Abstract

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 Colorado Boulder 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 first on pole-mount, or buoy-mount deployments, with evolution to balloon, experimental aircraft, UAV and space systems environments. After several years of component testing, qualification and characterization, the project is being tested, first on roof-mounts at Embry Riddle Prescott. 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 security and environmental science applications to complement satellite remote sensing. The SDMSI is being installed at Embry Riddle Prescott in 2016 to test continuous image data acquisition (recorded to network attached storage) compared to on-instrument processing of long-wave and visible images for fusion, stereo images, 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 used by the SDMSI to form expectations for observing. The goal for near term research is to complete experiments to compare to human review of continuous imaging with smart image processing using saliency metrics and fusion transforms in terms of a receiver-operator curve (P-R, F-measure), 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.

Longer term, the vision for the SDMSI includes basic research in computer and machine vision, interactive security and science instrumentation. Fusion of images from the visible range of 0.35 microns to .75 with infrared images ranging to 14 microns provides a super-human capability. At the same time, humans have excellent scene understanding. The goal for the SDMSI is to create an interactive monitoring capability for science and security to extend awareness in the extended range to long-wave infrared, but also with scene understanding including 3D and image saliency. The value of binocular vision to humans is irrefutable – it has been fundamental to survival. Yet, the physiology, psychology, neural systems interface, and processing for the human three dimensional internal model of the world is not fully understood. At the same time, humans are limited to seeing a very small portion of the overall electromagnetic spectrum between 390 and 700 nanometers. Extending vision into the thermal infrared region with multi-spectral (red, green, blue plus infrared bands) and hyper-spectral (many bands between visible and thermal) allows for detection of otherwise invisible features and an ability to discern not only where objects are, but to some degree, what they are composed of as well. Computer Vision is the pursuit of understanding human vision by building emulating systems with computers and photometers. It has fundamental value to research on how human vision systems work, but with computers and radiometers (that can see a broader spectrum); we can also enhance and extend human vision for security, search and rescue, safety, environmental monitoring, agriculture and intelligence gathering. This is well-know, but only recently have the sensors become widely available at low-cost and with the ability to be integrated into a “smart” multi-spectral or hyper-spectral cameras more like a human observer, but actually with super-human capabilities of extended vision. This concept was made popular and well understood through the character Geordi La Forge on Star Trek – the ability to interactively use a vision prosthetic, not only to restore vision, but to improve to super-human vision covering a much wider spectrum.

Background

Embry Riddle Aeronautical University has a unique research and education focus related to aviation, unoccupied aerial systems, cybersecurity, aircraft and avionics systems where the use of instrumentation to extend human sensing, situational awareness, and perception is critical. Many of these systems require or involve interactive instruments, graphics and digital video. Students at ERAU with interest that includes and goes beyond their curriculum required computer and software engineering courses are learning the fundamentals to engineer mobile and embedded interactive computer vision system designs and are gaining experience hands-on with software and hardware solutions for systems. As such, this proposal would allow software engineering and computer engineering students to engage in computer vision research and applications for UAV/UAS and the RV-12 experimental aircraft project.
Specifically, students and Dr. Sam Siewert, have interest in exploring field use of a custom 3D Computational Photometer, that we would like to build using funds requested in this proposal along with typical computer vision algorithms like edge transforms, shape finding transforms (Hough linear, elliptical, and general) and stereo image registration and ranging [Duda 72] as demonstrated in early robotics research, but not perfected for field use. These cameras can be dropped in place, battery powered, and used in applications like security and safety monitoring, flown on UAV (Unmanned Aerial Vehicles) and perhaps could open up collaboration with other Arizona state and federal agencies interested in mapping and resource surveys that could benefit from multi-spectral and passive 3D mapping from UAV/UAS.

The SDMSI, which has been designed, fabricated, and is presently being tested and verified with funding through a DHS program with University of Alaska, industry support, and will be further integrated into a department undergraduate research lab and available for field research for undergraduates at ERAU. What the SDMSI does is to provide visible and long-wave infrared image fusion, information fusion (ADS-B, S-AIS), binocular (stereo) vision in real-time with continuous and interactive computer vision where scenes are not only captured, but parsed and understood using software running OpenCV (Open Computer Vision) [OpenCV] and the PCL (Point Cloud Library) [PCL] with co-processor acceleration (GP-GPU, FPGA, DSP). The co-processing is critical to real-time interactive image fusion, 3D mapping, saliency determination and scaling of the SDMIS as shown in Figure 1.

