Software-Defined Computational Photometry

Arctic Multi-Spectral and Passive 3D Imaging Project

May 2015 - Status
The Goal

- Low-Cost Multi-Channel Imager
  - Primary: Visible + IR for Multi-spectral Imaging
  - Secondary: Two Channel Visible for Passive 3D Imaging

- Smarter “Go-Pro Like” Instrument for Safety, Security, Resource Monitoring (DHS, USGS, …)
  - Integrate Off-the-Shelf LWIR, Visible and LIDAR for Fusion
  - Drop-in Place on UAV, Marine Vessel, Buoy, Port
  - Smarter, Multi-Channel
  - Potentially Wearable
  - Power Efficient
  - Intelligent Uplink

- 3D and Multi-Spectral Fusion using GP-GPU or FPGA Co-processing
SmartCam – Computational Photometry

- Low-cost, software-defined, smart “Go-Pro” style device with visible and multi-spectral image fusion
  - Efficient energy use with image analysis on the device itself
  - Emphasis on software intelligence for automatic detection, tracking, and data fusion analysis

Examples

Visible image of a forest fire obscured by smoke (left), while a thermal satellite image indicates hot spots (right), leading to calculation of Normalized Burn Ratio (SWIR, NIR) [O’Connor, Exelis]. SmartCam on a UAV could provide higher resolution, real-time data for situational awareness.

Bergy bits may be difficult to detect with a search light (left) but could be automatically detected by SmartCam software with a thermal camera (right) using machine learning [FLIR].

Automatic hazard and threat identification and annotation from a car [nVidia PX] could be adapted by SmartCam for marine environments.
Ideas for Field Testing

- Monitor Unimak and Bering Strait (Visible, LWIR, [LIDAR])
  - Current Tracking is Voluntary S-AIS and VHF Radio Communications
  - Limited Communications and USCG Patrol in this Region

Unimak Strait is a 12 mile wide Transit for Majority of Great Circle Shipping Traffic Passing Through Arctic

Existing USCG Infrastructure Can Be Leveraged to Place a SmartCam

SmartCam System Could Be Used with LWIR + Visible Long-Range Optics
And/Or Low-Cost LIDAR Sensors

Cross Check S-AIS with Secondary Record for Improved Domain Awareness
Marine Traffic Spotting, Tracking, ID

- Low-Cost Visible, LWIR, and LIDAR Testing Can be Completed in Similar Geographic Regions for Feasibility
  - E.g. Channel Islands, San Francisco Bay, Etc. for Feasibility Test
- Transition to Unimak (Accessible by Alaska Marine Highway and a Hike)
- Transition to Bering Strait
- Much Like Air Traffic, Goal is to Cost Effectively Track Vessels not Using S-AIS and Not Maintaining Radio Contact
- Research Goals – Feasibility of Vessel Spotting, Tracking and Identification with More Intelligence and Lower Cost than RADAR stations
- Complements Rotary FLIR for SAR-Ops
Marguerite Ace

- Visible Identification at 200mm
- LWIR Detection and Tracking at 25mm
Marguerite Ace

- Detected, Tracked and Identified Departure from Long Beach
- Correlated to S-AIS
Feasibility Testing in Marine Domain

- Basic Vessel Detection, Tracking, Identification
- At Ports Light Stations, and In Straits (E.g. Unimak Strait – Great Circle Route to Asia, Bering Strait)
- Big Data Analytics Combined with Sensor Networks (Potential To Enhance Situational Awareness)

- Marguerite Ace Leaves Long Beach
- HD visible imaging of departures
- And transits with ID
- LWIR night/fog detection and tracking
- Correlation to S-AIS and DBMS
- (Field Test – June 2015, Long Beach)
Add camera systems to Cutters (around, mast)
Detect bodies in the water, Port trespassing, Complements Aircraft FLIR

Surfers in the Water
Hand-held, Cutter Mounted, Buoys
Complements Existing Helicopter and C130 FLIR
(Field Test – June 2015, Malibu)

Trespassers at Night Shown on Jetty
Hand-held, Port Drop-in-Place, Buoys
Complements Existing Security
Off-Grid Installations
(Field Test – June 2015, San Pedro)
Milestones Achieved

- Testing power consumption
  - Low power (0.6W) to normal (6W at 3000mAh → 2-3 hours); need sleep and wakeup with periodic sense if off the grid
  - Couple with hybrid power, OTS leveraging

