QUARTERLY PROGRESS REPORT

March 1, 2018 – May 31, 2019

PROJECT TITLE: Detection and Separation of Recyclable Plastics from Municipal Solid Waste (Year 1)

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AFFILIATION: University of Central Florida

COMPLETION DATE: August 31, 2019 **PHONE NUMBER:** 407-823-4575

PROJECT WEB SITE: https://www.nanoscience.ucf.edu/research/hinkley-project.php

Work accomplished during this reporting period:

Task 1: Hand-Held Device Design and Integration

- A proof-of-principle design for a fieldable spectrometer, which does not require the use of a laboratory grade spectrometer, has been completed. This design utilizes a ZnSe prism to disperse reflected MIR light off the plastic samples.
- Components for this design have been procured and assembled on an optical bench. The system is currently being aligned.
- A computer workstation dedicated to this system has been connected to control the rotation stage which scans the reflected spectrum across a cooled HgCdTe detector. The output of this detector is also connected to the computer workstation via a voltage measurement device. The programming of this data acquisition and control system is underway.

Remote handheld scanner development: In our current work we are developing a stand-alone MIR spectrometer as a testbed for producing deployable solutions to plastic recycling at multiple levels. An infrared light source is reflected off a test sample and the reflected light is gathered into a small collimated beam and passed through a zinc selenide (ZnSe) prism. This prism passes light in the region from 0.6 to 16 microns and spreads this spectrum by wavelength. A rotating mirror scans this spectrum across an infrared detector, thus recording reflected energy vs. wavelength for the plastic sample. The optical system schematic is shown in Figure 1.

This design could be used to produce a fieldable prototype, but it is even more valuable as a starting point, or testbed, to investigate modifications that could be deployed in multiple fieldable implementations. Data gathered on this spectrometer can be used to investigate the specific spectral characteristics necessary for discrimination of plastic types. The following possibilities are examples of the system requirements we will investigate.

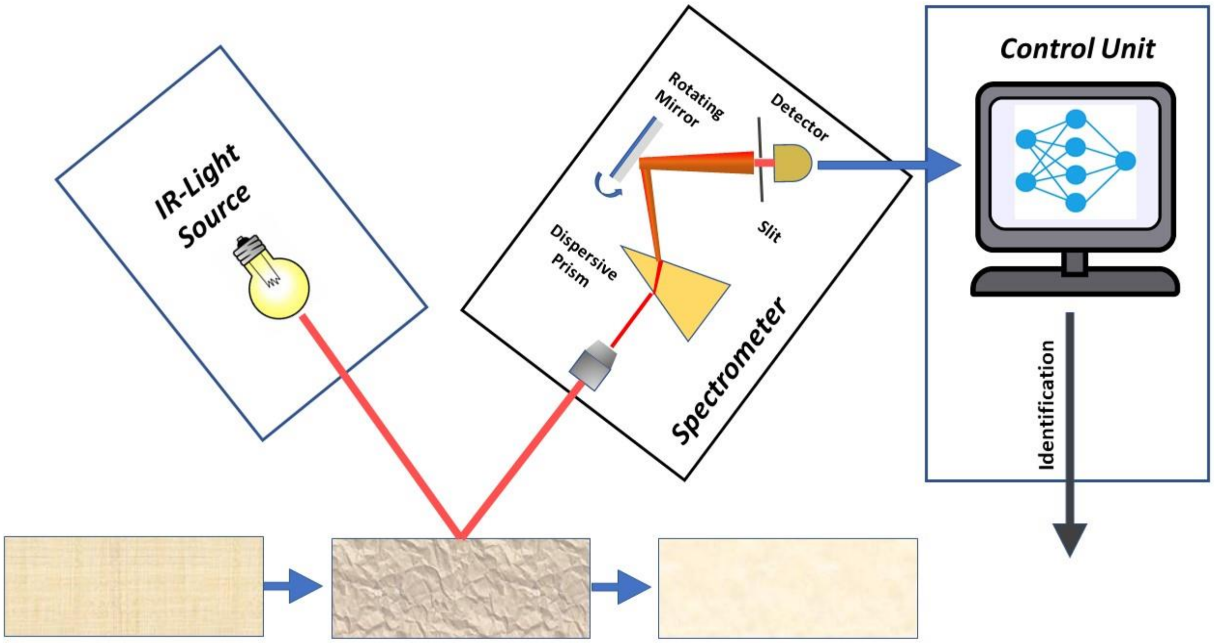

Figure 1. Schematic of the IR optical system showing the light source, the light collection and spectrometer, and the control and data processing modules.

