(Extended abstract submitted to) AIAA SciTech, Grapevine, Texas, January 2017

Image and Information Fusion Experiments with a Software-Defined Multi-Spectral Imaging System for Aviation and Marine Sensor Networks

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The availability of Internet, line-of-sight and satellite identification and surveillance information as well as low-power, low-cost embedded systems-on-a-chip and a wide range of visible to long-wave infrared cameras prompted Embry Riddle Aeronautical University to collaborate with the University of Alaska Arctic Domain Awareness Center (ADAC) to prototype a camera system we call the SDMSI (Software-Defined Multi-spectral Imager). The concept for the camera system from the start has been to build a sensor node that is drop-in-place (self-powered, self-contained) for simple integration into aviation, marine, pole-mount, or buoy-mount environments in Alaska. After several years of component testing, qualification and characterization, the project which is a part of the overall ADAC AIFC (Arctic Information Fusion Concept), is being tested, first on roof-mounts at Embry Riddle Prescott and University of Alaska Anchorage. The roof-mount testing demonstrates simple installation for the low-power, low-cost, high spatial, temporal and spectral resolution imaging system for security and safety applications of value to aviation and marine systems situational awareness. The goal is to define and develop new technology to provide better awareness for organizations like the US Coast Guard, US Geological Survey and National Oceanic and Atmospheric Administration to complement satellite remote sensing and human patrol and monitoring of key resources and assets in Alaska such as marine ports, shipping lanes, airports, roadways, and other critical infrastructure in this vast area. The SDMSI is being installed at Embry Riddle Prescott in summer 2016 as well as University of Alaska Anchorage and continuous image data (recorded to network attached storage) is being compared to long-wave and visible image fusion, stereo images, with processing to assess the saliency of images to form smart compression of data compared to the continuous recording. Users of the SDMSI can pair with it via wireless to browse salient image thumbnails. Further, both ADS-B (Automatic Dependent Surveillance-Broadcast) and S-AIS (Satellite Automatic Identification System) data are

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This material is based upon work supported by the U.S. Department of Homeland Security under Grant Award Number, DHS-14-ST-061-COE-001A-02. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

used by the SDMSI to form expectations for observing. This paper presents the results of several experiments and compares human review of continuous imaging with smart image processing using saliency metrics and fusion transforms in terms of a receiver-operator curve, total power used, and quality of images produced compared to raw data images. The experiments will continue to run for a full year until summer 2017, but here we present results from initial operation, including survivability and maintenance of the camera system.

