The Computational Photometer

Hybrid FPGA Digital Video Transformation for 3D – Joint UAA and CU-Boulder Project
The CP Team

- Sam Siewert – PI, UAA, Adjunct CU-Boulder
- Vitaly Ivanov – BS Student, UAA, Verification, Lab Content
- Jay Khandhar – MS Student, CU-Boulder, DE2i & Linux
- Randall Meyers – TME, Mentor Graphics, PCB layout
- Jeries Shihadeh – Ph.D. Student, CU-Boulder, HW and FW
- Sagar Sidhpura – MS Student, CU-Boulder, Linux Real-Time Kernel

Sponsors:
- Intel Embedded Education and Research Program (DE2i)
- Mentor Graphics, Longmont Colorado (DxDesigner, Randall Meyer’s PCB Work, Fabrication)
- Altera University Program (DE0, DE4)
Computational Photometer

Computational Photography Extension – Continuous Computer and Machine Vision Processing Acceleration in Embedded Systems

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
2D & 3D Passive Computational Photometry

Analog Camera #1 LEFT (NIR, Visible)

Analog Camera #2 RIGHT (NIR, Visible)

Altera FPGA CVPU (Computer Vision Processing Unit)

USB 2.0, PCIe Host Channels

2D Hough Transform

2D Skeletal Transform

3D Disparity & Depth Map

Networked Video Analytics

Mobile Sensor Network Processor (TI OMAP, Atom)

Flash SD Card

HD Digital Camera Port (Snapshot)
Simple Continuous Image Processing

- \( P = \text{clamp} \left[ \{Q\} \times \alpha + \beta \right] \) – Brightness & Contrast
- Sequential
- Vector Instructions – SSE, NEON, Altivec
- Thread Grid – Multi-Core
- Thread Grid with Vector Instructions - GPU
- Concurrent State Machine Co-Processor – FPGA, ASIC
A Few More Issues ...

- Temporal and Spatial Locality (Memory Access) - Halide API (E.g. OpenCV) vs. Language (E.g. Halide)
- Hardware Acceleration – GPU, DSP, Codec, FPGA
- Embedding and Efficiency – Watts / Frame/sec
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>
<thead>
<tr>
<th>Configuration</th>
<th>Cost</th>
<th>Openness</th>
<th>Performance</th>
<th>Efficiency</th>
<th>Score</th>
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<tr>
<td>CP</td>
<td>Low (3)</td>
<td>Open HW, FW, SW (3)</td>
<td>*RT (3)</td>
<td>High (3)</td>
<td>12</td>
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<tr>
<td>Digital Camera Port (^5)</td>
<td>Low (3)</td>
<td>Proprietary HW, Open FW, SW (2)</td>
<td>Variable (1)</td>
<td>High (3)</td>
<td>9</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>
<td>RT (3)</td>
<td>Low (1)</td>
<td>9</td>
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<tr>
<td>CameraLink (^4)</td>
<td>High (1)</td>
<td>Proprietary HW, IP FW, Open SW (1.5)</td>
<td>RT (3)</td>
<td>High (3)</td>
<td>8.5</td>
</tr>
<tr>
<td>USB Webcam or Active Depth Mapper</td>
<td>Low (3)</td>
<td>Proprietary HW, FW, Open SW (1)</td>
<td>Variable (1)</td>
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<tr>
<td>Ethernet CCTV (^6)</td>
<td>Medium (2)</td>
<td>Proprietary HW, FW, Open SW (1)</td>
<td>Predictable</td>
<td>Low (1)</td>
<td>6</td>
</tr>
<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>
<td>5</td>
</tr>
</tbody>
</table>

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CP Interface PCB Design

- Dual TI Video Decoders, DE0 Cyclone III or or DE2i
- Cyclone IV FPGA FIFO with Transform State Machines,
- Dual FTDI Uplink, I2C Configuration

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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
Compare to Video Analytics Configurations (All OTS)

- Power Efficiency, Embedded Applications, High-End Computer & Machine Vision Performance, Open

Compare to GP-GPU, Many-Core and Back-hauling DV from Wireless/OTA and Ethernet Cameras to Data Centers

1. Placing Computation at Camera Interface (Innovation)
2. Acceleration of Multi-Channel Bio-Inspired Algorithms for 3D and Multi-Spectral Active/Passive Perception (Research)
3. Enabling Student R&D (Education)
3D Scene Parsing - Research

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

Machine Vision Methods
1. Structure from Motion (Suitable for UAV, Photogrammetry Elevation Estimations) - Passive
2. Binocular Stereopsis (Two Channel Registration and Triangulation with Camera Extrinsic and Intrinsic Calibration) - Passive
3. Structured Light Projection (PrimeSense) - Active
4. Time of Flight (LIDAR) - Active

Active Methods vs. Passive

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

- Continuous Feature Vector Keypoint Generation
- Requires Pyramid 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