- If the spectral region to be scanned can be limited to a single octave, that is, a factor of 2, then the prism could be replaced by a diffraction grating. Examples of possible octaves would be 3 to 6 microns, 4 to 8 microns, or 6 to 12 microns, each spanning a factor of 2 in wavelength. Use of a diffraction grating rather than a prism simplifies the ultimate design, making it smaller and easier to produce for a handheld device.
- Work last quarter indicated that 100 data points could be adequate for plastic spectral identification. If the required spectral resolution can be further reduced, to 10 points for example, slit sizes can be increased and spectral dispersion requirements can be relaxed. This would allow a design that is more compact and easier to align, with less attenuation of reflected light signal.
- It is possible that the spectral sampling can be limited to a few, say 4 or 5, specific wavelengths. If this is the case, the design could be modified to use tunable IR lasers or IR LEDs as the light source. This would yield a version of the design especially suited to be deployed to scan large volumes of plastic travelling on conveyor belts.

This spectrometer could be useful in its current configuration as a fieldable solution, but it is hoped it will point the way to even more useful implementations.

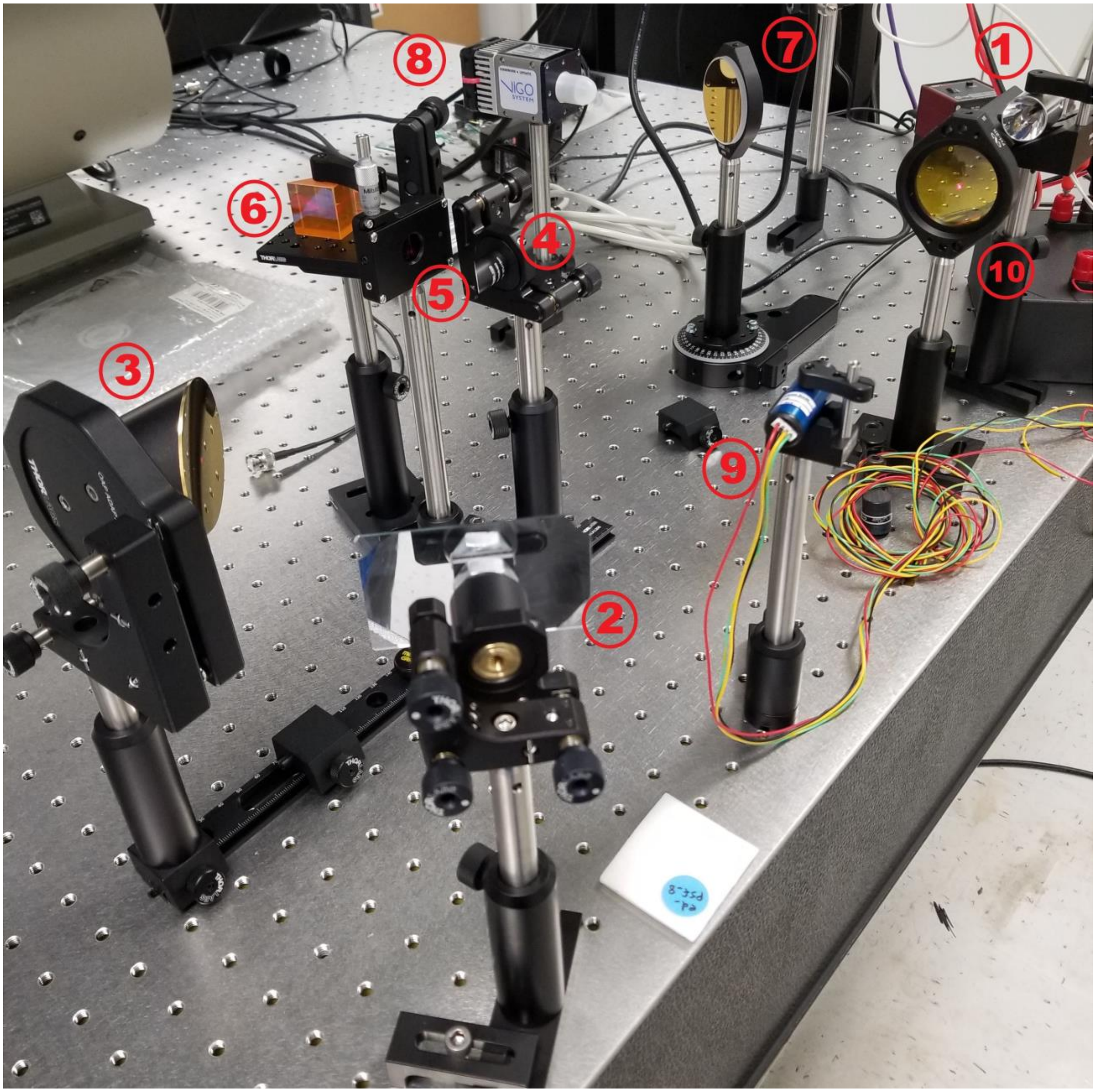

Figure 2. Layout of the miniaturized IR spectrometer system.

Figure 2 is a photograph of the current configuration of the spectrometer in the Infrared Lab at NSTC. Annotations on the figure show the components of the spectrometer. A collimated infrared light source at (1) projects broadband infrared energy towards the sample holder at (2). Currently, the sample holder is equipped with a mirror for alignment purposes. Energy reflected off the sample is gathered by an off-axis parabolic mirror at (3) which focuses the energy onto a smaller mirror at (4), concentrating the energy from a 25 mm beam to a 2 mm beam. This beam is further restricted by an adjustable slit at (5), then the narrow beam passes through the prism at (6), where it is spread in spectrum. This spread spectrum is scanned across the detector at (8) by the rotating mirror at (7). Alignment is made difficult by the fact that the energy transported through the apparatus is invisible. To alleviate this problem, a red laser at (9) is reflected off the

ZnSe beamsplitter at (10) so as to be coaxial with the infrared light source's beam. The laser beam can then be aligned through the apparatus, aligning the path of the infrared energy as well.