**Figure 1. – The SDMSI – Computer and Machine Vision Processing**

The SDMSI is a versatile platform for binocular vision using a wide range of USB3 and analog cameras with highly concurrent and time accurate image registration (the process of finding common points in images viewed from different viewing locations) and the ability to correlate to higher definition 2D snapshots. Further, the SDMSI can transform and process images using vector co-processing (GP-GPU) or a standard microprocessor running OpenCV and the PCL (Point Cloud Library). Processing that is not possible on the SDMSI can be uplinked to a Cloud based computer with scalable processing resources. The following experiments with the binocular SDMSI are in progress and planned:
1) Real-time acquisition of binocular images with known baseline and gaze angles with microsecond accurate time stamps and photometric and/or feature registration for stereo ranging.

2) Visualization of data acquired by photometric and feature registration using PCL (Point Cloud Library), and open source software processing library to assist in the construction of PCL models – ideally as a stretch goal, we’d like to make this real-time interactive leveraging previously funded hardware including GP-GPU (General Purpose Graphics Processing) and MICA (Many Integrated Core Architecture) co-processors.

3) Visualization of data encoded into 3D extensions for H.264 and H.265, the Motion Picture Experts Group methods for 3D entertainment encoding.

4) Compare data acquired with the SDMSI and 3D registration to traditional security cameras and determine how the added visual cues can potentially increase security and safety in environments like ports.

5) Use of the DRS Technologies un-cooled microbolometer for development of simple sensor fusion using OpenCV with commonly available NTSC off-the-shelf visible cameras

Methodology and Approach

The research includes three basic hypotheses to test:

1) Much higher efficiency real-time computation using either GP-GPU computer architecture can enable more intelligent multi-channel computer vision applications in terms of scene understanding at high resolutions and frame rates compared to current off-the-shelf architectures with substantially longer battery life – this will establish the value of a CVPU (Computer Vision Processing Unit), which has commercial and research significance, much like the GPU did in the early days of graphics. It is believed that this can be accomplished with new FPGA and ASIC co-processors or through extension of existing GP-GPUs to optimize them for use in computer vision.

2) Multi-channel interfaces can be built at reasonable cost and will vastly improve the value of UAV/UAS sensing and fill a gap between satellite and ground-based systems with value to missions for agencies like DHS, USGS, and others who need to correlate satellite intelligence with ground based operations and UAV/UAS.

3) The use of multi-spectral and passive 3D computational photography in real-time can improve situational awareness for UAV/UAS operations, but the bio-inspiration provided by fundamental human models of the visual system can also be incorporated into improved passive 3D and multi-spectral computer vision applications.

Past Experiments

1. Early ADAC Field Testing with LWIR and visible cameras
2. SPIE power study

Planned Experiments

1. Roof-top Real-time Interactive Information and Image Fusion – Small Dark Aircraft Study
2. Integration with IoT (Internet of Things) BLE (Bluetooth Low-Energy) Sensor Network
3. Long Term Pole or Buoy Mount Environmental Surveys

Approach

1. Image saliency for image storage and uplink compression, ranking and segmentation
2. Visible and infrared image fusion in real-time
3. Information (ADS-B, S-AIS) fusion with observations
4. Passive 3D mapping

The experiments to compare continuous transform efficiency using the GP-GPU will use an NVIDIA Jetson system as shown in Figure 2 and will use OpenCV on Linux to implement both sensor fusion panchromatic algorithms for the multi-spectral configuration as well as 3D stereopsis for the dual-channel visible configuration.

Preliminary feasibility research has been done including field testing of LWIR and visible cameras in embedded form factors using Linux in Alaska as detailed in this report - [http://mercury.pr.erau.edu/~siewerts/extra/documents/CP-Current.pdf](http://mercury.pr.erau.edu/~siewerts/extra/documents/CP-Current.pdf) Early work on custom interface boards has resulted in selection of new FPGA and GP-GPU SoC procession (System-on-a-Chip) that
is more power efficient and easier to embed. The technology also shares parallel development goals with intelligent transportation and other commercial uses that will drive down cost and improve efficiency and ensure availability of sensors and the SoC processors, enabling long-term software-defined photometer solutions. The code to be used is based on pre-existing applications and example code developed by Dr. Siewert, which includes numerous OpenCV examples of real-time transformation in Linux using built-in and external cameras. This code can be found here - http://mercury.pr.erau.edu/~siewerts/extra/code/computer-vision/.

