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## **OIL SPILLS DETECTION BY MEANS OF UAS AND INEXPENSIVE AIRBORNE THERMAL SENSORS**

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OIL SPILLS DETECTION BY MEANS OF UAS AND INEXPENSIVE  
AIRBORNE THERMAL SENSORS

By  
Ausama Al-Shammari

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Integrated Geospatial Technology

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This thesis has been approved in partial fulfillment of the requirements for the  
Degree of MASTER OF SCIENCE in Integrated Geospatial Technology.

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## **Table of Contents**

List of Figures.....	v
List of Tables.....	vii
Acknowledgements.....	viii
Abstract.....	ix
<b>1. Overview of Oil Spills Detection and Mapping.....</b>	<b>1</b>
1.1 Introduction.....	1
1.2 Remote Sensing Methods for Detecting Oil Spills and disaster management.....	4
1.3 Using Satellite Remote Sensing for Oil spills and slicks Detection.....	6
1.3.1 Using Airborne and UAS Systems for Oil Spills and Slicks Detection.....	8
1.3.2 Active and Passive Remote Sensing Techniques.....	12
1.3.3 Overview of sensors used for oil spills and slicks detection.....	13
1.3.3.1 Radar Sensors.....	14
1.3.3.2 Laser Sensors.....	15
1.3.3.3 Ultraviolet Sensors (UV).....	16
1.3.3.4 Visible Sensors (VIS).....	16
1.3.3.5 Passive Microwave Sensors.....	19
1.3.3.6 Infrared Sensors (IR).....	19
1.3.3.6.1 Thermal Infrared Sensors (TIR).....	20

<b>2. Thermal IR Usage Considerations.....</b>	<b>21</b>
2.1 Oil Type and Layer (Film) Thickness.....	21
2.2 Environmental Conditions.....	22
2.3 Thermal IR Sensor Capabilities.....	23
2.3.1 Commonly Used Thermal Sensors.....	24
2.3.1.1 TIMS.....	24
2.3.1.2 ASTER.....	25
2.3.1.3 MODIS.....	25
2.3.1.4 Landsat.....	25
<b>3. Methods.....</b>	<b>27</b>
3.1. Study Area and Experiments Details.....	27
3.2. Equipment Used for the Data Collection.....	30
3.2.1 Raspberry Pi, Thermal IR Sensor.....	30
3.2.2 DJI Phantom 4 Unmanned Aerial System.....	32
3.2.2.1 DJI Phantom 4 Specifications.....	34
<b>4. Study Results .....</b>	<b>37</b>
4.1. Creating Classification Maps.....	37
4.2. Conclusion.....	51
4.3. Recommendations.....	54
<b>Copyright Permissions.....</b>	<b>55</b>
<b>References.....</b>	<b>57</b>

## List of Figures

<b>Figure 1.1.</b> Oil spill effects on wild life (Sea Otter), (USGS, 2014).....	2
<b>Figure 1.2.</b> UAS deployment for offshore platforms routine inspections (Sky-Futures, 2017).....	3
<b>Figure 1.3.</b> San Diego and Vicinity shorelines on ESI map, (NOAA, 2017).....	5
<b>Figure 1.4.</b> The electromagnetic spectrum, (NASA, 2016).....	6
<b>Figure 1.5.</b> Unmanned aerial system UAS example, (NASA, 2017).....	9
<b>Figure 1.6.</b> Aerostat assisting a spill response unit, (Aqua-Guard, 2018).....	9
<b>Figure 1.7.</b> Manned aircraft supporting oil spill response (Fototerra, 2017).....	10
<b>Figure 1.8.</b> Active and passive remote sensing, (NASA, 2012).....	12
<b>Figure 1.9.</b> Oil spill appearance offshore, (Bonn, 2016).....	18
<b>Figure 3.1.</b> Study area map showing the location of KPSC.....	27
<b>Figure 3.2.</b> Oil-Water contamination experiment.....	28
<b>Figure 3.2.</b> Water Temperatures (A) Before Heating (B) After Heating.....	29
<b>Figure 3.3.</b> Oil temperature measurements (A) Before heating (B) After 3 hours heating.....	29
<b>Figure 3.4.</b> Lepton thermal sensor, (Karlsson Robotics, 2017).....	30
<b>Figure 3.5.</b> Raspberry Pi NoIR camera, (Karlsson Robotics, 2018).....	31
<b>Figure 3.6.</b> First mounting of the Raspberry Pi box on the side of UAS.....	35
<b>Figure 3.7.</b> Using mesh wire to ease the airflow underneath UAS.....	35

<b>Figure 3.8.</b> The final system used in the data collection.....	36
<b>Figure 4.1.</b> KPSC location image captured using DJI Phantom 4 UAS.....	38
<b>Figure 4.2.</b> Lepton thermal sensor resized Image.....	39
<b>Figure 4.3.</b> Image-to-Image Registration Results.....	40
<b>Figure 4.4.</b> The fused image product (Field Experiment).....	41
<b>Figure 4.5.</b> Classification map for the DJI phantom 4 RGB image.....	42
<b>Figure 4.6.</b> Classification map for the fused image.....	43
<b>Figure 4.7.</b> Map showing the locations used for the accuracy assessment.....	46
<b>Figure 4.7.</b> Canon 600D image used in the water-oil experiment.....	47
<b>Figure 4.8.</b> Lepton thermal image used in the water-oil experiment.....	48
<b>Figure 4.9.</b> Water-Oil experiment <i>Image to image</i> registration.....	48
<b>Figure 4.10.</b> Fused image of the water-oil experiment.....	49
<b>Figure 4.11.</b> RGB image classification where red is water and black is oil.....	50
<b>Figure 4.12.</b> Fused image classification where yellow is water and blue is oil.....	50

## List of Tables

<b>Table 1.1.</b> Oil spill detection bands and their wavelengths coverage and the related instruments, (Goodman, 1994).....	14
<b>Table 1.2.</b> Visible oil appearance on a calm water surface, (Merv Fingas, 2000)....	17
<b>Table 1.3.</b> Visible Oil Appearance, Thickness, (Bonn, 2016; Leifer et al., 2012)...	18
<b>Table 2.1.</b> TIMS channel designation, (Palluconi, 1985).....	24
<b>Table 3.1.</b> UAS classification, (Levin, 2016).....	32
<b>Table 3.2.</b> U.S FAA Regulations for Flying UAS for Recreational/Educational Purposes, (FAA, 2017).....	33
<b>Table 3.3.</b> List of the DJI Phantom 4 Specs, (Drone World, 2017).....	34
<b>Table 4.1.</b> Accuracy assessment for RGB classified image.....	44
<b>Table 4.2.</b> Accuracy assessment for fused classified image.....	45



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## **Abstract**

This thesis provides an overview of oil spill scenarios and the remote sensing methods used for detection and mapping the spills. It also discusses the different kinds of thermal sensors used in oil spills detection. As UAS is becoming an important player in the oil and gas industry for the low operating costs involved, this research involved working with a cheap thermal airborne sensor mounted on DJI Phantom 4 system. Data was collected in two scenarios, first scenario is collecting data in Michigan's Upper Peninsula at a petroleum company location and the second scenario was an indoor experiment simulating an offshore spill. The aim of this research is to inspect the capability of Lepton LWIR inexpensive sensor to detect the areas contaminated with oil. Data processing to create classification maps involved using ArcGIS 10.5.1, ERDAS Imagine 2015 and ENVI 5.3. Depending accuracy assessment (confusion matrices) for the classified images and comparing classified images with ground truth, results shows the Lepton thermal sensor worked well in differentiating oil from water and was not a good option when there are many objects in the area of interest. Future research recommendations are presented in this document.

# **1. Overview of Oil Spills Detection and Mapping**

## **1.1 Introduction**

Oil spills are a major factor that affects the environment in the first place as well as its contribution to huge economic losses especially for countries who are completely depending on oil products as one of their main resources because a major oil spill could be a major loss and a big hit to the economy. Oil products are still widely used, mainly for transportation and producing electricity besides many industries uses oil products intensively such as but not limited to production of fertilizers and plastics. Oil spills could occur in any step during oil wells drilling, treatment facilities, export pipelines and shipping. Remote sensing plays a major role in the monitoring of spills and slicks. There are different sensors that work for oil spill detection and surveillances depending on the spill conditions (onshore, offshore). Remote sensing oil detection and mapping contributes to supporting decisions for emergency response preparedness and disaster management as well as directing cleanups crews. It is vital to know where the spills and areas it covers are and knowing where are the thick layers of oil to have plans of controlling the rapid spread of oil and their directions especially in offshore scenarios. The spread of oil on land is affected by the type of soil and its moisture content as well as the type of oil (M. Fingas, 2005). A special case is the offshore spills because there are different factors affecting the spread of oil such as winds, tides that could make the spill spread very quickly. Governments has very strict legislations for oil explorations and production to prevent oil spills because of its associated risks with damaging the environment and wildlife habitats but these legislations are not going to prevent spills and their risks completely.



**Figure 1.1.** Oil Spill Effects on Wild Life (Sea Otter) Adopted from (USGS, 2014)

Knowing that it's a case by case to use remote sensing sensors depending on the conditions involved and the availability of data, Satellite imagery is not always available all the time due to its revisit times and other factors like cloud effects for example plus High-resolution satellite imagery is expensive to purchase frequently. The imagery available free of cost is of medium-low spatial resolution and it's important to mention that the unavailability of high resolution TIR and SWIR for optical imaging (Partington, 2014). Medium-Low resolution imageries are good for monitoring vegetation uses for instance. Medium-low satellite imagery is not the best option for emergency response and disaster management purposes especially the critical impact of oil to the environment and coastal communities like anglers or touristic places. Sometimes a critical project requires an immediate response and for this, different techniques could be used to enhance the available resources, which could maximize the uses of the available data. Unmanned aerial systems (UAS) are being widely used nowadays in oil & gas related projects for the flexibility it has to

fly and having its data very quickly and process it even in the field instantly, which saves loads of money especially for routine inspection purposes and this also minimizes the danger exposure and human risks involved. UAS could have different types of sensors attached to it. The selection of sensors depends on different factors such as working during the day or night times, the weather conditions and clouds, amount of discharged oil and its relative thickness on ground for oil spills studies.

UAS Flight and imagery processes consists of firstly a preflight process, which determines the best flight route, position, altitude according to the site conditions as well as camera and sensors capabilities. Secondly, the image acquisition process, after reaching required altitude and angle shooting a trigger to capture the images of video required and/or position. Finally the post processing stage, which involves working with different platforms to process the geospatial data and make the best use of it such as Erdas, ENVI ArcGIS etc.



