.org/wiki/Mass_surveillance
2 http://www.globalsecurity.org/intell/systems/angel-fire.htm

time or for forensic analysis to record the movement of and activities of objects. Current instantiations of WAMI technology include the Blue Devil airship that is used by the Department of Homeland defense as well as the KESTREL system.

Exploitation systems, or rather programs, have utilized WAMI data for further analysis. For example PeSEAS and PerMIATE software developed methods of observing, tracking, recording objects in video. The tracking of objects in WAMI includes short tracks, or tracklets, such that movements are detected. Benefits of WAMI include global coverage so as to link these short tracks to develop a long-duration track. However, limitations of WAMI are also included such that the boundaries from the camera segments produce artifacts that disrupt the linking of tracks. Thus, as both a benefit and limitation, track stitching is needed to combine the various tracks.

Viewers have also progressed at the same time as WAMI, such that many groups have their own visualizes. A popular viewer is PURSUER[3] which enables user interaction with the WAMI data. PURSUER, as well as other viewers such as KOLAM, extend methods of the NASA World Wind visualization such that the overhead WAMI image can be projected to the ground (on a flat Earth) from anywhere in the world. New types of viewers expand user access, such as a Transparent Sky WorldWind based viewer that is portable to all computer OS as well as the CityShield native mobile viewer. The advances in viewers, along with tracking technology, allow both the imagery and exploitation products to be seamlessly utilized for situation awareness.

3. LITERATURE REVIEW SUMMARY

In the literature review, we only included open-source publications in databases that featured techniques associated with the sensor design, exploitation methods, and supporting developments that include WAMI or WAS. It is noted that many other developments in optics, photogrammetry, projection geometry, and platforms that could have been included, but many of these techniques are precursors that enabled the development and exploitation of WAMI systems. Figure 3 provides an organization of the literature uncovered. The columns in Figure 3 represent areas of research interest while the rows are themes. For example, the physical sensor models aid in registration, that when aligned support 3D terrain analysis. The optics with geometry support segmentation for vehicle detection that support event processing over a spatial and temporal correlation. Finally, as tracking is based on measurements from detections, it is the computational challenges that lead to activity-based intelligence [4].

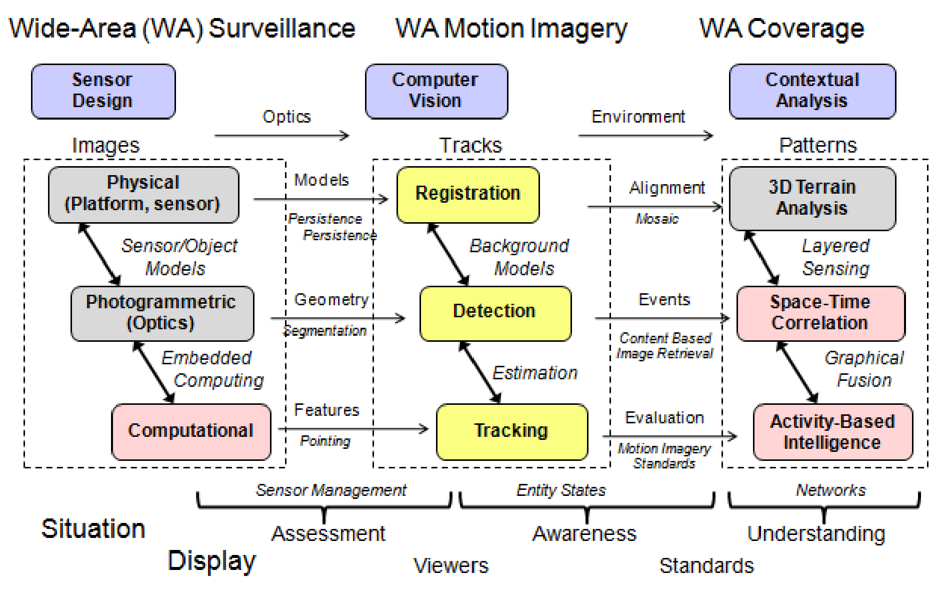

Figure 3: WAMI Processing Techniques. The colors denote areas of development with the Gray boxes as physical designs, yellow boxes is software exploitation, and pink is hardware techniques.

