“Drone Net”

Using Tegra for Multi-Spectral Detection and Tracking in Shared Air Space
Significance

Motivation – Large Numbers of sUAS
  – **Droneii, FAA, Sandia, ASSURE**
  – **Counter UAS Challenge**
  – senseFly Catalog of **Uses**

Problem – Default solution
  – **Part 107** for sUAS and beyond
  – ADS-B for sUAS insufficient, infeasible
  – RADAR/LIDAR feasibility

Drone Net hypothesis
  – Networked, multi-modal (passive/active), information and sensor data fusion
  – EO/IR + acoustic, spectral fusion, machine learning
  – Compare to and validate with LIDAR/RADAR, ADS-B
The sUAS Market is Vigorous [Droneii]
Proposed and State of Art

- **Counter UAS [DARPA, ONR, SRC, Mitre]**
  - RADAR/LIDAR, IFF
  - Neutralization, Jamming, Interception

- **Security [FAA, DHS, FBI, Sandia]**
  - EO/IR, RADAR/LIDAR, Geo-fencing
  - Detection Field Testing [FBI at JFK]

- **Safety and Compliance [DOT FAA]**
  - **Part 107** - sUAS Registration, Pilot Certification, Classification
  - ADS-B NAS, See/Sense-and-avoid
  - **PrecisionHawk** LATAS (Low-Altitude Traffic and Airspace Safety)
  - **NASA / Verizon UTM** [UAS Traffic Management]
Goals and Objectives

- EO/IR sUAS Detection Feasibility
  - Baseline – UAS, GA, Wildlife, Insects, …
  - DNN, DBN, SVM Machine Vision and Learning Classification, Identification

- Passive, Passive + Active
  - Performance Evaluation
  - ROC, PR, F-measure, Confusion Matrices
  - Data, Image, Information Fusion
  - Acoustic Camera, LIDAR [Next Steps]

- Complimentary Spatial, Temporal, Spectral Resolution
  - flightradar24.com – Enhanced aggregation
  - Network of Sensor Fusion Nodes
  - Long baseline [optical and acoustic localization]
  - Campus Drone Net
  - Geo-Net [Florida, Alaska, Arizona, Colorado]
Method – Information Fusion

- EO/IR Multi-spectral imaging
  - Visible, NIR to LWIR
  - Pixel Level and Feature Level Registration
  - Lower Cost than common bore-sight
  - Test sUAS with “Flash Pop” Stimulators

- Link Drone Net Nodes [wireless, wired]

- ADS-B aggregation
  - Drone Net receivers - Garmin, Appareo, etc.
  - Test UAS transceivers – e.g. uAvionix ping1090, ping2020

- Acoustic cameras and cues [improve classification]

- Active LIDAR [RADAR]

- GP-GPU Real-time Processing

ERAU – Performance, Verification, Validation and Algorithm Compare “Student / Researcher” Competitions
Method – Machine Vision & Learning

Machine Vision using SoC Linux
- Salient Object Detection
  - Shape, Behavior and Contrast/Color/Texture in Multiple Bands
  - Performance [ROC, PR, F-measure, confusion matrices]
- Real-Time Detection, Segmentation, Tracking, Classification, Identification

Machine Learning (Traditional, ANN)
- Expert systems
- Bayesian inference, Dempster-Shafer reasoning [DBN]
- PCA [Principal Component Analysis]
- SVM [Support Vector Machines]
- Clustering [e.g. K-means]
- GPU Accelerated DNN (cuDNN)
- Supervised, Unsupervised learning

Leverage Open Source: ROS, OpenCV, PyBrain, PyML, MLpack, cuDNN, Caffe

Drone ROC for Motion Detect

University “Open Research” – Goal for replication similar to early Internet
Conceptual Configuration

Jetson Tegra X1 With GP-GPU Co-Processing

Panchromatic, NIR, RGB

LWIR

Many multi-spectral focal planes ...

