RESEARCH PERFORMANCE PROGRESS REPORT

SUBMITTED TO:

U. S. Department of Energy
National Energy Technology Laboratory

WORK PERFORMED UNDER AGREEMENT: DE-FE0029020

PROJECT TITLE:

Smart Methane Emission Detection System Development

SUBMITTED BY:

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SUBMISSION DATE: July 28, 2017

DUNS NUMBER: 007936842

RECIPIENT ORGANIZATION:

Southwest Research Institute
6220 Culebra Road
San Antonio, TX 78238

PROJECT/GRANT PERIOD:

October 1, 2016 through September 30, 2017

REPORTING PERIOD END DATE:

June 30, 2017

REPORT TERM OR FREQUENCY: Quarterly

SIGNATURE OF SUBMITTING OFFICIAL:

Maria S. Araujo

<u>ACCOMPLISHMENTS</u>

What was done? What was learned?

As anticipated, and defined in the Project Management Plan (PMP), activities during this quarter focused on performing simulated methane release tests, acquiring additional data and continuing the development and refinement of the detection algorithm. The design and development of the embedded software was another major focus during this quarter. Finally, the design of the Smart Methane Leak Detection System (SLED) mechanical enclosure was also a focus of this quarter,

- **What are the major goals of the project?** The major objective of this DOE research project is to develop an autonomous, real-time methane leak detection technology, the SLED, which applies machine learning techniques to passive optical sensing modalities to mitigate emissions through early detection. The goal during Phase 1 is to develop the prototype methane detection system with integrated optical sensors and the embedded processing unit. The goal for Phase 2 will be to integrate and field-test the prototype system, and then demonstrate the capabilities to DOE.

To accomplish these goals, SwRI has identified a comprehensive schedule with milestone dates for important activities that will evidence progress on the project. The milestone schedule, with actual completion dates, is shown below.

Phase	Milestone Description	Verification Method	Planned Completion	Completion Date
1	Prepare and Submit the PMP	Delivery to DOE	10/29/16	10/29/2016
1	Update PMP with DOE Comments	Delivery to DOE	12/2/16	11/16/2016
1	Update the Data Management Plan	Delivery to DOE	12/16/16	12/16/2016
1	Develop the Algorithm	Assessment Results	9/15/17 (revised per PMP submitted on 6/13/17)	
1	Develop and Assemble Prototype	Testing Results	9/22/17 (revised per PMP submitted on 6/13/17)	
2	Integrate and Test Prototype	Testing Results	4/23/18	
2	Demonstrate the System to DOE	Demonstration	8/21/18	

On June 13, 2017, a revised PMP was submitted to account for the higher level of complexity of the problem and the level of algorithm tuning required. However, there is no anticipated cost impact to the project related to these date changes nor any delay to overall project schedule.

- Revision of delivery dates and project schedule to reflect new planned dates for:
    - Initial Leak Detection Algorithm: from 6/13/17 to 9/15/17.
    - Embedded Software Executable and Source Code: from 7/31/17 to 9/22/17.
    - Develop and Assemble Prototype: from 6/13/17 to 9/22/17.

- **What was accomplished under these goals?**

<u>Controlled Tests</u>

- SwRI continued to perform several methane release tests under realistic conditions to continue to increase the database containing methane leaks of various concentrations, distances, and scenarios. A portable rig was constructed to allow for gas discharges through various leak geometries while controlling pressure and leak rate. This was captured on video (see Figure 1). The test conditions included varying ambient temperature conditions, cloud cover, presence and lack of obstacles (such as piping), and varying wind (including stagnant) conditions.

Figure 1: Niatros™ and FLIR MWIR Cameras Acquiring Data During a Supervised Methane Release

<u>Algorithm Development</u>

During this quarter, the following algorithm developments were made:

- SwRI performed further data collection in order to diversify the training sets for both methane imagery and false positives. It has been observed that the visibility of the methane plume, both to the human eye and to the algorithm, is highly dependent on the brightness of the object behind the methane plume, since the primary detection mechanism relies on the absorption properties on the methane.

- For this reason, special emphasis was placed on collecting data with backgrounds of various emissivity characteristics in the Mid-Wave Infrared (MWIR) spectrum. These included bright and dim backgrounds, vegetation, and camera shots with the plume against the sky. Figure 2 shows a few interesting cases of the plume visibility on various backgrounds.

