CAAP Quarterly Report

Date of Report: *December 31, 2020*

Contract Number: 693JK31950005CAAP

Prepared for: *USDOT Pipeline and Hazardous Materials Safety Administration (PHMSA)*

Project Title: *An Unmanned Aerial System of Visible Light, Infrared and Hyperspectral Cameras with Novel Signal Processing and Data Analytics*

Prepared by: *Missouri University of Science and Technology (Missouri S&T)*

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For quarterly period ending: *December 31, 2020*

Business and Activity Section

(a) General Commitments – Dr. Genda Chen directed the entire project and coordinated various project activities.

Dr. Bo Shang, a post doc at Missouri S&T, joined the research team in February of 2020. Dr. Shang is responsible for the hardware and software integration of visible light, infrared and hyperspectral cameras and associated validation tests under Dr. Chen's supervision. Mr. Pengfei Ma, a Ph.D. student in civil engineering at Missouri S&T, was on board since November 15, 2019. Mr. Ma is responsible for the laboratory and field tests of an integrated system of visible light, infrared and hyperspectral cameras and for image analysis under Dr. Chen and Shang's supervision. Mr. Jiao Pu, another Ph.D. student in civil engineering at Missouri S&T, was on board since October 1, 2019. As needed, Mr. Pu is responsible for the finite element model of an unmanned aerial system with cameras.

(b) Status Update of Past Quarter Activities – Detailed updates are provided below by task.

This project aims to:

1. Develop and integrate a robust and stable, semi- or fully-automated UAS with multiple sensors for multi-purpose pipeline safety data collection,
2. Explore and develop novel signal and image processing techniques for data analytics, damage assessment, and condition classification, and
3. Evaluate and validate field performance of the integrated UAS for pipeline safety inspection.

These objectives will be achieved through analytical, numerical, and experimental investigations in three tasks:

1 To design and prototype the UAS for the collection of cohesive types of images from visible light, infrared, and hyperspectral cameras, and demonstrate the potential of the collected images for the evaluation of ground conditions and pipeline risks for decision makers;

2 To develop and validate one-dimensional (1D) spectral analysis at each pixel of a hyperspectral image, two-dimensional (2D) image classification of changes, spatial analysis of a hyperspectral image and its fusion with other images for increased probability of detection, and three-dimensional (3D) object establishment for volume estimates; and

3 To develop a physically-interpretable, deep learning neural network for the selection of images (frames) with regions of interest from long hours of video footage, recorded as the unmanned vehicle flies along a pipeline, and demonstrate in field conditions the UAS performance in the assessment of pipeline and surrounding conditions, population-impacted changes, above-ground

objects, accident responses, and mapping system accuracy.

Task 1. To design and prototype the UAS for the collection of cohesive types of images from visible light, infrared, and hyperspectral cameras, and demonstrate the potential of the collected images for the evaluation of ground conditions and pipeline risks for decision makers

1a Quantitative analysis of drone stability

Drone flight stability is critical to data quality, we noticed that our test quadrotor is flying better outside than in our drone net. Therefore, we investigated the flight log to get some quantitative analysis of drone stability. Our quadrotor is based on the ArduPilot project, therefore, it has many kinds of log files. After the drone arms, it produces a bin log file in the microSD card in autopilot. The ground control station software Mission Planner produces telemetry log (tlog) and raw log (rlog). We used a software called MAVProxy to connect a tracking camera and a drone control script to autopilot, therefore, MAVProxy also produces “tlog” files. "tlog” files need to be converted to a format that is easier to be analyzed. **Fig. 1** shows that we can use Mission Planner to convert tlog files to three formats: TXT, CSV and MATLAB. Also, we can use a function in pymavlink to convert tlog files to two formats: CSV and JSON.

