Detection and Separation of Recyclable Plastics from Municipal Solid Waste

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Final Report

PROJECT TITLE: Detection and Separation of Recyclable Plastics from Municipal Solid Waste

PRINCIPAL INVESTIGATOR: Debashis Chanda, PhD

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

PROJECT DURATION: December 1, 2019 – April 30, 2021

ABSTRACT:

The proposed project aims to construct a prototype of polymer resin identification system based on mid-infrared (MIR) reflection spectroscopy. The MIR reflectance spectrum contains the chemical information of the material. This fingerprint, in contrast to the popular near-infrared (NIR) spectroscopy, contains much more molecular vibrational resonance information, which we will use to construct a multi-spectral and multi-dimensional library of all plastics commonly encountered in the municipal solid waste stream. The main component of the system is the spectroscopic optical reading system. With this element, the MIR reflection spectrum is measured to retrieve the chemical information of the sample. This important component must be carefully designed to ensure the acquisition of a high signal to noise ratio needed to accurately identify plastics under field-type working conditions. We will design and customize a commercial MIR spectrometer and a high power IR source to integrate them into a hand-held unit. Once the first prototype version is built, characterization experiments will be performed to evaluate and optimize the system performance in several aspects including its fidelity of the measured optical and detection algorithm. The objectives of the research are to: Objective #1: Adapt the laboratory setup to a field compatible configuration, Objective #2: Collect a statistically relevant set of plastic samples with associated MIR scans, and Objective #3: Optimize the detection algorithm to minimize the detection uncertainties.

Key words:

Infrared spectroscopy, Plastic recycling, Sorting.

METRICS REPORTING

Student Researchers:

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Metrics:

1. List research publications resulting from **THIS** Hinkley Center project.
   Under preparation.

2. List research presentations resulting from **THIS** Hinkley Center project.

   The research has been presented as invited talks at University of Antioquia, Colombia in March and June, 2019.

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

4. How have the research results from **THIS** Hinkley Center project been leveraged to secure additional research funding? What grant applications have you submitted or are planning on submitting?

   We submitted the full proposal based on the preliminary work funded by Hinkley Center to EREF.

5. What new collaborations were initiated based on **THIS** Hinkley Center project?

   Based on the same detection technique, we are helping University of Antioquia, Colombia to establish a coffee and avocado quality assessment process

6. 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.

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  We gratefully acknowledge the funding from the Hinkley center. We thank TAG members for providing valuable input and suggestions. We thank UCF recycling center for providing us with wide range of plastic samples.

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Executive summary

The proposed project aims to construct a prototype of polymer resin identification system based on mid-infrared (MIR) reflection spectroscopy. The MIR reflectance spectrum contains the chemical information of the material. This fingerprint, in contrast to the popular near-infrared (NIR) spectroscopy, contains much more molecular vibrational resonance information, which we will use to construct a multi-spectral and multi-dimensional library of all plastics commonly encountered in the municipal solid waste stream. The main component of the system is the spectroscopic optical reading system. With this element, the MIR reflection spectrum is measured to retrieve the chemical information of the sample. This important component must be carefully designed to ensure the acquisition of a high signal to noise ratio needed to accurately identify plastics under field-type working conditions. We designed and customized a commercial MIR spectrometer and a high power IR source to integrate them into a hand-held unit. Once the first prototype version is built, characterization experiments will be performed to evaluate and optimize the system performance in several aspects including its fidelity of the measured optical and detection algorithm. The objectives of the research are to: Objective #1: Adapt the laboratory setup to a field compatible configuration, and Objective #2: Collect a statistically relevant set of plastic samples with associated MIR scans, and Objective #3: Optimize the plastic identification algorithm to minimize the detection uncertainties.

Introduction

The US EPA estimated that among 258 million tons of municipal solid waste (MSW) generated in 2014; plastic accounted for about 33 million tons. Worldwide plastics represent 35% of MSW. Despite a focused effort on diverting plastics from the waste stream, recycling rates in the US for PET bottles are 31.3% and for HDPE, 28.2%. The additional 14 plastic types commonly found in MSW are recovered and recycled at much lower rates. Recovery and recycling of plastics is important because plastic waste is generated at high rates (mostly from single-use objects), it relies largely on a nonrenewable material for production, it has high energy content, and, if placed in a landfill or improperly disposed of, plastic will resist degradation for centuries. Communities are providing more opportunities to separate plastics and appropriately dispose of them to increase recovery and recycling efficiency. These typically rely on the consumer to make correct decisions regarding disposal. The ability to more efficiently identify and communicate the resin used to produce the plastic object will ensure maximum accuracy in disposing of waste materials whether it is at the curb, at a receptacle in shopping centers, institutions, or business, or while separating materials in a materials recovery facility.

