FINAL REPORT
Project WP#422: Consolidated Research Program, Right of Way Automated Monitoring Threat Prevention (Topic Area #1); Leak Detection (Topic Area #2)

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Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety

Project Title Project #422, "Consolidated Research Program,
Right of Way Automated Monitoring Threat Prevention (Topic Area #1;
Leak Detection Topic Areas #1 and #2)"

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Background

Preventing unauthorized intrusions on pipeline Right of Ways (ROWs) and mechanical damage due to third party strikes by machinery is a constant challenge for the pipeline industry. Equally important for safety and environmental protection is the detection of leaks from pipeline systems. This consolidated research and development program was initiated to develop, test, and deploy an integrated technology package for automated monitoring, assessment, and reporting of various threats to energy transportation pipelines.

The Consolidated Program is being implemented through primary projects focus areas – 1) ROW Threat & Change Detection and Identification, and 2) Leak Detection. The main goal is to use technology to provide "near real-time" detection and reporting of the main threats, with the ultimate objective to develop and deploy advanced sensors and data processing systems on various platforms (ground patrol, manned aircraft) to patrol energy pipeline ROWs and similar-oriented linear features/infrastructure using automated processes.

The program includes developing integrated sensing suites to provide improved and cost effective aerial surveillance for detecting unauthorized activity and changed conditions and communications systems for prompt reporting of threats. This will include on-board data processing systems for identification and screening of threats, data archiving and storage, and could include advanced methods of data analysis and predictive modeling for assessing threats to pipelines. This Consolidated Program will substantially meet many of the challenges currently confronting the pipeline industry for damage prevention, threat identification, and leak detection, and will improve pipeline safety and reliability of service by advancing the state of current technologies for pipeline ROW monitoring and surveillance.

The overall objective of this project is to develop a new generation of surveillance management systems by delivering a step-change improvement in the proactive prevention of threats to pipelines. Technologies developed will be used for the detection, identification, and communication of threats and vulnerabilities to underground pipeline infrastructure. The program will develop an integrated, autonomous sensor/detector system for near real-time automated detection, identification, and notification of threats and leaks.

Electricore received notification from DOT on October 28, 2011 of the intent to terminate the project in accordance with the Termination Provision of Prime Contract Agreement, Article III, Section 3.02. In accordance with this notification, all PHMSA sponsored activities on the project were stopped with a final project termination date of November 28, 2011. This Final Report provides a summary of the work that was completed during the active project period. As the project was terminated by DOT prior to the project completion, the original project goals and objectives were not achieved.

Technical Status

The team completed the following technical activities prior to the termination of the project on November 28, 2011.

Task 1 Project Kickoff: The project team conducted a two day project planning meeting at NASA Ames Research Center in Moffett Field, CAwith Electricore, PRCI, and NASA. Following this planning meeting, a subsequent kick off meeting was conducted with the DOT PHMSA COTR Sam Hall in attendance.

Task 2: Technology Evaluation and Assessments— Technology Review & Gap Assessment – RFI: NASA Ames and the project team have conducted thorough and extensive evaluations of available technologies related to the development of the multi-sensor RAM Program technology package. Based on the evaluations and pre-screening of technologies relative to the RAM Program requirements and Concept of Operations, several meetings and presentations have been held and included:

- American Aerospace Advisors, Inc.
- ATE Aero Surveillance
- Lockheed Martin
- MJ Harden GeoEye
- Piccaro

These meetings were held to better understand the current use of machinery threat detection systems, data processing systems, and target identification and change detection algorithms that are either being provided on a commercial basis (for a variety of needs) or being developed. The focus was on evaluation of change detection approaches, capabilities, data interfaces, and recommended solutions for developing an integrated technology solution for automating ROW monitoring.

Task 3.1: Test Flights- Leak Detection— Automation Technique and sensor assessment from flight tests: Based upon the results of the pre-test of the Piccaro's methane detection system aboard the Sierra UAS during a NASA program in Railroad Valley, NV, the technical team at NASA recommended inclusion of the Piccaro system in further leak detection system flight tests originally planned for 2012.