[3] http://www.wpafb.af.mil/news/story.asp?id=123209399

Wide-Area Motion Imagery begins with Wide-area surveillance needs as emerging from difficulties of searching for track initiation; maintain tracks, as well as track-track association (or stitching) from narrow-view full motion video. In a similar manner, the wide area surveillance, imagery, and coverage correspond to the capabilities of situation assessment, awareness, and understanding. For example, situation assessment is enabled by advanced surveillance capabilities. One can maintain awareness by updating the objects and their tracks. Finally, understanding the situation can be furthered from layered sensing and activity based intelligence.

Wide-area implies that **surveillance** which can be accomplished from a big picture. One assumption is that the sensor optics have enough resolution to be able to detect the targets of interest from high altitudes and a nadir viewpoint. WAMI developments included platform routing to point the sensor to a spot on the ground to maintain persistent surveillance [5]. It was the sensor and platform designs (routing) that enabled persistence to coverage a wide area with enough resolution to detect targets and be able to track [6].

Moving from wide-area surveillance to WAMI required an analysis of the large image sizes. The large images reduced the frame rate from which different methods were used to accommodate for the low update rate [7]. The first and pervasive issue associated with the low-frame rate is the difficulty in registering the images [8], from which preliminary techniques were developed to make use of collected data [1]. Even with the low frame rate, emerging techniques allowed for some activity analysis across the multiple tracks [9], interactive search [10], and track initiation [11]. A first comprehensive analysis was reported by Reid Porter that overviews the developments at Los Alamos National Laboratory (LANL) [2].

Building on the possibilities for wide-area surveillance from the data, large numbers of tracks could be developed [12] and extend video analytics [13]. As WAMI is typically focused on electro-optical and infrared (EO/IR) technology, there are other instances of using moving synthetic aperture radar (SAR) to conduct persistent wide-area surveillance. Combining WAMI for WAS could also be facilitated for sensor fusion through layered sensing. As many other types of sensor data collections could be used for global coverage, we restrict ourselves to the literature that is focused on WAMI. For other applications, a recent book by Asari in WAS reports on variations of the theme from academic analysis to applications [14].

4. SENSOR DESIGN FOR WIDE-AREA SURVEILLANCE

4.1 Sensors

Since WAMI is mostly focused on cameras, it is natural that groups focused on designs and analysis of sensors using EO/IR systems as that deployable on UAVs. The first set of papers reporting on WAMI issues include imaging requirements [15], performance gains from sensing systems, as well as a discussion about the implications of emerging WAMI systems such as the ARGUS-IS [16]. Recent methods have discussion working with other WAS such as Moving Target Indicator (MTI) [17]. As the sensor designs evolved, it was well understood that gimballing the entire WAMI sensor would induce extra motion challenges, so the sensors were fixed to the platforms [18].

4.2 Layered Sensing

Arguably, the major developments and funding sources came from the US Air Force and more specifically AFRL with contributions from DAPRA. Many of the developments were not reported directly from DARPA and deployed systems due to the nature of the research, some trade magazine issues have emerged to highlight developments (see the history chapter). AFRL motivated the WAMI discussion as part of a layered sensing design where the WAMI sensor was one but of many sensors observing the battlefield. The first development was architectures of WAMI sensors in layered sensing [19]. In this case, as related to the models of the possible sensing characteristics, physics trade studies were reported [20, 21]. Within the developments of the architecture included capabilities to visualize the data at multiple levels [22]. AFRL, led by Priddy and Uppenkamp produced the PURSUER system so that other developers could quickly see their results [3]. Other techniques exploring physics-based sensing included hyperspectral sensors [23]. Extensions to these techniques by inter-collaborations discussed challenges, tracking results [24], as well as performance models [25].

Inherent in these developments were focused efforts on extending georegistration and compression which leads to WAMI exploitation.

5. WAMI EXPLOITATION ANALYSIS

5.1 Georegistration

Tracking and WAMI exploitation is based on the ability to have registered data. Both tracking (association) helps with registration (correlation) as well as registration (correlation) is aided by tracking (association). The first such study reported includes the AFRL open-source data called Columbus Large Imagery Format (CLIF) [1]. The CLIF data collection allowed numerous researchers to have conducted exploitation results of which links are provided in this book as well as code to do registration and exploitation. The registered CLIF data was explored through numerous methods [1]. However, further analysis was conducted by Pritt and LaToruette in a series of papers. They explored real-time (or near-real time) registration [26], error results as related to a terrain model [27, 28], and multiple camera systems [29]. For most of the tracking results, researchers had some method to register the data to produce the high-quality results [30].