**Figure 1.2.** UAS Deployment for offshore platforms routine inspections

Adopted from (Sky-Futures, 2017)

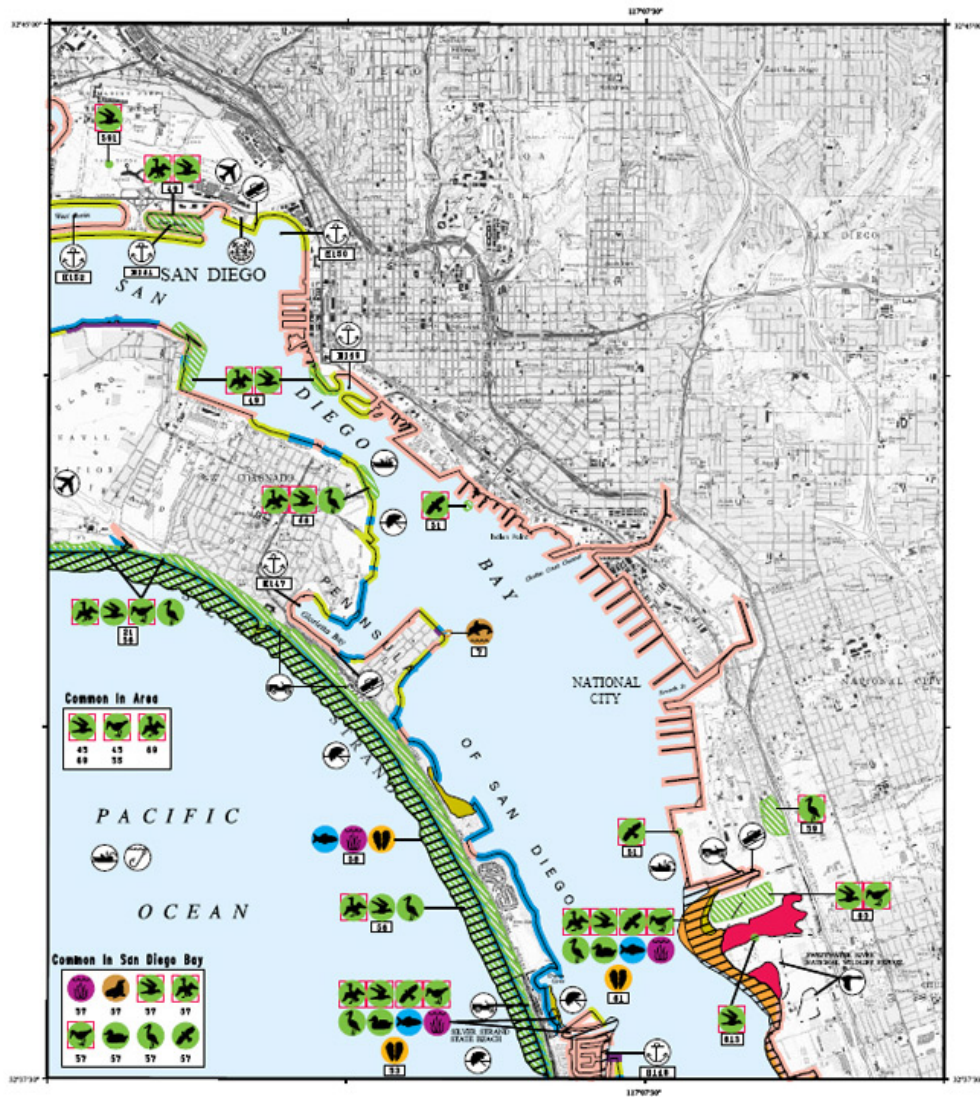
## **1.2 Remote Sensing Methods for Detecting Oil Spills and disaster management**

Today's technology for oil spill detection using remote sensing gives much information about the location and spread behavior of oil spills and the environmental impacts associated with the spills. (Merv Fingas, 2000) says there are many sensors (Satellite or airborne platforms) that are useful for oil detection and mapping. It is not practical to use a single sensor and gain all the information required (C. Brown & Fingas, 2001). In the same time, there is a broad range of applications and software packages that works with data acquired from the different sensors to process and create output maps that are crucial to the disaster management and planning teams, decision makers.

Remote sensing data for oil detection and mapping comes from:

- Satellite Remote Sensing platforms
- Airborne and UAS Remote Sensing platforms

The integration and processing of remote sensing data from different data sources in GIS creates strong tools that is very useful for decision makers. Environmental sensitivity index (ESI) or sensitive environmental mapping for instance is a GIS tool that is developed by national oceanic and Atmospheric Administration (NOAA) and it gives free access to the U.S. shoreline data of sensitive areas to offshore oil spills like animal habitats, marshlands, beaches and parks (NOAA, 2017a). This tool could be utilized in assessing potential offshore oil spills risks and mitigations and the planning of cleanups after disasters.



**Figure 1.3.** San Diego and Vicinity Shorelines on ESI Map

Adapted From (NOAA, 2017)

Different sensors can provide useful information about oil spills and slicks that can assist in monitoring the spread and its direction and the planning for cleanup processes and this is a great input for environmental specialists to control and minimize the environmental impacts of oil spills hazards to the environment.

### 1.3 Using Satellite Remote Sensing for Oil spills and slicks Detection

Available Satellites systems provide a coverage in wide range of the electromagnetic spectrum wavelengths. Satellites are equipped with different kinds of sensors that detect different wavelengths ranging from short optical to long microwave. This variety of sensors and their capabilities gives an advantage to analysts to interpret more than what a human naked eye can detect (a human eye is able to detect only the visible portion of the electromagnetic spectrum). Another advantage of some satellite sensor platforms is their abilities of not being affected by the weather or clouds (Partington, 2014) such as thermal and radar sensors for instance.

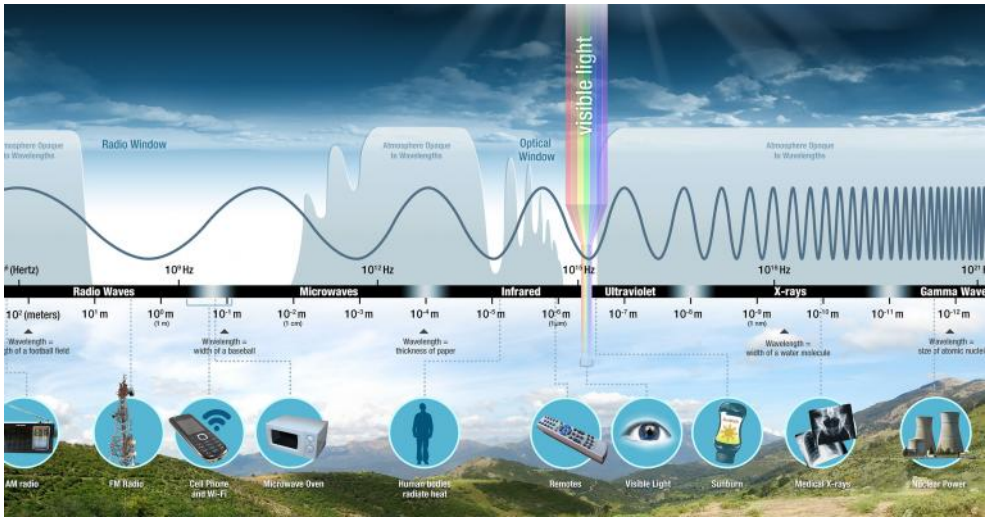


Figure 1.4. The Electromagnetic spectrum

Adapted From (NASA, 2016)

There are two different types of space-borne remote sensing instruments, Geostationary instruments are the ones collecting observations of a constant position on earth while the polar orbiting instruments have a coverage due to its continuous processing around the earth (Partington, 2014).



Each satellite sensor platform has various bands covering different parts of the electromagnetic spectrum. It is important to mention that not all the bands are useful for specifically oil detection and mapping. Even the ones that are useful, they cannot be useful at all -times because weather changes affects the suitability of some sensors if it is raining or even if it is foggy like visible, UV and infrared bands (Goodman, 1994), or the site or oil spill conditions.

The atmosphere plays a major role in energy losses and influencing the spectral response patterns. These energy losses significantly differs from satellite sensors to UAS sensors. Satellite sensors are basically observing the sunlight reflectance from objects on earth's surface after the sun light makes its way through the earth's atmosphere twice (in and out). In UAS the paths travel distances are considered much shorter compared to satellites hence, UAS has a very less amount of the atmospheric scattering if comparing the signal travel path distances. In general the atmosphere affects radiance or brightness values for any given point to some extent, this also means a thermal sensor is less affected by signal scattering because it is basically recording the objects emitted energy which means there is only one travel path (Lillesand, Kiefer, & Chipman, 2014).

Satellites sensors are being used effectively for monitoring and oil spills and their movement directions as well as the discharged oil quantities making use of satellites consistent revisit times that gives a good data availability especially if using more than one satellite platform. Using more than one satellite platform supports filling the need of data when required in certain times. Each satellite platform has different properties from the others but they are all working with the same concept of having an active or passive sensing equipment on board and sometimes both. "Active" sensors are emitting and receiving energy to record information whereas "Passive" sensors only recording emitted energy from other sources such as but not limited to the sun energy.

### **1.3.1 Using Airborne and UAS Systems for Oil Spills and Slicks Detection**

The deployment of airborne systems is becoming a vital technique for oil spills area identification especially for offshore operations because of its remoteness. Satellite sensors provides a good constant coverage but unfortunately, the availability of data sometimes is restricted to many factors. The major factors are: temporal resolution, weather conditions or cannot provide enough details for the calculations of oil film thickness because of the very few satellites sensors that relate to oil film thicknesses. In addition, satellites are not able to provide enough early high spatial resolution information for polluters' investigation (in offshore cases if multiple oilrigs platforms are working within the same area). Different oil spill scenarios requires special techniques which supports deciding if either an airborne, UAS or an aerostat system is required to get the right data needed.



**Figure 1.5.** Unmanned aerial system UAS example

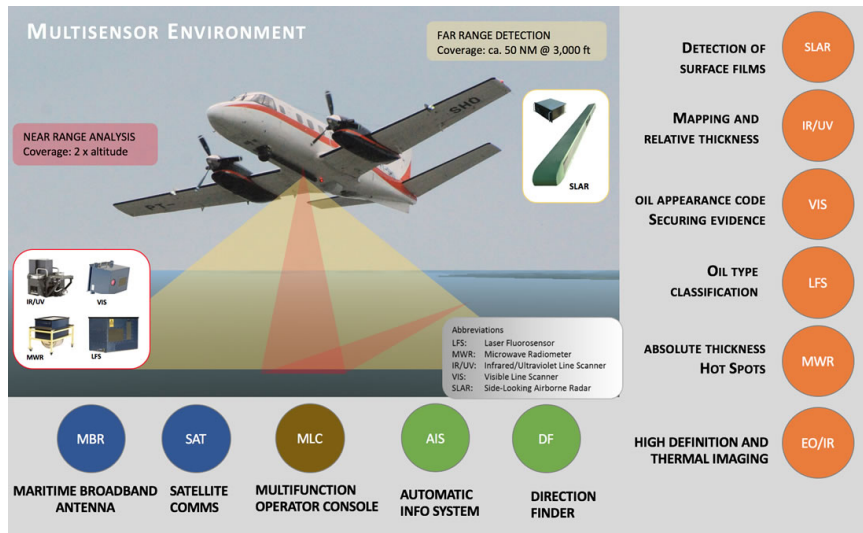
adapted from: (NASA , 2017)



**Figure 1.6.** Aerostat system assisting a spill response unit

adapted from (Acqua Guard Spill Response Inc., 2018)

UAS are able to fly with low altitudes below clouds, which minimizes the cloud effects in imaging. If compared to manned aircrafts, this helps in providing better resolution imaging besides the cost involved in a UAS project to collect data is 1/3 of the cost if manned aircraft is being operated (Lomax, 2005).