Task 3.2: Tests Flights - Threat/Change Detection—Test Flights for Data Collection and Sensor Evaluation: NASA prepared a detailed outline and draft of the Flight Testing Plan to guide preparations and field activity for the first set of flight tests. NASA also prepared a detailed data specification and verification plan for the Flight Testing Plan, including a statistical assessment of target sample sizes for equipment and non-equipment threats to be positioned in the test venue and chart targets to test for key elements (resolution, coverage, angle of view, etc.).

Task 4.2: Data Analysis & Algorithm Development - Threat/Change Detection—2010 Algorithm Report; Change Detection Algorithm Gap Study Report: NASA algorithm development included:

- Implementing the multi-class classifier for reducing false alarms.
- Completing modifications to the fast detection algorithm in order to report precise contours around the regions of interest instead of bounding boxes.
- Continuing packaging/documenting the threat detection algorithms for eventual use by development partners/vendors and open source release.
- Developing processes for automating/troubleshooting field verification tests for data/image acquisition including resolution, alignment and coverage tests based on chart targets.

Task 5: Technology Integration & System Design/Architecture—System Requirements and Preliminary Architecture - CONOPS Report; Design and Flight test of data processing: NASA finalized a version of *Concept of Operations* for the "Interim RAM system".

Results and Conclusions

The project team held a Preliminary Design Review of the Roll Pointing Camera on June 8, 2011, via web conferencing. The meeting included participants from the project team, NASA Ames, PHMSA and technology providers. Key aspects of the projects Concept of Operations, System Requirements and System Features were presented to industry technology developers and providers for feedback and comment. The following summarizes the information presented during the meeting and the current status of the Roll Pointing Camera development:

Concept of Operations

- Airborne Sensing; multiple sensors to detect threats
    - Penetrating equipment (blades, buckets, augers, trenchers)
    - Leaks (liquid and gas products)
    - Change (subsidence, erosion, encroachment)
- Image Processing Element
    - On-board processing of sensor data for immediate detection of threats (penetrating equipment and leaks)
- Communications
    - Transmitting location and type of detected threat to ground information distribution center within a few minutes of detection
- Ground element
    - Additional image processing
    - Dispatch (One Call center)
    - Archive

Design Requirements

- Aircraft / Environmental
    - Adaptable to existing patrol fleet – Cessna 170 & 180 Series
        - STC or 337 for upper wing strut or step
        - Limited mass, and drag, torsional limit to strut strength
        - 120 watts cabin power
        - Vibration spectrum

  - All weather operation
  - NASA ARC JO-5 Manual emergency landing Inertial loads
    - 10G forward and downward, 3 G lateral
- On-board Processing
  - Near real time threat identification
  - ROW intrusion of machine threats (blades buckets, augers, and trenchers)
  - Image processing algorithms – orthogonality, edges, color, change, other
  - Corroborating sensors - morphology, polarimetry, magnetometry, spectral domain (multispectral, SAR, TIR)
- Imaging
  - ROW domain – 200 ft swath, complex path
  - VNIR – 1”-2” GSD, +/- 15 degrees of nadir
  - TIR - 8” GSD, co-aligned with VNIR to allow pixel mapping
- Communications Options
  - Satcom (Irridium, Inmarsat)
  - 3-G and 4-G networks

Sensor Design Approaches

- Fixed Cameras
  - Very high resolution (e.g. 30 Mpix) camera / camera clusters
  - AHRS for knowledge of part of image containing ROW, critical for autocorrelation based geo-registration for change detection.
  - Ingest all image data and segment out ROW in post processing
  - Programmable readout to read only Region of Interest
- Roll Pointing Cameras
  - Moderate image size and data bandwidth
  - AHRS for knowledge of roll pointing angle to center of ROW, autocorrelation based geo-registration for change detection.
  - High level of roll pointing control
- Trades
  - Camera Cost – favors pointing system
  - Data bandwidth and on-board processing power – favors pointing system
  - Complexity – favors fixed camera

Design Approach

- Roll Pointing Cameras
  - VNIR 2000 cross track pixels, 1.2” GSD, 200‘ swath, 11.5 deg FOV at 1000 ft AGL
  - TIR, FLIR Tau 640 class, TBD
  - Data Interface Gig-E, with separate Power (IEEE 1394b also has advantages)
  - Asynchronous Trigger
- MEMS AHRS with WAAS GPS augmentation
  - Kalman filtering
  - 1-2 degree pointing knowledge accuracy
- Rotary Actuator
  - Hollow shaft for flex wiring interface (no slip ring required)
  - High level of roll pointing control
- Seals