Task 2: Sample Collection and Characterization

- The team has partnered with UCF Recycles program in order to collect a statistically relevant plastic sample population.
- In this quarter, the number of samples in the spectral library has been expanded from 127 to 259, with approximately 10 new samples being added weekly. Many of these new samples are contaminated in various ways and are being scanned both with contaminants intact and after cleaning. So far, it appears that normal contamination levels do not interfere significantly with MIR spectra. Samples gathered this year are generally larger than those gathered in the initial year to conform more closely to real world conditions, scanning larger areas as opposed to using a microscope objective for gathering data.

Task 3: Optimization of the Identification Algorithm

- Neural networks trained on the sparse spectral data available last quarter gave encouraging results, but further development of these algorithms requires a more robust set of samples. Spectral features used are focused on compatibility with both the lab spectrometer and the proposed fieldable device. Further work on this task was postponed until the fourth quarter, when this enhanced data set will be available.

Artificial intelligence based spectral fingerprint search: Initial stages of this investigation simply matched the spectral features found in the reflectance spectra with those stored in the multi-resonance library. To automate the identification with a large library of diverse spectra, however, as the library expands, especially when considering polymer resin blends or fillers, necessitates the use of computer pattern recognition techniques. Classification tools based on neural networks, the multilayer perceptron for example, have proven to be useful for numerous similar problems.

The first step in the approach for automating classification with machine learning was to reduce the dimensionality of the input. The spectral signature produced by the spectrometer consists of 3271 data points of reflectance vs. wavenumber. As a first simple attempt at data reduction, we averaged the reflectance over 100 equally-spaced consecutive wavelength intervals. Figure 5 displays the raw spectral signature of PVC, while Figure 6 shows the result of this wavelength averaging process on the PVC spectral signature. This process reduced the spectral resolution from 3271 data points to 100 points.