- Mosaics (Stitching)
- Stereopsis
- Recognition
- Structure from Motion

Left-Eye Right-Eye

Awareness, Recognition, Security, Safety
Testing and Research Plans

Enable UAA and CU-Boulder and University and Developer Programs (Open Hardware)

1. UAA – Ice Formation (Multi-Spectral NIR + Visible Channels) at Port of Anchorage

2. CU-Boulder – Plant Growth Chamber (NIR + Visible)

3. Wound Care – (RGB-D Active, TI DLP Module with NIR + Visible)
Active RGB-Depth OTS Alternatives

- Occipital – Boulder Colorado Kickstarter (Mobile Phone RGB-D)
- ASUS Xtion (Prime Sense) – We are testing with OpenNI
- Microsoft Kinect
- PrimeSense Developer Cameras
- Intel Creative Camera and Perceptual SDK

- We are testing all of them and comparing – None are Open Hardware
- Many run OpenNI Middleware, but Hardware is Proprietary

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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)
2D & 3D Passive Computational Photometry

- **Analog Camera #1**
  - LEFT (NIR, Visible)

- **Analog Camera #2**
  - RIGHT (NIR, Visible)

- **Altera FPGA CVPU**
  - (Computer Vision Processing Unit)

- **USB 2.0, PCIe Host Channels**

- **Mobile Sensor Network Processor**
  - (TI OMAP, Atom)

- **Flash SD Card**

- **HD Digital Camera Port (Snapshot)**

- **3D Disparity & Depth Map**

- **2D Skeletal Transform**

- **Networked Video Analytics**

- **2D Hough Transform**
FPGA State Machines

- YCrCb FIFO for Decoder Pixel Output

- Basic Frame Operations on FIFO Data
  - Time Decimation (Nth frame)
  - Pyramid Resolution up and down conversion (SD 4:3 AR)
  - Pixel Re-encoding, for example to RGB from YCrCb

- FTDI USB 2.0 Uplink from Each Channel

- Advanced Transformation
  - Sobel and Canny Edge Detection
  - Hough Transforms (Linear, Elliptical, General)
  - SIFT/SURF (Stitching, 3D Correspondence, Recognition)
  - HMAX (Dr. Martin Cenek at UAA)
3D Active Computational Photometry Concept (Rev-A + TI Kit)

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)
Flash SD Card
Networked Video Analytics

Depth Map

IR Pattern Projection

Analog Camera #2 (Near Infrared)
Analog Camera #1 RGB (Visible)
Alterra FPGA CVPU (Computer Vision Processing Unit)

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

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2D Computer Vision Transforms

- Enable Intelligent Systems with Human-like Vision, but Wider Spectrum (Visible & Infrared)
- Real-Time 2D Scene Parsing & Understanding (OpenCV)
3D is a Simple Concept, but Difficult in Practice

- Triangulation is Basic Concept
- Camera Characteristics Complicate (Intrinsics)
- Binocular Apparatus Errors (Extrinsics)
- Common Reference Point (Left/Right) – Registration
- Far From Matching Human Capability
- RGB-D Scanning Becoming More Accurate, but Active

Simplified Planar Triangulation With Perfect Lenses and Detectors And Simple Point Registration

\[ \Delta \text{centroid} = (d_l + d_r) \]
\[ \frac{\Delta \text{centroid}}{\Delta \text{centroid}} \]
\[ \frac{f}{b} = \frac{d}{d} \]
\[ f = \text{focal-length} \]
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
Breadboard Prototype Tested Summer 2013

- NTSC -> TI Decoder -> Cyclone-III FPGA -> FTDI -> Beagle xM / Beagle Bone Black (Linux)
- Model-Sim Verification, Data-Flow Verification
- FTDI Interface and Linux USB Custom Driver (Stubbed)
- Spec to Mentor Graphics for PCB Layout, 4-Layer Fab
Goal to Release in 2014

- Verification In Progress – PCB Layout Done
- Driver Stubbed in Linux for USB and UVC
- Working on FPGA Transforms and Applications
- Testing with DE2i for 150K LE Transform Engine
Schedule

2013
- High Level Design
- Schematic Capture
- PCB Layout
- Rev-A Boards Fabricated December 2013
- Rev-A Board Verification Started

2014
- Prototype CU-Cam / CP Linux Driver Based on UVC Ready for Testing
- Dataflow Tests from CU-Cam FTDI to DE2i Linux Driver (Beagle xM Driver)
- Rev-1.0 Computer Vision Lab Materials Complete for Internal Review and Testing with Students in CS&E A485 – Spring 2014
- FIFO Decimation, Resolution Down/Up-Conversion, Pixel Format Transformation Tests
- Stereo Vision Application Testing with OpenCV
- Advanced Pixel, Macroblock, Frame Transformations on DE2i
- Battery Power and Field Testing During Summer (Anchorage)
- Post Reference Designs on Intel and Mentor University Program Sites
Summary

- 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 that Can Be Battery Powered