Thermal Fusion Assessment

Saliency & Behavioral Assessment

Cloud Analytics and Machine Learning

Flash SD Card (local database)

2D/3D Spatial Assessment
Experimental System Block Diagram

- 2 Watts at Idle, Plus 1.5 Watts per Camera = 6.5W
- E.g. Sobel, 30Hz, 20 Mega Pixels/Sec/Watt, 7.3W Peak – SPIE Sensor Tech + Apps

1) Sync’d Capture
2) Resolution Match
3) Image Registration
4) Detection
5) Classification
6) Identification
Needs Debugging – Literally!

- Many Insects Detected in Visible to LWIR
- Opportunity to work on Bird / Aviation Interaction Testing
2015/16 – ADAC & ERAU Sponsored

- **UAA – ADAC, SmartCam**
- **ERAU (Undergraduate Research Team)**
  - Dr. Sam Siewert, PI, Assistant Professor
  - Demi Matthew Vis – AE/SE Student
  - Ryan Claus – SE Student
  - Nicholas DiPinto – SE Student
  - Arctic Power Team – Power Team Poster
- **CU Boulder – Embedded Systems Engineering Graduate Program**
  - Ram Krishnamurthy – MS EE
  - Surjith Singh – MS, ESE
  - Akshay Singh – ME, ESE
  - Shivasankar Gunasekaran – ME, ESE
  - Swaminath Badrinath – ME, ESE
- **Industry Advising/Collaboration Participants**
  - Randall Myers, Mentor Graphics

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2016/17 Team – ERAU Sponsored

**ERAU – Drone Net**
- Dr. Sam Siewert, PI, Assistant Prof.
- Dr. Iacopo Gentilini, Co-I
- Dr. Stephen Bruder, Co-I
- Dr. Mehran Andalibi, Co-I
- Demi Matthew Vis – AE/SE Student
- Ryan Claus – SE Student

**CU Boulder – Embedded Systems Graduate**
- Ram Krishnamurthy – MS EE
- Surjith Singh – MS, ESE
- Akshay Singh – ME, ESE
- Shivasankar Gunasekaran – ME, ESE
- Omkar Seelam – ME, ESE

**Industry Advising/Collaboration Participants**
- Randall Myers, Mentor Graphics (PCB, CAD, Systems)
- Joe Butler, Intel Corporation (IoT)
Detection Experiments for Aircraft and UAS

Preliminary Roof-top Field Trials at ERAU Prescott
AIAA – Drone Net Feasibility
Results

S. Siewert, M. Vis, R. Claus, R. Krishnamurthy, S. B. Singh, A. K. Singh, S. Gunasekaran,
“Image and Information Fusion Experiments with a Software-Defined Multi-Spectral Imaging System for Aviation and
Marine Sensor Networks”,
Open Reference SDMSI Configuration

- 2 Basler Pulse Visible Cameras
- 1 FLIR Vue LWIR Camera with ZnSe Window
- Jetson TK1, Panda Wireless, USB3 Hub, Power, NEMA Enclosure
Smart Camera Deployment - Aerial

- UAV Systems - ERAU ICARUS Group
- Experimental Aviation and Small Aircraft - ERAU
- Kite Aerial Photography, Balloon Missions (ERAU, UAA, CU Boulder)
Actual - Roof Mount Experiment

- Starting point – evolve to aircraft, buoy and UAS later
- Embry Riddle flight line provides lots of light aircraft traffic
- Simple UAS testing in Campus (semi-Urban) environment
- Wildlife – insects, bats, birds, etc.
Information Fusion Concepts

Integration and System of Systems Between ADS-B and S-AIS for Vessel / Aircraft / UAS Awareness

Smart Cameras Can Monitor and Plan Uplink Opportunity as Well as Wake up and Uplink

System Fusion For Uplink
Baseline Motion Trigger Detection

- Difference Images over Time (adjustable)
- Threshold - Statistically Significant Pixel Change
- Filters (Atmospheric, Cloud, Constant Background Motion) – Dispersion of Changes
- Detection Performance – **ROC**, **PR-Curve**, F-measure [TP, FP, FN, TN analysis]
- Classification/Identification - Confusion Matrix