5.2 Compression

Registration and layered sensing are important concepts for WAMI exploitation, however, large data formats and issues still are application issues. One common thread throughout WAMI analysis is compression. Even at the beginning of WAMI research, compression was an issue to make use of the data [31]. Current WAMI methods are still being evaluated as to the effects of compression in relation to the WAMI exploitation [32, 33]. It is understood that if the compression artifacts are at the level of the pixel feature analysis for tracking, then compression will compromise the value of the WAMI use. Thus, it is important to understand the tradeoffs of compression in data and temporal processing savings as to that of the effectiveness for target identification and tracking accuracy. Quantifying the compression loss [34] is important for the end result of the application such as target detection and tracking [35].

5.3 WAMI Computational Analysis for Detection

With the large data sets of WAMI there was a need for software and hardware analysis for low frame-rate analysis. Since the WAMI output provides a large area view, it is important to consider developments from other Geographical/Geospatial Information Systems (GIS) techniques such as overhead imagery, weather analysis, and high-altitude sensing [36]. To utilize WAMI imagery efficiently and effectively requires *software* approaches for joint data management that does a tradeoff between data collection, target detection, and target motion analysis [37, 38]. Inherently, in the joint data management is the effects of the low frame rate update [39], and sparse detection updates [40].

WAMI detection includes the scene content such as roads and buildings, recognition and classification of targets [41], as well as assessing object-level change detection of targets [42].

From the *hardware* analysis, various design tradeoffs need to be considered such as the architecture, on-board processing, and the mission [43]. For example, an architecture mission analysis includes the features detected that lead to efficient measurement updates and pixel contrast such as a likelihood approach [44]. The balance between the software and hardware analysis creates unique challenges versus standard EO/IR tracking [45, 46] to include visualization [47], user interaction, tracking [48, 49], feature extraction [50], and presentation [51].

5.4 WAMI Tracking

We divide methods for motion analysis into scene-independent and scene-dependent approaches. Scene dependent approaches will be covered in contextual tracking (Section 6) as context aids in the analysis to include roads, dynamic movement, and spatial analysis.

Scene-independent (or context-independent) tracking focuses on the pixels. One aspect of WAMI exploitation is that the pixel resolution is small for the targets of interest. Thus, local methods, such as histograms have been used [44, 52] as well as focusing on regions or tiles [48, 51, 53]. Building on the notion of few pixels for each target includes small targets [54], tuned operations [55], as well as vector fields [56]. Recent results build on previous applications of WAMI tracking [2] to include using correspondence for high-density scenes [57] and appearance-based tracking approach to extend tracklife [58]. While WAMI tracking is a component of exploitation, it also is used to provide situation assessment of contextual analysis to include target locations, scene content, and patterns of life.

6. WAMI CONTEXTUAL ANALYSIS FOR EXTENDED COVERAGE

Given the sensor design to enable WAMI data, exploitation methods such as detection and tracking, the third area of WAMI developments includes coverage for scene analysis, context tracking, and activity analysis.

6.1 WAMI Tracking Enhancements

Current tracking developments have been extended to WAMI methods. For example, Rimey, *et al*., looked at WAMI tracking as a network of sensors to aid WAMI tracking [59]. Prokaj and Medioni have looked at 3D scenes [60], multiple target tracking [61], and activity analysis [62]. Currently, the move towards machine analytics [63] has forced research into scalability issues [64] as well as compression (see above).

6.2 WAMI Context-Aware Tracking

The developments in WAMI tracking have followed efforts in EO/IR tracking and classification/identification [65, 66, 67]. To enable tracking requires *detection* of the targets in the WAMI data. Approaches to detection include kernel learning [41], moving target context [68], spatial context [69], and temporal context [70]. These various approaches for using context for detection enable *context-aware* tracking [71] which have been evaluated for consistency [72] and localization in emerging testbeds [73].

7. FUTURE WAMI DEVELOPMENTS

WAMI techniques include surveillance, motion analysis, and coverage. Current approaches include methods for 3D terrain analysis as an extension of georegistration, space-time correlation of WAMI data with other sensor modalities, and activity-based intelligence with WAMI data. Future techniques will see developments for situation awareness, community standards, and common viewers for user interaction over a variety of applications.