- Permit all weather operation
- Teflon shaft seal (Smaller diameter for low motor drag)
- O-rings for fairings

- Data System and controller
  - Modest processor power
  - Solid state hard disk (speed and vibration resistance)
  - Planning algorithm to determine image timing, roll pointing angle
  - Meta data, base-map autocorrelation approach to geo-registration

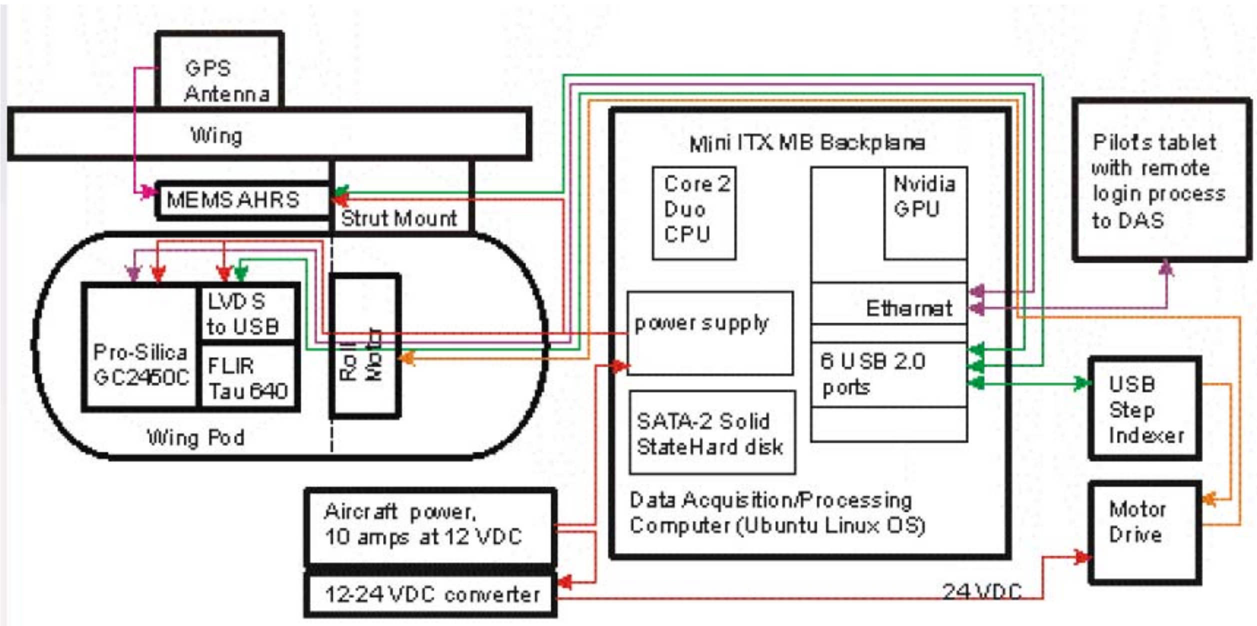

Figure 1: Block Diagram and Interfaces of the Roll Pointing Camera System

Instrument Models

- Camera models
  - Flight line altitude and grounds speed
  - GSD & Swath
  - Image Timing (2.5 Hz @ 0.66 overlap), asynchronous capture for multiple sensors
  - Trapezoidal distortion
  - Lens distortion, pixel mapping to correlate multiple cameras
  - Data requirements

- Flight Planning model
  - Inputs
    - Complex path shape file
    - Aircraft handling qualities (bank angle, turn radius)
    - Desired altitude
  - Outputs
    - Flight line Waypoints
    - Image timing and corresponding roll pointing angle command (fraction of commands that exceed +/- 15 degree requirement)

