Automatic Thermal Infrared Panoramic Imaging Sensor

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ABSTRACT

Panoramic cameras offer true real-time, 360-degree coverage of the surrounding area, valuable for a variety of defense and security applications, including force protection, asset protection, asset control, security including port security, perimeter security, video surveillance, border control, airport security, coastguard operations, search and rescue, intrusion detection, and many others. Automatic detection, location, and tracking of targets outside protected area ensures maximum protection and at the same time reduces the workload on personnel, increases reliability and confidence of target detection, and enables both man-in-the-loop and fully automated system operation. Thermal imaging provides the benefits of all-weather, 24-hour day/night operation with no downtime. In addition, thermal signatures of different target types facilitate better classification, beyond the limits set by camera's spatial resolution.

The useful range of catadioptric panoramic cameras is affected by their limited resolution. In many existing systems the resolution is optics-limited. Reflectors customarily used in catadioptric imagers introduce aberrations that may become significant at large camera apertures, such as required in low-light and thermal imaging. Advantages of panoramic imagers with high image resolution include increased area coverage with fewer cameras, instantaneous full horizon detection, location and tracking of multiple targets simultaneously, extended range, and others.

The Automatic Panoramic Thermal Integrated Sensor (APTIS), being jointly developed by Applied Science Innovative, Inc. (ASI) and the Armament Research, Development and Engineering Center (ARDEC) combines the strengths of improved, high-resolution panoramic optics with thermal imaging in the 8 – 14 micron spectral range, leveraged by intelligent video processing for automated detection, location, and tracking of moving targets. The work in progress supports the Future Combat Systems (FCS) and the Intelligent Munitions Systems (IMS).

The innovative, automated thermal imager with 360° field of view (FOV) optics provides situational awareness and instantaneous full horizon detection, location, and tracking of multiple targets. It features pixel limited resolution, advanced sensor node in a network of intelligent, distributed sensor arrays. Integration of commercial off the shelf (COTS) components is maximized in the APTIS design to reduce cost and time to market. The APTIS is anticipated to operate as an intelligent node in a wireless network of multifunctional nodes that work together to serve in a wide range of applications of homeland security, as well as serve the Army in tasks of improved situational awareness (SA) in defense and offensive operations, and as a sensor node in tactical Intelligence Surveillance Reconnaissance (ISR).

The novel ViperView™ high-resolution panoramic thermal imager is the heart of the APTIS system. It features an aberration-corrected omnidirectional imager with small optics designed to match the resolution of a 640x480 pixels IR camera with improved image quality for longer range target detection, classification, and tracking. The same approach is applicable to panoramic cameras working in the visible spectral range. Other components of the ATPIS system include network communications, advanced power management, and wakeup capability. Recent developments include image processing, optical design being expanded into the visible spectral range, and wireless communications design. This paper describes the development status of the APTIS system.

1. INTRODUCTION

Applied Science Innovations, Inc. (ASI) and the Armament Research, Development and Engineering Center (ARDEC) are jointly developing the Automated Panoramic Thermal Imaging Sensor (APTIS) - a new thermal imager with 360° field of view small optics to provide instantaneous full horizon detection, location and tracking of multiple targets[1],[2]. The innovative ViperView™ optical design of the imager provides for small size and low cost, combined with the high resolution, matching pixel resolution of the state-of-the-art uncooled thermal infrared sensors. The high resolution is key in increasing the target detection range, extended target identification range, and reduced target acquisition time. The integrated APTIS imager design

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includes global positioning system (GPS) navigation and communication interfaces to serve as an advanced sensor node in a network of intelligent, distributed sensor arrays. Power-save mode and remote wakeup capability will serve for extended unattended operation.

Conventional cameras have limited field of view in the horizontal dimension, failing to display objects and event beyond the FOV. Unlike this "tunnel vision" of a camera with conventional optics, human vision includes peripheral vision, with the filed much wider than the high-resolution portion of the field around the forward direction. Peripheral vision allows us to readily detect large objects, contrast colors, and fast motion. Pan-tilt-zoom (PTZ) cameras may cover full horizon, but fall short of full-time, full horizon coverage and are prone to missing rapid events.

The ViperView™ thermal imager of the APTIS sensors may serve to complement a separate conventional camera to mimic human vision and exceed its capabilities, with full-time 360^o coverage, day/night, all-weather operation, and automatic target detection and tracking for maximal situational awareness.