- Testing LWIR range and Night/Fog Conditions
  - Can see vessels **2 to 13 kilometers** with out with 25 degree field of view (25mm lens)
  - Can see vessels **TBD** miles with out with 9.6 degree field of view (65mm lens) – Next Planned Test
  - Can identify Vessels with HD Visible (200mm lens)
  - Visible + IR Fusion Feasibility Testing (Night, Day)
Multi-Spectral & Passive 3D

- Real-Time Fusion of IR + Visible **with FPGA Efficiency**

![Image of real-time fusion of IR and visible data with FPGA efficiency]

- Passive 3D Depth Mapping with FPGA Efficiency

![Image of passive 3D depth mapping with FPGA efficiency]

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Machine Learning Intelligence

- Detection of Safety and Security Threats (Visual)
- Threat Assessment and Characterization
- Annotation and Fusion with Real-Time Digital Video
- E.g. Potentially Unsafe Approach at Ted Stevens
Scene Understanding

- Behavior Modeling of Targets and Threats
- Skeletal Transformation, Posture, Threat Assessment
Comparison Baselines

- Passive 3D and Multi-spectral Fusion with OpenCV (software only) and OTS hardware using GP-GPU and Multi-core
  - FPGA vs. GP-GPU Efficiency and Battery Life
  - Hybrid Reconfigurable vs. All Software Approach

- Active RGB Depth Mappers – E.g. PrimeSense
  - Limited to Indoor Robotics Typically
  - Less Useful for DHS, USGS, NOAA and other Outdoor Missions

- Goal is to Offload to a Purpose Built CVPU (Computer Vision Co-Processor) and Open up CPU and GPU for Intended Purposes – Machine Learning and Graphics
OTS Uncooled LWIR – Many Options

High Resolution (640x480, 1024x768)
- **DRS Tamarisk** 640 - NTSC, 640x480, 8-14 micron (6.8-65mm lens), $6K OTS
- **FLIR Tau 2 640** - NTSC, 640x480, 7.5-13.5 micron (7.5mm-100mm lens), $TBD OTS
- **ATOM 1024** – GigE, 1024x768, 8-12 micron, (9.5-50mm), $TBD OTS

Medium Resolution
- **SEEK Thermal XR**, USB2 AOS, **206x156**, 7.2-13 micron, (36 & 20 degree FoV), $250 OTS
- **Therm-App**, USB2 AOS, **384x288** 17 micron (6.8-35mm lens), $939 OTS

Low Resolution (80x60)
- **ATOM80** USB2, 80x60, $900 OTS
- **FLIR Lepton** MIPI & SPI, 80x60, 8-14 micron, SDK Available, $183 OTS

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LWIR – Thermal Imaging

- LWIR 8 to 14 micron
  [8000 – 14000 nm]
- NIR 0.74 micron to 1 micron
- Visible 350-740 nm
- DRS 640

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The Current CP Team

Sam Siewert – PI at ERAU, Adjunct CU-Boulder
Ryan Claus, Dylan Schindler, Matthew Vis, Michael Riley, Chris Johnson - ERAU Undergraduates, OpenCV/OpenCL Software on NVIDIA Jetson
Nicholas Mallott on DE1 FPGA Board, OpenCL for FPGA
Randall Myers, Mentor Graphics – TME, PCB design
Vivek Angoth, Saurav Srivastava, CU – MS Students, Camera Interfaces, OpenCL for FPGA and GP-GPU

Previous Team Members:
- Nilendra Nimbalkar, CU – MS Student, OpenCV Software
- Jeries Shihadeh, CU – Ph.D. Student, CU-Boulder, HW and FPGA FW
- Vitaly Ivanov, UAA – BS Student, UAA, Verification, Lab Content
- Jay Khandhar, CU – MS Student, CU-Boulder, DE2i & Linux
- Sagar Sidhpura, CU – MS Student, CU-Boulder, Linux Real-Time Kernel
- Arielle Blum – CU BS/MS Student, Capstone Program, PCB Design

Current Sponsors: Arctic Domain Awareness Center - DHS Center of Excellence, ERAU Internal Research Grant
University Collaborators: ERAU Prescott, UAA, CU Boulder
Past Industry Sponsors: Intel, Altera, Mentor Graphics
Sensor Fusion - Basic Concepts

Visible Image Includes 3 Wavelengths
- Red, 650 nanometers
- Green, 510 nanometers
- Blue, 475 nanometers

Add Thermal LWIR Imaging
- Thermal Image Intensity
- False Color?
- Match Resolution and Overlay with Visible?