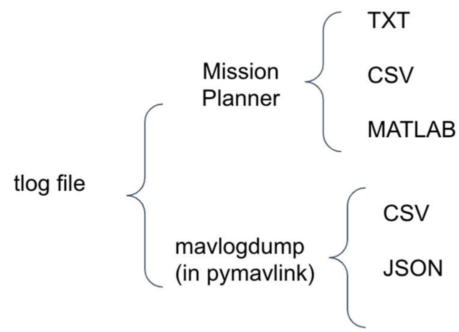


Fig. 1 Converting flight log files

In order to find the time interval that is appropriate for evaluation, we use a web-based tool called UAV log viewer (https://plot.ardupilot.org/#/). **Fig. 2** shows that the appropriate time interval for stability analysis is from 50 m 50 s to 51 m 30 s.

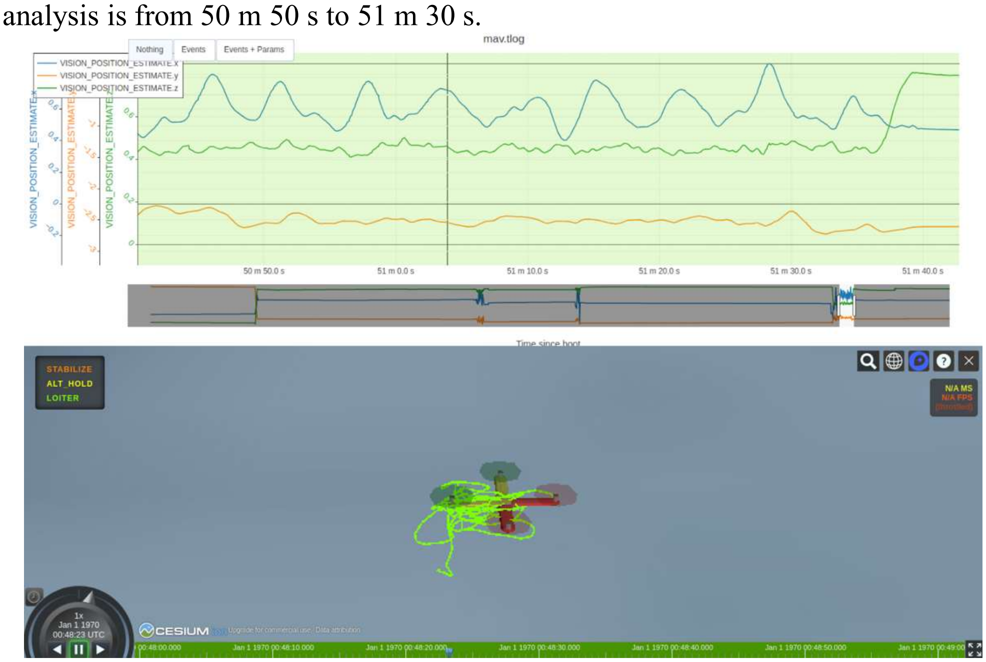


Fig. 2 Using UAV log viewer to find an interested time interval

Fig. 3 compares the position fluctuation (in meter) of drones when flying indoor and outdoor. An indoor flight resulted in a significantly more severe fluctuation than an outdoor door. Then we tried different ways to improve the indoor flight stability, including flight without the drone net, flight heading different directions, and increase of visual features. None of these methods seem working. So the reason for poorer indoor stability is that our drone size is too large to fly in the small room.

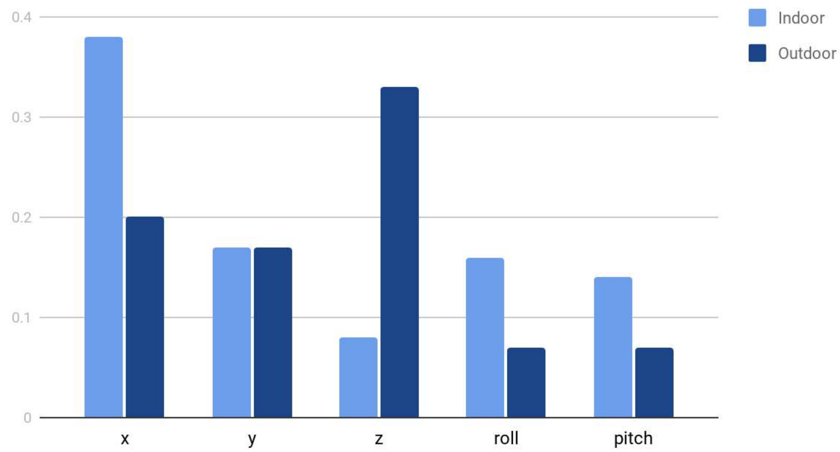


Fig. 3 Comparing indoor with outdoor flight stability using the fluctuation of drone position in each degree of freedom