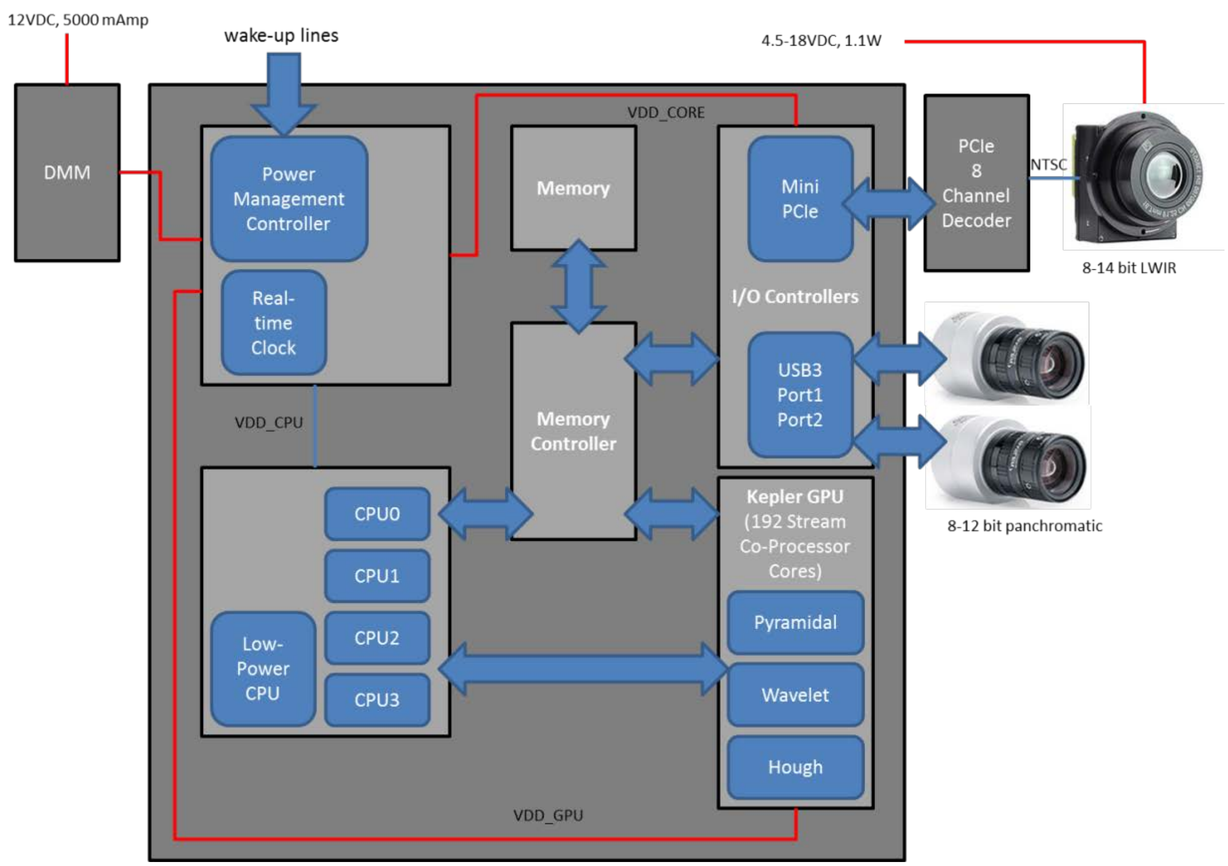
Nomenclature

ADS-B = Automatic Dependent Surveillance – Broadcast, aviation identification and tracking
AIFC = Arctic Information Fusion Concept, an ADAC sensor network prototype
CBONS = Community Based Observing Network System, or human field monitoring
CUDA = Compute Unified Device Architecture, GP-GPU acceleration
DMM = Digital Multi-Meter, used for current monitoring and power use analysis
FoV = Field of View
FPGA = Field Programmable Gate Array
GP-GPU = General Purpose Graphics Processing Unit
LWIR = Long Wave Infrared, typically 8-15 micron wavelength electromagnetic radiation
MWIR = Medium Wave Infrared, typically 3-8 micron wavelength electromagnetic radiation
NIR = Near Infrared, typically 0.75-1.4 micron wavelength electromagnetic radiation
NOAA = National Oceanic and Atmospheric Administration
OpenCV = Open Computer Vision, an open source library in C/C++
Panchromatic = Visible and part of VNIR electromagnetic radiation in 0.45-0.8 micron range
PCIe = Peripheral Component Interconnect Express, a device interface bus
RoC = Receiver operator Curve, a comparison of false positive and negative counts
S-AIS = Satellite Automatic Identification System – automatic marine tracking service
SDMSI = Software Defined Multi-Spectral Imager
SWIR = Short Wave Infrared, typically 1.4-3 micron wavelength electromagnetic radiation
TAP = Trans Alaska Pipeline
USB3 = Universal Serial Bus, Revision 3, operating at 5 gigabits per second (625MB/sec)
USCG = US Coast Guard
VNIR = Visible and Near Infrared, typically 04.4-1 micron wavelength range