High image resolution of a panoramic imager in a sensor ensemble increases the coverage area, extends the range of effective target detection, location, and tracking, reduces the number of sensor nodes necessary, thus reducing the overall cost. Existing panoramic imagers, e.g., with parabolic or hyperbolic reflectors, have optical aberrations, which typically are reduced by imaging at low image numerical apertures. This approach is well known in optics and photography: at small apertures, any lens operates in a "near-pinhole" mode; this approach to reduction of aberrations comes with a significant loss of light. Reflector aberrations may significantly compromise image resolution, especially at high apertures. High apertures ("fast" optics) are required in such applications as low light imaging and thermal imaging. In low light, large optical apertures translate into higher light throughput. In thermal imaging, the diffraction spot size increases as the ratio of the wavelength to the aperture diameter. The longer wavelength of the infrared range therefore requires larger apertures to offset the effect of the longer wavelength and keep the optical resolution in a match with the pixel resolution of the senor. The larger aperture of the optics reduces the effect of diffraction and improves image quality. In panoramic catadioptric systems, the mirror size affects the effective aperture. High image quality is easy to achieve with large mirrors placed at long distances from the camera. In other words, larger catadioptric panoramic cameras have lower aberrations and produce better images, at the expense of the overall larger size of the optics. On the other hand, small panoramic optics with low aberrations presents a design challenge. The challenge is even higher for thermal optics, where diffraction of the longer wavelength dictates large apertures, regardless of the light throughput, in order to match the diffraction limited spot size with the pixel pitch of the sensor.

Unless aberrations of the optics are corrected, the image spot size may significantly exceed the pixel size of the sensor, compromising the investment in a high-resolution long-wavelength infrared (LWIR) sensor. In the APTIS panoramic thermal imager, effective collection of thermal IR radiation necessitates high numerical apertures, exceeding those typical of existing panoramic imagers. The requirement for small size of the sensor calls for reduced mirror size. Our development included optical design effort that resulted in an integrated panoramic imager with small optics, large effective aperture for maximum collection of IR radiation, and uncompromised image resolution, matching the resolution of a 640 x 480 LWIR sensor.

2. DESIGN APPROACH

APTIS is a new automated thermal imager with 360° field of view (FOV) optics to provide instantaneous full horizon detection, location and tracking of multiple targets. The small, high-resolution optics of the sensor has been designed to match the focal plane array thermal imager with 640x480 pixels potential to provide day/night detection of personnel, aircraft and vehicles even when camouflaged. The high resolution, low cost imager will provide for longer target detection range, extended target identification range, and reduced target acquisition times. The novel combination of the high-resolution thermal imager with 360° FOV optics will enable accurate target bearing, temperature profiles, and rough order of magnitude target imaging which can aid classification, discrimination and identification of targets.

The new panoramic optics of the thermal imager has been designed, built, and demonstrated. Development of the integrated sensor is now under way through integration of the panoramic imager with other components including GPS, digital compass, tilt sensor, target image processing, and wireless communications for ad-hoc networking. All of these components are available commercially.

The approach selected in this development is based on the ViperView panoramic thermal imager with 360-deegree horizontal field of view and small, high-resolution optics for maximum detection range. The APTIS design is optimized for operation in a "man in the loop" network of intelligent sensor nodes. Automated detection of targets in protected area reduces workload on the human operator.

The integrated APTIS sensor suite is designed for field deployment with battery-powered imager sensor nodes. Advanced power management subsystem is designed to conserve the power provided by the battery. Components of the APTIS system fall into three major groups, based on the level of battery power consumption. The first group includes wakeup and power management, consuming negligible amount of battery power, such that the battery life with these sensors alone is practically the same as the shelf life of the battery. A portion of network communications (in the receiver mode) is included in this group as well for getting cues form other sensor nodes. This first group of components is “Always On” to provide a wakeup signal to the thermal imager and other “power hungry” components.

The second group includes a Global Positioning System (GPS) receiver, which operates intermittently, e.g., once every 10-15 minutes. The reason for this operation mode is that it takes a GPS receiver approximately one minute on average to acquire satellites before the latitude and longitude can be determined and store in the memory of the APTIS processing hardware. An additional function of the GPS component is timing synchronization over the network.