**Figure 1.7.** Manned Aircraft Supporting Oil Spill Response

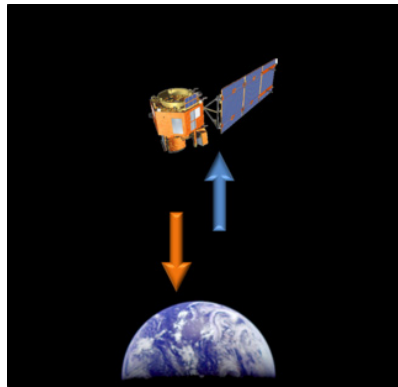
Adapted from (Fototerra, 2017)

Advanced sensors are used very often to extract useful information about oil spills film thicknesses and characterization such as laser fluorescence sensor for instance (Zielinski, 2006). The film thickness details is still a matter in research but it's very important and necessary to detect where are the thicker oil patches (M. Fingas, 2016). Basic sensors the most used sensors on airborne systems such as Side looking radar, visible and IR/UV sensors. For offshore disaster management purposes and to identify who is the polluter there is a very recent thermal imaging technique is now being used by introducing an image intensifier equipment which could detect the labels or names of vessels or platforms even without the need to the day light which maximized the use of thermal sensors and imaging (Zielinski,

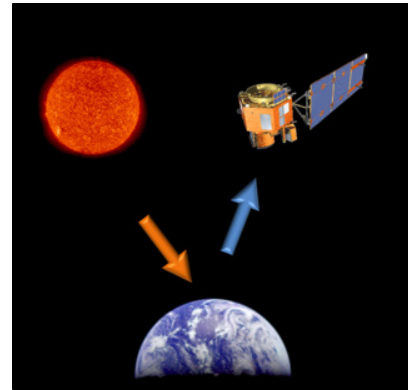
2006). Unmanned aerial system are now the new technology that is used by international oil companies and governments. UAS technology is now commercially growing fast and showing very promising attitudes that it is cost efficient and minimizes human risks (Allen & Walsh, 2008). UAS is now being deployed in different sectors starting with disasters, environmental management applications, law enforcement and engineering applications. UAS is currently a great addition to shoreline surveys, onshore engineering and is still limited for remote areas (Allen & Walsh, 2008). The capability of having multiple sensors mounted to UAS is what makes it a very effective tool to the oil industry nowadays.

There are many restrictions for UAS such as international borders, import and export of data, Weather suitability for flight. The most important challenge is the battery life of UAS because on average, 20 minutes is the average flight time hence, tethered UAS is helping in overcoming this restriction as well as flying UAS from different locations around the target helps in increasing the ability to use its original batteries.

### 1.3.2 Active and Passive Remote Sensing Techniques



Active Sensing



Passive Sensing

**Figure 1.8.** Active and Passive Remote Sensing (NASA, 2012)

Active and passive remote sensors are two types of technology used to sense and measure earth features reflectance of energy. Both types of sensors could be either space borne like in satellites or airborne such as but not limited to unmanned aerial systems. The difference between them is that active sensors are radar instruments and it transmits and measure its own transmitted signals after it hits the ground features on the earth and travel back to the sensor as a reflected signal. while the passive sensors are only measuring the reflected signal from a different source of energy other than the sensor itself like the sun energy example and this sensor type is a microwave instrument (NASA, 2012).

Active Sensors used in oil spills detection and mapping:

- Radar
- Laser

Passive Sensors used in oil spills detection and mapping:

- UV
- Visible Sensors
- Infrared
- Thermal Infrared

### **1.3.3 Overview of sensors used for oil spills and slicks detection**

There are many oil spill disaster scenarios whether if it is onshore or offshore, oil spill characteristics are different in each condition depending on the various factors such as in offshore oil spills, if it's on calm water or not. Winds effects also plays a major role in changing oil movement direction hence changes the spread and thickness of oil layers which reflects on the appearance of oil and this would have an impact on remote sensing procedures for locating and quantifying the spill. On the other hand, there are other different factors affecting locating and quantifying onshore spills, its more complex than offshore oil spill detection due to having various medians like concrete, soil, vegetation, metals etc. where in offshore operations there is only water and oil.

That means different techniques utilizing different sensors depending on their suitability for the specific condition are to be used in the processing of remotely sensed products.

**Table 1.1.** Oil spill detection bands and their wavelengths coverage and the related instruments (Goodman, 1994)

<b>Band</b>	<b>Type of Instrument</b>	<b>Wavelength</b>
<b>Radar</b>	SLAR/SAR	1-30 cm
<b>Ultraviolet</b>	Film, video cameras and line scanners	250-350 nm
<b>Visual</b>	Film, video cameras and spectrometers	350-750 nm
<b>Near Infrared (NIR)</b>	Film and video cameras	1-3 $\mu\text{m}$
<b>Passive Microwave</b>	Radiometers	2-8 mm
<b>Mid-band infrared (MIR)</b>	Video cameras and line scanners	3-5 $\mu\text{m}$
<b>Thermal infrared (TIR)</b>	Video cameras and line scanners	8-14 $\mu\text{m}$

### 1.3.3.1 Radar Sensors

Radar sensors are active sensors that transmit its own energy in the microwave region, as a coherent radiation, of the electromagnetic spectrum (Partington, 2014). These sensors are effective for oil water discrimination in offshore operations of oil slicks detection. The ocean's Capillary waves reflects the radar signals, therefore, radar images of the offshore spills shows oil patches as a dark figure and the water is shown as a bright figure (C. E. F. Brown, M.; Hawkins, R., 2003). Radar sensors cover from millimeter to decimeter range of wavelengths where the measured radiation is mostly sensitive to surface roughness. Radar systems are very useful in all weather conditions and in day or night operations but satellite radar sensors has a small swath width and they are expensive adding to it that the revisit frequency is very low. Radar data interpretation is very complicated due to its surface conditions



sensitivity (Partington, 2014). For offshore oil spill detection, the most common sensors are the synthetic aperture radar as well as the side looking airborne radar. SAR has a higher range and spatial resolution if compared to SLAR (M. F. Fingas & Brown, 1997). In the same time, SLAR is commonly used because it is less expensive than SAR systems. A major problem using radar sensor is the false detection. wind speed has an influence on oil spill detection (C. E. F. Brown, M.; Hawkins, R., 2003) as oil cannot be detected while high wind speeds because it will be dispersed in the water and if winds speed is low, thick and thin oil slick will not be distinguished. some films on sea surfaces produced by organic substances such as seaweeds may also results in a false detection of oil using radar data (Jones, 2001).

### **1.3.3.2 Laser Sensors**

There are more than one kind of laser sensors used in oil detection. Laser sensors are transmitting and receiving light echoes and though they are considered active optical sensors. Laser sensors could be used is day or night operations. Laser sensors are expensive and its signals are affected by atmospheric attenuation in certain conditions like if it is a cloudy or foggy weather (Partington, 2014). Laser sensors could be used for offshore and onshore oil spills and slicks detection. So far laser sensors are considered very effective in oil detection and classification because of its ability to detect it on any surface such as in ice conditions, water, soil or even on weeds (M. N. Jha, 2009). Lidar (Light Detection and Ranging) is a function of laser sensors in which a distance to targets can be measured according to the signal travel time and it can also provide surface elevations (Partington, 2014). Laser acoustic sensor is a specific laser sensor that is used to detect oil spills and also measure the thickness of oil layers by calculating the travel time of the ultrasonic waves in oil (N. M. Jha, Levy, & Gao, 2008). The laser acoustic sensor detects oil

depending on its mechanical properties and not according to the electromagnetic properties (N. M. Jha et al., 2008).

### **1.3.3.3 Ultraviolet sensors**

Comparing oil to water reflectivity in the ultraviolet region of electromagnetic spectrum (0.32-0.38), even a very thin layer of oil would reflect much stronger than water knowing that the ultraviolet sensors are passive sensors and capable of detecting a thin oil sheen of 0.1 micron thickness but not more than 10 micron.

The downsides UV sensors are firstly it cannot be operated during night times because it depends on sunlight reflection and secondly Many factors affect the detection using UV sensors for example in offshore operations, wind and sun glint even sea weeds forces UV sensor to give false detection (M. N. Jha, 2009).

### **1.3.3.4 Visible Sensors**

Since 1970, the most common sensors used in airborne remote sensing were the visible and thermal scanning systems along with aerial photography (Wadsworth, Looyen, Reuter, & Petit, 1992). Visible sensors are passive sensors and colors are used to detect oil spills and its characteristics (Partington, 2014). Visible sensors are useful in showing oil in onshore and offshore locations but still gives wrong interpretations sometimes due to the surrounding colors, for instance in offshore locations sun glint and surface currents changes due to high winds gusts may give water a shining effect or sometimes dark shorelines could be misinterpreted as oil. Also the difference in thicknesses of oil spills offshore is misleading as it is hard to visually detect thin oil sheens. Oblique angles imaging also makes it difficult to detect oil spills offshore with visible sensors (Merv Fingas, 2000). Fingas has also explained the appearance of oil on calm water surfaces according to film thicknesses in the following table:

**Table 1.2.** Visible Oil appearance on a calm water surface

Adopted from (Merv Fingas, 2000)

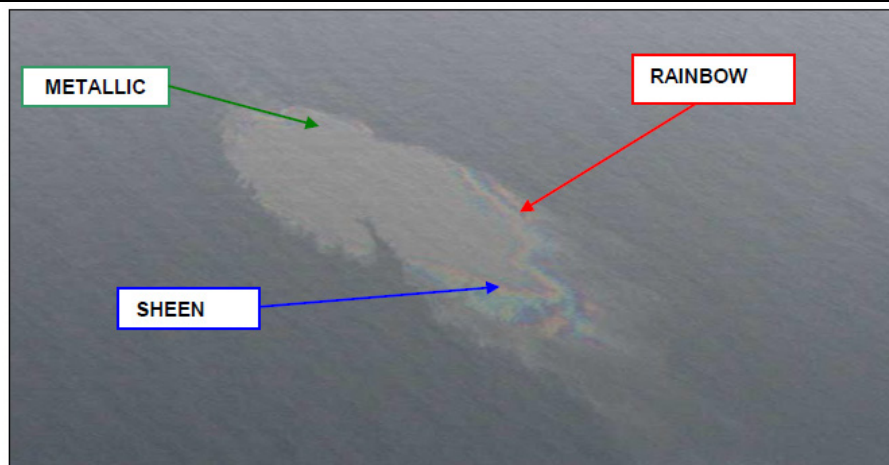
<b>Oil Appearance</b>	<b>Approximate Film Thickness</b>
Dark brown-Black	50.00 $\mu\text{m}$
Oil colors dark	10.00 $\mu\text{m}$
Brown color	2.00 $\mu\text{m}$
Red-Brown sheen	0.50 $\mu\text{m}$
Rainbow sheen	0.15 $\mu\text{m}$
Silvery Sheen	0.05 $\mu\text{m}$

Although visible sensors are not an option for night operations because it basically measures sunlight reflectance from objects on earth, its broadly used in basic assessments and also creating initial standardized reporting for being inexpensive and easy to use and mount on aircrafts. American society of test materials (ASTM), 1996 and Bonn Agreement, 2004 has put together the standards for the visual appearance of oil spills on water and their relative thicknesses shown in table 1.3.

**Table 1.3.** Visible Oil Appearance, Thickness

Adopted from (Bonn, 2016; Leifer et al., 2012)

Code	Description/appearance	Bonn, layer thickness ( $\mu\text{m}$ )	ASTM, layer thickness ( $\mu\text{m}$ )	Bonn, liters per km <sup>2</sup>
1	Sheen (silvery/gray)	0.04 to 0.30	0.1–0.3	40 to 300
2	Rainbow	0.30 to 5.0	0.3–0.5	300 to 5000
3	Metallic	5.0 to 50	~ 3	5000 to 50,000
4	Discontinuous true oil color	50 to 200	> 50	50,000 to 200,000
5	Continuous true oil color	200 to > 200		200,000 to > 200,000



**Figure 1.9.** Oil Spill Appearance Offshore Adopted from

(Bonn Agreement, 2016)

The difference between the thickness measurement between ASTM standard and the Bonn agreement standard is because both didn't consider the petrol types sand relevant slick appearance and not even the solar angles (Lehr, 2010). A lot of development on sensors occurred during the past few decades and because of the continuous developments on optical sensors is hyperspectral sensors. Hyperspectral sensor have a high spectral and spatial resolution and these sensors are able to hold hundreds of spectral bands and is being used in oil spills detection and mapping as they can deliver a spectral signature and a lot of spectral information that could be used to differentiate objects (M. N. Jha, 2009).