Many Applications for LWIR Multi-Spectral
- Cold Spots and Hot Spots - Ice, Fire Hazards
- Vegetation, Soil Moisture
- Animals and People
- E.g. SEEK Imager, 206x156, 7200 to 13000 nanometers

USGS Landsat Images
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Software-Defined / Computational Photometry

Computational Photography Extension – Continuous Computer and Machine Vision Processing

CV Co-Processor – Between Photometer and CPU
- Performs Function Like a GPU, but For CV
- Computer Vision Turing Test - Inverse Rendering
- Create a World/Scene Model From Image Sequence
- Multi-Channel (Passive 3D, Multi-Spectral)

Open Hardware Reference, Low-Cost, Real-Time Performance

Black Bear Visits to Port of Anchorage & Government Hill

Concept: 2 Channel, Computationally Advanced Multi-Spectral - UAV / Drop-in-Place and Cost
Research Goals

Near Term (2016)
- Hardware Acceleration – GP-GPU vs. FPGA
- Embedding and Efficiency – Watts / Transform / sec
- Fusion Algorithms for Near Field LWIR+Visible
- Basic Target Tracking and Threat Detection, Standards Algorithms, Improved Performance

Longer Term (2017)
- Battery Life and Power from Solar Re-charge, Super-capacitor and Fuel Cell
- Opportunistic Uplink/Downlink
- Test Deployment in Arctic (Port, Vessel, Buoy)

Fundamental
- Passive 3D and Multi-Spectral Scene Understanding Algorithm Improvements, Invention
- Layered Architecture From Scene Segmentation to Machine Learning Recognition and Threat Assessment
- Wider Application (Intelligent Transportation, SAR, SLAM)
OTS Block Diagram

Sensor Fusion Processing – TI OMAP / Atom Microprocessor running OpenCV or *Networked Video Analytics in Cloud*

- Analog Camera #1 LEFT (NIR, Visible)
- Off-the-Shelf NTSC-to-USB Frame Grabber
- USB 2.0, PCIe Host Channels
- Mobile Sensor Network Processor (TI OMAP, Atom)
- Flash SD Card
- HD Digital Camera Port (Snapshot)

- Xenics Rufus, FLIR Tau-2, DRS Tamarisk, L3, DST 640
- Analog Camera #2 RIGHT (LWIR, TIR)

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Software CP Bottleneck

Sensor Fusion in the Cloud
Pass through – no intelligence

Analog Camera #1
LEFT (NIR, Visible)

Analog Camera #2
RIGHT (LWIR, TIR)

Off-the-Shelf NTSC-to-USB Frame Grabber

USB 2.0, PCIe Host Channels

Mobile Sensor Network Processor
(TI OMAP, Atom)

2D Hough Transform

2D Skeletal Transform

Networked Video Analytics

Flash SD Card

HD Digital Camera Port (Snapshot)

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Concept #1 - FPGA Acceleration

Thermal Map Threat Assessment

Dynamic Hazard Assessment

Cloud Analytics and Machine Learning

HD Camera #1 (NIR, Visible)

Vector Processing CVPU (Computer Vision Processing Unit) DE1-SoC

USB 3.0, GigE Vision Host Channels

Mobile Sensor Network Processor

Flash SD Card (local database)

HD Digital Camera Port (Snapshot history)

Many multi-spectral focal planes …

HD Camera #N (LWIR, UV)

2D/3D Spatial Safety Assessment

Threat assessment With Annotation
Concept #2 – GP-GPU Acceleration

Thermal Map Threat Assessment

Dynamic Hazard Assessment

HD Camera #1 (NIR, Visible)

Jetson Tegra X1
With GP-GPU Co-Processing

Flash SD Card (local database)

Cloud Analytics and Machine Learning

2D/3D Spatial Safety Assessment

HD Camera #N (LWIR, UV)

Many multi-spectral focal planes …

Threat assessment With Annotation
Concept #1 - FPGA

- Transforms / second / Watt
- Linux OS and FPGA Fabric OpenCL Kernel
- DRS NTSC LWIR
- ATOM80 LWIR, Logitech USB Visible
Concept #2 – GP-GPU

- Transforms / second / Watt
- Linux OS and GP-GPU Vector Co-Processor OpenCL Kernel
- CSI MIPI Cameras [TBD]
- ATOM80 LWIR, Logitech USB Visible

ATOM80 LWIR

HD Visible

OV5640
Arctic Power

Fuel Cell Operation (Winter – 4380 hours)
- H2 PEM
  - 12W PEM Fuel Cell
  - 552L H2 Supply
  - 10% to 50% for Continuous Operation (0.6 to 6W for Jetson)
  - 0.18L/min, 0.09L/min to 0.009L/min is 100 to 1000 hours
  - Test Configuration Cost - $420.00 + $299.00

- Methanol Reforming Fuel Cells - Ultracell
  - 50W Cell
  - Methanol + Water
  - Cost Unknown, Lifetime 2 Weeks at Peak Output (20+ Weeks?)