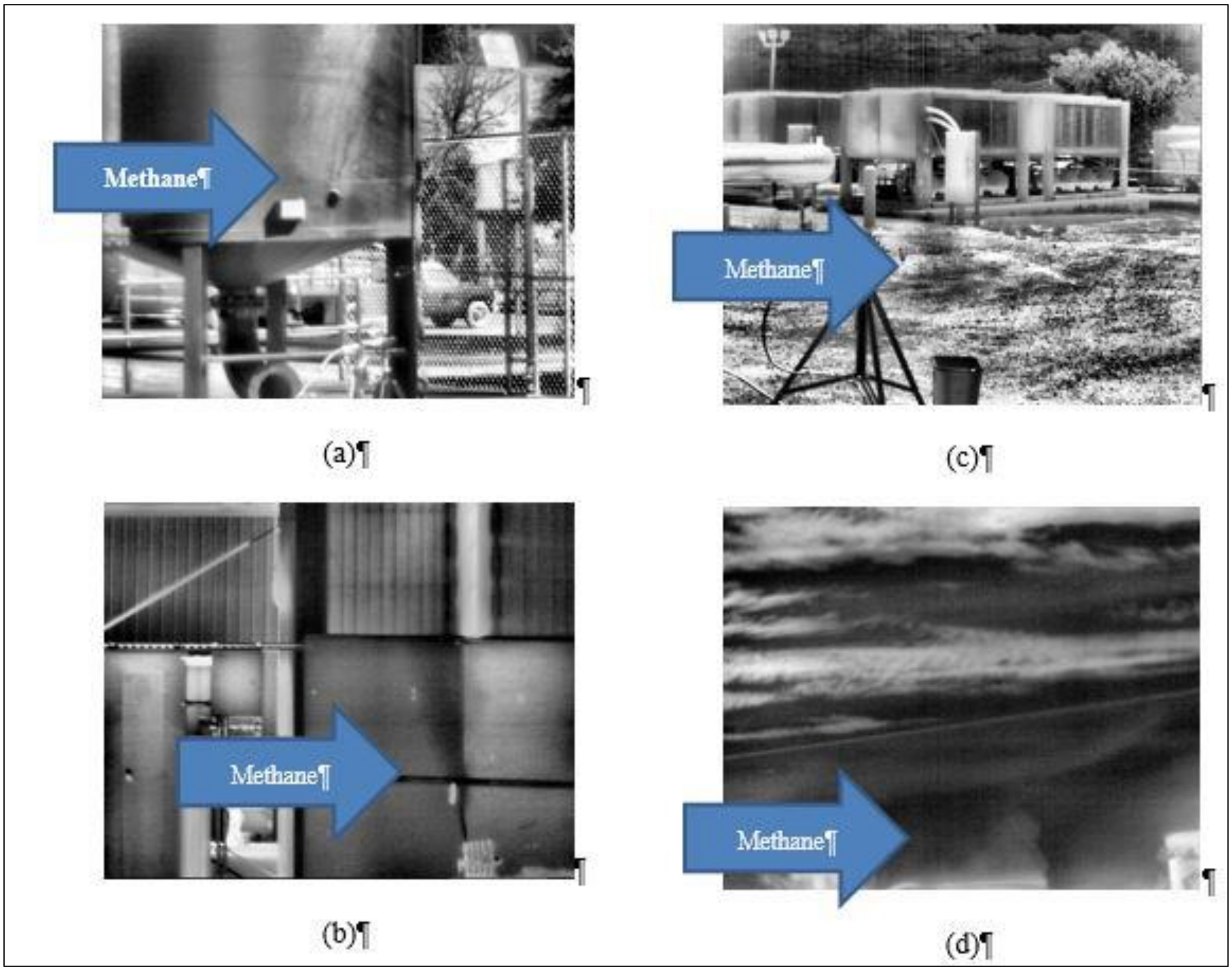

Figure 2: A Methane Plume on Background Surfaces of Various MWIR Intensities: (A) A Bright Background Object, (B) A Dark Background Object, (C) A Noisy Background Object, (D) The Sky, Which Acts as an Infinitely Absorbing (Dark) Background and the Methane Plume

- The chosen algorithmic approach uses three separate steps.
    - Firstly, preprocessing is used in order to make the methane more apparent in the MWIR imagery.
    - Secondly, the preprocessed frames are classified using a segmentation neural network.
    - Thirdly, the output of the neural network is interpreted by a clustering algorithm that implements a clean tunable threshold for how sensitive the alarm reporting should be.
    - Figure 3 shows the high-level data flow of the algorithm.

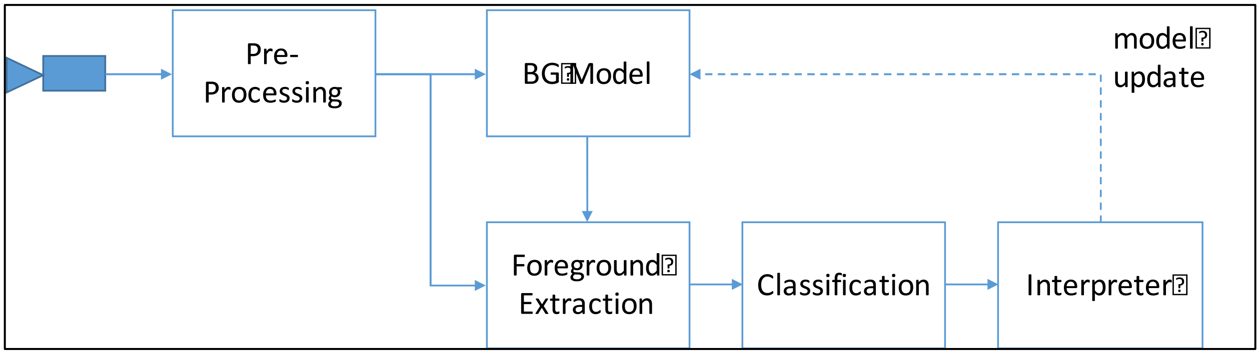

Figure 3: A Flow Chart Depicting the Data Path From Camera Acquisition to the Reporting Mechanism

- Extensive work was done to identify the best-suited classifier for this detection task.
  - The classifier must be sufficiently complex to learn the nuances of a methane plume detection while still small enough to fit within the hardware footprint of the embedded Tegra System on Chip (SoC).
  - A variety of classifier techniques were researched and tested. Additionally, a variety of data processing and pre-processing architectures were researched.
  - Based on this extensive effort, a processing architecture and classifier was chosen, which provided optimal results and performance.
  - The chosen algorithm, a convolutional segmentation network, has been implemented in such a way that it will currently consume 25% of the shared memory between the Central Processing Unit (CPU) and Graphics Processing Unit (GPU).
- Results from the classifier have improved drastically over the prior period of performance. Figure 4 through Figure 8 highlight some of the current test results from the algorithm as well as some remaining issues that need further adjustments and training to resolve.