1b Development of a large drone net

To improve the flight stability of indoor tests, we built a large drone net in HyPoint facility. **Fig. 4** shows the large drone net we built. Flight tests show that the drone can fly more stable in this large drone net than the previous small drone net.

Fig. 4 A large drone net in HyPoint facility

Task 2. Develop and validate 1D spectral analysis at each pixel of a hyperspectral image, 2D image classification of changes, spatial analysis of a hyperspectral image and its fusion with others for increased probability of detection, and 3D object establishment for volume estimates.

Task 2 can be divided into four sections: 1D spectral analysis of pixels from hyperspectral images, 2D image classification, spatial analysis of hyperspectral images for fusion, and 3D object establishment for estimation of the leakage volume.

Progress has been made in terms of one-dimensional (1D) spectral analysis at each pixel. 1D analysis includes three aspects. The original reflectance response spectrum is cleansed with wavelet transformation (WT) because WT can provide different levels of decomposition and prevent any overfitting, and provide approximate continuous functions for differentiation as a way for detecting abnormality. Interpolation in hyperspectral data is needed due to the low spectral resolution of Headwall hyperspectral camera, which is 3 nm in visible spectrum (VI) and near infrared (NIR) spectrum, and 6 nm in short wave infrared (SWIR) region. Cleansed 1D spectra promote further 2D hyperspectral image analysis and data fusion.

2a 1D analysis – cleansing

The spectral data cube yielded from the hyperspectral camera incorporates ambience influences. Cleaning is needed before any further analysis. WT technique was introduced to decompose the original data and then reconstruct the signal at a particular level by reducing the noise. Specifically, 'sym3' is the wavelet utilized to maintain a balance between wavebands and frequency. Besides, the symmetric property of 'sym3' greatly ease the phase distortion problem. As **Fig. 5**(a) shows, the original spectrum is significantly smoothed in the range of 400 nm – 500 nm and in the NIR region. The first order derivative (FOD) of the spectrum, termed as slope, also indicated the performance of the cleansing.

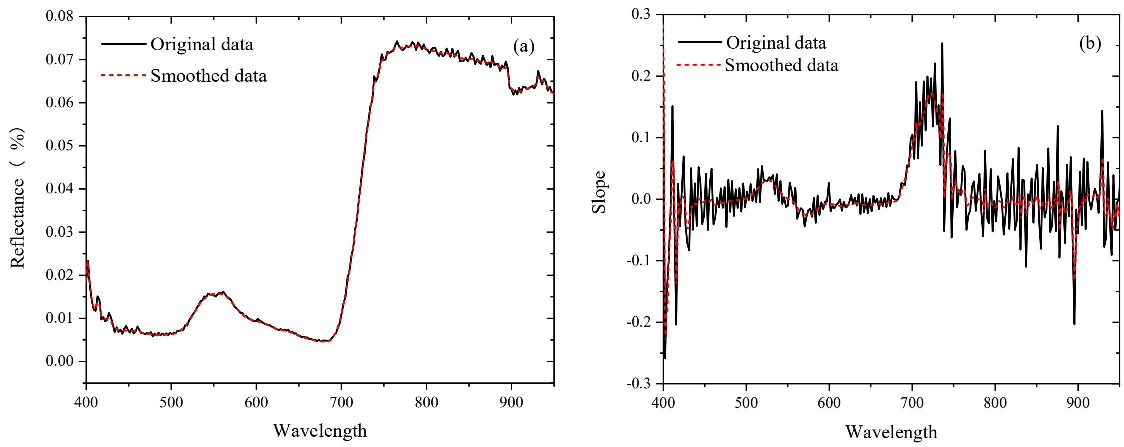


Fig. 5 Comparing original with smoothed data: (a) spectrum and (b) first-order derivative