A major goal for this proposed work is to improve examples, to better tailor the code to align with UAV/UAS and student and faculty research at ERAU. The code base can of course be used for power efficiency and throughput bench testing for configurations as well as UAV/UAS and RV-12 field testing.

Power consumption will be measured by continuous runs until the Beagle Juice battery is exhausted, but will also make use of a current probe (clamp) to measure the current use actively during tests.

**Figure 2: NVIDIA Jetson Software with GP-GPU Configuration**

A set of benchmarks common to 3D mapping and image fusion have been run on a DE1-SoC (Cyclone V SoC) [Altera 13] and power efficiency compared to the Figure 2 Jetson TK1 (Tegra K1 SoC). Results from this power efficiency experiment revealed that the Jetson was more efficient for the SDMSI [Siewert 16]. The FPGA transforms were implemented with OpenCL and the CUDA and OpenCL equivalent transforms used for this study are available (https://github.com/siewertserau/fusion_coproc_benchmarks).

**Image Saliency**

Automation of image saliency for the purpose of segmenting images and ranking level of interest relative to mission such as “small dark aircraft” is critical to the SDMSI interactive concept. Saliency algorithms are being researched, compared and evaluated for the SDMSI in terms of P-R, F-measure and RoC analysis during the roof-top tests planned for AY 2016/17.
Sensor Fusion

Sensor fusion algorithms to combine infrared satellite images with visible, known as panchromatic, have been in use for decades by NASA for Landsat and earth remote sensing for vegetation surveys, but this proposal suggests adaptation of these algorithms for use on UAV/UAS and for short-range multi-spectral sensing and image presentation to users. Similar work has of course been done for defense related devices such as night scopes and binoculars for interactive use, with methods to match resolution of microbolometers to visible, but the goal here is to provide this fusion with power efficiency and purpose built for UAV/UAS surveys of vegetation, animals, search-and-rescue and to identify security threats at this intermediate range between satellite imagery and hand-held use.

The value of multi-spectral fusion is the additional information that can of course be gathered in the infrared spectrum as shown in Figure 3. This is a start at the hypothesis of this research that the combination of 3D passive depth mapping and multi-spectral fusion can have high value for near-field security and safety applications.

![Figure 3: IR and Visible View of a Scene and Threat Detection](image)

Many simple human observing tasks for safety, for example control towers and visual observation of approaches and safety could perhaps be automated with passive 3D and multi-spectral monitoring for applications in aviation as shown in Figure 4.

![Figure 4: Visible Safety Assessments](image)

Passive 3D Stereo Mapping

Passive 3D mapping has many advantages over active methods such as time-of-flight, structure-from-light, and LIDAR (Light Detection and Ranging) in that there is no emission, so for security and defense applications, use of passive 3D mapping is less likely to alert an adversary to the use of the instrument. Furthermore, it is typically lower cost (although structure-from-light, time of flight and LIDAR costs is decreasing) and from a research perspective, work on passive depth mapping furthers the science and understanding of the human vision system. Stereo correspondence as shown in Figure 5 is the main visual cue used by computer vision applications, but as shown by James Cutting and Peter Vishton, over 15 cues are used in human
passive depth mapping [Cutting 95]. So, along with the potential for zero emission depth mapping, passive methods also promise better understanding of human vision and potentially may be key to creation of visual prosthetics for humans, both to assist sight impaired and to provide super-human vision capabilities for security and safety workers by incorporating human cues with beyond human capability such as vision in infrared and spectrum beyond the human tri-stimulus.