### **1.3.3.5 Passive Microwave Sensors**

These sensors works according to the emissivity of the objects (radiation). Passive microwave sensors work in the microwave region of the electromagnetic spectrum and this sensor works according to the same concepts of the thermal IR sensors but weather has very less effects on its data (Partington, 2014) as compared to Thermal IR data. The passive microwave sensors are of high cost and its spatial resolution is not high but it could be used in day or night operations. These sensors are not able to provide thickness details of oil slicks offshore but they can only provide relative thickness measurement if they were calibrated (Merv Fingas, 2000).

### **1.3.3.6 Infrared sensors (IR)**

Infrared sensors covers the region of spectrum which is right after the visible sensing region (it covers what a human eye cannot detect) and they are passive sensors (Partington, 2014).

Partington mentioned in his report the IR absorption frequencies that works in oil detection and defined them as “1.19, 1.21, 1.72, 1.73, 1.75, 1.76, 2.37, 3.3  $\mu\text{m}$  “and he also mentioned that short wave IR is useful because it can penetrate through fog, thinning cloud and haze.

Infrared sensors can detect only thick oil slicks offshore greater than 100  $\mu\text{m}$ , therefore, its imaging is enhanced by fusing UV images and creating an overlay map and as a result of this, IR sensors are enhanced to detect the thinner slicks (Merv Fingas, 2000).

IR sensors are commonly used by the cleanup vessels where they usually affix the sensor on top of the ship mast and the oblique image of the IR sensor is good enough to direct the crew on where to steer for a short range and locating the thick portions (Merv Fingas, 2000).

### **1.3.3.6.1 Thermal Infrared sensors (TIR)**

Thermal IR sensors or sometimes called forward-looking IR sensors (FLIR) are passive sensors that work with emissivity and temperatures of objects. Emissivity is the ratio of radiation of an object to the radiation of a black body at the same temperature (Lillesand et al., 2014). Thermal sensors could be used in day or night times which makes it considered one of the best options for critical oil detection and disaster management projects. In an offshore scenario, the oil behavior at night is different from the daytime, oil absorbs the sun energy during the day more than water thus it looks as a hotter area if using thermal sensors but during the nighttime oil tends to show a cooler behavior than the water. Thermal IR covers the region 8-14  $\mu\text{m}$  on the electromagnetic spectrum as shown in figure 1.1. Thermal IR sensors data is also able to indicate the oil layer thickness to some extent in offshore operations but not emulsions of oil in water because these emulsions water content in these is approximately 70% which makes it respond to thermal sensors the same as the response of the background water (M. F. Fingas & Brown, 1997).

Thermal sensors sometimes becomes misleading to false alarms for example in offshore cases, sea weeds for instance are a good example of giving a false target. In onshore locations, it is misleading because of the possibility of having many objects of different materials in the oil spill location that might be having the same temperature at the time of the data collection and can sense it as a false target.

## **2. Considerations for Using Thermal IR Sensing of Oil Spills and Slicks**

### **2.1 Oil Type and Layer (Film) Thickness**

Oil has significantly different physical properties depending on the oil type in which effects its response to the solar radiation. In other words, heavy oils (like crude oil) responds significantly different from light oils.

The physical properties of oil in general shows that oil gains and releases heat quickly. This indicates that oil spills in the day time when exposed to the sun's energy, it gains heat where at night time they appear to show a cooler behavior than the surroundings (Zhao, Temimi, Ghedira, & Hu, 2014). For example, having only water and oil (like in an offshore crude oil spill case), the thermal band of Landsat TM observation (at a room temperature) shows a 0.6 °C difference in brightness temperature if there is a 0.01 difference in emissivity between oil and water (J. W. Salisbury, 1993). Oil thickness has also an input on the response to thermal energy, spills with > 150 μm thickness is shown as a hotter spot than thinner oil spills and surroundings during the daytime while absorbing sun's heat but it looks cooler than surrounding water at nighttime (Leifer et al., 2012b). The brightness temperature is related to surface temperature and surface emissivity as shown is in the following equation:

$$TB = TS * \epsilon^{0.25} \quad (1)$$

Where:

TB is the Brightness Temperature

TS is the Surface Temperature

$\epsilon$  is the Surface Emissivity

$\epsilon$  is calculated through the equation  $\epsilon = 1 - R - TR$  (2)

Where R is the Reflected Energy, TR is the Transmitted Energy

## **2.2 Environmental Conditions**

Oil spills occurs without a prior notice. It might be a desert or a jungle or even an underwater export pipeline break, export trucks or ships leaks, onshore or offshore treatment or central processing facility, well blowout (onshore or offshore). Each of the previously mentioned scenarios involves different techniques to discriminate oil from the other medians, which helps supporting the environmental protection teams and assisting decision makers to plan the cleanup processes and estimating losses and costs involved.

Oil spill detection using thermal IR sensors on different platforms (Satellites, Airborne and UAS) has shown a better result in offshore scenarios because of having only two medians especially in remote deep waters because sometimes near shores or shallow waters, algae blooms or seaweeds for example, affects the thermal sensors response and gives a false oil detection.

Onshore cases are more complex to use thermal IR sensors because of having multiple medians in the same area of a spillage (Road blacktop, Storage Tanks, Vegetation etc.). Each of these medians responds in its own way that is different from the oil spill depending on their physical properties, which relates to their solar



radiation response of thermal sensors and this gives misleading false results especially at times when other mediums are having the same temperatures as the oil is emitting.

## **2.3 Thermal IR Sensor Capabilities**

The radiant emitted energy from objects on earth is what thermal sensors or scanners duty to detect. As previously mentioned, there are different platforms for thermal IR sensors like satellites, airborne (manned or unmanned). Some satellite platforms offer thermal IR bands that works with different parts of the electromagnetic spectrum but focuses on the region 8-14  $\mu\text{m}$  because object's peak emission occurs at 9.7  $\mu\text{m}$  for objects of 80° F- 27°C- 300K based on Wien's Law. Other sensors are covering the region 3-5  $\mu\text{m}$ . It is important to mention that not all satellites are having a thermal sensor. Some satellites are operating for educational and research purposes and these sensors mostly gives users an open access free of cost, there are other satellites that are operating for commercial uses that provides a high end data and resolution.

## 2.3.1 Commonly Used Thermal Sensors

Airborne scanners are the most effective for oil spills and slicks monitoring. Satellite thermal sensors are not providing all the needed information about spills as well as the low-moderate thermal bands resolution, cloud cover, revisit time affects working with satellite thermal imagery. This led the researches to develop a more flexible and powerful scanners and sensors that are mounted on manned or unmanned aircrafts or even aerostats. Below is a review for the most common thermal scanners and sensors used in oil spill disaster management projects.

### 2.3.1.1 TIMS

TIMS stands for “Thermal Infrared Multispectral Scanner”, TIMS work with mineral information (signatures). TIMS is an airborne sensor (aircraft mounted), covers the region 8.2-12.2  $\mu\text{m}$  on the electromagnetic spectrum having six multispectral bands that are sensitive to 0.1  $^{\circ}\text{C}$  (NASA, 1995). TIMS is very useful when an accurate measurement of earth surface temperature or spectral radiance is required.

**Table 2.1.** TIMS Channel Designation adopted from (Palluconi, 1985)

Channel	1	2	3	4	5	6
Wavelength	8.2 –8.6	8.6–9.0	9.0-9.4	9.4-10.2	10.2-11.2	11.2-12.2
Bandwidth	0.4 $\mu\text{m}$	0.4 $\mu\text{m}$	0.4 $\mu\text{m}$	0.8 $\mu\text{m}$	1.0 $\mu\text{m}$	1.0 $\mu\text{m}$

### **2.3.1.2 ASTER**

“Advanced Space-borne Thermal Emission and Reflection Radiometer” is what ASTER stands for (NASA, 2004). ASTER sensor is onboard the Terra satellite, 8.1-11.6  $\mu\text{m}$  is the range ASTER’s five thermal bands cover on the electromagnetic spectrum range. ASTER thermal bands are of 90m spatial resolution. ASTER has 14 bands in total that covers visible, NIR and SWIR besides TIR and its data is available on the USGS earth explorer website.

### **2.3.1.3 MODIS**

MODIS stands for “Moderate - resolution Imaging Spectroradiometer”. It has 36 multispectral bands, 16 of them collect thermal radiance but the resolution is significantly low (1000m). Terra and Aqua satellites have the MODIS on board, Terra satellite passes over the earth in the morning time, north to south while Aqua satellite passes over the earth in the afternoon from south to north. In 1-2 days (NASA, 2017b), Terra and Aqua satellites cover the entire earth surface and this helps significantly in monitoring fires or burning oil rather than spilled oil.

### **2.3.1.4 Landsat**

Landsat missions provide a variety of thermal sensors on board of their satellites (NASA, 2017a). Landsat 3 was the first mission to have a thermal sensor on board but a sensor failure occurred just a while after launching it. 120 m thermal resolution is provided through Landsat 4 and 5 in a single thermal band (band 6) that covers the region 10.40-12.50  $\mu\text{m}$  on the thematic mapper sensor and the 120 m resolution has been resampled to be 30m. Landsat 7 included a similar band on ETM+ but Landsat 8 has (TIRS) a standalone thermal IR sensor, band 10, 11 are the

thermal bands. The spatial resolution for Landsat 8 thermal bands is 100 m but its actually resampled to 30 m just like Landsat 4, 5 and 7. (10.60-11.19, 11.50-12.51) are what Landsat 8 thermal bands 10, 11 covers on the electromagnetic spectrum respectively.

Low resolution satellite thermal bands requires a bigger spill area to be detected because for instance the 100 m thermal band resolution of Landsat 8 means that the size of each pixel is 100m\*100m and it's impossible to identify features within one pixel because it will all be shown the same. On the other hand working with satellite thermal imagery is straightforward and its not difficult to calculate the land surface temperatures. Such satellite sensors works well if its a big oil spill such as the 2010 BP disaster in the Gulf of Mexico (Deep Water Horizon) in which the total discharge was around 4.9 million barrels for instance.

### 3. Methods

#### 3.1 Study Area and Experiments Details

Due to the strict environmental legislations and the quick control for oil spills in the U.S, it is very unlikely to find a random oil spill and that made it difficult to find a study area. In order to get the study done, two approaches were taken to collect data to represent oil contaminations in different medians. For the onshore case study, The Keweenaw Petroleum Services Company (KPSC) has a location in Houghton, Michigan in which they load and unload oil tankers to serve the community in Houghton and Hancock areas.

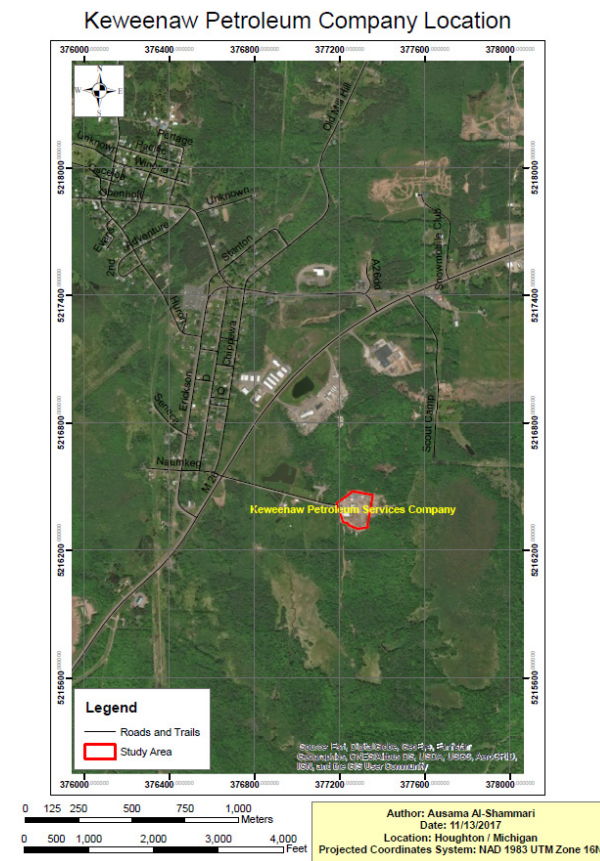


Figure 3.1. Study Area Map Showing the Location of KPSC

After getting the permission from local Police department and the KPSC site manager, a Phantom DJI 4 drone system was flown to observe the very little contaminated soils, concrete floorings in the company location to study the capability of the “Lepton long wave thermal IR Sensor”.