Figure 4: Comparison Showing Good Tracking on Steady Background

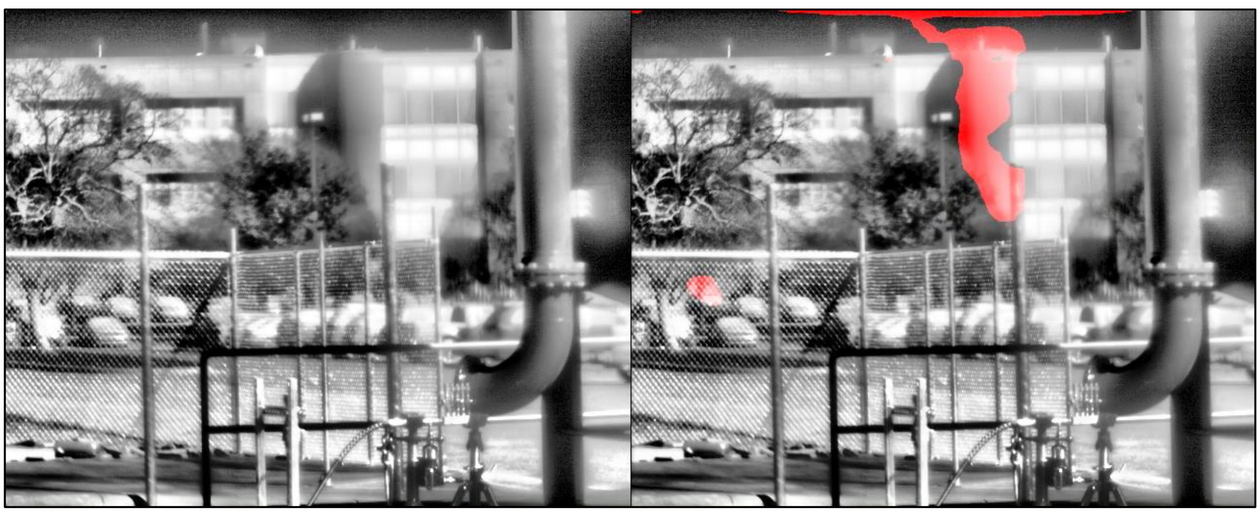

Figure 5: Comparison Showing Steady Tracking on Noisy Background, Methane Plume Not Apparent to Human Eye in Video

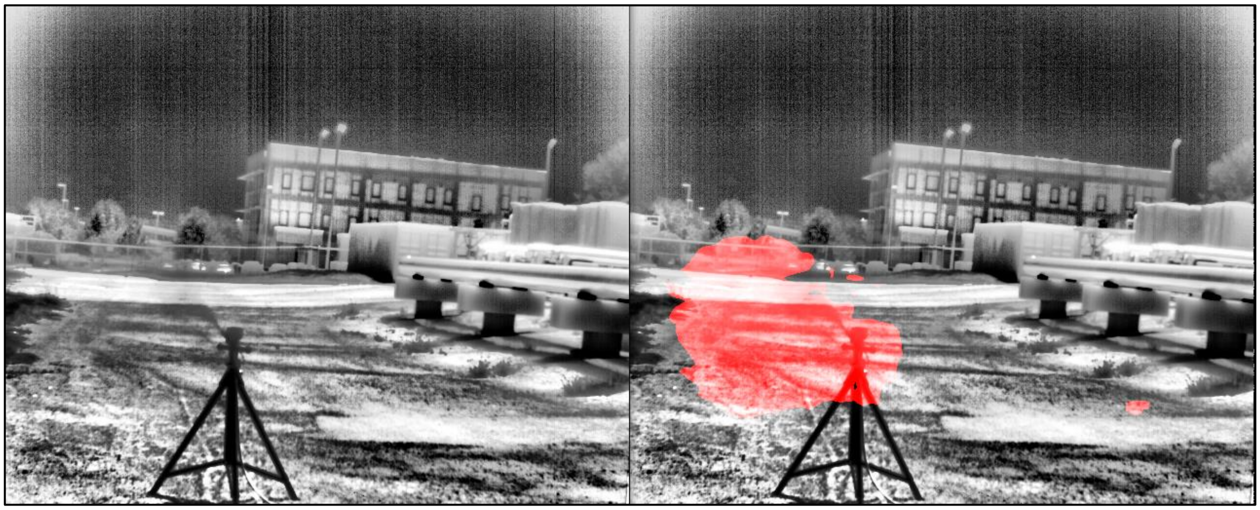

Figure 6: Comparison Showing Good Tracking on Noise Mixed Background; Persistent False Positive Present on Right Side of Image