Results and Methods

Task 1: Infrared spectrometer device prototype

- The optical benchtop setup from last year was modified and multiple iterations were performed to optimize the alignment of the collected signal as well as the signal-to-noise ratio at the detector.
- The workstation software was developed to automate the process of scanning the movable mirror while simultaneously measuring the detector signal at different

wavelength parameters. The software allows interactive control of parameters without modifying the code.

Remote handheld scanner development: This year we developed 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.

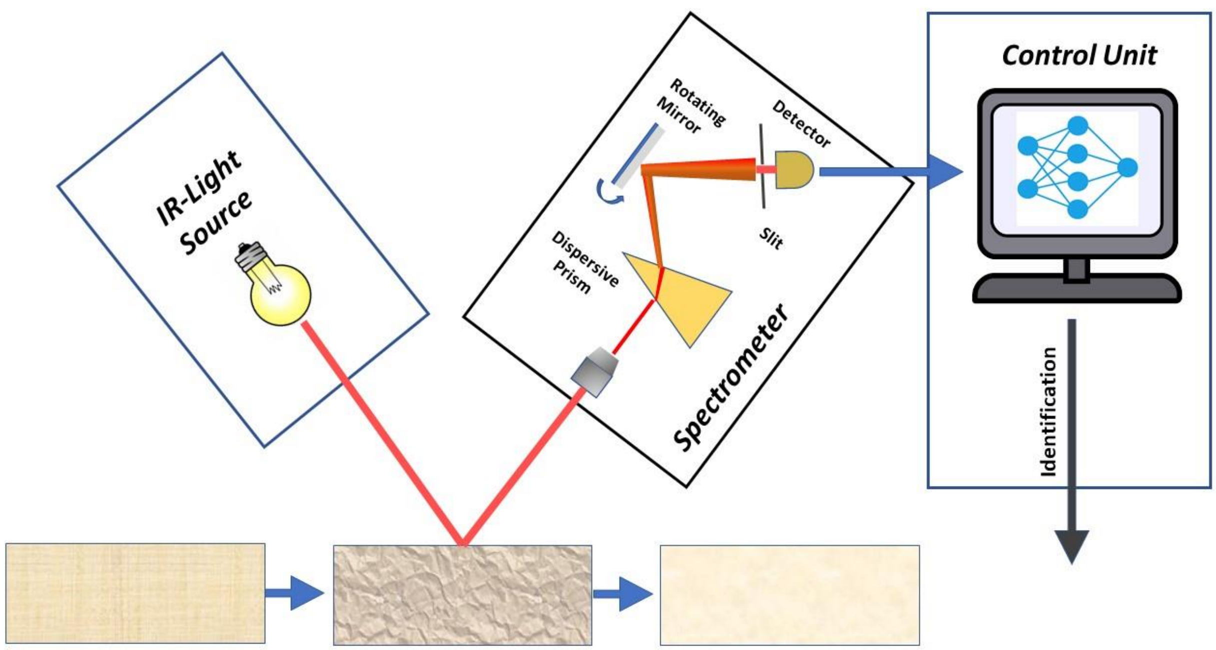

Figure 1. Schematic of the IR optical system showing the light source, the light collection and spectrometer, and the control and data processing modules.

- 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 year 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.