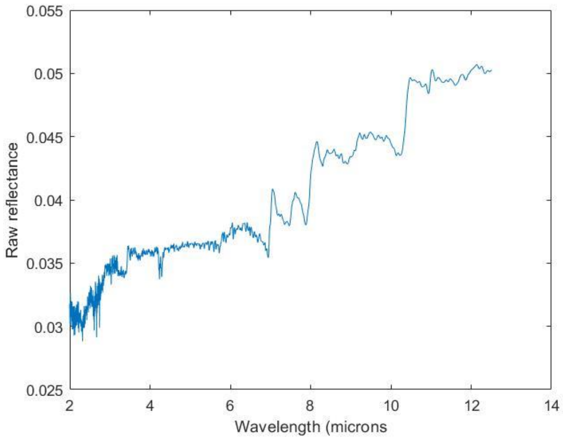

Figure 3. Raw spectrometer data (3271 points)

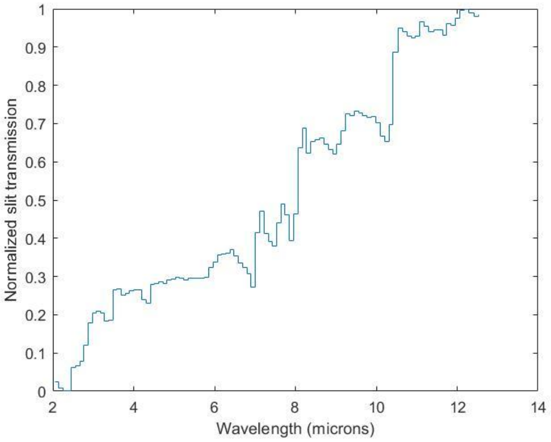

Figure 4. Wavelength average data (100 points)

These 100-point signatures were used as inputs for a multi-layer perceptron neural network with a single hidden layer. This neural network was trained on 2 scans of 5-6 samples of 7 different plastics to produce the results shown in confusion matrix form in Figure 7. In the network training confusion matrix, the labels along the top row indicate the actual ground truth category of plastic for that column, while the labels in the left column show the classification assigned by the neural network. Therefore, the diagonal elements show the number of samples correctly identified by the neural network, while off-diagonal elements show classification errors. For example, the box containing the number 2 shows the neural network incorrectly classified 2 samples of HDPE as LDPE, an understandable error as both are forms of polyethylene.

It is important to note that the confusion matrix shown is an accumulation of training, cross-validation, and test results, as the number of available signatures is small. This is therefore an optimistic prediction as data used in training the neural network was also used in testing it. This situation will be remedied as the project progresses and the spectral signature library grows. Neural network performance generally improves with a larger number of training samples, so these early results are encouraging.

	Acetyl	**HDPE**	**LDPE**	**PET**	**PP**	**PS**	**PVC**
Acetyl	12	0	0	0	0	0	0
HDPE	0	9	1	0	0	0	0
LDPE	0	2	10	0	1	0	0
PET	0	1	0	12	0	0	0
PP	0	0	1	0	11	0	0
PS	0	0	0	0	0	12	0
PVC	0	0	0	0	0	0	10

Figure 5. Neural network training confusion matrix for various randomly selected plastics.

Work to be completed next quarter

- Align and test the proposed prism spectrometer, including interfacing with the data acquisition and control workstation (Task 1).
- Continue to expand the plastic spectral library (Task 2).
- Analyze data and implement neural network and other classification algorithms (Task 2 & 3).

Metrics:

1. List graduate or postdoctoral researchers who were funded by this Hinkley Center project.

Name	Rank	Department	Professor	Institution
Pablo Manuel Cencillo Abad	Postdoctoral Researcher	NanoScience Technology Center	Debashis Chanda	University of Central Florida

2. List undergraduate students who worked on this Hinkley Center project.

Name	Rank	Department	Professor	Institution
Ed DeRouin	Undergraduate Student	Physics	Debashis Chanda	University of Central Florida
Juan Perilla	Undergraduate Student	Mechanical Engineering	Debashis Chanda	University of Central Florida

3. List research publications resulting from this Hinkley Center project.
   Ans: Under preparation.

4. List research presentations resulting from this Hinkley Center project.
   Ans: The research has been presented as invited talks at University of Antioquia, Colombia in March and June, 2019.

5. List who has referenced or cited your publications from this project?
   N/A

6. How have the research results from this Hinkley Center project been leveraged to secure additional research funding?
   Ans: We submitted the full proposal based on the preliminary work funded by Hinkley Center to EREF.

7. What new collaborations were initiated based on this Hinkley Center project?
   Ans: Based on the same detection technique, we are helping University of Antioquia, Colombia to establish a coffee and avocado quality assessment process.

8. How have the results from this Hinkley Center funded project been used (not will be used) by the FDEP or other stakeholders?

   - None to date