In-line Quality Control of PEM Materials

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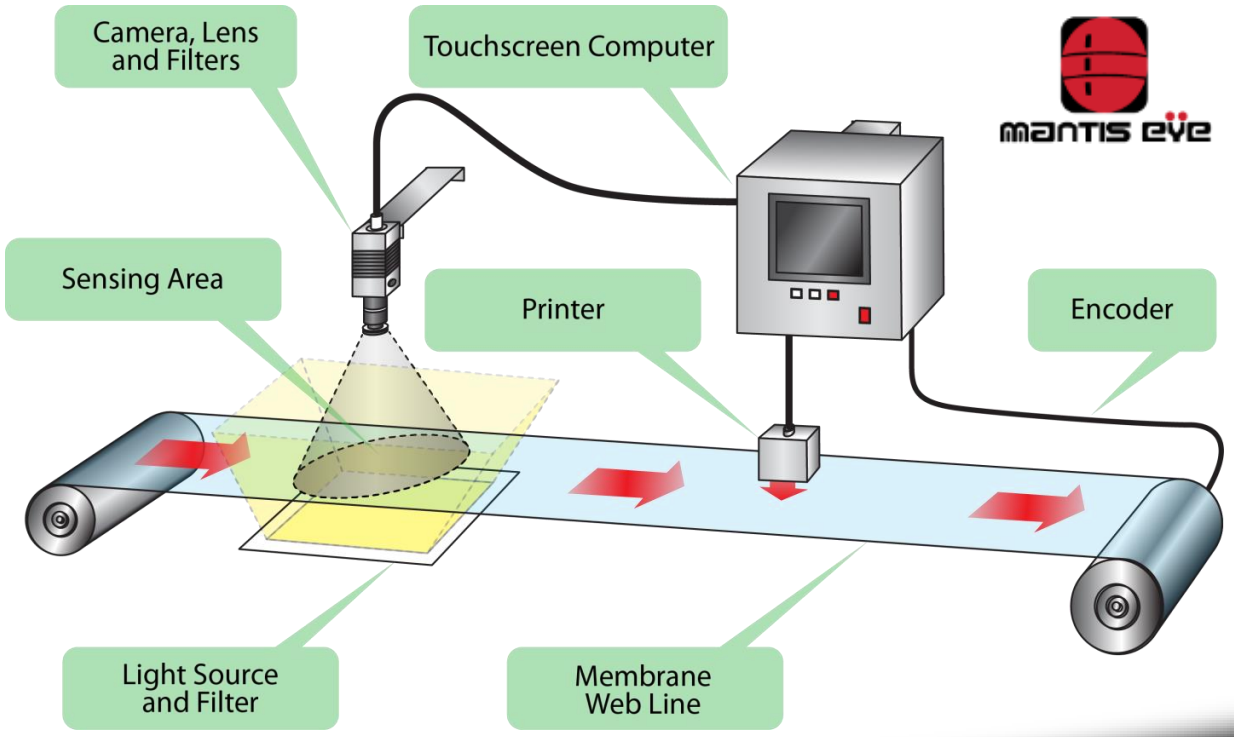
Project Goal

- **The overall goal of this program is to demonstrate, test, validate, and iterate on the production-intent Mantis Eye™ Optical Scanner to commercialize a turnkey quality control solution to reduce costs and waste throughout the entire PEM fuel cell manufacturing process including membrane, gas diffusion layers, catalyst, and assemblies**



Overview

Timeline and Budget

SBIR Phase IIC

- Project Start Date: 8/21/20
- Project End Date: 8/21/22
- Total Project Budget: $140k
  - Total DOE Share: $70k
  - Total Cost Share: $70k
  - Total DOE Funds Spent: $70k
  - Total Cost Funds Spent: $70k

Technical Targets

Phase IIC

- Deliver prototype instrument
- Operate successfully for 1 year

Barriers Addressed

- **E. Lack of Improved Methods of Final Inspection of MEAs**
- **H. Low Levels of Quality Control**

Partners

- Ionomr Innovations
  - Next generation ion exchange membrane technology

Relevance

- **DOE Objectives: Improved quality control to improve reliability and reduce automotive fuel cell stack costs to $20/kW by 2020 at 500,000 units/year**