Battery and Solar Recharge Operation (Summer – 4380 hours)
- Automotive Batteries

Super-capacitors (Quick Charge)
- Combine with Batteries and/or Fuel Cell
Computational Photometer Goals

1. **Education** – Reference Hardware, Firmware, Software for Students (Analog IR/Visible Photometer Interface, CameraPort HD Snapshots)

2. **Innovation** – Product Exploration and Definition for CV Applications (Wound Care, Ice Hazards, UAV natural resource surveys, Robotics & Automation)


4. **Fundamental Research** – Emulation, Interaction and Augmentation of Human Visual System
Why Build a New Camera Interface?

Cost, Open, RT Performance, Battery Power, 2+ Channel, Flexible Optics, Continuous Image Processing


<table>
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<tr>
<th>Configuration</th>
<th>Cost</th>
<th>Openness</th>
<th>Performance</th>
<th>Efficiency</th>
<th>Score</th>
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<td>CP Analog (Digital)</td>
<td>Low (3)</td>
<td>Open HW, FW, SW (3)</td>
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<td>Digital Camera Port&lt;sup&gt;5&lt;/sup&gt;</td>
<td>Low (3)</td>
<td>Proprietary HW, Open FW, SW (2)</td>
<td>Variable (1)</td>
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<tr>
<td>Analog Camera with PC Frame Grabber</td>
<td>Low (3)</td>
<td>Proprietary HW, Open FW, SW (2)</td>
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<td>Low (1)</td>
<td>9</td>
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<tr>
<td>CameraLink&lt;sup&gt;4&lt;/sup&gt;</td>
<td>High (1)</td>
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<tr>
<td>USB Webcam, GoPro or Active Depth Mapper</td>
<td>Low (3)</td>
<td>Proprietary HW, FW, Open SW (1)</td>
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<tr>
<td>HD and SD-SDI</td>
<td>High (1)</td>
<td>Proprietary HW, FW, SW (0)</td>
<td>RT (3)</td>
<td>Low (1)</td>
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</tr>
</tbody>
</table>
CP Interface PCB Design

- Dual TI Video Decoders, DE0 Cyclone III or DE2i
- Cyclone IV FPGA FIFO with Transform State Machines,
- Dual FTDI Uplink, I2C Configuration
Small CP Interface PCB + System

- CP Custom PCB
- Replaces Lucite on DE0
- Cyclone III FPGA (50K LEs) – DE0
- 2 Component Inputs
- Dual USB 2.0 Uplinks
- Suitable for UAV Use
- Drop-in-Place
- Robotics & Automation
- Beagle CameraPort for Leopard HD Cameras
- Any NTSC Optics + CCD
- TI-OMAP + Linux

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3D Scene Parsing - Research

Human Depth Cues (Physiology, Psychology, Physics)
- Between 9 and 15 Recognized Cues – James Cutting, Peter Vishton

Machine Vision Methods (Active vs. Passive)
1. Passive
   • Structure from Motion (Suitable for UAV, Photogrammetry Elevation Estimations)
   • Binocular Stereopsis (Two Channel Registration and Triangulation with Camera Extrinsic and Intrinsic Calibration)

2. Active
   • Structured Light Projection (PrimeSense)
   • Time of Flight (LIDAR)

IEEE RAS Paper on CV Improvement with 3D – “Change Their Perception”, December 2013 IEEE RAS
Feature Vector Key-points

- Continuous Feature Vector Key-point Generation
- Requires Pyramidal Gaussian Resolution Decimation and Interpolation for Up-conversion (FPGA)
- **OpenCV Image Pyramids** – Low Pass Filtering (Gaussian kernel convolution) followed by pixel decimation (removal of odd or even numbered rows and columns)
- Requires Gradient (Edge) Computations
- Software-based Storage and Search