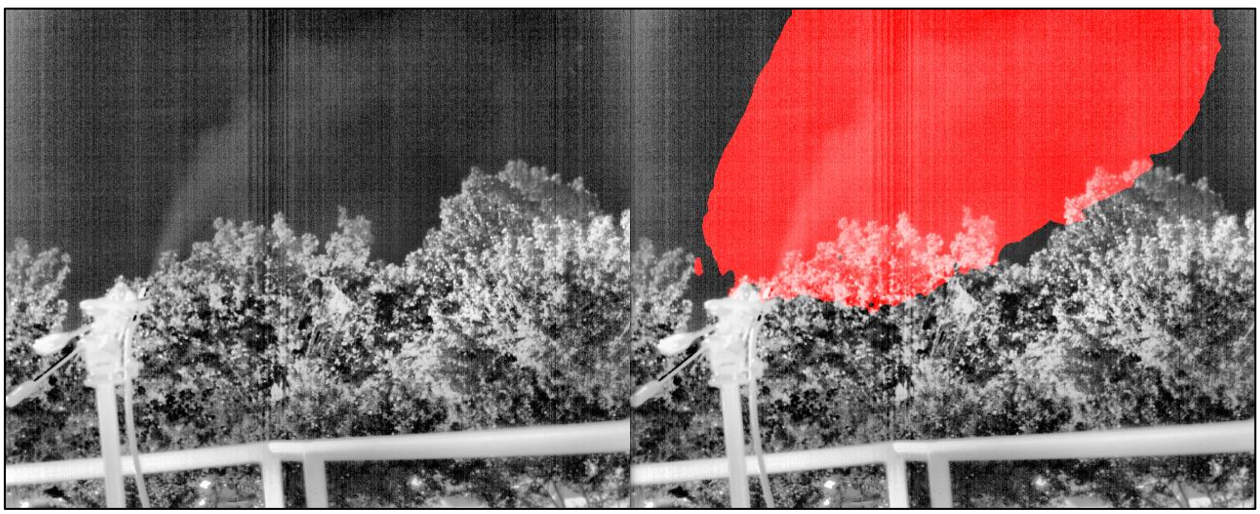

Figure 7: Comparison Showing Good Tracking of Plume in a Region of Sky, Where Optical Dynamics Vary Drastically From a Plume In Front of a Solid Reflective Background

Figure 8: Comparison Showing Good Tracking on Solid Background Again, Failures Present on Bottom-Left of Highlighted Area: Problems Persist Where High-Reflectivity Background Converges with the Plume

<u>Embedded Processor Code Development</u>

- This task encompasses porting the algorithm detection to an embedded system in a deployed platform. The embedded system will support the camera interface, execute the detection algorithm, and provide a user interface for system monitoring and event triggering.
- For this task, progress in the last quarter includes:
  - Completion of embedded software detailed design and documentation.
  - Completion of integration and testing of the MWIR camera.
  - Continued creation of beta software baselines (current version is v0.5).
  - Continued integration and testing of the detection algorithm.
  - Continued integration and testing of user interface software.
- As a reference, the refined system architecture is seen in Figure 9, and the detailed software architecture outlined in Figure 10.