The other case study was the oil spills in waters; the experiment was done using a moderate size bucket of water and manually contaminate it with used engine oil (not crude oil). The field work at the KPSC was done when the temperature was 16 °C (60.8 °F) and the contaminated water experiment was done in a room temperature condition (20.6° C, 69.1° F). To have a simulation similar to real world conditions, the water bucket was exposed to an indirect heating source using two light bulbs each of 1500 Lumen for three hours and temperatures were checked after and before the heating process using a thermometer.



**Figure 3.2.** Oil Water Contamination Experiment

The three hours heating shows a difference in water temperature of 2.5° F (1.8° C) as the temperature measurements were (Before heating: 17.4° C, 64.2° F– After heating: 19.2° C, 66.7° F). in the same time temperatures were measured for the oil layer floating on a controlled area using a smaller plastic container that also had water inside it to treat the oil contamination similar to if it was floating on any part of the bigger water bucket. Oil temperature difference showed a 7.5° F (4.2° C). Oil Temperatures were 66° F, 18.8° C before heating and 73.5° F, 23° C after the heating. This experiment showed technically how oil absorbs more thermal energy than background water if exposed to the same source and same amount of time.



**Figure 3.2.** Water Temperatures (A) Before Heating (B) After Heating



**Figure 3.3.** Oil Temperature Measurements (A) Before Heating (B) After 3 Hours Heating

## 3.2 Equipment Used for The Data Collection

### 3.2.1 Raspberry Pi, Thermal IR Sensor

Lepton® longwave infrared was the thermal sensor used in both experiments. The Lepton sensor is considered as the world's tiniest thermal camera and its capable of providing an array format of 80 X 60 progressive scan (Horizontal, Vertical respectively). Lepton thermal camera works in the range of -40 to +80 °C. its weight is around 0.55 grams and the pixel size is 17µm ("OEM Cameras and Components," 2017).

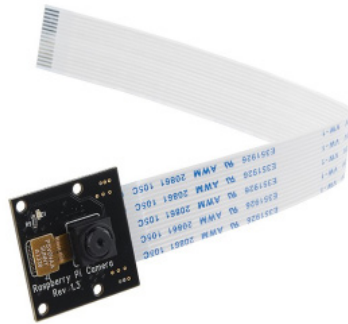


**Figure 3.4.** Lepton Thermal Sensor Adopted From

(Karlsson Robotics, 2017)

The raspberry pie system has also a Pi NoIR camera that cost around 20-30\$. Pi NoIR camera is manufactured by the Raspberry Pi foundation and its useful to collect data in the infra-red wavelength.





**Figure 3.5.** Raspberry Pi NoIR Camera Adopted From  
(Karlsson Robotics, 2018)

The cost of the Lepton LWIR sensor is currently around 260\$ and it requires some software and hardware installations and development to be able to collect data on flight. The raspberry pie single board computer works on a Linux platform and it was programmed to integrate the Lepton LWIR sensor and collect thermal data every 10 seconds and it also had the visible sensor integrated into the system but it was not of a good use because of the low resolution. The whole system was set in Nwazet pi camera box that is just a little bigger than a pack of cigarettes to easily mount it on a UAS

The system required an external power inlet and for this case a mini power bank was very useful to power the system. The data was logged to an SD card fixed in the Raspberry Pi system and it could be accessed and copied to a thumb or hard drives after operating the Linux system and accessing the files.

The fisheye effect in the Pi NoIR camera due to the low focal length (3.6 mm) (RASPBERRY PI BOARD REVISION, 2017) makes it not necessary as long as a high quality visible camera is onboard the UAS. The other problem with the Pi NoIR camera is there is no shutter which contributes to giving distorted images when the camera in movement (Aden, Bialas, Champion, Levin, & McCarty, 2014).

### 3.2.2 DJI Phantom 4 Unmanned Aerial System

The unmanned aerial system used in the field experiment data collection was the DJI Phantom 4. It was flown on an altitude of 75 m above ground level (FAA regulation is 500 feet, 152.4 m) to cover the area of interest with the 12 MP camera sensor mounted on the UAS. UAS systems are classified as either small or medium or large depending on their weights and normal operating altitudes and speeds. The following table shows the details of UAS classifications:

**Table 3.1.** UAS Classification Adopted from (Levin, 2016)

Category	Size	Maximum Cross Takeoff Weight (lbs)	Normal Operating Altitude (ft)	Airspeed (knots)
Group 1	Small	0-20	<1,200 AGL	<100
Group 2	Medium	21-55	<3,500 AGL	<250
Group 3	Large	<1320	<18,000 MSL	<250
Group 4	Larger	>1320	<18,000 MSL	Any airspeed
Group 5	Largest	>1320	>18,00	Any airspeed

\*Note that MSL means Mean Sea Level and AGL means Above Ground Level

Flying the UAS complied with the U.S Federal Aviation Authority (FAA) regulations for recreational / educational purposes that are in the following table:

**Table 3.2.** U.S FAA Regulations for Flying UAS for Recreational/Educational Purposes Adopted from (FAA, 2017)

<b>Requirements</b>	<b>Recreational / Educational Flying</b>
<b>Pilot Requirements</b>	No pilot requirements
<b>Aircraft Requirements</b>	Unless exclusively operated in compliance with Section 336 of Public Law 112-95 (Special Rule for Model Aircraft), the aircraft must be registered if over 0.55 lbs.
<b>Location Requirements</b>	Unless exclusively operated in compliance with Section 336 of Public Law 112-95 (Special Rule for Model Aircraft), the aircraft must be registered if over 0.55 lbs.
<b>Operating Rules</b>	<p>Must ALWAYS yield right of way to manned aircraft</p> <p>Must keep the aircraft in sight (visual line-of-sight)</p> <p>UAS must be under 55 lbs.</p> <p>Must follow community-based safety guidelines</p> <p>Must notify airport and air traffic control tower before flying within 5 miles of an airport</p>
<b>Example Applications</b>	Educational or recreational flying only
<b>Legal or Regulatory Basis</b>	<p>Public Law 112-95, Section 336 – Special Rule for Model Aircraft</p> <p>FAA Interpretation of the Special Rule for Model Aircraft</p>

### 3.2.2.1 DJI Phantom 4 Specifications

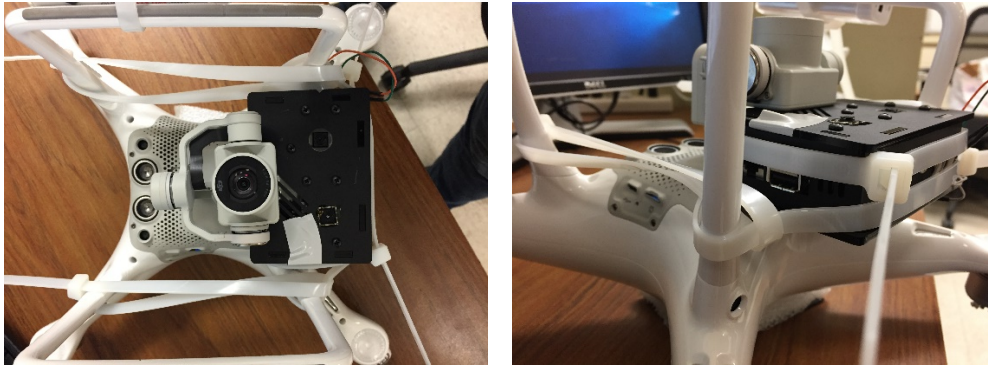
**Table 3.3.** DJI Phantom 4 Drone System Specifications adopted from  
(Drone World, 2017)

Weight	3 lbs.
Max Ascent Speed	13.4 MPH
Max Descent Speed	8.9 MPH
Max Forward Speed	45 MPH
Max Ceiling	400 ft. (Electronically Limited)
Max Flight Time	28 min.
Operating Temp	32° to 104°F
Satellite Systems	GPS & GLONASS
Obstacle Sensory Range	2 to 49 ft.
Gimbal Control Range	-90° to +30° Pitch
Camera Sensor	1/2.3"
Lens FOV	94°
ISO Range	100-3200
Max Image Size	4000x3000
Max Video Size	4096x2160
Max Video Bitrate	60 Mbps
File Systems	FAT32, exFAT
Photo Formats	JPEG, DNG
Video Formats	MP4, MOV, MPEG
Charger Specs	17.4v, 100w
Remote Frequency	2.400-2.483 GHz
Max Transmission Range	3.1 mi.
Battery Model	Intelligent Flight PH4
Battery Specs	5,350 mAh, 15.2v

The DJI Phantom 4 UAS showed great quality pictures with minimal / no distortions and a very good stability in flying without additional sensor attachments. Its gimbal stabilization is of three axis (roll, pitch and yaw) and the angular control accuracy is  $\pm 0.02^\circ$ .

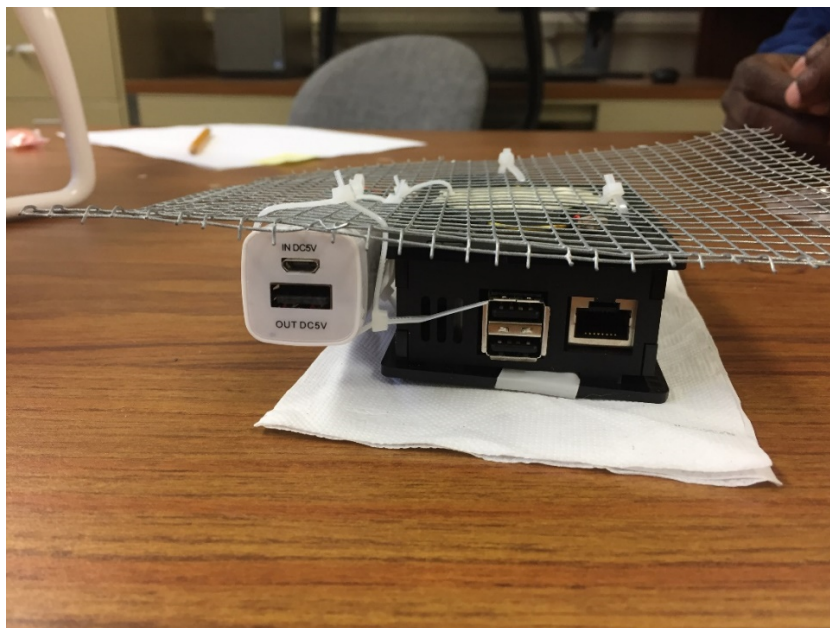
Attaching the Raspberry pie box was tricky because attaching it on one side of the UAS and flying it caused some instability to the drone and it was moving towards the heavier side where the sensor was attached and it was very hard to control the

drone to hover over a certain location or even landing it. It apparently affected the aerodynamics. The figure in next page shows how it was mounted the first time:



**Figure 3.6.** First Mounting of the Raspberry Pi Box on The Side of UAS

To avoid this, the Raspberry Pi box needed to be in the center. A mesh wire was used to be the top of the box that has the power band and the Raspberry Pi system for not interrupting the drone aerodynamics, the figure below shows how it was done.