Introduction

The purpose of the research presented in this paper is to evaluate the hypothesis that pole-mount cameras on buoys, buildings or towers, and marine vessels can improve situational awareness for the US Coast Guard, NOAA, and USGS compared to satellite remote sensing alone with occasional human monitoring. The assertion is that a multi-spectral imaging system defined by software providing fusion and mapping features such as passive 3D, can also be defined and improved through software upgrades over time to perform better than security camera continuous monitoring. Finally, that the result will be better spatial, temporal, and spectral resolution observing of key areas of interest in Alaska and the Arctic compared to current methods employed by these agencies. Once this hypothesis has been tested thoroughly, the concept of a smart SDMSI might also have value for aerial surveys and surveillance. The SDMSI system design that is being built and tested in Arizona and Alaska is shown in Figure 1 below. The camera system includes a Tegra K1 SoC (4 processor cores and 192 vector co-processor cores), wireless 802.11, Ethernet wired, USB3, a PCIe card interface, and is able to support 2 USB3 visible cameras and between one and four analog cameras including long-wave infrared. As such, the hardware is a system composed of sub-systems that can be upgraded and the features and function of the SDMSI are totally defined by the software and capabilities of the components in terms of resolution, optics, and frame rates, spectral and dynamic range.

Figure 1. – SDMSI Test Configuration



The system allows for hardware, firmware and software to be open systems, based on embedded Linux running on the processor and emphasis is on the transforms that can be completed in real-time with power efficiency to support advanced monitoring and observing modes. The power analysis leading to the selection of a GP-GPU co-processor for the SDMSI is presented in detail in previous work [1].   An SDMSI system will be mounted for testing on the roof of the University of Alaska Anchorage College of Engineering for a full winter during 2016 to 2017 and remotely upgraded and accessed, but with continuous recording of images to compare to for validation of intelligent image selection tests. Likewise, a control SDMSI will be mounted on the roof of the College of Engineering at Embry Riddle Prescott. Three main experiments are planned including: 1) sky monitoring of overflying aircraft, 2) natural area monitoring for wildlife activity, and 3) monitoring of human activity. The goals include acquisition and storage of images of interest that are unexpected based on criteria such as targets of interest (aircraft not reporting on ADS-B), animal activity for known dangerous animals (Moose, Bear, Javelina), and human activity that is suspect (presence in dangerous areas). The criteria require both information fusion and sensor and image fusion for success. Performance for results collected from experiments to date up to finalization of this paper and the presentation at SciTech will primarily include RoC analysis based on human review of the continuous data and total power used during the experiment.

Information Fusion

Information fusion is simple in concept, but requires constant monitoring of aggregated ADS-B information for example to provide expectation for aircraft that should be in view as well as unexpected aircraft detected. The same information fusion can be used in marine environments with S-AIS, but based on the experimental locations; this will not be validated at this time. For remote installations on buoys the SDMSI would require line-of-sight ADS-B or satellite ADS-B, which is true as well for marine AIS. The results collected to date show promise, as depicted in Figure 2, where for example in marine environments, the use of visible fused with long-wave infrared can provide information such as engine and exhaust configuration, which can be compared to database information for S-AIS.