- Number of cloverleaf turns required

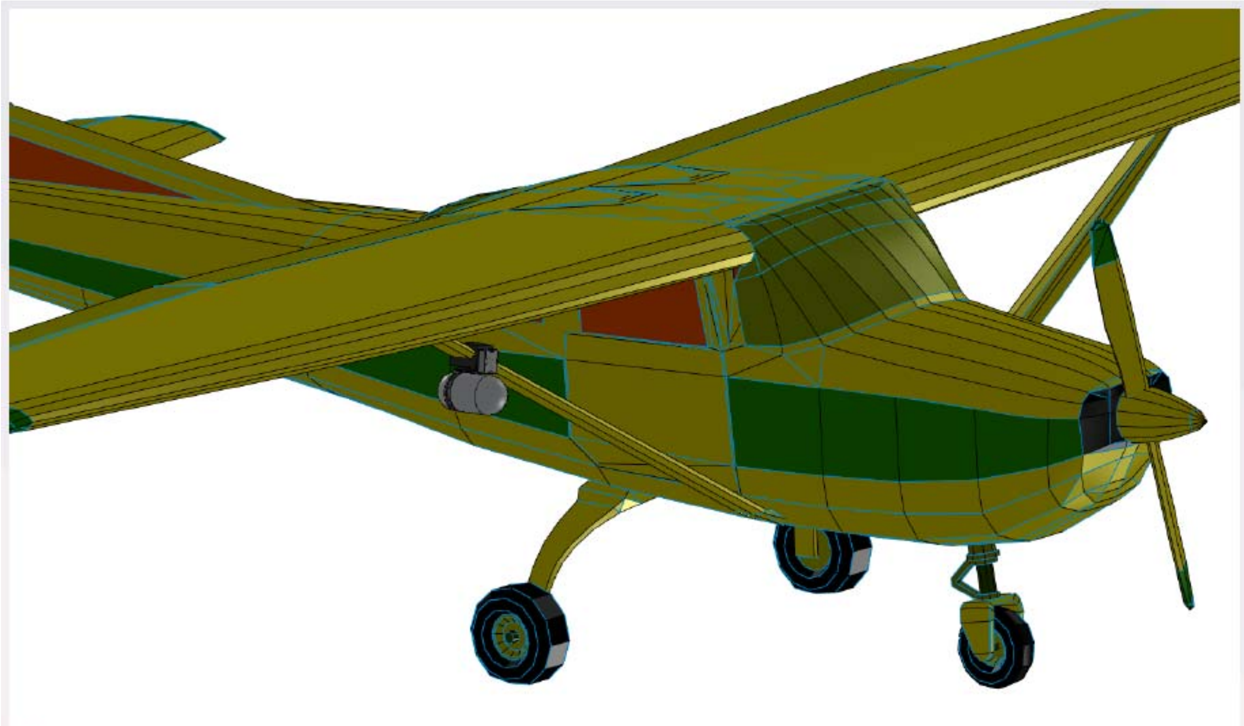

Figure 2: Concept Illustration of the Wing Mounted Camera System

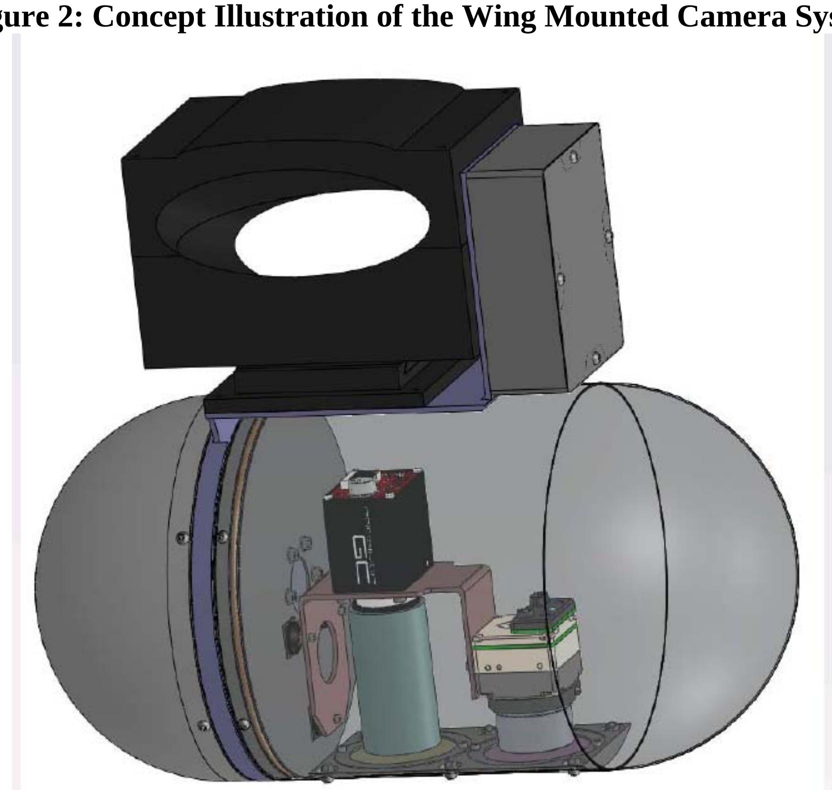

Figure 3: Concept Illustration of the Camera Pod

Components

- VNIR camera & lens
- TIR camera/lens
- Windows
- Roll motor
- Mounting Clamp
- AHRS
- Seals

Analysis

- Stress analysis
- Drag load at offset induces torsional moment into Strut
- Can replace tail cap with fairing to reduce drag
- Can place canister behind strut clamp to reduce offset
- Emergency landing loads analyzed for ultimate stresses
- Clamp placement at end of strut reduces bending stresses
- Vibration analysis
- Vibration isolation required for 1”-2” GSD
- Elastomeric vibration isolators between camera mount and rotating baseplate,
- symmetrically surrounding CG of camera cluster
- Tuned to float cameras in direction normal to optical axis at dominant
- Vibrational frequencies
- Aero shell shields cameras from turbulence

Component Features

- VNIR Camera - AVT Prosilica GC2450C
  - 5 MPIX industrial vision camera with Bayer array color, 400-700 nm sensitivity.
  - Matched Schneider lens, low distortion, high performance MTF, 400-1000 design range
- Roll Motor - Orientalmotor DG-60 rotary actuator, Deep Groove large radius ball bearing sets, operational loads include 8 in-lbs torque, 22 lbf axial and 17 in-lb moment.
  - Accurate pointing resolution: 0.04 to 0.002 deg; Lost motion error 0.03 deg
  - 24 VDC power supply; built in resolver and control loop closure
- AHRS - Xsens MTi-G
  - Real-time computed GPS-enhanced attitude/heading and inertial enhanced, position/velocity data; UTC referenced
  - 1 deg dynamic accuracy for roll, pitch, heading
  - Integrated AHRS, GPS and static pressure sensor
  - On board DSP, running sensor fusion algorithm to provide high update rate (120 Hz)
  - Individually calibrated for temperature, 3D misalignment and sensor cross-sensitivity
- Shaft Seal - Parker FlexiSeal
  - PTFE (Teflon) lip seal for low drag, moisture resistance.