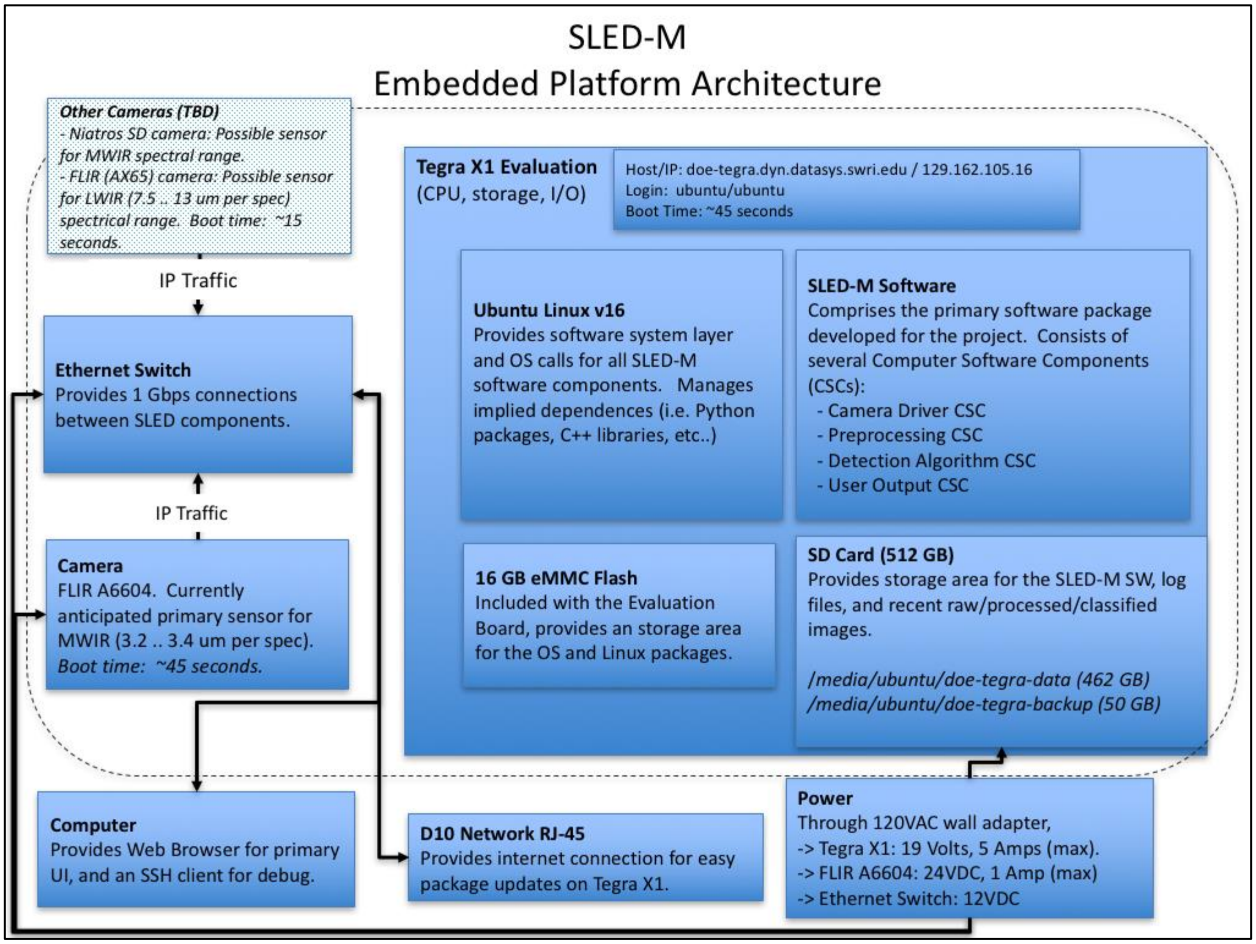

Figure 9: SLED/M Embedded Platform Architecture

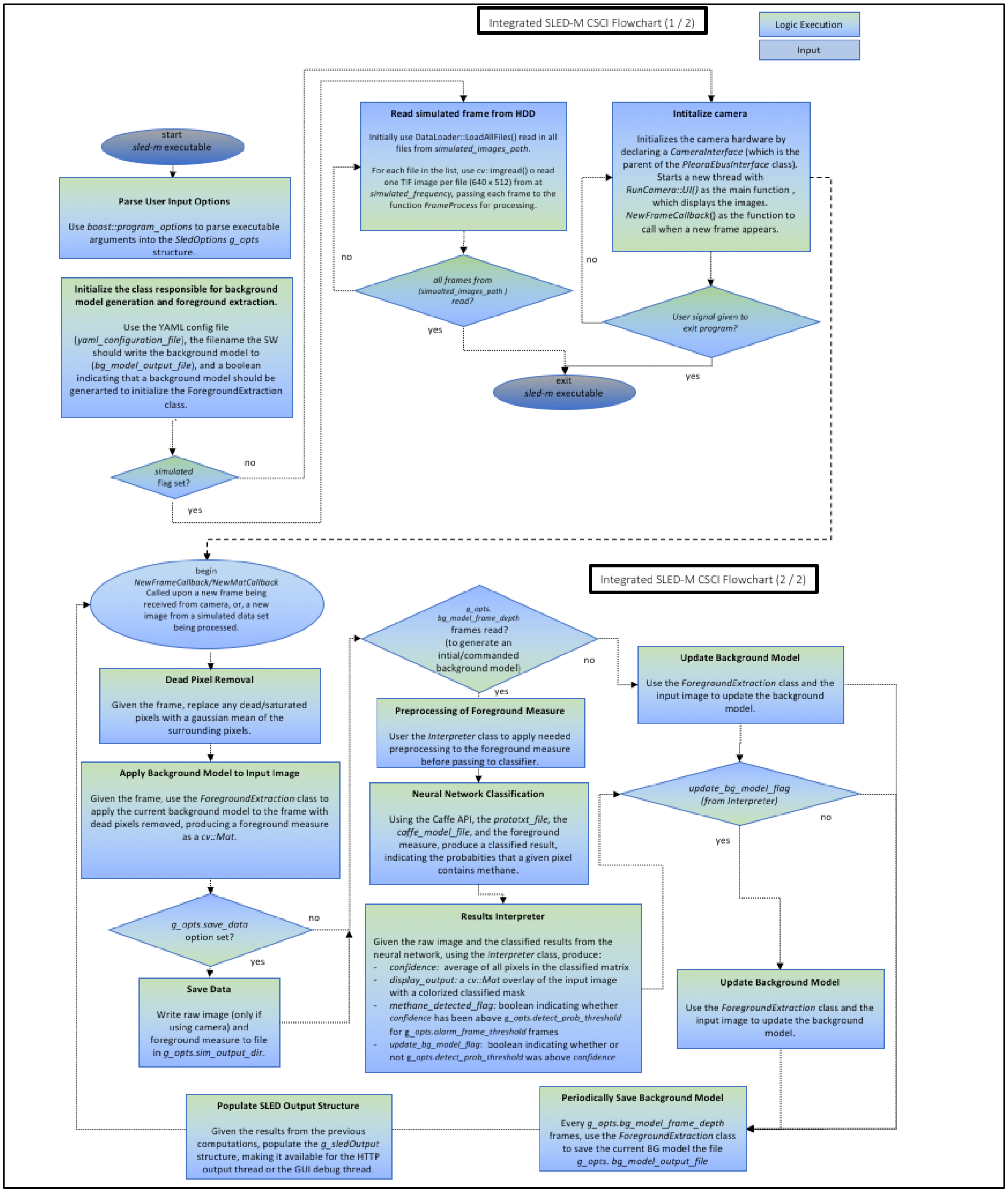

Figure 10: SLED/M Embedded Software Architecture

- Next steps on this task include:
  - Embedded code optimization for real-time performance
  - Completion of integration and testing of detection algorithm software.
  - Completion of integration and testing of user interface software.
  - Testing of the software in the prototype system.