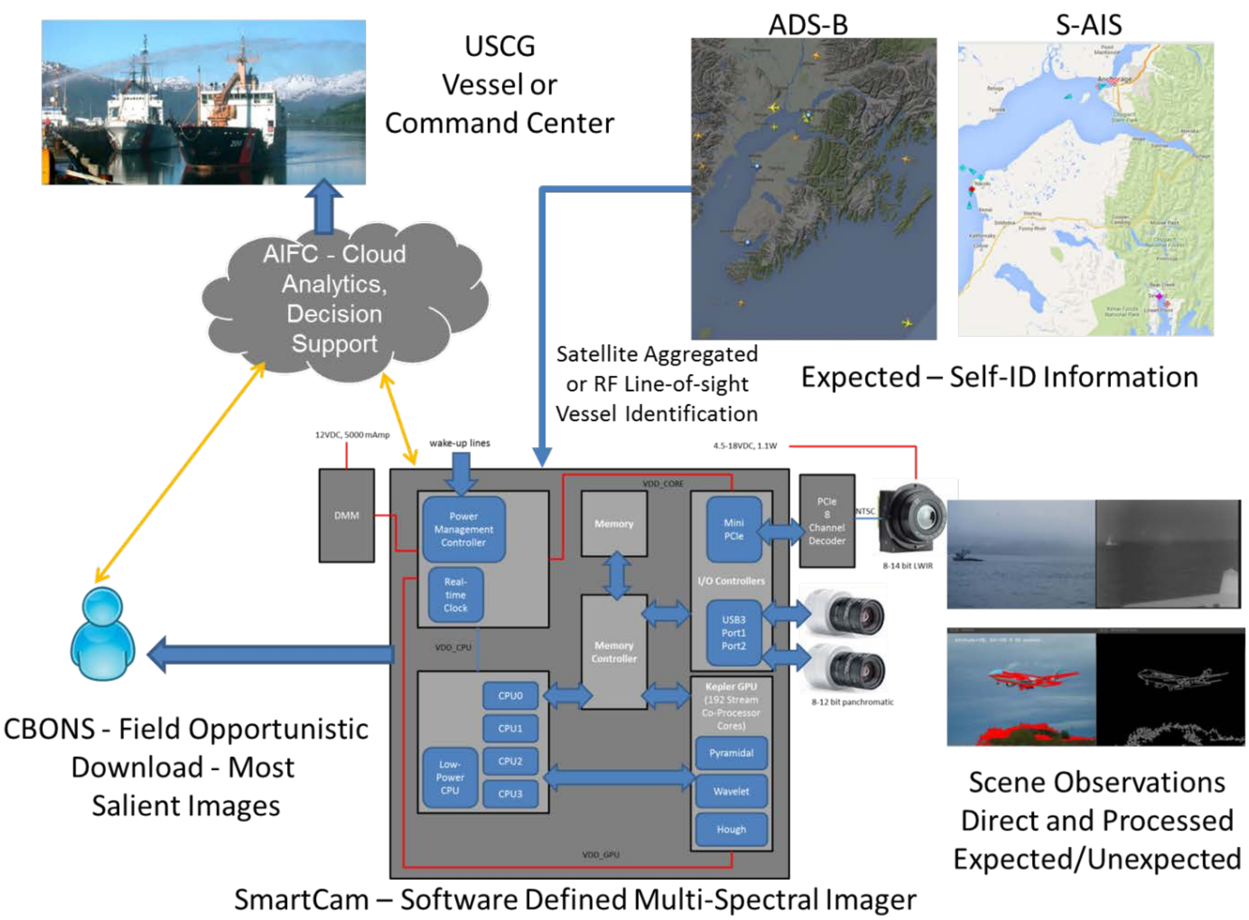
Figure 2. – Example of Marine Vessel Observation in Valdez Alaska of S-AIS reporting Vessels

Note in Figure 2, we see not only the obvious fishing vessel in 10-14 micron LWIR, but also the engines and exhaust system of the Supertanker at the TAP (Trans Alaska Pipeline), which is more evident with a narrower field of view as shown in Figure 3, but still obscured by fog. With image fusion, the thermally hot pixels in the LWIR image can be overlaid on the visible image in a single image with proper image registration and resolution matching.

Figure 3. – Supertanker detected by LWIR in Figure 2, partially visible with narrow field of view

In general, the concept of information fusion for aircraft and marine vessel situational awareness with the SMSI used in a larger sensor network is shown in Figure 4.

Figure 4. – Integration of the SDMSI into AIFC After Field Trials and Experiments