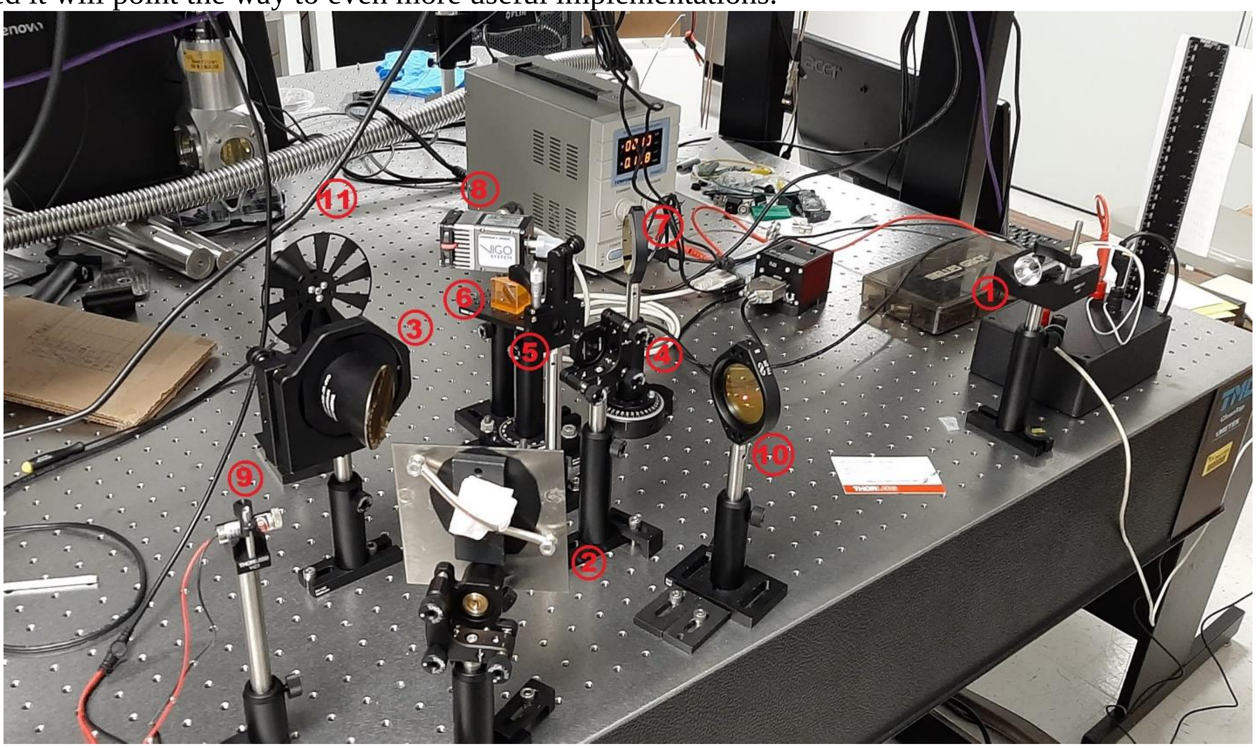

Figure 2. Layout of the miniaturized IR spectrometer system

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) passes through an IR-transparent ZnSe window at (10) and projects broadband infrared energy towards the sample holder at (2). 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 motorized 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 visible red laser at (9) is reflected off the ZnSe window 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. A chopper wheel, shown at (11), is placed between the two off-axis parabolic mirrors, near their common focal points. This addition was necessary as the infrared energy reaching the detector is too small to be measurable. The signal modified by the chopper gives a 100 to 1000 times improvement in detection. With the use of a lock-in amplifier, the signal dispersed by the prism is now measurable.

The sample mount, labeled (2) in Figure 2, was replaced with a more stable custom-made stainless-steel plate to provide more repeatable positioning from sample to sample. The previous mount was simple to build and use but required too much re-alignment between samples.

Last year we discussed the problem that total internal reflection at 0.65-micron wavelength does not allow the red laser alignment beam to get past the prism. Calculations showed that a laser with a wavelength of 0.66 microns or greater would not have this problem and could be refracted through the prism. A new alignment laser emitting at 0.67 microns was procured and placed in the apparatus. This improvement allows the beam exiting the prism to provide a reference for determining the absolute wavelength value for any angle of the rotating mirror.

Task 2: Sample Collection

- The team continues its partnership with UCF Recycles program in order to collect a statistically relevant plastic sample population.
- Most of the effort in this quarter has focused on improving the spectrometer design and operation, hence the effort in processing new samples has been reduced. New samples continue to be gathered but await processing until they are needed.
- Particularly since March, efforts of collecting new samples for library measurements have been challenging due to the ongoing COVID pandemic resulting in new restrictions and regulations. Focus has been diverted to optimize the optical setup and train the neural identification program.

Figure 3 shows a sampling of some soiled plastic samples that have been scanned into the plastic signature library. The FTIR MIR spectrometer focuses IR energy down to a small point and gathers the reflected energy. Of course, when the small spot focuses on a thick piece of contaminant, very little energy is reflected. However, when focused on a less severely soiled area, the generally unaffected plastic signature is reflected. The testbed spectrometer reflects IR energy over a broad area of the sample (> 6cm^2) and should be robust to sample contamination.

Figure 3. Examples of contaminated plastic samples.

Task 3: Optimization of the Identification Algorithm

- Neural networks trained on the sparse spectral data available in Year 1 gave encouraging results, but this year's effort was planned to identify plastics based on the output of the test bench spectrometer. The restrictions imposed by the Covid-19 pandemic prevented this from being accomplished.
- The Center for Research in Computer Vision (CRCV) has been engaged to provide expert neural network development with the possible use of deep learning for plastic identification using this new data when it becomes available. This group has been provided with data from Year 1 so that they may become familiar with the project and they await the new scans to be provided.

Artificial intelligence based spectral fingerprint search:

In Year 1, 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 4 displays the raw spectral signature of PVC, while Figure 5 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.