**Figure 3.7.** Using Mesh Wire to Ease the Airflow underneath UAS

Another challenge in mounting the sensor this way was when landing the UAS the camera and thermal sensors are going to touch the ground as they are in the bottom and the UAS will be sitting on it. This may scratch the lenses or even breaking the whole box if there was a big impact in landing on a hard surface as well as it leads to a landing failure, which may break the UAS itself. Some working sites like in refineries or drilling locations considers this as an incident that might be fatal due to the risks involved in these locations. Another idea is to conclude the sensor box and the power bank in a small lightweight carton box that has strong edges to be the landing platform. The figure below shows the UAS and the attachment.



**Figure 3.8. The Final System Used in the Data Collection**

This explained process required having two flights instead of just one because the visible camera sensor is covered with the carton box and could not be used unless the Raspberry Pi system is unmounted but this process worked perfectly and the drone was very stable in flying and hovering except it became a little bit slower in maneuvering.

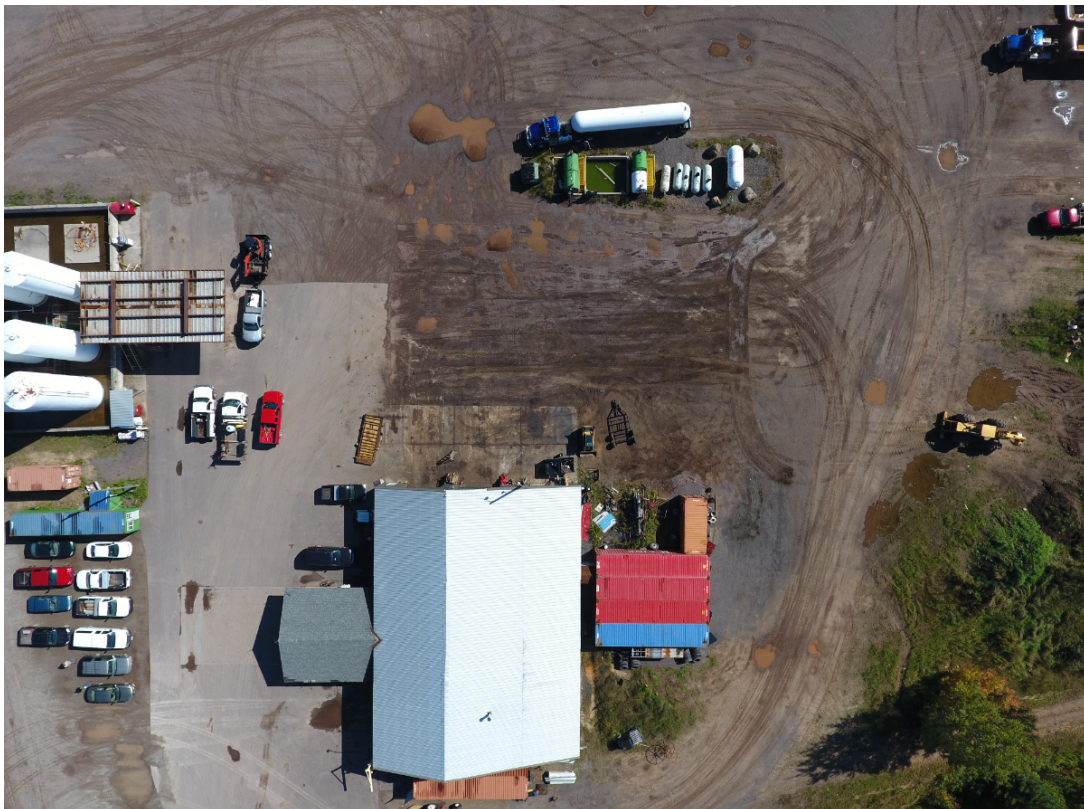
## 4. Study Results

### 4.1 Creating Classification maps

After the images were collected using the DJI Phantom 4 drone system, and a canon 600D for the indoor water experiment, as well as the data collection using Lepton thermal sensor, we created a classification map for every image taken before and after fusing the thermal images into the RGB images. This method was considered to see the behavior of the thermal sensor used and how this reflects on the classification results.

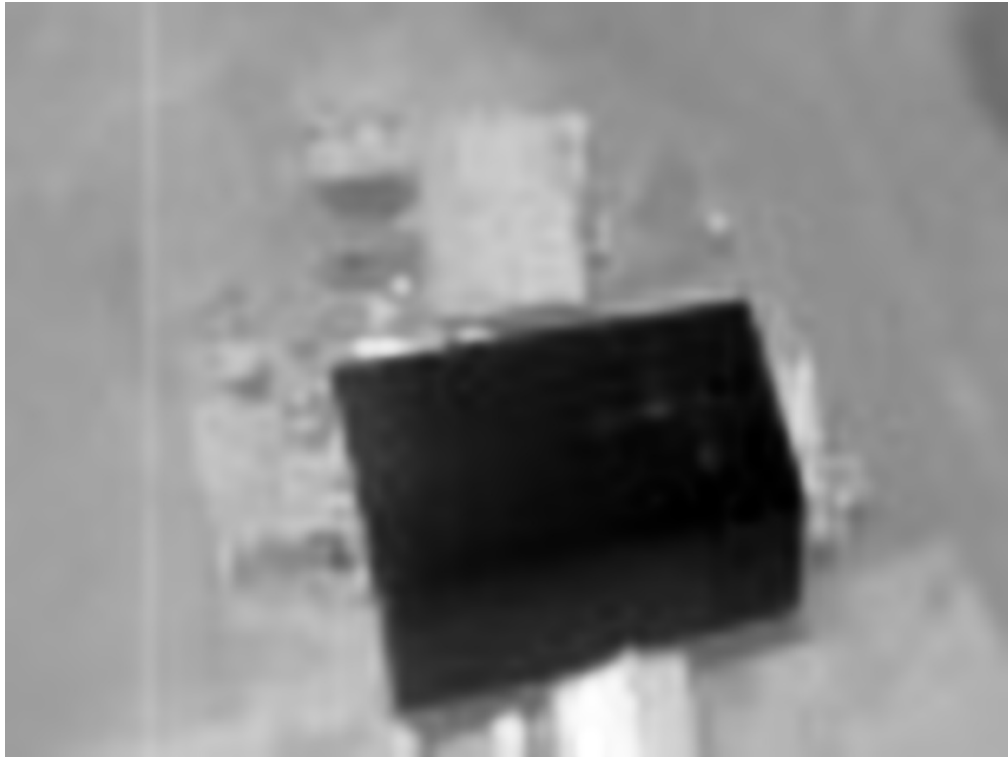
Unfortunately, the Lepton thermal sensor did not provide temperature values as it only produces digital numbers representing the heat variations in the resulted image. Unlike satellites, which could provide it throughout running equations that calculates land's surface temperatures. Working with the symbology in ArcMap V. 10.5.1, an ESRI software helped in differentiating nominal cool from hot areas in the images to an extent. This lead to integrate the thermal images as a synthetic color into the RGB images of the same locations and treat the thermal images as a band to replace the red band from the RGB images for enhancing the RGB images for classification purposes. The first step was separating high quality images from lower quality ones based on image visualization for distortions and area coverage. Secondly, there was a need to clip the images to have the area of interest covered by both sensors. Before clipping images, they had to be georeferenced using *image-to-image* registration due to the unavailability of a predefined coordinates system in the drone system and not having ground control points (GCPs). Thermal images were 60 X 80 pixels whereas the RGB images were 3000 X 4000 pixels for the DJI Phantom 4 camera and 1209 X 859 for the Canon 600D camera. Images did not line up perfectly on top of each other because of the different focal lengths of lenses and the capability of area coverage as well as the sensor rotation while capturing the images. Therefore, thermal images where resized to the max (3068 X 3699) pixels

and after using the extract by mask tool in ArcMap, DJI image for the area of interest (in the KPCS) size was 2227 X 2283 Pixels. The thermal image was resized to match the DJI image pixels number in order to fuse them because fusing both images without having the same pixel size and number of pixels results in an error of having a not matching spatial extent (ENVI was used to generate the fused images). The resulted ground resolution distance was approximately 27 mm by dividing a known distance by the number of pixels in the image. I used the width of the containers (2.44 meters standard) as the known distance.



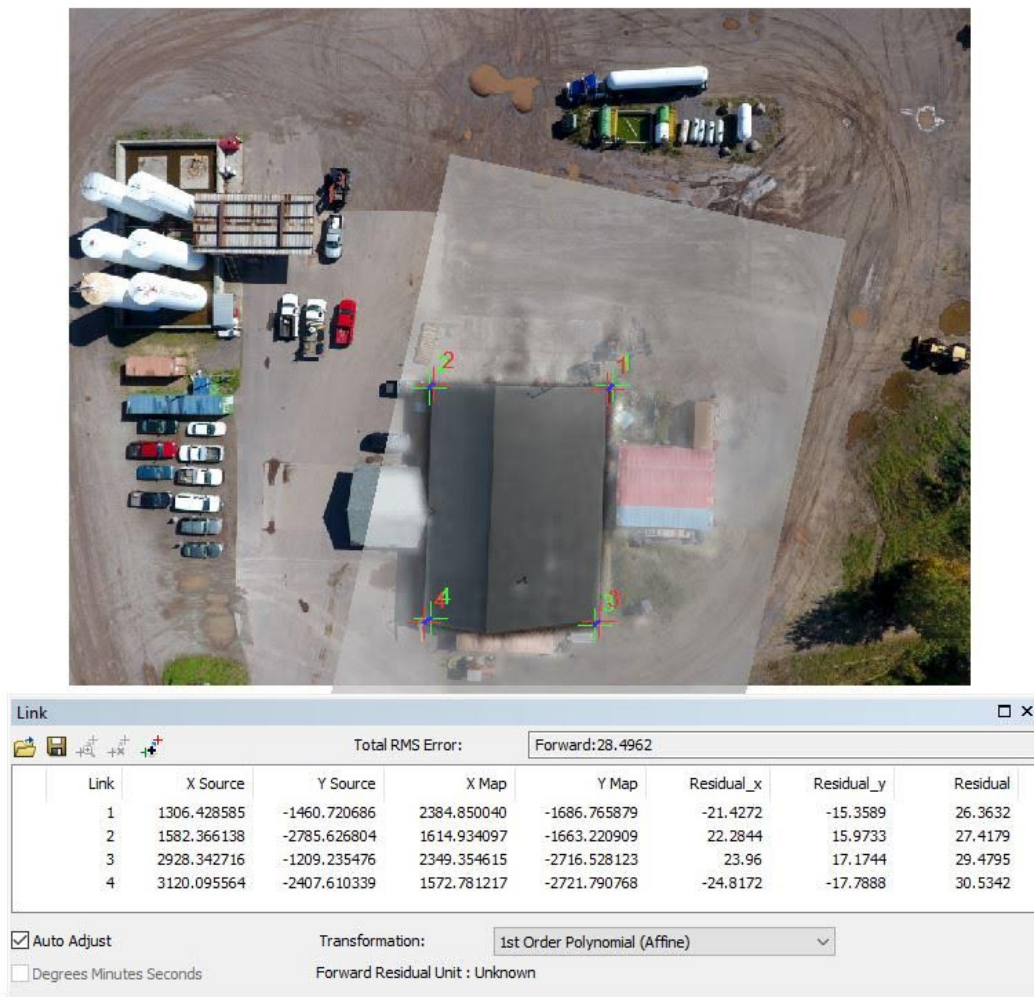
**Figure 4.1.** KPCS Location Image Captured Using DJI Phantom 4 UAS