<u>Mechanical and Electrical Design</u>

- For this task, progress in the last quarter includes:
  - Development of detailed design and documentation.
  - Figure 11 shows the top-level mechanical sketch for the SLED/M enclosure and internal components.

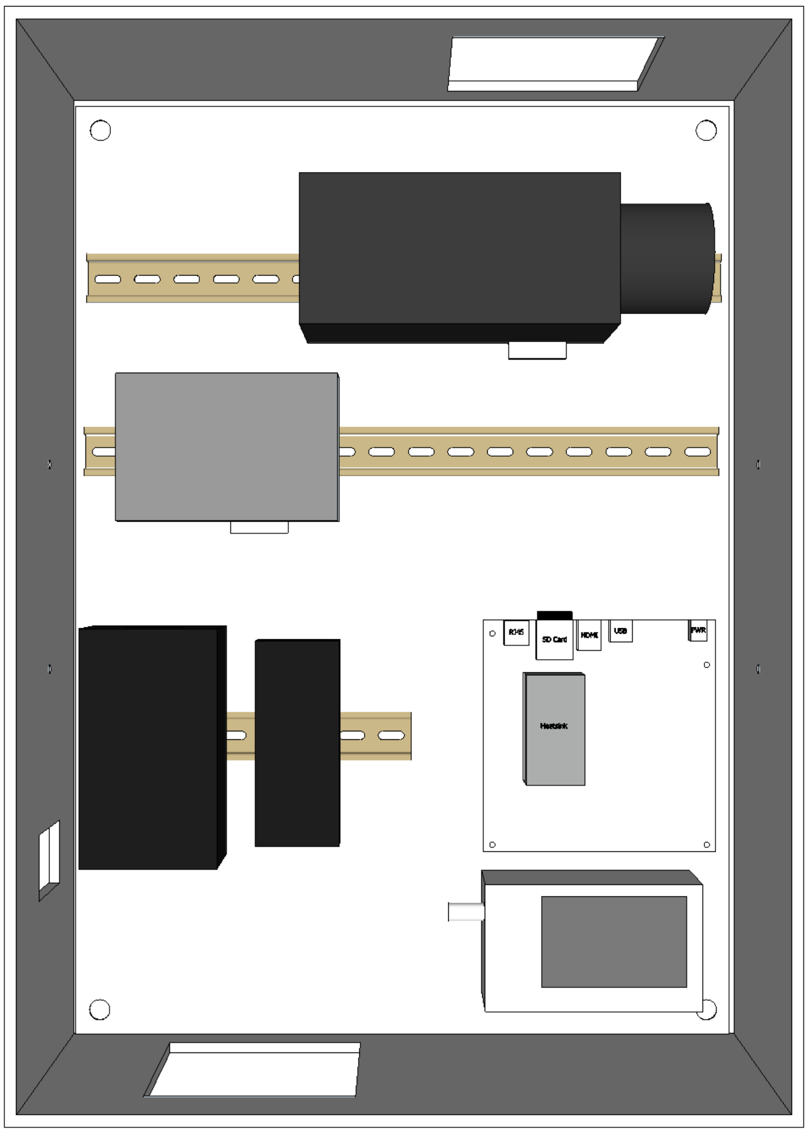

Figure 11: SLED/M System Enclosure and Mechanical Layout Sketch

- Next steps on this task include:
  - Completion of mechanical design.
  - Procurement of mechanical components and parts.
  - Assembly of SLED/M system.

- **What opportunities for training and professional development has the project provided?**

  Nothing to report during this reporting period.

- **How have the results been disseminated to communities of interest?**

  - With the concurrence of the DOE PM, Mr. Joseph Renk III:
    - Maria Araujo will be presenting at the Western Regional Gas Conference in San Diego, CA on August 30, 2017 with a presentation titled "Bringing Smarts to Methane Emissions Detection: An Update on the DOE Smart Methane Emissions Project."
    - Team plans on presenting at the Pipeline and Energy Expo in Tulsa, OK in April 2018 with a presentation titled "Automated Leak Detection Using Machine Learning and Multi-Platform Remote Sensing."
  - The team is also looking at additional conferences/venues to divulge this work.
  - Additionally, several high-level articles regarding the work being done on this project were published and aired on television. Some references are noted below:
    - http://www.naturalgasintel.com/articles/108067-texas-laboratory-developing-methane-leak-detection-system-for-doe
    - http://www.rigzone.com/iPhone/article.asp?a_id=147295
    - http://www.klrn.org/blogs/station-news/swri-developing-smart-technology-to-detect-methane-leaks/
    - http://www.oilandgaslawyerblog.com/2017/02/high-tech-detect-pipeline-leaks.html
    - https://www.ksat.com/news/swri-working-on-oil-and-gas-leak-detection

- **What does SwRI plan to do during the next reporting period to accomplish the goals?**

  During the next reporting period, SwRI will:

  - Continue fine-tuning algorithm performance. This will include incorporating more training data from the collection stage, searching through the classifier's settings to find the optimal conditions, and modifying the network structure to improve the feature learning.
  - Continue to implement the supporting processing modules such as the live background subtraction algorithm and the classifier result interpreter.
  - Continue embedded processor code development.
  - Purchase mechanical components for the system's enclosure.
  - Build physical system.
  - Finalize initial detection algorithm for delivery.