2b 1D analysis – interpolation

The low spectral resolution of Headwall camera does not allow the detection of subtle shifts in the FOD of spectrum. Thus, it is imperative to interpolate the spectrum to allow differentiation. The interpolation is usually mathematically conducted. The math method is opted out for the reflectance at a band that has a complex physical basis. In this study, we used a MATLAB or IDL (interactive data language) platform calling for the integrated *spectral data analysis* module from ENVI software, which is especially developed to process remote sensing data and interpolate the smoothed spectrum. The apparent resolution can be increased from 6 nm to 1 nm.

2c 1D analysis – band selection

Band selection is the premise to construct indices. The detection in this context is highly dependent on the indices derived from the band combination in all three spectral regions (VI, NIR, and SWIR). There are quite many developed indices in the literature, some of which have already proved efficient. However, any single index cannot guarantee a reliable detection. To achieve a robust and efficient detection, band selection is a priority in order to develop more indices.

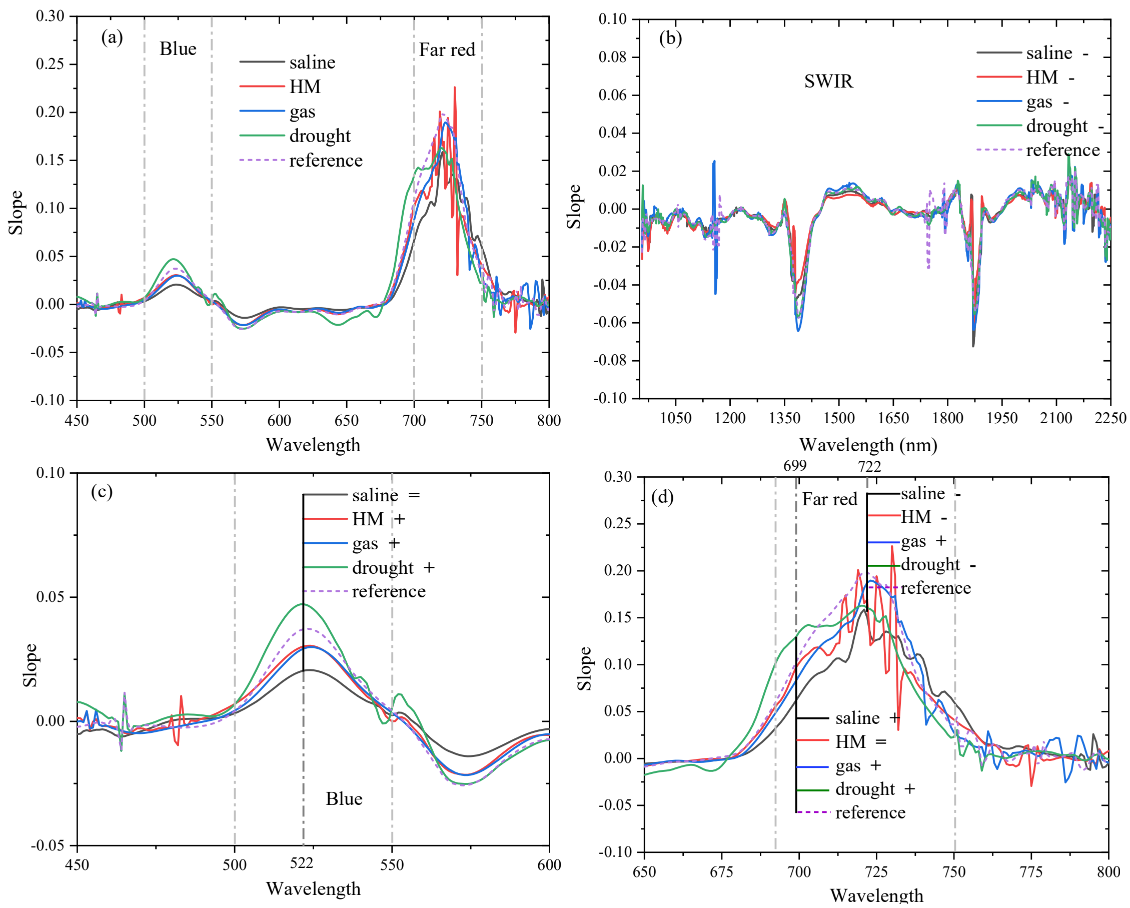
2d spectral indices

Spectral indices are used to reflect any changes in vegetation surfaces and then identify what account for the changes. The changes are associated with the composition of the component on leaf surfaces.