- **DOE Manufacturing R&D Activities**
  - Develop in-line diagnostics for component quality control and validate performance in-line
  - Increasing the uniformity and repeatability of fabrication
  - Reduce labor costs and improve reproducibility by increasing automation
  - Identify cost drivers of manufacturing processes

- **Mainstream Engineering Targets**
  - Deliver prototype system and operate in the field for 1 year without issues
    - Scan the materials with 100% coverage
    - Real time automated in-line defect and thickness mapping
    - Physical defect marking and electronic logging of entire roll

In-line QC of PEM Materials

- **Mainstream is developing a suite of instruments to provide full turnkey inspection for MEA production including catalyst coated membrane and other opaque materials**
- **In previous phases, we developed and commercialized the Mantis Eye™ machine vision system for automated, continuous monitoring of films and web converting equipment**
  - Transparent and thin films for coating lines
  - Reflectance for opaque materials
  - Single uniform platform for real-time processing
- **Previously worked with NREL to determine key defect sizes and features that lead to cell failure**

Phase IIC Technical Approach

- Develop rapid prototyping capabilities to test a new material for Mantis Eye™ viability in less than one day (Complete)
- Construct and deliver a working production unit for evaluation (Complete)
- Create a training program to teach operators and end-users in a one day in-person training (Complete)
- Operate the production unit for 1 year without significant issues and receive quarterly reports on user feedback, issue identification, system performance, and any desired new features (Ongoing)
- Continue to bring in industry partners and demonstrate capabilities (Ongoing)

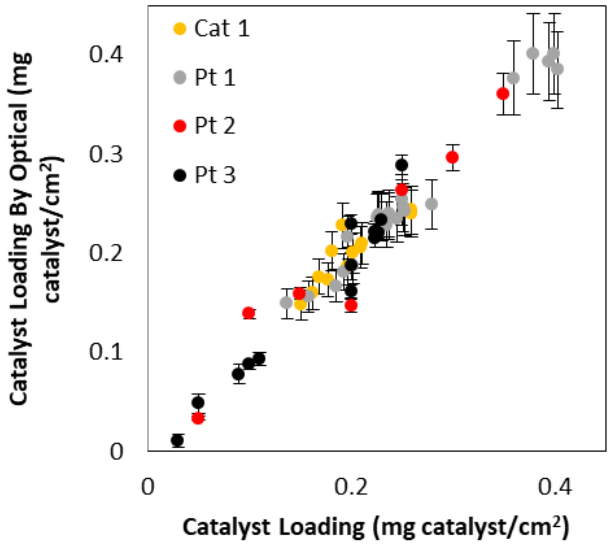
- Year 1 Milestone: Deliver system for production testing (Complete)
- Year 2 Milestone: Successful operation for one year (Ongoing)

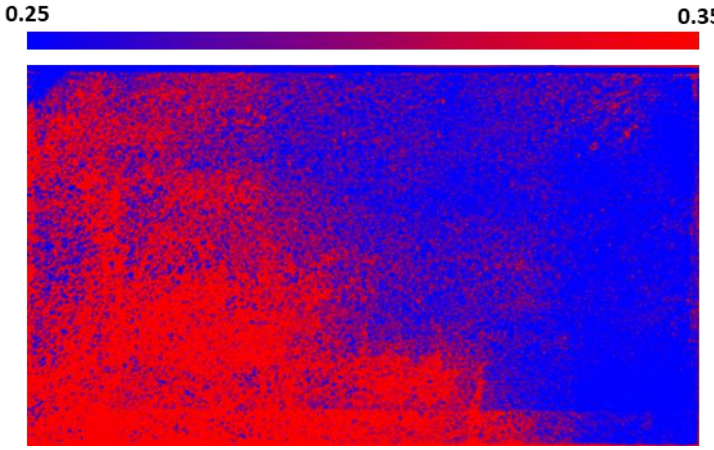
Mantis Eye™ Optical Scanner

- **Modular system can be installed in a variety of webline locations**
  - Reflectance, transmission, or both
- **Co-located industrial controller and inspection platform**
  - Real-time defect, web, and image display
  - Electronic logging of all data
- **Can be packaged with winder/rewinder**
  - Examine material on either side of the roll
  - Splice in test samples
  - Process in real-time above 30 ft/min
- **Can operate on 100 – 240 V, 50 – 60 Hz**
- **https://mainstream-engr.com/energy_and_sustainability/?mantis_eye**
- **User manual and one-day training**