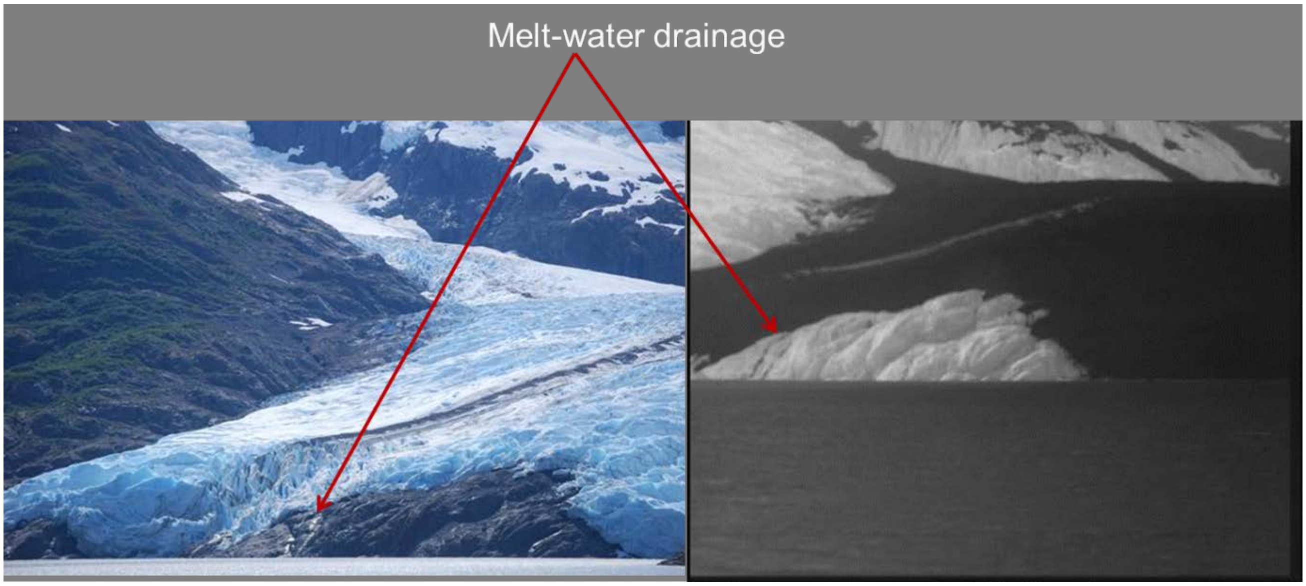


Overall, the goal for information fusion is simply to observe what is expected, but also to note any targets of specific type (marine vessels) that are unexpected based upon saliency metrics for that target type including shape [14], motion, thermal signature and behavior. The marine examples shown in this extended abstract were tested using a prototype of the SDMSI on a tripod, so the main results to be presented in this paper are more rigorous in-place tests, with similar goals, but with skyward observations in visible and 10-14 micron long-wave infrared of aircraft over weeks of time or longer.

Image Fusion

Image fusion requires spatial registration [3][4][5][7], matching of resolution through pyramidal up-conversion and/or down-conversion at a common aspect ratio and finally blending of pixels if a single fused image is desired rather than side-by-side comparison. Part of the challenge of performing image fusion in real-time is processing and power required, but based on previous work, we have shown this is quite possible for a system operating well below 10 Watts of total power continuously up to 30 Hz [1]. Furthermore, based on early work, we have determined that this does not require custom hardware [2]. The value of image fusion, into a single blended image, is reduction in storage and bandwidth required for salient images. Figure 4 shows a tidal glacier with both visible and long-wave images, both which indicate presence of melt-water on the rocks, but with pixel-level fusion can be enhanced.