Software Requirements

- Camera data acquisition (~2.5 Hz)
  - Read AHRS (position, velocity)

  - Compute time for image acquisition
  - Issue asynchronous trigger; synchronized (bore sighted) cameras
  - Read frame
- Roll pointing (~50 Hz))
  - Read AHRS (position and attitude)
  - Compute roll angle to point camera to pipeline
  - Issue roll pointing command
  - Readout position
- On-board near real-time threat detection
  - load image frame into RAM
  - Run edge/corner detect test
  - Run color contrast test
  - Run change detection test
  - Run thermal detection test
  - Run 3-D shape matching test
- Communications
  - Segment image for detected threat
  - Send Detect and threat thumbnail to 1-call center

Termination of the project prior to the completion of the RFP did not allow for flight tests to be performed using the roll-cam or the RFP package developed with the specifications defined by NASA. While the flight tests were not performed, the supporting documents provide the basis for developing a technology solution for automated monitoring along pipeline ROW corridors and a Concept of Operations for the entire ROW Automated Monitoring process.

Business Status

Electricore received notification on July 28, 2011, from USDOT to renegotiate the terms of the Agreement such that the USDOT funds 100% of the project and industry co-funding is removed. Subsequently, on November 28, 2011 USDOT terminated the program.

Electricore and its subcontractors had total project costs, including close out costs, for this agreement of $1,187,003. This included:

$645,174	confirmed cash to NASA Ames for activities in Q3-Q4 2010
$501,000	confirmed cash to NASA Ames for activities in 2011
$28,090	confirmed Electricore expense through December 2011
$12,739	estimated PRCI expenses through December 2011 and Electricore expenses through final close-out.
$1,187,003	Total Project Costs

These total project costs include $291,329 of DOT share and $895,674 team cost share committed to the project.