**PR best for Image Retrieval**
E.g. [https://images.google.com/](https://images.google.com/)

**ROC best for Target Detection**

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**Precision** = \[	ext{true positives} / (\text{true positives} + \text{false positives})\]

**Recall** = \[	ext{true positives} / (\text{true positives} + \text{false negatives})\]

[https://en.wikipedia.org/wiki/Precision_and_recall](https://en.wikipedia.org/wiki/Precision_and_recall)
Frame by Frame Analysis

- TP – Determined by Human Review
- Frame by Frame
- Alternative is by Physical Experiment Design
- “Autoit” Program to Analyze

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Aircraft Detection Performance - Baseline

Video Links – Aircraft, Bugs, FP, TP+FP, [TN], [Full]

Aircraft ROC for Motion Detect

- True Positive Rate
- False Positive Rate

- MD
- RAND
UAS Detection Performance – Baseline

Video Link – UAS+Aircraft, Bugs, FP, TP+FP, [TN], [Full]

Drone ROC for Motion Detect

- True Positive Rate
- False Positive Rate

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Candidate SOD (BinWang14) - Aircraft

- Modified to Run BinWang14 SOD => MD Baseline
- Video Links – TP+FP, [TN], [Full]
Candidate SOD (BinWang14) - UAS

- Modified to Run BinWang14 SOD => MD Baseline
- Video Links – TP+FP, [TN], [Full]
AIAA – Drone Detection Conclusions

- Drone Net Likely Requires Custom Detection – SOD
- Classification Based on Shape, Behavior and Contrast/Color/Texture in Multiple Bands (RGB, NIR, LWIR)
- Considering Acoustic Cue Fusion
- Cross Check with ADS-B, RADAR/LIDAR Data
- Produce Improved flightradar24.com Meta-data
- Find Ghost UAS and Aircraft [Non-compliant], Log Others
SPIE – Benchmark Results

# FPGA Results - Sobel

- ALUTs: 10187
- Registers: 13,561
- Logic utilization: 7,427 / 32,070 (23 %)

Table 2. Sobel Continuous Transform Power Consumption by Cyclone V FPGA

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Transform (Watts)</th>
<th>(Pixel/sec) per Watt</th>
<th>Saturation FPS</th>
<th>Bus transfer rate (MB/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320x240</td>
<td>5.655</td>
<td>2,050,716</td>
<td>151</td>
<td>11.06</td>
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<tr>
<td>640x480</td>
<td>5.700</td>
<td>2,107,284</td>
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<tr>
<td>1280x960</td>
<td>5.704</td>
<td>2,143,506</td>
<td>9.95</td>
<td>11.66</td>
</tr>
<tr>
<td>2560x1920</td>
<td>5.696</td>
<td>2,157,303</td>
<td>2.50</td>
<td>11.72</td>
</tr>
</tbody>
</table>
FPGA Results – Pyramidal

- ALUTs: 24456
- Registers: 34,062
- Logic utilization: 17,721 / 32,070 (55%) (55%)

Table 3. Pyramidal Laplacian Resolution Up-Conversion Continuous Transform Power

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Transform (Watts)</th>
<th>(Pixel/sec) per Watt</th>
<th>Saturation FPS</th>
<th>Bus transfer rate (MB/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320x240</td>
<td>6.009</td>
<td>889,546</td>
<td>69.6</td>
<td>5.10</td>
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<tr>
<td>640x480</td>
<td>6.013</td>
<td>904,281</td>
<td>17.7</td>
<td>5.19</td>
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<tr>
<td>1280x960</td>
<td>6.038</td>
<td>905,624</td>
<td>4.45</td>
<td>5.21</td>
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<tr>
<td>2560x1920</td>
<td>6.192</td>
<td>889,054</td>
<td>1.12</td>
<td>5.25</td>
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</tbody>
</table>

Table 4. Pyramidal Gaussian Resolution Down-Conversion Continuous Transform Power