Figure 5. – Visible and LWIR Images of Tidal Glacier and Meltwater



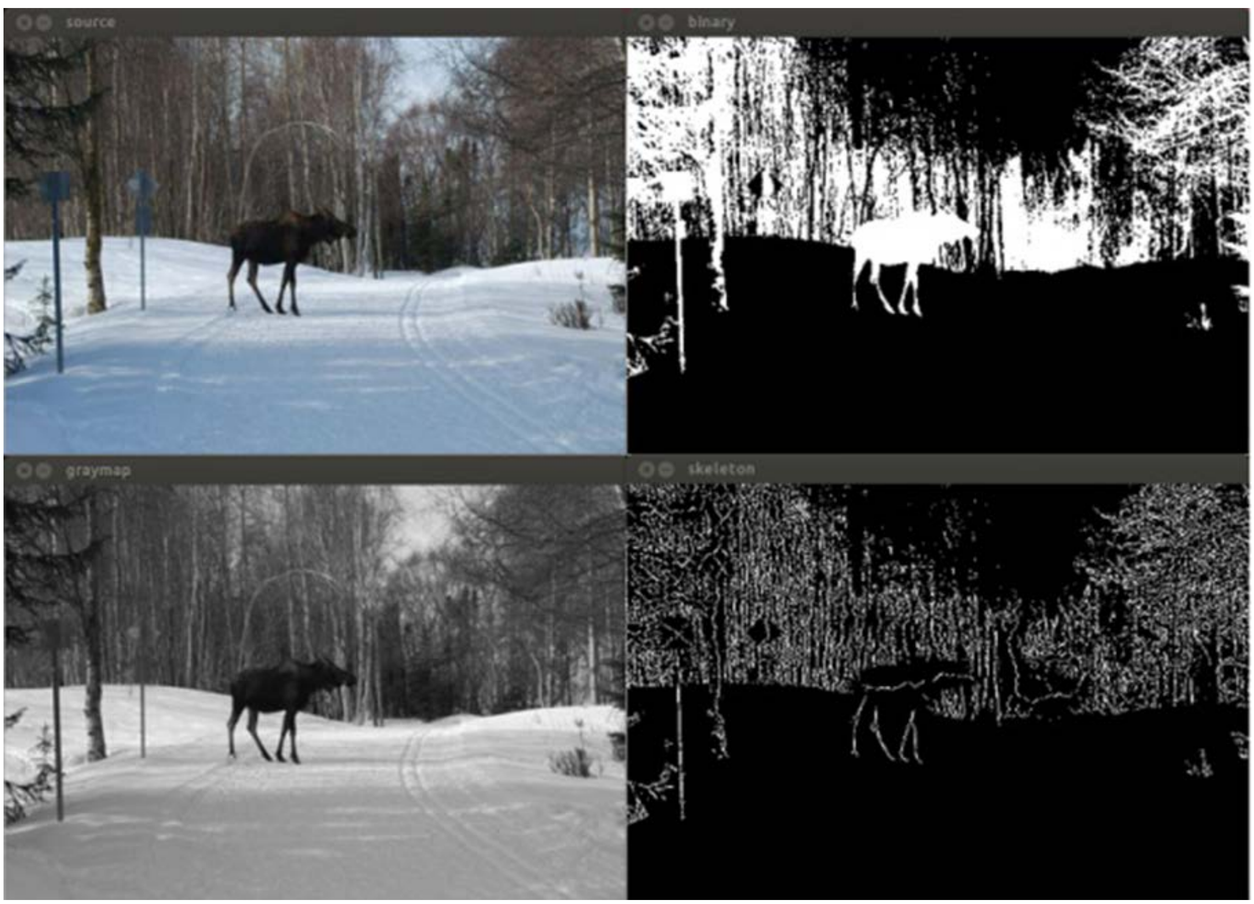
The use of LWIR and visible extends the spectral resolution at a common spatial and pixel resolution with much better temporal resolution than occasionally over flights by satellite remote sensing for field monitoring of geological locations of interest.

The mathematical and algorithmic methods for co-registration of images from fixed mount cameras (that don't share a common bore-sight) and pixel-level fusion are well established [8]. However, use for a range of targets of interest for the experiments planned can also benefit from specifics of the targets of interest, requiring additional image analysis in real-time.

Image Analysis

Image analysis for saliency and to determine whether targets that are either expected or unexpected might pose a threat or may be going through significant change requires more advanced and intelligent computer vision such as segmentation, identification of components of foreground targets and behavior. For example, a Moose in Alaska is a significant threat to human safety and to motorist safety and the animal can not only be recognized by shape, but by a skeletal transform which can also indicate behavior as sown in Figure 6.

Figure 6. – Skeletanization of a Moose Crossing Roadway



Saliency of foreground targets can range from simplistic motion triggered capture to much more complex threat analysis that involves machine learning, for example of animal gate and postures which indicated aggressive behavior [9][10][11][12][13]. Once the camera systems are in place, a wide range of saliency metrics will be evaluated by using OpenCV algorithms along with CUDA accelerated transforms to compare methods.