- Finalize embedded code for delivery.

PRODUCTS

What has the project produced?

- **Publications, conference papers, and presentations:**
  - **Journal publications -** Nothing to Report During This Period.
  - **Books or other non-periodical, one-time publications** - Nothing to Report During This Period.
  - **Other publications, conference papers and presentations** - Nothing to Report During This Period.
    - Maria Araujo will be presenting at the Western Regional Gas Conference in San Diego, CA on August 30, 2017 with a presentation titled "Bringing Smarts to Methane Emissions Detection: An Update on the DOE Smart Methane Emissions Project."
    - Team plans on presenting at the Pipeline and Energy Expo in Tulsa, OK in April 2018 with a presentation titled "Automated Leak Detection Using Machine Learning and Multi-Platform Remote Sensing."
  - **Website(s) or other Internet site(s)** –
    - http://www.naturalgasintel.com/articles/108067-texas-laboratory-developing-methane-leak-detection-system-for-doe
    - http://www.rigzone.com/iPhone/article.asp?a_id=147295
    - http://www.klrn.org/blogs/station-news/swri-developing-smart-technology-to-detect-methane-leaks/
    - http://www.oilandgaslawyerblog.com/2017/02/high-tech-detect-pipeline-leaks.html
    - https://www.ksat.com/news/swri-working-on-oil-and-gas-leak-detection
- **Technologies or techniques –** A technique for autonomously detecting methane using MWIR cameras and machine learning is currently under development, with promising results.
- **Inventions, patent applications, and/or licenses –** Assuming successful results and with DOE's concurrence, SwRI plans on filing an invention disclosure of the technique for autonomously detecting methane using MWIR cameras and machine learning.
- **Other products -** Nothing to Report During This Period.

<u>PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS (optional)</u>

Who has been involved?

- **What individuals have worked on the project?**

  The following individuals were the main contributors to this project during this reporting period:

  1. **Name:** Maria Araujo
     a. **Project Role:** PI
     b. **Nearest person month worked:** 1
     c. **Contribution to Project:** Ms. Araujo oversees the project and technical direction. She participated on the simulated tests and holds weekly meetings with the project team.
     d. **Funding Support:** N/A
     e. **Collaborated with individual in foreign country:** No
     f. **Country(ies) of foreign collaborator:** N/A
     g. **Travelled to foreign country:** No
     h. **If traveled to foreign country(ies), duration of stay:** N/A
  2. **Name:** Edmond DuPont
     a. **Project Role:** Co-PI
     b. **Nearest person month worked:** 1
     c. **Contribution to Project:** Dr. DuPont assisted with tests performed and algorithm development during this reporting period.
     d. **Funding Support:** N/A
     e. **Collaborated with individual in foreign country:** No
     f. **Country(ies) of foreign collaborator:** N/A
     g. **Travelled to foreign country:** No
     h. **If traveled to foreign country(ies), duration of stay:** N/A
  3. **Name:** Daniel Davila
     a. **Project Role:** Developer
     b. **Nearest person month worked:** 3
     c. **Contribution to Project:** Mr. Davila assisted with tests performed and algorithm development during this reporting period.
     d. **Funding Support:** N/A
     e. **Collaborated with individual in foreign country:** No
     f. **Country(ies) of foreign collaborator:** N/A
     g. **Travelled to foreign country:** No
     h. **If traveled to foreign country(ies), duration of stay:** N/A
  4. **Name:** Samantha Blaisdell
     a. **Project Role:** Developer
     b. **Nearest person month worked:** 2
     c. **Contribution to Project:** Ms. Blaisdell assisted with tests performed and algorithm development during this reporting period.
     d. **Funding Support:** N/A
     e. **Collaborated with individual in foreign country:** No
     f. **Country(ies) of foreign collaborator:** N/A

   g. **Travelled to foreign country:** No
   h. **If traveled to foreign country(ies), duration of stay:** N/A
5. **Name:** Christopher Jelesnianski
   a. **Project Role:** Developer
   b. **Nearest person month worked:** 2
   c. **Contribution to Project:** Mr. Jelesnianski assisted with embedded software development during this reporting period.
   d. **Funding Support:** N/A
   e. **Collaborated with individual in foreign country:** No
   f. **Country(ies) of foreign collaborator:** N/A
   g. **Travelled to foreign country:** No
   h. **If traveled to foreign country(ies), duration of stay:** N/A
6. **Name:** Kirk Busche
   a. **Project Role:** Developer
   b. **Nearest person month worked:** 2
   c. **Contribution to Project:** Mr. Busche assisted with algorithm development during this reporting period.
   d. **Funding Support:** N/A
   e. **Collaborated with individual in foreign country:** No
   f. **Country(ies) of foreign collaborator:** N/A
   g. **Travelled to foreign country:** No
   h. **If traveled to foreign country(ies), duration of stay:** N/A
7. **Name:** Shane Siebenaler
   a. **Project Role:** Co-I
   b. **Nearest person month worked:** 1
   c. **Contribution to Project:** Mr. Siebenaler oversaw methane release tests performed during this reporting period.
   d. **Funding Support:** N/A
   e. **Collaborated with individual in foreign country:** No
   f. **Country(ies) of foreign collaborator:** N/A
   g. **Travelled to foreign country:** Yes
   h. **If traveled to foreign country(ies), duration of stay:** 1 week

- **What other organizations have been involved as partners?**

  There are no other planned partner organizations besides the cost share partners.