Previous Results – CCMs and GDLs

- **Determined catalyst loading on gas diffusion electrodes and catalyst coated membranes based on image data**
- **Calibration depends on Pt/C %, ionomer ratio, and catalyst**
  - Can input parameters and determine loading
- **Measurements well predict loading**
- **Loading map is auto-generated based on the image and calibration**
- **Trace out edges of GDL/GDE/seal and determine dimensional measurements**
  - Linearity, gaps, distances
- **Can have loading out of range be considered defective and marked as such**
- **Expectation is uniform loading and thickness, however previous XRF and ICP tests have indicated some of the perceived variance is due to real changes**
- **System can detect changing loading, and spatially map dimensions as well as loading**





Sample Catalyst Loading (0.25-0.35 mg Pt/cm²) Using Optical Measurement Technique

Example dimensional measurements of a flat sheet with an edge detection machine vision filter

Milestones

Phase IIC Milestones (Year 2)	Results (Year 2)
Construct and deliver a working production unit for evaluation	-Delivered and installed in Q4 2021
Operate the production unit for 1 year without significant issues and receive quarterly reports on user feedback, issue identification, system performance, and any desired new features	-Ongoing

Prototype Unit – Fabrication and Installation

- Drawings were completed and parts fabricated
- Addition of light shroud for stray environmental light and reduced noise
- Prototype was constructed, shipped, and installed in manufacturer's facility
- Testing is ongoing

Mantis Eye after FAT and ready for crating

Mantis Eye installed

Real-time Automated Software - Update

- **User interface was updated to be easier to use and have improved layout with industrial kiosk**
- **All settings and operations remain**
- **Automated settings with real-time machine vision processing**
  - Raw images, processed images with features highlighted, dimensional measurements (sheets, CCMs, MEAs), electronic log of features, real-time software viewing
- **Defect Identification**
  - Aspect ratio, size, area, location, appearance
- **Defect Characterization**
  - Light, dark, combined to determine different defects and characterize them
- **Groups images to less than 50 MB for processing/viewing**
- **Saves locally, connects to intranet to export**
- **Simple csv output feature file, images saved in tiff and bmp for raw and features**
- **Remote log-in features if on internet for live help**
- **Printing on parts for defects**
- **Fully automated processing with real-time display and electronic logging on industrial kiosk interface**