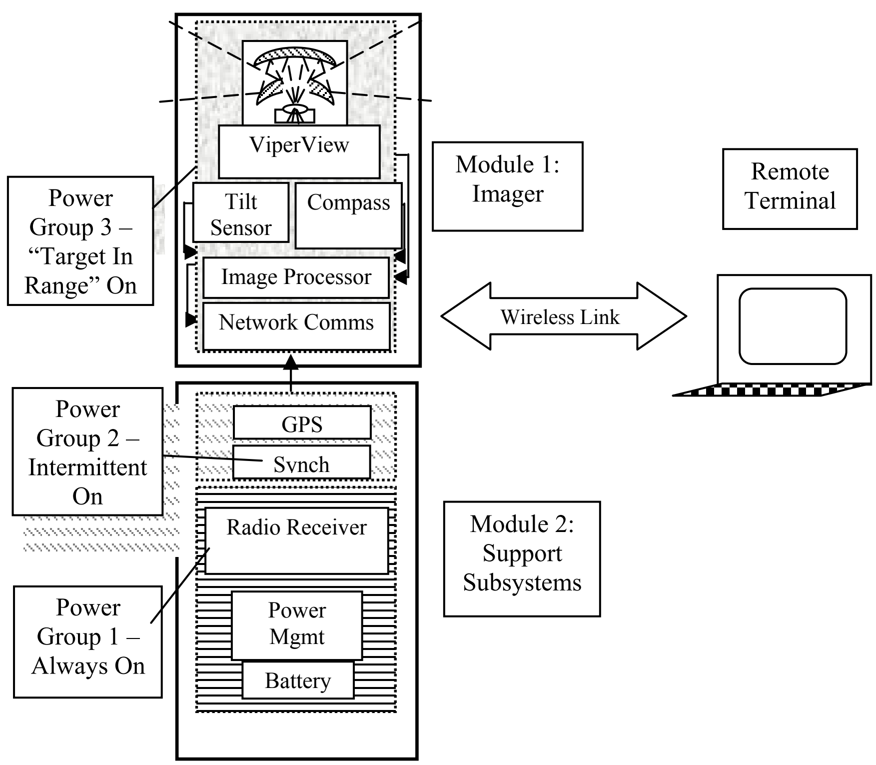

Figure 1. Block diagram of the APTIS system

The third group of components includes the power-consuming components: panoramic thermal imager; processing hardware for target detection, location, and tracking, and the wireless network communications. The electronic compass and the tilt sensor are also included in this group. This group is powered once at the time of deployment. In combination with the GPS, electronic compass, and the tilt sensor, this brief initial operation results in a determination of the location and orientation of the unit in space, as well as provides learning of the surrounding area by the intelligent sensor software responsible for automatic detection, location, and tracking of targets. This learning process serves for effective target discrimination against background, including moving objects such as shrubs and trees. The electronic compass and the tilt sensor provide to the processor unit the true North direction and the vertical axis, necessary for translating pixel coordinates of the target into the absolute location and direction to target. The third group of sensor component also powers up on every wakeup signal from the first group.

Once the wakeup signal brings the integrated APTIS sensor to full operation mode, the panoramic thermal imager acquires images at the video frame rate of 30 fps and sends the video stream to the processor unit. The processor detects moving targets from the video stream. The software is capable of intelligently separating meaningful target motion from motion clutter, such as produced by trees, shrubs, and similar natural objects. The software uses a set of rules for detection and identification of targets. The rules can be fine tuned by the operator at any time. They include criteria such as target location, speed, direction/heading, size, altitude, and confidence.

A remote terminal receives over a wireless link real-time imagery acquired by the panoramic camera. The terminal is equipped with software for image processing, which includes image transformation ("unwrapping"), with targets highlighted. In addition, up to five regions of interest surrounding targets are shown separately.

For every detected target, communicated to the central node (remote terminal, man-in-the-loop) are 1) target coordinates, speed, direction/heading, and altitude; 2) image regions of interest (ROI) containing the targets or target clusters; 3) "unwrapped" full frames, with targets marked, in near-real time as provided by the bandwidth of the communications channel. This allows the operator to identify and track targets, as well as direct other sensors and assets to the target or targets as necessary.

Mechanical design of the APTIS prototype includes a lightweight, low cost mounting adapter that enables several mounting options of the imager. The main mounting options are "ground low" on a small tripod, providing the "guard dog's point of view", compatible with munitions systems and unattended ground sensor applications; "ground high" on a tripod 6 to 8 feet high, in a reverse orientation for area monitoring form an elevated point; and vehicle mount of application on regular and unmanned ground vehicles, applicable to remotely controlled robots and to vehicle protection.

After a preset period of time with no targets being detected by the imager, the imager and the other components of the "power hungry" group are turned off until another wakeup signal.