- **Have other collaborators or contacts been involved?**

  No other collaborators or contacts have yet been involved.

IMPACT (optional)

What is the impact of the project? How has it contributed?

Although SwRI fully expects this project to provide significant impacts that benefit the nation, development is not yet to a point where impacts have been realized or quantified. However, with the approval of the DOE, the team has already been engaging in conversations with oil and gas companies about how the SLED/M technology could potentially improve their efficiency and safety.

- **What is the impact on the development of the principal discipline(s) of the project?**

  The development of the SLED/M technology allows for mitigation of fugitive emissions via the early detection of methane leaks. The technology is real-time and autonomous, thus allowing for facilities to be monitored with minimal human resource involvement and, therefore, reducing the overall monitoring costs and improving the reliability of detections.

- **What is the impact on other disciplines?**

  The technology being developed in this project has a variety of applications beyond methane emissions monitoring, such as carbon monoxide monitoring; agricultural land use analysis and crop prediction; water management and soil moisture analysis; natural hazards monitoring and prediction; and ecosystem monitoring and conservation.

- **What is the impact on the development of human resources?**

  Nothing to Report

- **What is the impact on physical, institutional, and information resources that form infrastructure?**

  Nothing to Report

- **What is the impact on technology transfer?**

  Nothing to Report

- **What is the impact on society beyond science and technology?**

  The byproducts of this project will allow for more effective mitigation of methane emissions, which are a major greenhouse effect contributor. By reducing fugitive methane emissions, climate change impacts caused by greenhouse gas emissions are also reduced.

- **What dollar amount of the award's budget is being spent in foreign country(ies)?**

  Nothing to Report

CHANGES/PROBLEMS

SwRI does not anticipate any significant changes in the project or its direction. If this should occur, SwRI is fully aware of its responsibility to provide all relevant details, and to obtain prior written approval from the Contracting Officer.

- **Changes in approach and reasons for change –**

  Nothing to report during this reporting period.

- **Actual or anticipated problems or delays and actions or plans to resolve them –**

  On June 13, 2017, a revised PMP was submitted to account for the higher level of complexity of the problem and the level of algorithm tuning required. However, there is no anticipated cost impact to the project related to these date changes nor any delay to overall project schedule.

  Revision of delivery dates and project schedule to reflect new planned dates for:

  - Initial Leak Detection Algorithm: from 6/13/17 to 9/15/17.
  - Embedded Software Executable and Source Code: from 7/31/17 to 9/22/17.
  - Develop and Assemble Prototype: from 6/13/17 to 9/22/17.

- **Changes that have a significant impact on expenditures –**

  Nothing to report during this reporting period.

- **Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards –**

  Nothing to report during this reporting period.

- **Change of primary performance site location from that originally proposed –**

  Nothing to report during this reporting period.

SPECIAL REPORTING REQUIREMENTS

SwRI is not aware of any special reporting requirements in the award terms and conditions.

BUDGETARY INFORMATION

The cost status is provided on the next page. It identifies the baseline cost plan, actual incurred costs, and variance.

Budget Reporting Quarter	Budget Period 1								Budget Period 2							
	Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q4	
	10/1-16 - 12/31/16		1/1/17 - 3/31/17		4/1/17 - 6/30/17		7/1/17 - 9/30/17		10/1-17 - 12/31/17		1/1/18 - 3/31/18		4/1/18 - 6/30/18		7/1/18 - 9/30/18	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Budget Cost Plan																
Federal Share	$49,000	$49,000	$160,000	$209,000	$165,000	$374,000	$143,407	$517,407	$27,748	$545,155	$27,747	$572,902	$27,747	$600,649	$27,747	$628,396
Non-Federal Share	$39,345	$39,345	$39,345	$78,690	$39,345	$118,035	$39,345	$157,380	$0	$157,380	$0	$157,380	$0	$157,380	$0	$157,380
Total Planned	$88,345	$88,345	$199,345	$287,690	$204,345	$492,035	$182,752	$674,787	$27,748	$702,535	$27,747	$730,282	$27,747	$758,029	$27,747	$785,776
Actual Incurred Cost																
Federal Share	$9,846	$9,846	$128,947	$138,793	$151,515	$290,308										$290,308
Non-Federal Share	$2,461	$2,461	$32,237	$34,698	$37,879	$72,577										$72,577
Total Incurred Costs	$12,307	$12,307	$161,184	$173,491	$189,394	$362,886										$362,886
Variance																
Federal Share	$39,154	$39,154	$31,053	$70,207	$13,485	$83,692										$338,088
Non-Federal Share	$36,884	$36,884	$7,108	$43,992	$1,466	$45,458										$84,803
Total Variance	$76,038	$76,038	$38,161	$114,199	$14,951	$129,149										$422,890

The variance for Q3 is shown above. Overall project expenditures have been below the original plan, but SwRI expects to make up much of this variance during Q4.