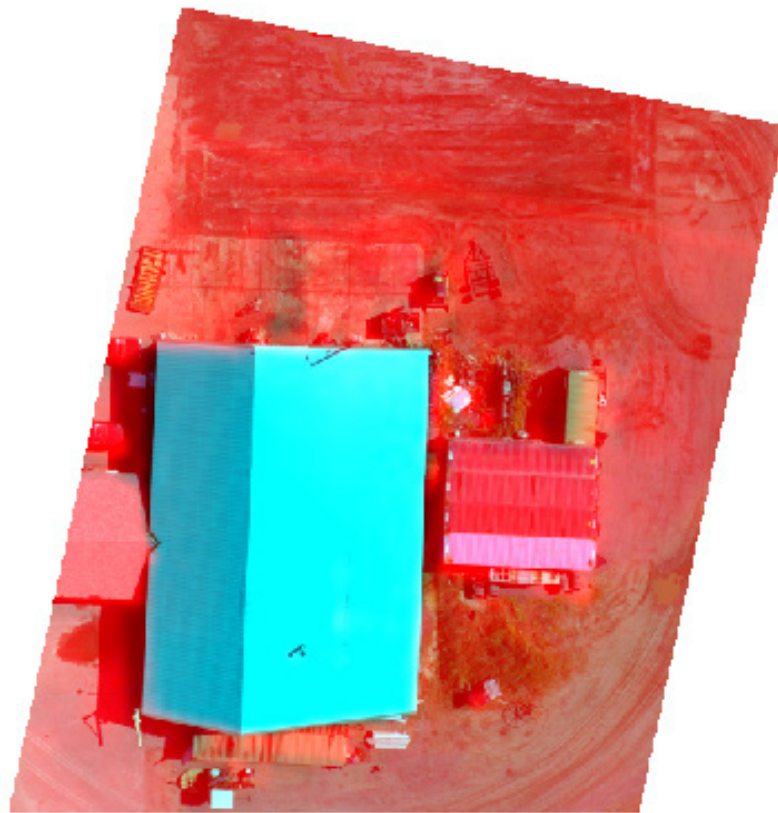
**Figure 4.2.** Lepton thermal sensor resized Image

(notice the presence of false data strip recorded in the top quarter of the image)



**Figure 4.3.** Image to Image Registration Results

The image to image registration using ArcMap resulted in a total RMS error of 28.49 pixels (using a 1<sup>st</sup> order polynomial method) due to the very small area covered and having a very limited features on site that could be observed in both images and this is considered a negative point for this UAS system.



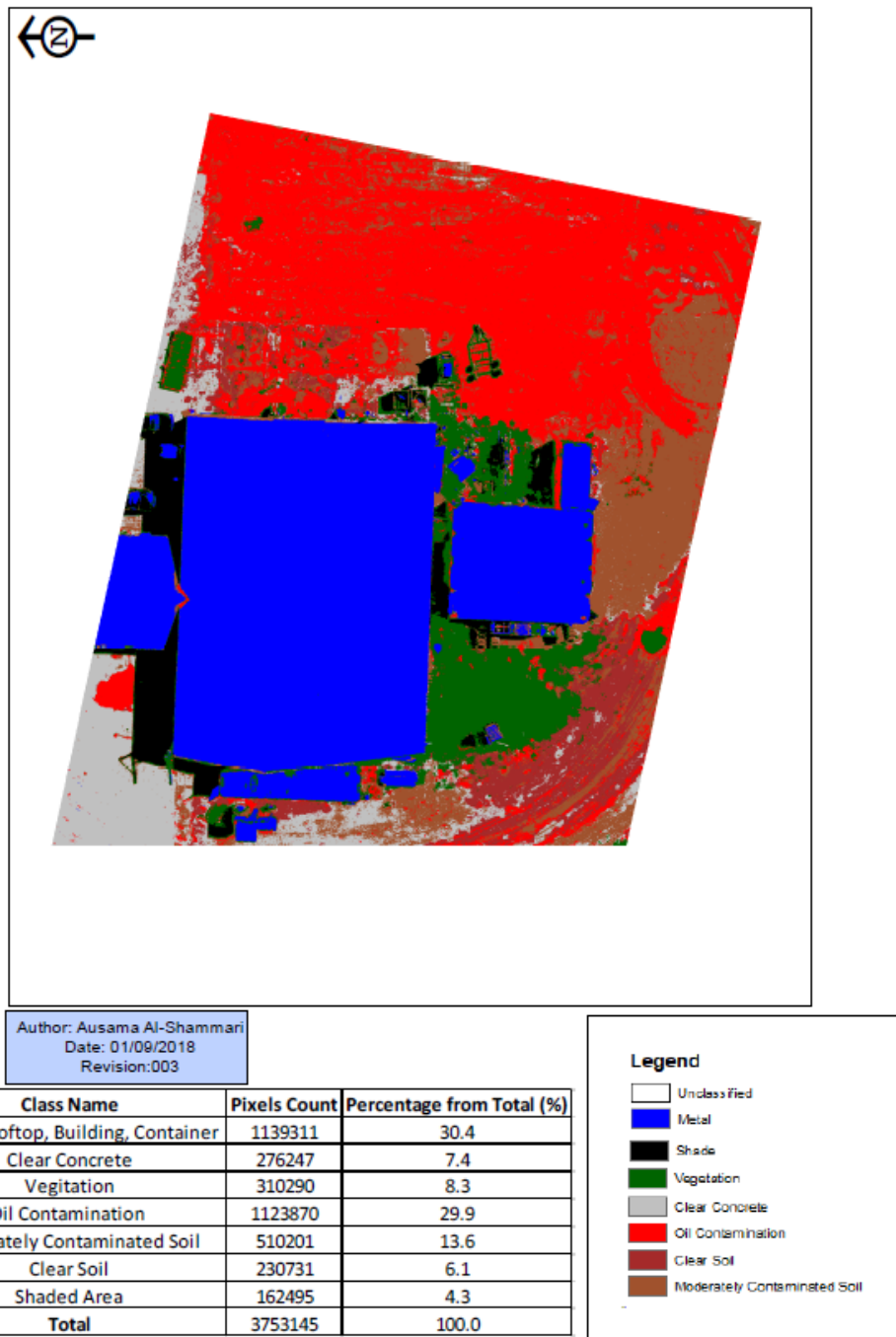
**Figure 4.4.** The fused image product (Field Experiment)

(Cyan represents the cool objects and red represents hot objects)

As we can see in the fused image (Fig. 4.4.) the presence of the false recorded thermal data line and also the little shift in the thermal data on top of the visible image due to the image registration with no proper ground control points.

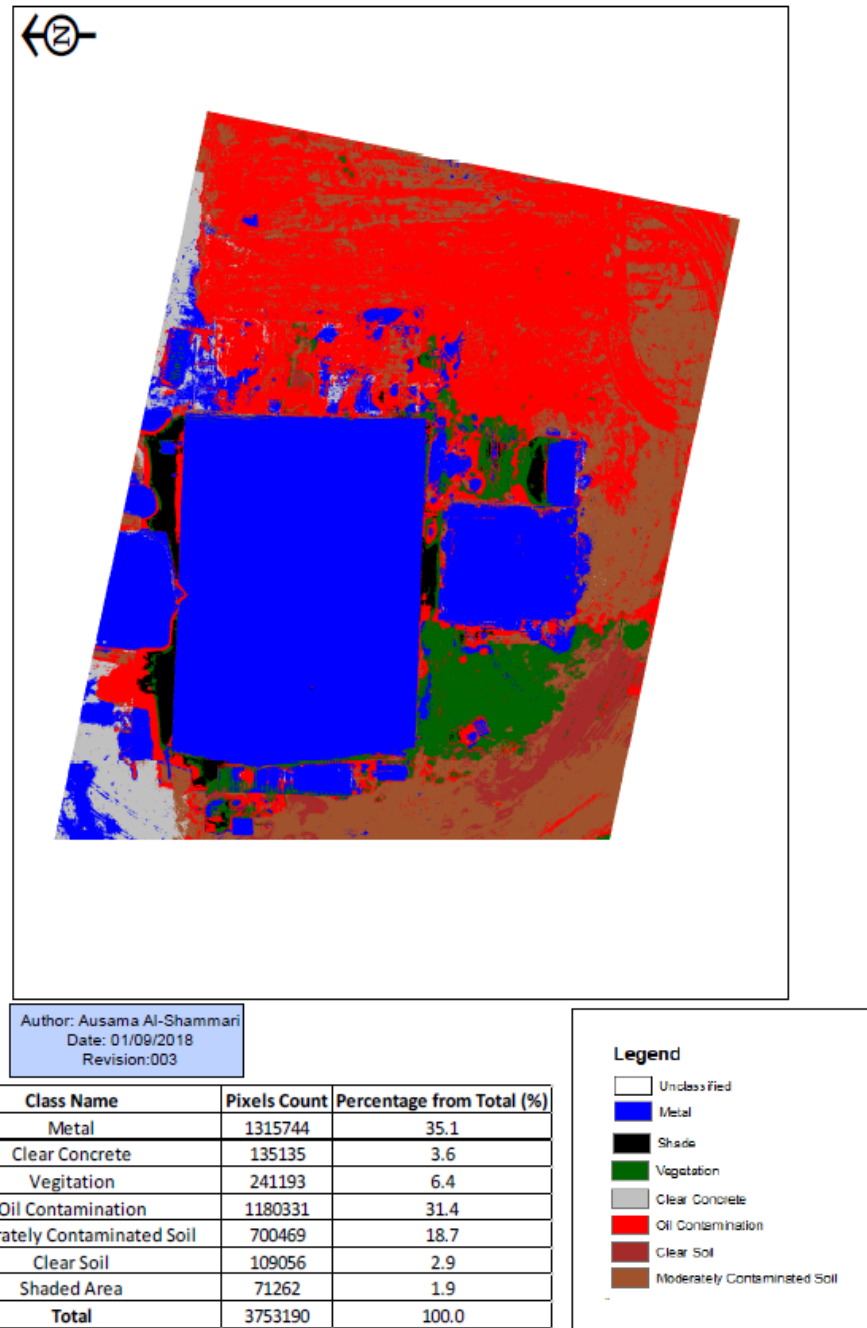
The last step after having the fused image ready is running a supervised classification method for both the original RGB image product from the DJI phantom 4 UAS camera and the fused image product using a maximum likelihood parametric rule and 5 training sites for the signature file for each feature as well as 10 training sites for the oil contaminated locations.

## DJI Phantom 4 RGB Image Classification Map



**Figure 4.5.** Classification map for the DJI phantom 4 RGB image

## Fused Product Classification Map



**Figure 4.6.** Classification map for the fused image

From interpreting the previous maps, each image has misleading results and confusions that lead to generate confusion matrices (Accuracy Assessment) for both RGB classified image as well as the fused classified image.