L=0, e.g. 9x9
L=1, 5x5
L=2, 3x3

Rows 0…8, Col 0…8
Drop rows 1,3,5,7 to go to L=1 5x5
Drop rows 1,3 to go to L=2 3x3
Image Correspondence for Depth

- Mosaics (Stitching)
- Stereopsis
- 3D Recognition
- Optical Flow
- Structure from Motion

Awareness, Recognition, Security, Safety

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Alaska Arctic Applications - DHS

- Ice Flow Monitoring, Hazards – UAV and Drop-in-Place Roadway, Port, Runway – Animal Hazards, Shipping
- Volcanic and Geothermal Activity – UAV, Drop-in-Place

Pavlov Volcano Eruption, Alaska

Winter Tidal Ice Flow on Turnagain Arm, Cook Inlet

Arctic Shipping Security & Safety
http://www.arcticsecurity.org/?p=490

“If you Live with an 800 pound gorilla, you should listen to and observe every burp and hiccough” – Michio Kaku
Security, Safety, and Resource Management Applications

- **USGS** – Counting Animals, Ground Truth for Vegetation, Water Resources, Crop Damage – Surplus Raven SUAV

- **DHS** – Low-Cost Remote Sensors for Arctic Monitoring, with focus on low power (solar) and ad-hoc sensor networking protocols to uplink data with minimal power and opportunistic uplink to maritime vessels and UAVs.
Research & Education Goals - Summary

Education
- Open Hardware, Firmware and Software – Analog layer, Digital, Firmware, and Linux Software
- Probing and Tracing at All Layers
- Starting Point for Capstone Design and Student Research

Research
- Compare Passive Binocular Vision with Computational Photometry Parallelism to Active RGB-Depth
  - Binocular = 2 Visible Coordinated Channels (UAV)
  - RGB-D = Active Structure IR Projection, IR & Visible Channel
- Low-Cost Infrared + Visible Computational Photometer for Remote Sensing and Safety/Security Applications
- Addition of IMU-on-Chip for Proprioception (Coordinated 3D Vision and Robotic Actuation)
3D Active Computational Photometry Concept (Rev-A + TI Kit)

Analog Camera #1
RGB (Visible)

Analog Camera #2
(Near Infrared)

Altera FPGA CVPU
(Computer Vision Processing Unit)

TI DLP Light-crafter Kit
http://www.ti.com/tool/dlplightcrafter

HD Digital Camera Port
(Snapshot)

USB 2.0, PCIe Host Channels

Mobile Sensor Network Processor
(TI OMAP, Atom)

Depth Map

IR Pattern Projection

Photo credits and reference:
Dr. Daniel Aliaga, Purdue University
https://www.cs.purdue.edu/homes/aliaga/

2D Computer Vision Transforms

- Enable Intelligent Systems with Human-like Vision, but Wider Spectrum (Visible & Infrared)
- Real-Time 2D Scene Parsing & Understanding (OpenCV)

Canny Transform

Skeletal Transform

Hough Linear Transform

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3D Computer Vision Transforms

- Long Range ( > 5 meters) Using Passive Binocular Methods
  - Impractical to Project from a UAV or Long Range Observer
  - Requires Image Registration
  - Accurate Camera Intrinsic (Camera Characteristics) & Extrinsic (e.g. Baseline)

- Short Range ( < 5 meters), Structured IR Light Projection for RGB-D
  - Compare to ASUS Xtion and PrimeSense – Off-the-Shelf
  - Robust Depth Maps with Less Noise
  - Showing Significant Promise to Improve CV Scene Segmentation and Object Recognition Compared to 2D

Noise in Passive Depth Maps

Robust Active Depth Map

The UAA Computer Engineering Prototype and Assembly Lab

- Supports Operating Systems (with Hardware)
- Computer Vision Lab – DE2i, DE0, TI-OMAP
- Alaska Space Grant Fellowship Lab (Autonomous Submersible, Computer Vision Guided)
- General Computer Engineering and Capstone
Related Research & Education

- Temporal and Spatial Locality (Memory Access) - Halide API (E.g. OpenCV) vs. Language (E.g. Halide)
- Impact of Lossy Compression on Computer Vision
- Impacts of Encode/Decode on Latency
Open Reference Design for Distribution by Mentor Graphics and Intel Embedded Education and Research Program

Exposes Students to High Quality 3D Vision

Configurable Research Platform for 3D Passive & Active Mapping and Multi-spectral

Low Cost Research Platform, Battery Powered, Drop-in-Place or UAV