3. PANORAMIC IMAGE UNWRAPPING

Pictures taken with the panoramic camera contain 360º surrounding views. The "donut" image is not easy to view for the human operator. To improve the visual viewing effect, image unwrapping is needed to present the obtained panoramic camera into a 360º unwrapped panoramic view. In the APTIS application, near real time imagery is to be unwrapped with virtually no additional time delay. For this purpose, fast image processing software routine has been developed for image unwrapping. Figure 2 shows the approach used in the unwrapping algorithm.

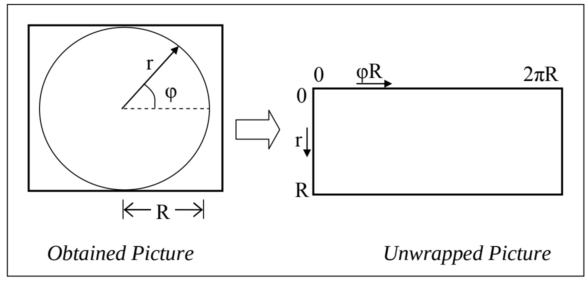

Figure 2. Principle of the panoramic image unwrapping

The "donut" image is mapped onto the output frame using coordinate transformation from polar to rectangular. The fast mapping routine was written in C and implemented on a PC computer. Transformation of a 640x480 24-bit image was demonstrated at frame rates in excess of 20.

Figure 3 shows an image taken with a panoramic camera. The image size is 640 x 480 pixels. Unwrapping this image into a rectangular panoramic view results in a reproduced panoramic picture with a maximum height of 240 pixels, equal to the "donut" semi-diameter of the picture in Figure 3. The width of the unwrapped image is 480π, i.e., 1508 pixels.

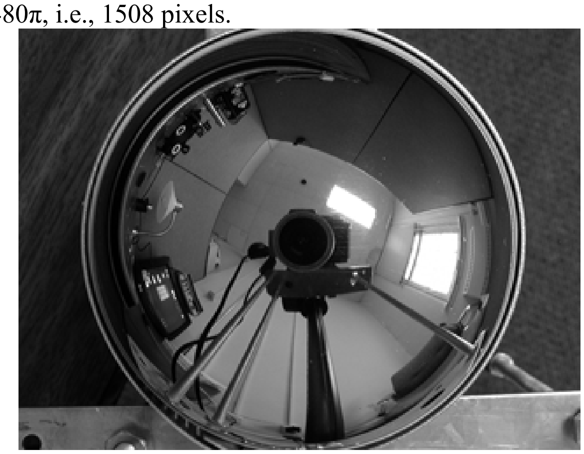

Figure 3. Photo taken by the panoramic imaging sensor with visible light.

Figure 4 shows the unwrapped image of Figure 3. It is the full 360-degree view of the scene. The size of the picture is 1584 x 240, with a minor overlapping at the ends.

Figure 4. Unwrapped image; image size is 1584 x 240

4. DETECTION RANGE

The detection range is a function of the number of pixels on the target and the angular magnification of the optics. The number of pixels required varies with the target to background contrast and depends on the image quality produced by the camera, which also affects the contrast (modulation transfer function, or MTF). Other factors affecting the detection range include the detection algorithm, which distinguishes the "meaningful" motion of the target from background motion, such as trees or shrubs in the wind, flying birds, and similar natural objects and events.

In addition, the number of pixels required and the related detection range are a result of a tradeoff that involves the rate of false alarms. Considering all of these factors, it is reasonable to assume two pixels across the horizontal dimension of the target as an estimate of the required number of pixels for automatic detection.

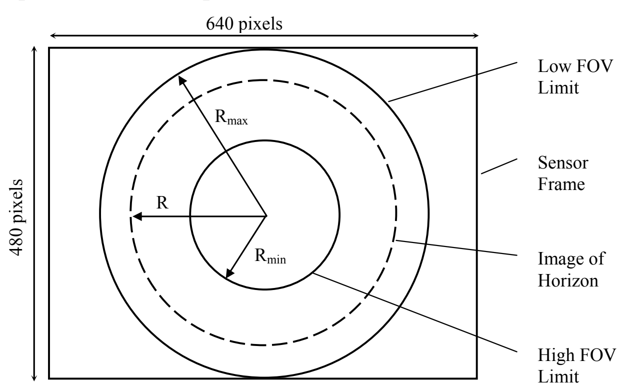

Figure 5. Effect of the FOV and horizon location on resolution

With this assumption, the detection range can be estimated as follows.

$$L_{det} = \frac{d}{n_{pix\_det}} \cdot \frac{2\pi R}{360deg} \qquad (1)$$

Here L_{det} is the detection distance; d – target size; n_{pix_det} – number of horizontal pixels on target required by the software for detection; R – radius, in pixels, of the image of horizon on the sensor. The latter radius can be estimated as

$$R = R_{min} + \left(R_{max} - R_{min}\right) \cdot \frac{VFOV_1}{VFOV_1 - VFOV} \qquad (2)$$

where R_{min} and R_{max} are the "donut" radii, as illustrated by Figure 5; $VFOV_1$ and $VFOV_2$ – positive ("up") and negative ("down") vertical fields of view of the imager.