For human monitoring, location of individuals, such as the trespassers shown in Figure 7 on a USCG facility caught in field testing. Trespassing is most often detected through motion, but for example the distinction of human trespassers compared to wildlife activity is a more intelligent form or image saliency. The acceleration provided by GP-GPU at the transform layer is critical to provide for example real-time skeletal transformation, shape saliency and other more advanced metrics to distinguish wildlife from human activity.

The results from the three basic planned experiments (aviation monitoring, wildlife, and human activity) will be analyzed and presented to support or refute the basic hypothesis that a low-cost situated SDMSI can add value to overall situational awareness when put into a network as well as whether spatial, temporal and spectral resolution can be improved locally compared to other existing options such as satellite remote sensing, human patrol, or continuous capture security cameras systems.

Figure 7. – Trespassers Detected by Audio Cues and LWIR Motion

Analysis and Results

The paper will focus on false positive and false negative rates in an RoC for each of the three experiments as well as total power used in Watt-hours sampled on a periodic basis for each experiment. Tabular results will include the saliency metric tested and the theory of operation for it as well as the RoC performance and power used.

Outline of tabular and graphical results to be presented for each of the three planned experiments for September, October and November of 2016 including:

- Daily power consumption by the system test configuration
- Saliency driven capture tests results summarized by RoC analysis graphics
- Metrics related to co-processor, main CPU, memory, bandwidth and I/O
- Comparison of total data captured at continuous rate of 1 to 30 Hz to compression by salient selection; e.g. for a full year at 1 Hz (31,557,600 frames per camera) at 640x480 = 3 cameras x 1 plane each x 640x480 x 31557600 frames = 27.1 TB of data uncompressed
- Test capture examples at 1 to 30 Hz for duration of three experiments to show false positives, false negatives and examples that compose the RoC for each experiment
- Software updates, improvements, capabilities made in tabular form and why

The three experiments will be run for approximately one month each after each camera is installed and tested for basic functionality by August 15, 2016 at both sites.
The ultimate goal for the field trials and experiments with the SDMSI is to determine feasibility and value of using this software defined smart cameras for deployments such as buoys, vessels and UAV systems as depicted in Figure 8. The current bill of materials for the experimental configuration is well under $3,000, which is very low cost for a multi-spectral sensing system that has similar spectral resolution to Worldview 2 and 3 (panchromatic, NIR multi-spectral, and longer wave infrared bands) for example if NIR and SWIR cameras are added to the system [15] [16]. Clearly with far less coverage, but with spatial resolution as good or better than sub-meter resolution from satellite remote sensing systems and with far better, continuous temporal coverage of specific areas of interest. The final manuscript will include comparative Worldview 2 image data of the same regions where the cameras are located at times where salient images were collected to compare overall situational awareness provided and to compare spatial, temporal and spectral resolution and features of both as well as cost of monitoring by both methods.

Conclusion

The SDMSI demonstrates the value of software-defined image analysis systems design, which allows for low-power, low-cost high spatial, temporal, and spectral resolution commonly found in more costly, less compact larger instruments. The software definition requires significant processing capability, but system-on-chip technology enables on-camera transform, fusion, and saliency processing such that uplink of images is selective and pre-processed to reduce bandwidth requirements. The ease of use has been demonstrated and the design allows for upgrade of the SDMSI over time, both hardware components and software. The smart image ranking and selection features provide a significant advantage compared to continuous image capture with processing done only in the cloud, but reducing storage and link bandwidth requirements. The total power is such that the SDMSI can be operated from a LiPo battery for stand-alone aviation deployments or from fuel cell and alternative energy sources in remote Arctic locations. The long term intent of the project is to provide and open hardware, firmware and software design so that other researchers can reconfigure and reuse elements of the SDMSI test configuration presented here, to realize the software-defined goals. For some applications, the cost of custom multi-spectral instrumentation can be reduced by using a software-defined approach as presented here if similar or better overall spatial, spectral and temporal resolution can be provided by multiple cameras integrated and fused by software processing.

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