**Figure 5: Simple Stereo Correspondence – Author’s OpenCV Example**

Results to Date

This project has been underway through previous grants from industry, internal grant support from ERAU and U. of Alaska, and voluntary participation by students and faculty at ERAU, CU Boulder and the U. of Alaska Anchorage. Some field tests in Alaska with an LWIR (Long Wave Infrared) have been captured and show the value of applications such as ice break-up tracking for the Arctic region and detection and tracking of vessels in dangerous yet congested waters in the Arctic. Use of LWIR with visible fusion on USCG (Coast Guard) cutters and vessels used in the Arctic (currently the USCG has forward looking infrared on helicopters and aircraft, but not cutters or other small vessels) has been discussed with search and rescue operations in Anchorage. Other potential uses being explored include improvements to port security in Arctic.

Figure 6 shows an LWIR and visible image of a tidal glacier in Alaska and the ability to better segment ice features in LWIR compared to visible. These images can be fused to improve segmentation and classification performance compared to visible or LWIR processing alone. This is a multi-spectral computational solution that can be extended to hyper-spectral image “cubes” of data in X, Y, and many bands including red, green, blue and hundreds of infrared bands.

**Figure 6: Multi-Spectral Feature Correspondence – Author’s LWIR+Visible Field Use Example**
As the cost of multi-spectral imaging with sensor fusion and hyper-spectral imaging with cameras that produce data cubes (images with many channels at a wide range of wavelengths), the challenge becomes data processing and uplink selection from the camera to the Cloud and datacenters for analysis. Likewise, the ability to flood datacenters with information even when high bandwidth uplink is available can overwhelm human analysts, so the need for intelligent selection of images that have saliency. Saliency metrics have been derived for simple graymaps and tri-color images, but work to extend this to multi-spectral and hyper-spectral needs to be done to prevent an information overload [Wagstaff 2013].

Also, work to improve machine learning and data analytics methods require more investigation for multi-spectral and hyper-spectral imaging to make good use of these new low-cost field-use sensors for applications such as search and rescue and security safety use [Siewert 14].

Figure 7 shows detection of ice bergs (bergy bits) in the water around a tidal glacier in Alaska. Note that detection in LWIR is much more obvious than visible. The LWIR (14 micron) band is also quite useful for detection of drainage, soil moisture and any sort of thermal radiometric data between -40 degrees and 500 degrees Celsius. The software defined computational photometer is taking advantage of the rapid advancement in un-cooled microbolometer technology.

The challenge of this research is to get computer vision into wider field use and to improve upon what human observers can do in both an interactive scenario as well as unattended use of drop-in-place smart cameras.

Figure 7: Multi-Spectral Feature Correspondence – Bergy Bits in the Water

Figure 8 shows detection of vessels based on their engine and exhaust signatures in inclement weather where wide angle detection in visible is not possible. Combined with visible high zoom optics, smart cameras can provide confirmation of vessels detected by their LWIR signature as an interesting potential use of intelligent sensor fusion.

Figure 8: Multi-Spectral Detection of Vessels in Fog
**Educational Impact**

As shown in Figure 9, the LWIR camera combined with visible imaging can reveal not only visible information for aerospace testing such as the rocket test stand firing shown, but more advanced thermal imaging and eventually radiometric data providing plume temperature structure. Note that in Figure 9, the motor casing temperature profile is made much more apparent in LWIR. The present DRS Tamarisk 640 LWIR camera is now interfaced as an analog NTSC camera using a USB frame grabber and the Linux UVC driver to acquire images for processing. Next steps involve integrating a CameraLink to USB interface for Linux so that the Tamaris 24-bit color (radiometric) data can be acquired from this un-cooled microbolometer.

**Figure 9: Eagle Space Flight Group Solid Rocket Motor Test at ERAU Prescott (August 3, 2015)**

Matched optics, to the degree possible, and a common visible camera and LWIR camera baseline would improve the capability for fusing visible and LWIR images for tests like the Eagle Space Flight team’s solid rocket motor characterization.

Essentially, future versions of the smart camera will mount the LWIR and visible cameras in a single housing with a common baseline, co-aligned (ideally they’d share an optical path, but a common baseline is a starting point and feature key-points can be used to account for the extrinsic separation of the two cameras).

**Extension to Adjacent Areas**

The software-defined computational photometer can have uses in unoccupied aviation as well as marine and agricultural environments. For example for air-based search and rescue operations, perhaps for detect and avoid UAV applications using LWIR and fusion with visible imaging and/or various radio, LIDAR/RADAR solutions for UAV safety in commercial air space. The fundamental methods explored can be extrapolated to reduce cost, improve performance and enable intelligent sensing and fusion of imaging for a wide range of applications.