Assuming an upright person being the target (shoulder width d~50cm; 2 pixels required for detection), the following values can be used for estimating the detection range: d = 50cm; $n_{pix\_det} = 2$; $VFOV_1 = 45^o$; $VFOV_2 = -5^o$; $N_{pix} = 480$; $R_{min} = 120$; $R_{max} = N_{pix}/2$. Using these values in formulas (1) – (2), one arrives at the detection range of approximately 57 meters. It should be noted that a compromise exists between the "down" vertical field of view $VFOV_2$ and the detection range. When $VFOV_2 = 0$, L_{det} is 60 meters; if $VFOV_2 = -15$deg, L_{det} is 52 meters, if $VFOV_2 = -30$deg, L_{det} is 48 meters, and so on. This tradeoff is somewhat counter-intuitive and should be taken into account when choosing the mounting method for the imager. If the camera is installed at an elevated point, such as a tripod, one might intuitively expect a longer detection range. While this is true in terms of avoiding obstacles and obscurations covering the target, the minimal field of view needs to be chosen below zero to cover low elevation points near the camera. The associated reduction in value R (image of the horizon on the sensor; Figure 5) reduces the detection range of targets approaching from the horizon at or near zero elevation angles.

a) b) c)

Figure 6. ViperView optics - experimental demonstration: a) experimental optical system; b) sample image produced by the camera; c) zoomed-in fragment of the same image showing pixel-limited resolution

5. ABERRATION-CORRECTED VIPERVIEW OPTICS

A major problem in existing catadioptric panoramic optical systems, especially working at large apertures, is the resolution limitation imposed by optical components (lenses and mirrors). With optics-limited resolution, such panoramic cameras cannot benefit from high resolution imaging sensors (640x480 pixels or higher). Even at lower resolutions, some of the existing panoramic cameras have optics-limited resolution. ViperView optics, along with the small size, features aberration correction to a level adequate to match a 640x480 imaging sensor.

Optical design of the ViperView imager was performed by Applied Science Innovations using the OSLO Premium software. The orientation of the "donut" image on the sensor was selected such that the positive (above horizon) elevations projected towards the center, whereas negative (below horizon) elevations projected towards the periphery, with the horizon imaged close to the periphery of the image as well. This image orientation provided for optimal allocation of senor resolution, with the larger number of pixels for imaging the horizon, where targets are more likely to be located. The alternative image orientation, with the direction up imaged towards the outside of the "donut", was rejected as sub-optimal, with lower pixel count imaging the horizon, lower maximal elevation, and significant portion of the pixels imaging the ground in a close vicinity of the sensor. Optimization of the image quality was performed while maintaining small size of the optics and the desired vertical field of view. Several optical designs were produced, with the spot size smaller than the pixel pitch of a 640x480 sensor over the complete field.

Experimental implementation of the ViperView optics and sample images produced by it are shown in Figure 6.

The thermal camera used in these preliminary experiments had the pixel resolution 320x240. Integration of a high-resolution, 640x480 uncooled thermal imager into the APTIS prototype is now under way. The large numerical aperture of the optics was equivalent to that of a regular F/0.85 lens. As illustrated by the images captured, the resolution is clearly pixel limited, which proves that aberrations of the optics are well corrected.

6. AUTOMATIC TARGET DETECTION AND TRACKING

The video stream from the panoramic camera is sent to the video processor board for detection, location, and tracking of targets. Detection is preformed on the camera end of the communication link, on the "unwrapped", "donut" image. The processor board uses field-programmable gate arrays (FPGA) with intelligent video processing implemented. Several processing modes and detection and tracking rules are available. The choice of the processing algorithm and fine-tuning of the detection rules are preformed from the camera host computer over the standard serial interface. Currently, the rules are set prior to operating the APTIS system, using the camera computer. Future development will include providing the rule adjustment remotely, over the wireless communications link.