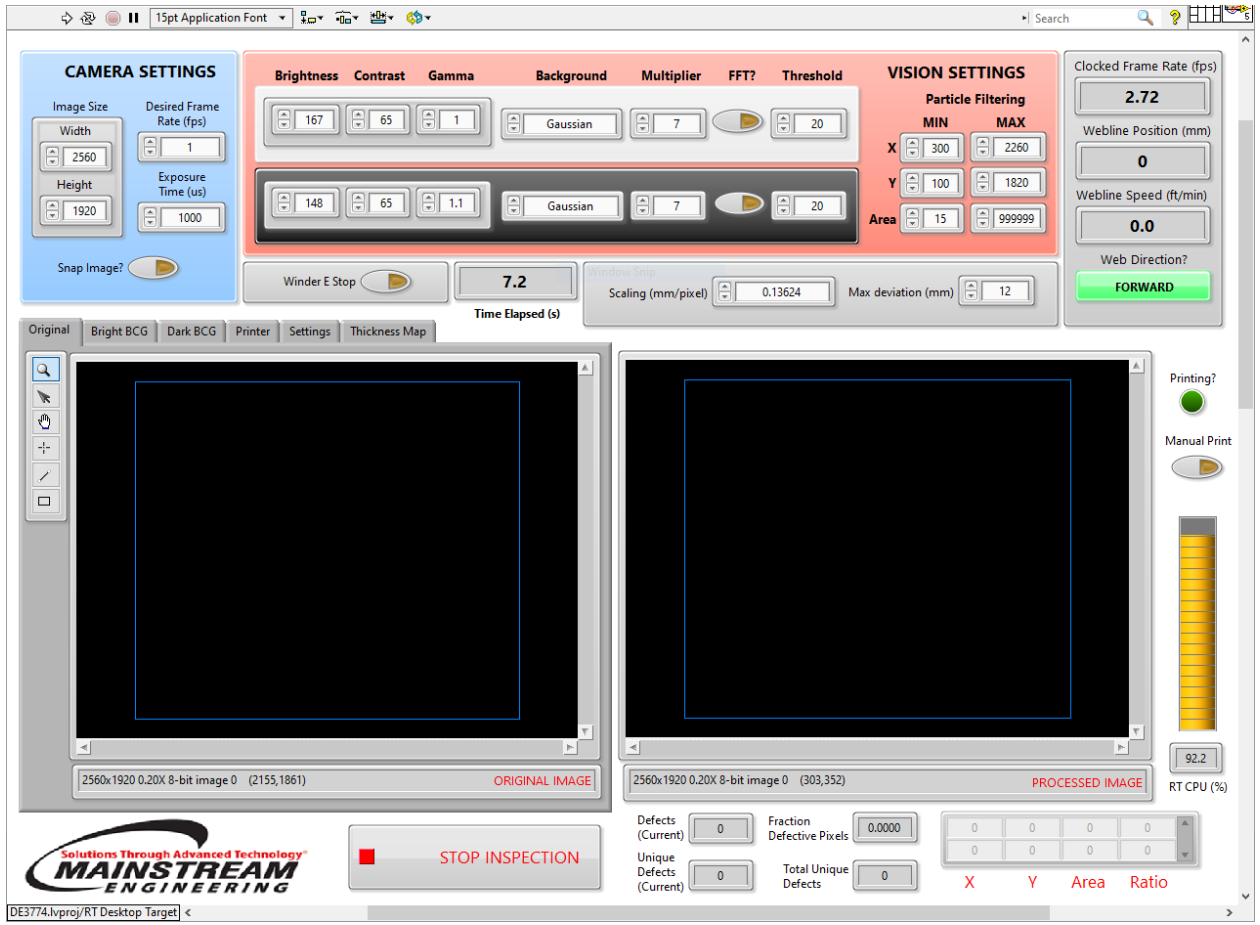


Image Number	Defect Number	X Position (pixels)	Y Position (pixels)	Area (pixels)	Aspect Ratio	Roll Position X (inches)	Roll Position Y (inches)	Defect Type
31	1	5839	2436	50	1	9.33	307.28	Pinhole
40	1	7355	3689	88	1	11.75	408.03	Pinhole

Training Development

- **Demonstrated and recorded in-person one-day training for equipment use**
- **Covered key objectives**
  - Winder operation
  - Front panel buttons
  - Real-time display
  - Vision hardware adjustment
  - Camera software settings
  - Vision software settings
  - New material setup and software adjustment
  - Logging and data storage
  - Safety

Response to Reviewer Comments

Summarized Reviewer Concerns from 2021 AMR	Response
• System should be useful for large rolls of delicate materials (e.g., GDLs with larger than 3-inch diameter rollers or 1,000 meter or longer rolls).	• Our system can be integrated onto existing weblines or other winding systems that can accommodate these materials
• The cost associated with defects and number and type of defects is not well described.	• Every manufacturer has different numbers for these and keeps them private. Different materials see different defects and our 1-day material analysis creates a basis of discussion for these points and the cost analysis.
• The team should expand the project to install equipment with a large-scale manufacturer (3M or W.L. Gore).	• We are actively looking for other large scale industrial partners and have a few possibilities that are being pursued.
• The cost of the equipment and the cost of defects needs additional attention.	• Cost for the commercialized technology is known and starts in the tens of thousands and ranges up depending on size, scale, and complexity. Earlier phases of this program examined the impact of defects.
• Other technologies may be useful and this program focuses on one specific aspect.	• Our optical technique is a platform and can incorporate reflectance, hyperspectral, thermal, or other 2-D roll-to-roll analysis. This is an area we are actively pursuing.
• Investigate alternative markets (e.g., PEM electrolyzers) and engage other DOE offices.	• Have evaluated multiple alternative materials for companies in need of improved QC and pursue funding and commercialization in other fields