Each stressor (salinity, heavy metal environment, gas leakage, and water deficit) yields different component changes since the vegetation responds to treatments differently. Besides, the compound change of some stressors might share similarity. Salinity and water deficit both work as osmatic stressors and the turgor which regulates cell transportation of carbon dioxide will accumulated under the salinity and drought circumstances. The similarity creates a challenge in detection of abnormality because of the overlapped characteristics of the two stressors. To overcome this challenge, spectral indices are introduced at three different levels: single band, combined band, and global reflectance magnitude.

1. Single-band indices

   Single-band indices are biochemically and biophysically dependent. A particular substance change like chlorophyll pigment proves efficient and reliable; it causes a displacement at a band or multipoint displacements at bands in a reflectance spectrum. In this study, four single-band indices are displayed in the disparity of treatments (salinity, heavy metal or HM, gas, drought), which can be categorized into the shifts of bands. Shifts are identified in blue light region, far red region, and SWIR as illustrated in **Fig. 6** in the case of Karl Foerster reed grass. In **Fig. 6**, the mark after a legend indicates its corresponding direction of the shift: '=' for no shift, '+' for a rightward shift, and '-' for a leftward shift. Figs. 6(a, b) show the reflectance spectra in visible and near infrared (VNIR) wavelength range, and short wavelength infrared (SWIR) range. Under all four treatments, the blue band, 522 nm, shifts rightward except the case in presence of salinity as shown in **Fig. 6**(c). As shown in **Fig. 6**(d), there are two conspicuous band shifts in the red edge region. The commonly used red edge position (REP) which is located by the maximum FOD peak at band 722 nm shifts to a shorter wavelength. The secondary peak at 699 nm has a reverse shift in contrast to the REP shift. As shown in **Fig. 6**(e), there is also a newly detected shift in SWIR at band 1389 nm. The valley at band 1389 nm downshifts for all four scenarios.



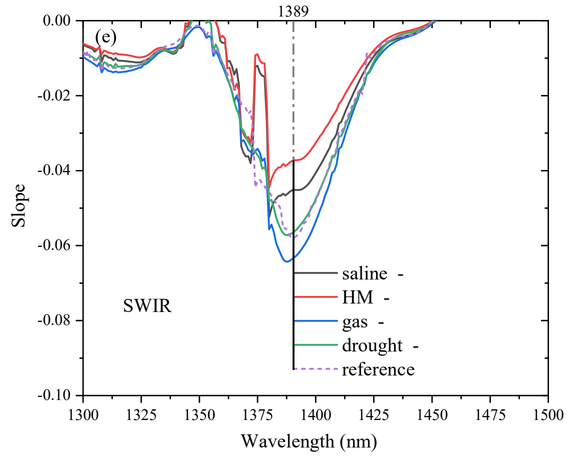


Fig. 6 Effect of four stressors on the Karl Foerster reed grass: FOD of smoothed reflectance spectra in (a) VNIR and (b) SWIR, and shifts in: (c) blue band, (d) far red band, and (e) SWIR band

2. Combined band indices

   Combined band indices are much more robust and widely used because they integrate reflectance at many bands simultaneously. Combination of bands also faces the same challenges as single-band indices. Such indices are not always explanatory because most of them were derived from a statistical or mathematical method. Thus, solid combined band indices are still under development.

3. Global reflectance response indices

   The global reflectance under different stressors varies due to variations in the regional reflectance. All three regions (VI, NIR and SWIR) together form a whole spectrum ranging from 400 nm to 2500 nm as shown in **Fig. 7**. The exact change in each region has been summarized in **Table 1**. Likewise, the mark '+' means increase, '-' is for decrease, and '=' for no apparent change.