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Continuous Transform Power (Watts)</th>
<th>(Pixel/sec) / Watt</th>
<th>Saturation FPS</th>
<th>Bus transfer rate (MB/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>320x240</td>
<td>5.968</td>
<td>2,445,040</td>
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<tr>
<td>640x480</td>
<td>6.018</td>
<td>2,399,202</td>
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<td>1280x960</td>
<td>6.023</td>
<td>2,427,813</td>
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<td>2560x1920</td>
<td>6.109</td>
<td>2,309,154</td>
<td>2.87</td>
<td>13.45</td>
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</table>
Table 5. Sobel Continuous Transform Power

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Continuous Power at 1Hz (Watts)</th>
<th>Continuous Power at 30Hz (Watts)</th>
<th>(pixels/sec) per Watt @ 1Hz</th>
<th>(pixels/sec) per Watt @ 30Hz</th>
<th>Saturation FPS</th>
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</thead>
<tbody>
<tr>
<td>320x240</td>
<td>4.241</td>
<td>4.932</td>
<td>18,109</td>
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<td>640x480</td>
<td>4.256</td>
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<td>288,045</td>
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<td>2560x1920</td>
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<td>7.326</td>
<td>1,136,462</td>
<td>20,127,764</td>
<td>55</td>
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</tbody>
</table>
Table 6. Pyramidal Up and Down Conversion Continuous Transform Power

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Continuous Power at 1Hz (Watts)</th>
<th>Continuous Power at 20Hz (Watts)</th>
<th>(pixels/sec) / Watt @ 1Hz</th>
<th>(pixels/sec) / Watt @ 20Hz</th>
<th>Saturation FPS</th>
</tr>
</thead>
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<td>320x240</td>
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<td>4.824</td>
<td>18,713</td>
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<td>640x480</td>
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<td>5.460</td>
<td>74,636</td>
<td>1,687,912</td>
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<td>1280x960</td>
<td>4.152</td>
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<td>295,954</td>
<td>5,370,629</td>
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<tr>
<td>2560x1920</td>
<td>4.224</td>
<td>13.44</td>
<td>1,163,636</td>
<td>10,971,429</td>
<td>20</td>
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</tbody>
</table>

Pyramidal Down followed by Up-Conversion - Power vs FPS

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SPIE On-going Work

- We Have Completed Hough Lines Continuous Transform Test, Available on GitHub

- Hough Power Curves Not Yet Produced – In Progress

- Goal to Identify all Continuous Transform Primitives Used in Infrared + Visible Fusion and 3D Mapping

- Pixel Level Emphasis, But Also Plan to Review Feature Level
  - Camera Extrinsic and Intrinsic Transformations
  - Registration
  - Resolution and AR Matching
  - Methods of Pixel Level Fusion in Review [10] [11], [12], [14]
SPIE Benchmark Conclusions

Please Download our Benchmarks
- https://github.com/siewertserau/fusion_coproc_benchmarks
- MIT License

Test on NVIDIA GP-GPU or FPGA SoCs (Altera, Xilinx)

Share Results Back Please

Help Us Add Benchmarks Critical to Continuous 3D Mapping and Infrared + Visible Fusion (Suite of Primitives)

Open Source Hardware, Firmware, Software for Multispectral Smart Camera Applications
Research References
References


References


Public SDMSI shared data web site for video sequences captured and used in two experiments presented in this paper - http://mercury.pr.erau.edu/~siewerts/extra/papers/AIAA-SDMSI-data-2017/ 


flightradar24.com, ADS-B, primary/secondary RADAR flight localization and aggregation services.

Drone Detection and Neutralization Companies

Leading Drone Detection Companies

- https://www.blacksagetech.com/
- https://www.droneshield.com/

List of Drone Detection Companies and Experiments

- Test at JFK by FBI - https://www.faa.gov/news/updates/?newsId=85546
- https://www.hgh-infrared.com/es/Aplicaciones/Seguridad/UAV-Detection