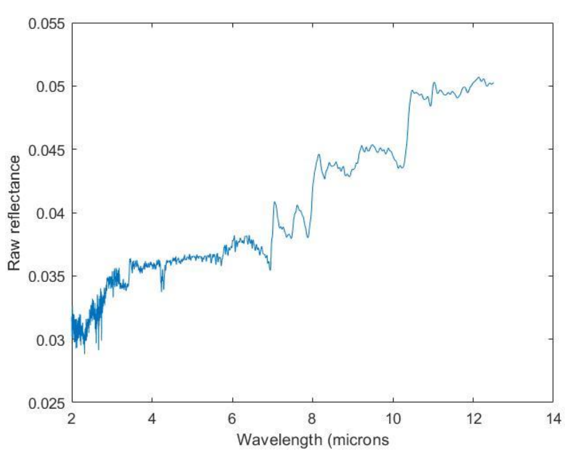

Figure 4. Raw spectrometer data (3271 points)

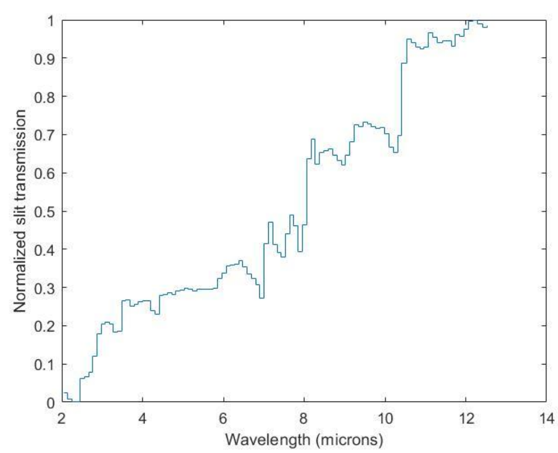

Figure 5. Wavelength average data (100 points)

When new data becomes available, the simulated data will be replaced with actual scans produced by the spectrometer. It is anticipated that the scans will have significantly lower resolution than that shown in Figure 5 and will appear to be much "blurrier". Perhaps the equivalent of a 20-point signature will be achieved.

Key Conclusions

- Despite the problems introduced by the pandemic, progress was made in maturing the spectrometer apparatus and its control and data acquisition software.
- The Al based spectrometer was built, tested and used for preliminary plastic identifications.

Future work

- Gather data scans from the AI spectrometer and provide them to our collaborators in UCF computer vision center (CRCV). Seek for improvements that may be made to increase signal-to-noise ratio strength at the detector and/or make the apparatus more compact and easier to align.
- Continue to expand the plastic spectral library and improve its quality. Investigate the value and feasibility of adding other plastic types to library.
- Analyze data and improve neural network and other classification algorithms. A particular approach of interest would be to train one network to discriminate a combined PE category containing both PE species, and use a second neural net trained with only two categories, HDPE and LDPE. This divide-and-conquer approach, illustrated in figure 10, could produce much better overall performance.

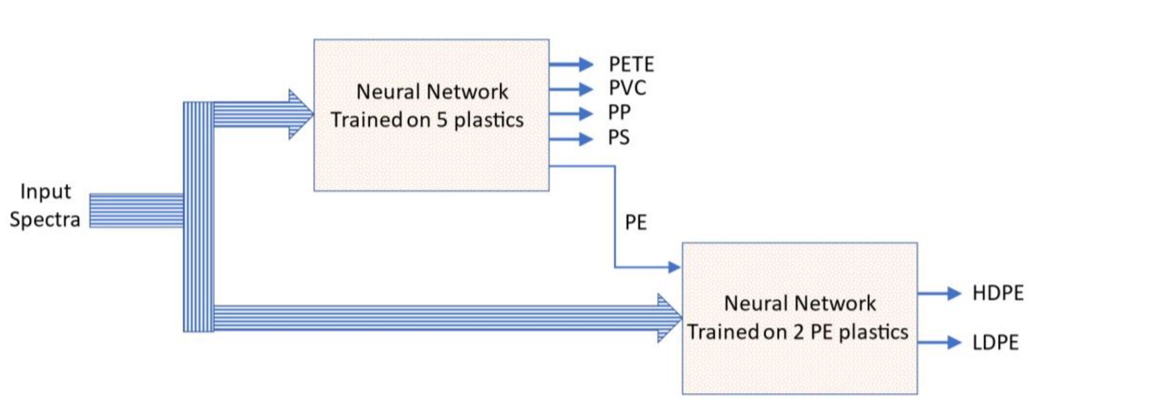

Figure 10. Neural network system employing a specialty neural network to discriminate between similar plastics types.

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