The intelligent algorithm running on the FPGA board automatically detects and tracks up to five targets. The input video is analog, in the NTSC format. The FPGA has a processing ability of horizontal resolution of 720 pixels and the vertical resolution of 242 pixels per field, i.e., 484 lines per frame, at 60Hz as provided by the

NTSC standard. The image includes a rectangular region containing the 360 degree panoramic view of the surrounding environment. The FPGA board outputs an analog video signal overlaid with detection symbology. The symbology and the target information are also served through serial data interface for target screening and further processing purposes.

Target acquisition and tracking can be performed in different detection and tracking modes. A primary target can be identified according to different criteria while information on additional targets is also served continuously, providing multiple target tracking. Multiple criteria for selecting the primary target are available, including location, intensity, speed, and others. In the thermal imagery produced by the ViperView camera, the target intensity and color (shade of grey) characterize the thermal signature of the target. This important characteristic is used for target detection and tracking along with other selection criteria. The target detection is fast, in the fractions of a second time frame, for both new targets and targets reappearing after hiding or being obstructed.

encrypted for secure transmission, preventing unauthorized access. Components are housed in weatherproof cases. The system consumes 3W power at each power injector when communicating. The output power reaches 400 mW.

All of the hardware on the camera side, including computer, camera, FPGA board, and wireless transmitter is put into hibernation at the client operator's command, provided no targets of interest are in range. To reduce the power consumption as much as possible, the wireless networking will cease to function when the APTIS server is in hibernation, in which power supply to the server computer, the wireless network hardware, the GPS receiver, and the electronic compass / tilt sensor will be disconnected. Wakeup of the APTIS server is provided by an ultra low power wireless wake up device currently being integrated into the prototype. At the operator's command on the client laptop, the receiver wakeup device on the server side will switch on the ATX power supply at the server, to resume the power supply to all the APTIS components. The embedded computer will resume all of the functions it was performing when put into hibernation.

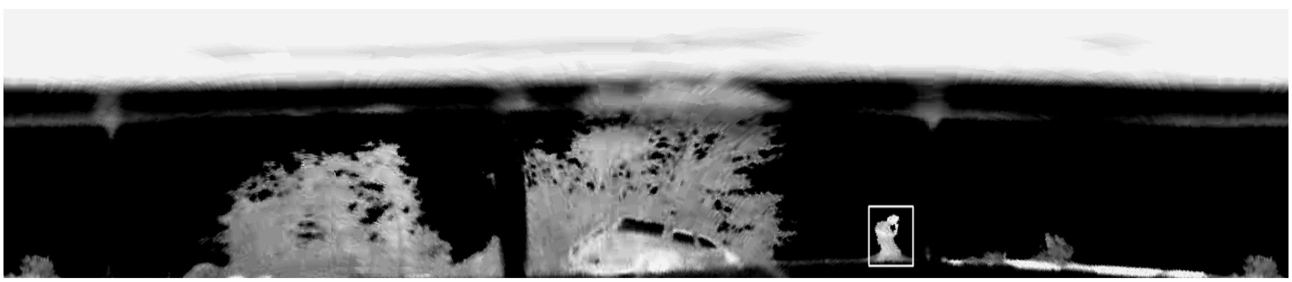

Figure 7. “Unwrapped” thermal imagery is displayed in the ATPIS GUI, with moving targets marked and target data registered in real time.

8. WIRELESS COMMUNICATIONS

The APTIS panoramic camera is hosted by an embedded PC104+ computer running a server application to relay collected data to a client computer. Communications between this server and the operator client rugged notebook computer are established through a secure wireless network. The wireless Ethernet is based on standard 802.11a technology and operates in the 5.3 and 5.8 GHz U-NII bands. The system of dual RF modules is as a plug and play CAT5 Ethernet cable replacement designed for use with standard Ethernet devices. The system transmits from 2500 feet to 30 miles at 20 Mbps digital data stream in standard mode and a 40 Mbps digital data stream in turbo mode. With a moderate-size antenna, the system operates up to 4 miles in light-of-sight conditions. The communication is currently determined by the MAC address of each transceiver. The signal between the RF modules is

CONCLUSIONS

Development of the Automatic Panoramic Thermal Imaging Sensor is under way. The sensor is designed as an intelligent node in an ad-hoc sensor network. The design features automatic detection, location, and tracking of multiple targets and advanced power management for extended battery life, enabled by remote wakeup capability. ViperView^{TM}, the small, high-resolution imager of the APTIS system has been designed, implemented, and demonstrated experimentally.

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