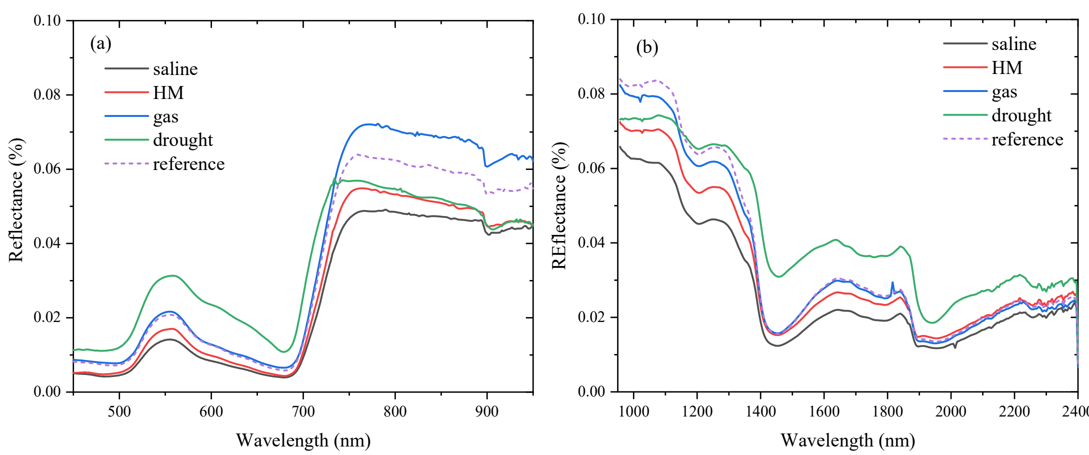


Fig. 7 global reflectance: (a) VI and NIR ranges and (b) SWIR range

Table. 1 Reflectance change in each region of the whole spectrum

	VI	NIR	SWIR
Saline	=	+	-
HM	-	-	-
Gas	-	-	+
Drought	+	-	+

From the perspective of detection, gas leakage can be distinguished by using the global reflectance change index. Each stressor yields a unique pattern in overall reflectance change. However, the reflectance is highly environment-dependent. The ambient disturbances significantly affect the reflectance. Thus, the change of reflectance itself is not a robust feature. Integration of all type of indices will eliminate the false alarm and enhance the detection efficiency.

Task 3. Develop a physically-interpretable neural network for the selection of images (frames) from video footage and demonstrate in field conditions the UAS in the assessment of pipeline and surrounding conditions, population-impacted changes, above-ground objects, accident responses, and mapping system accuracy.

This task just began.

(c) Planned Activities for the Next Quarter - The following activities will be executed during the next reporting quarter.

Task 1. Design and prototype the UAS for the collection of images from visible light, infrared, and hyperspectral cameras, and demonstrate the potential of the collected images for the evaluation of ground conditions and pipeline risks for decision makers.

A drone system equipped with hyperspectral and infrared cameras will be tested in laboratory drone nets and outside for potential field tests. Determine the final factors to include in the laboratory test and develop a thorough test plan. Have all necessary equipment, materials, space, and staff in place to fully prepare for laboratory tests and collect data for Task 2.

Task 2. Develop and validate 1D spectral analysis at each pixel of a hyperspectral image, 2D image classification of changes, spatial analysis of a hyperspectral image and its fusion with others for increased probability of detection, and 3D object establishment for volume estimates.

The 1D adaptive wavelet transform will be applied to extract the ground and material conditions along a pipeline through the abnormalities in space, which are represented by the changes in wavenumber. The effectiveness of the extended transform will be investigated using the data obtained in Task 1 from laboratory tests, once available.

(d) Problems Encountered during this Quarter and Potential Impact on Next Quarter – This project has been impacted by the COVID-19. At Missouri S&T, laboratories were closed on March 16, 2020, and re-opened on June 1, 2020 with social distancing and hand sanitizing practices in mind. To keep six feet apart between any two students in the laboratory, limited laboratory access is available to students. As such, students may have to work in different shifts.