A key aspect is the embedding of computer vision into systems with full frame-rate continuous computer vision compared to laboratory settings using MATLAB or other non-real-time image analysis methods. These approaches are fine for algorithm design, but do not extend well to low-power operations for field research. The research on the software-defined computational photometer includes low power consumption as well as novel power solutions including use of fuel cells, ultra-capacitors, wind and solar recharge as well as low-temperature batteries for deployment in the Arctic. Many of the challenges of operations in the Arctic include power and instrumentation technology that is transferrable to deep space and other related harsh environments where this technology is useful to extend human vision with less risk.

**Project Timeline for Future Experiments**
The current planned experiments are:

1) Roof mount long term survivability (summer 2016 to summer 2017)
2) ADS-B and secondary RADAR information (FlightRadar.com) fusion with observations of aircraft over-flights with visible and LWIR observations
3) Security observations of hazardous areas (human / animal interaction)

**Significance**

Human intelligence for scene understanding includes 15 depth cues in the red, green and blue (tri-stimulus) region of the visible spectrum. Today, researchers use very few cues (normally limited to stereopsis) to model and emulate human scene parsing and understanding. Likewise, remote sensing uses the full spectrum, but also lacks capabilities to segment, recognize and present scenes to users interactively so they can identify threats, targets of interest and use smart camera systems to aid for example aviation search and rescue missions, safety and security monitoring missions and general situational awareness. The goal of the research presented is to build a better smart-camera platform, a Computational Photometer as it is called here, that can lower cost, improve efficiency, and truly improve safety and security mission success. This device and the methods established could provide improvements for a wide range of computer vision missions ranging from UAV/UAS to deep space probes and safety and security monitoring in harsh environments.

The ability to process and understand scenes in real-time, continuously is what distinguishes computer vision from image processing and requires significant advancement in software-defined computation for embedded camera solutions that can act as a sensor network for Cloud-based analytics. The research proposed here involves the cybernetics, system of systems, and fusion algorithm research necessary to advance important applications such as search and rescue in harsh environments.

**Adequacy of Resources**

The resources required for this project are modest. The most costly item is the un-cooled microbolometer and Dr. Siewert already has one of these devices. The main goal of the funding request is to build a second test bench for use by students and to improve the test setup used in on-going research. Otherwise, the research is already in progress by Dr. Siewert and work in progress has been funded by a Department of Homeland security sub-contract through the University of Alaska Anchorage during AY 2014/15 and AY 2015/16. New sources of funding sought will allow Dr. Siewert to continue to involve ERAU undergraduates and to support spin-out projects they may come up with for UAV/UAS and RV-12 use, which will likewise provide benefit to future instrumentation research and proposals. The ERAU Prescott EE/CE/SE department has a student laboratory with an electrical bench suitable for this work available as well as the future potential to test the SDMSI on the RV-12 and/or UAV/UAS that have been constructed by students.

**Planned External Proposal Development**

The team lead by Dr. Siewert has completed Y1 and Y2 work for ERAU through the University of Alaska and the DHS Maritime Technology Center of Excellence with past funding as well as industry funding before that. Future opportunities to propose extensions to the work exist with other DHS COEs (Centers of Excellence) as well as NASA instrumentation programs (e.g. NASA AIST, IIP).

**Past Funding Support for Related Research and Education**

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<th>Year</th>
<th>Funding Details</th>
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| 2016-present | Actively seeking new support (DHS, NASA AIST 16 or 18, industry, internal grants)
| 2015     | Embry Riddle Aeronautical University – Internal Grant for Undergraduate Research  |
| 2014-16  | U. of Alaska Anchorage DHS Center of Excellence sub-contract for Smart-camera    |
| 2014     | University of Alaska, Anchorage - Faculty Leadership in Expanding Undergraduate Research |
| 2013     | Intel Computer Vision Research and Education Grant for University of Alaska Anchorage |
| 2012     | Intel Embedded Systems Research and Education Grant for University of Colorado, Boulder |
| 2011     | Intel Embedded Systems Research and Education Grant for University of Colorado, Boulder |
References


Low voltage differential serial CameraPort, as documented by Xilinx,