Collaboration and Coordination

Institution	Type	Extent	Role and Importance
Ionomr Innovation	Industry	Major	Conduct production evaluation of Mantis Eye™ Optical Scanner

- **Ongoing discussions and evaluations with multiple industry players in the membrane, CCM, GDE, and GDL space**
- **Previous phases of the program had collaboration with NREL and Georgia Tech for defect sizes and types that induce issues in MEAs**

Remaining Challenges and Barriers

- **Remaining Objectives**
  - Continue proving unit at manufacturer's facilities
  - Integrated database to hand off parts between different stages of production for full-stop facilities

- **Key Barriers**
  - Relevant fuel cell materials with defects must be procured to develop and demonstrate the project to be relevant to manufacturers
  - **Cost of improved quality control must outweigh system cost**
  - **Manufacturers must be at scale where automated quality control outweighs man-hours**

Proposed Future Work

- **Proposed Work**
  - Demonstrate reliability of packaged system for defect detection on industrial webline
  - Validate production hardware and software in actual industrial long-term use
  - Integrate other sensors into turnkey system
- **Methods to Mitigate Risk**
  - Demonstrate prototype system for industry customers using 1-day methodology
  - Focus on reducing cost at current defect targets
  - Disseminate results and expand manufacturing partners
- **Key Milestones**
  - Prototype deployed on industry webline
  - System evaluation for one year
    - 25 μm defects in CCMs and GDL
    - Operating in real-time at 30 ft/min
    - Identifying loading and thickness to within 10%
    - 5σ false-positive and negative rate
    - Customizable and packaged turnkey prototype able to be deployed

Summary

- **Mainstream is commercializing the Mantis Eye inspection system through industry testing, rapid material demonstrations, and a dedicated website for transmission, reflectance, and combined for a full turnkey solution**
- **Prototype system was constructed, shipped, and installed in Q4 2021**
- **Real material testing is ongoing**
- **Industrial touchscreen interface with co-located quality control hardware on winder or webline**
  - Real-time automated detection
    - Defects/Features
    - Thickness in membranes
    - Loadings of catalyst on membranes and GDLs
    - Dimensions of components
    - 2-D Mapping
  - Electronic marking
  - On-sample printing
  - 100% web coverage
- **Reliability statistics and customer requirements can be used with a cost function to determine the benefit of improved quality control for each material and webline depending on hardware/software requirements, data throughput, and minimum defect size targeted**
  - Identify improvement, return on investment, cost savings

Technical Backup and Additional Information

Technology Transfer Activities

- Mainstream is using SBIR funding to validate and demonstrate the system as a turnkey product and commercialize it
- While the PEM fuel cell market is the primary focus, the Mantis Eye technology is well-suited to many types of toll coating and other polymer films and we are conducting product demonstrations with multiple companies that are interested in the system
- Mainstream has a subcontract from UConn to leverage this technology developed in the SBIR program to build and deliver a quality control system as part of a project for improved catalyst design
- Mainstream has submitted two patents on this project

Progress Towards DOE Targets

- **DOE Manufacturing R&D Activities**
  - Develop in-line diagnostics for component quality control and validate performance in-line
    - Mainstream developed the Mantis Eye for automated quality control on weblines of transparent and opaque materials as well as for examining finished components
  - Increasing the uniformity and repeatability of fabrication
    - In-line real-time quality control improved uniformity and repeatability of a process as well as provides the ability for real-time quality control and correction
  - Reduce labor costs and improve reproducibility by increasing automation
    - Fully automated systems allows drastic reduction in labor and inspection time to validate materials
  - Identify cost drivers of manufacturing processes
    - Key cost drivers include scrap rates, catalysts, and other components
    - Mainstream's process reduces scrap rates and validates uniformity of catalysts and components, reducing wasted material

Publications and Presentations

- **No new publications during this Phase IIC period**