7.1 Situation Awareness

Providing a large area coverage from a single WAMI data enhances situation awareness much as linking multiple sensors [74]. Wide area surveillance allows for massive detection of events [75] as well the ability to link situation awareness results to semantic relationships [76, 77]. The future of WAMI will include developments from military and civilian results such as user workflow analysis from a control room monitoring multiple imagery collections [78]. Together, both individual WAMI platforms and multiple platforms will need to be network for extended situation awareness over time, space, and mission collections.

7.2 Standards

WAMI techniques are emerging and the Motion imagery Standard Board (MISB) has reported numerous efforts in SPIE towards a unification of analysis and operational consistency. Such standards build on detection, tracking [79], and activity recognition [80]. These standards are being continually refined for imagery [81], feature analysis [82], and operational deployment [83]. Consistent with any standard is methods for testing, evaluation, and software and hardware implementations. As an example, standards would be a common viewer.

7.3 Viewers

Users make decisions and WAMI enables enhanced analysis and discovery through wide-area persistent surveillance. Using the wide field of view could enable a user to reason over different hypothesis [84]. To viewers that enable processing of WAMI data with user interaction that build on NASA developments include the KOLAM [85] viewer and the PURSUER interface [3], and Transparent Sky's Interaction Devices, shown in Figures 4, 5, and 6; respectively.

PURSUER is a graphical user interface capable of assimilating wide-area motion imagery, ground-based sensor data, and narrow-field-of-view sensor overlays for review in one composite display composed of multisensor imagery and associated metadata. Dubbed Pursuer, the technology builds upon the NASA's World Wind Java, a software engine that overlays NASA and US Geological Survey satellite imagery, aerial photography, topographic maps, and publicly available geographical information system data on three-dimensional models of earth and other planets. Accordingly, AFRL's Pursuer provides a time model that enables users to step through a collection of sensor data in a "TiVo-like" (i.e., digital-video-recording-type) capacity. The technology also incorporates a variety of additional tools--such as frame-to-frame stabilization, brightness/contrast adjustment, user markup annotation, screen capture, distance calculator, manual tracking, and movie creation--enabling users to exploit the captured sensor data to the fullest possible extent. Pursuer is available in a collaborative software environment for developers. Interested (authorized) parties can access the Pursuer source code under the Spatially Diverse Electronic Attack (SPADE) project on Forge.mil [4].

Figure 4: KOLAM Viewer.

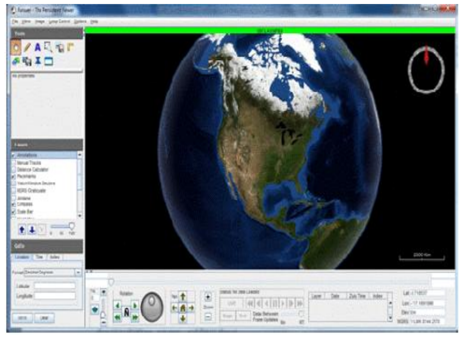

Figure 5: PURUER Interface.

Figure 6: Transparent Sky Viewers

A new set of viewers has been developed to maximize user access and ease of use by Transparent Sky. Of these, one is based on WorldWind, similar to PURSUER, but is cross-platform and supports Linux, OSX and Windows through a simple installation and link to data. The other is a native application with the same functions that runs on mobile devices.

Using the above techniques with hardware sensor designs, software tracking analysis, and user workflows would enable future exploitation capabilities. WAMI has afforded advances in situation awareness [86], road tracking [87], and resource management [88]. Such examples of emerging projects include: determining activities from persistence surveillance [89] and patterns of life from contextual analysis [90]. The future of WAMI would include methods for user interaction [91], fusion with other sensors [92], information management [93], and cloud-based applications [94].

8. CONCLUSIONS

WAMI has progressed rapidly in the last decade as the optics support high-resolution wide area surveillance, motion analysis, and are coverage. To effectively use the sensor technology, optics control (e.g., pan and zoom), platform routing and on-board computational approaches are needed. The key literature analysis was focused on exploitation to include registration, detection, and tracking. To aid in the tracking, techniques for 3D terrain analysis, contextual understanding, and activity recognition have been use cases for WAMI data. The future includes situation awareness, common standards, and user interaction with viewers. The literature review includes many of the prominent researchers driving the developments of which the key techniques were organized into three areas of surveillance, motion analysis, and coverage. The future will see various applications of WAMI technology for disaster relief, environmental analysis, and urban traffic monitoring [95].

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[4] PURSUER webpage: http://www.wpafb.af.mil/news/story.asp?id=123209399

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