**Table 4.1.** Accuracy Assessment for RGB Classified Image

Class	Metal	Shade	Vegetation	Clear Concrete	Oil Contamination	Clear Soil	Mod. Cont. Soil	Ground Truth
<b>Metal</b>	7	1	1	0	1	0	0	10
<b>Shade</b>	0	10	0	0	0	0	0	10
<b>Vegetation</b>	0	0	10	0	0	0	0	10
<b>Clear Concrete</b>	0	0	0	10	0	0	0	10
<b>Oil Contamination</b>	0	0	0	0	8	0	2	10
<b>Clear Soil</b>	0	0	0	0	0	10	0	10
<b>Mod. Cont. Soil</b>	0	0	0	0	1	0	9	10
<b>Total</b>	7	11	11	10	10	10	11	70

<b>Producer's Accuracy</b>	
<b>Metal</b>	100%
<b>Shade</b>	90.90%
<b>Vegetation</b>	90.90%
<b>Clear Concrete</b>	100%
<b>Oil Contamination</b>	80%
<b>Clear Soil</b>	100%
<b>Mod. Cont. Soil</b>	81.80%
<b>Overall</b>	92%
<b>Omission</b>	8%

<b>User's Accuracy:</b>	
<b>Metal</b>	70%
<b>Shade</b>	100%
<b>Vegetation</b>	100%
<b>Clear Concrete</b>	100%
<b>Oil Contamination</b>	80%
<b>Clear Soil</b>	100%
<b>Mod. Cont. Soil</b>	90%
<b>Overall</b>	91.40%
<b>Commission</b>	8.60%

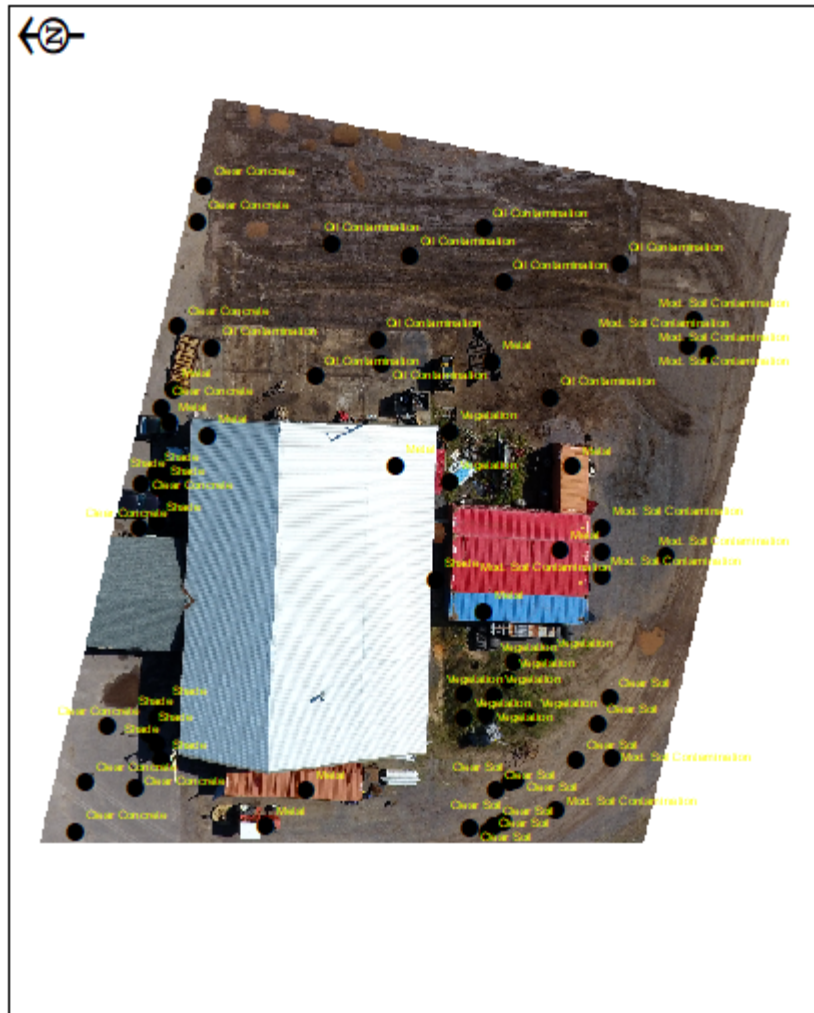
**Table 4.2.** Accuracy Assessment for Fused Classified Image

Class	Metal	Shade	Vegetation	Clear Concrete	Oil Contamination	Clear Soil	Mod. Cont. Soil	Ground Truth
Metal	7			0	2	0	1	10
Shade	1	4	0	0	5	0	0	10
Vegetation	2	0	8	0	0	0	0	10
Clear Concrete	3	0	0	6	0	0	1	10
Oil Contamination	0	0	0	0	9	0	1	10
Clear Soil	0	0	0	0	0	6	4	10
Mod. Cont. Soil	2	0	0	0	1	0	7	10
<b>Total</b>	<b>15</b>	<b>4</b>	<b>8</b>	<b>6</b>	<b>17</b>	<b>6</b>	<b>14</b>	<b>70</b>

Producer's Accuracy	
Metal	47%
Shade	100%
Vegetation	100%
Clear Concrete	100%
Oil Contamination	53%
Clear Soil	100%
Mod. Cont. Soil	50%
Overall %	78.57
Omission %	21.43

User's Accuracy:	
Metal	70%
Shade	40%
Vegetation	80%
Clear Concrete	60%
Oil Contamination	90%
Clear Soil	60%
Mod. Cont. Soil	70%
Overall %	67.14
Commission %	32.86

## Reference Points Locations Used for Accuracy Assessment



### Legend

● Reference\_Points

Author: A usa ma Al-Shamari  
Date: 01/31/2018  
Revision: 001

**Figure 4.7.** Map showing the locations used for the accuracy assessment

(10 Points used for each class due to the small area of interest)

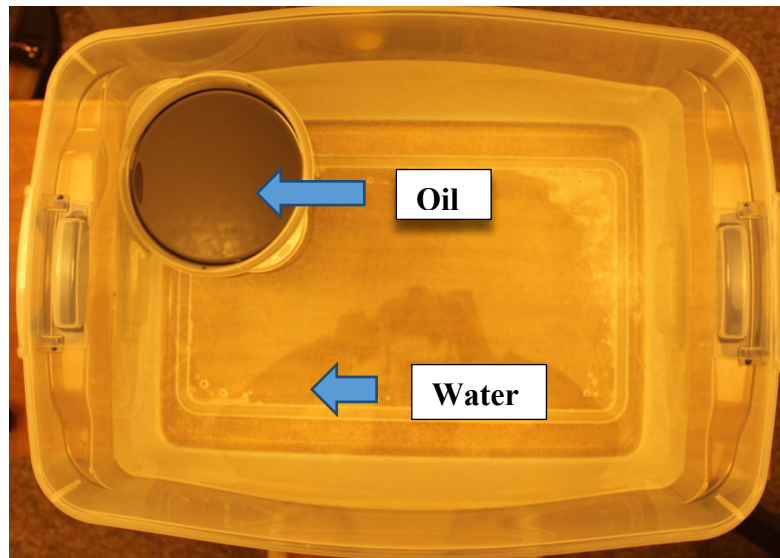


False results in the RGB image are due to the same brightness value for some objects while the false results in the fused image are due to the similar temperature values for multiple objects at that certain time of the day.

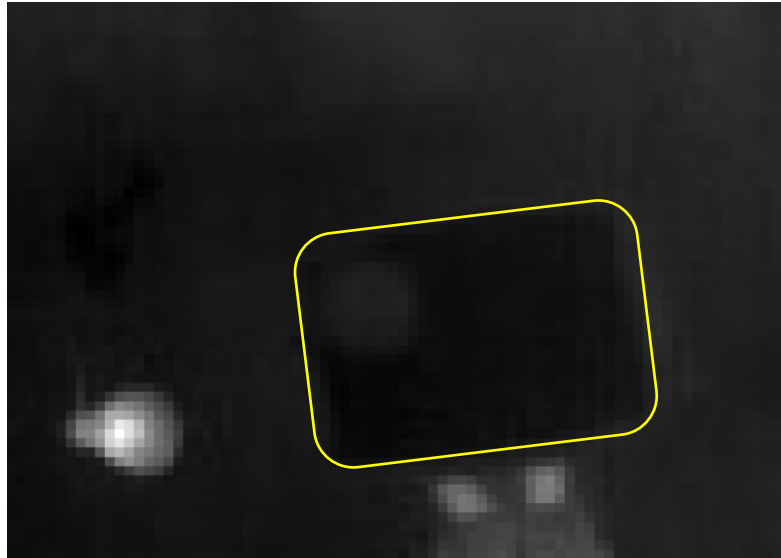
The lesson learned from this experiment is the thermal sensor is not the best option for the onshore operations where there is more than one object and there is a wide variation in temperatures around the contaminated area, this makes it nearly impossible to detect and differentiate the contaminated areas.

For this reason I conducted another experiment to see how the Lepton thermal sensor would work if there were only two mediums, water and oil.

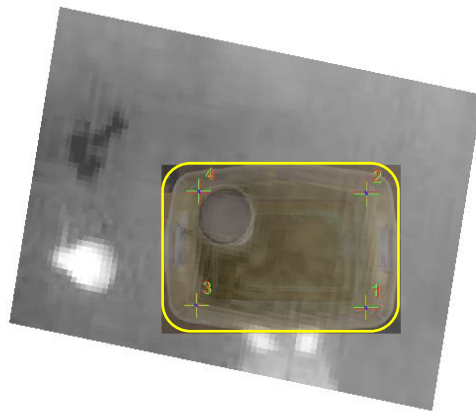
A Canon 600D camera replaced the DJI phantom 4 UAS system for this experiment to avoid flying and crashing it indoors due to the limited space and low ceiling as well as electromagnetic interference that cuts the connection between the drone and controller.



**Figure 4.7.** Canon 600D image used in the water-oil experiment



**Figure 4.8.** Lepton thermal image used in the water-oil experiment



Link

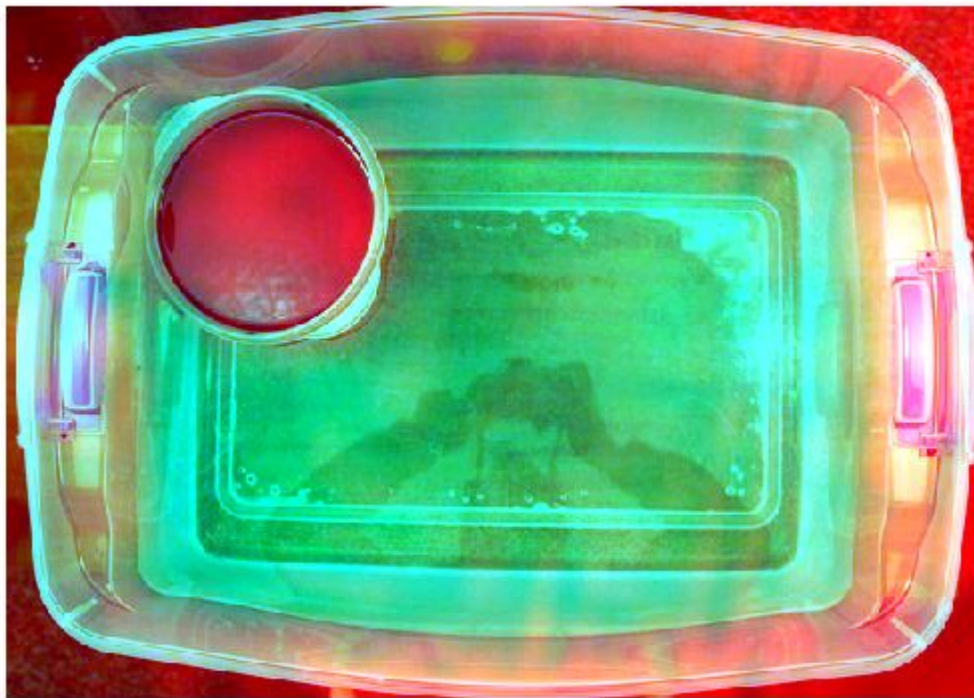
Total RMS Error: Forward:8.99642

Link	X Source	Y Source	X Map	Y Map	Residual_x	Residual_y	Residual
<input checked="" type="checkbox"/> 1	231.678158	-236.044471	1037.489705	-730.832882	6.63014	-6.12792	9.0283
<input checked="" type="checkbox"/> 2	277.564362	-537.002422	1032.429685	-139.141045	-6.64273	6.13956	9.04545
<input checked="" type="checkbox"/> 3	700.046541	-148.626187	167.028217	-708.758142	-6.57059	6.07288	8.94721
<input checked="" type="checkbox"/> 4	745.452041	-452.473923	190.108747	-136.268371	6.58318	-6.08452	8.96435

Auto Adjust      Transformation: 1st Order Polynomial (Affine)       Degrees Minutes Seconds      Forward Residual Unit : Unknown

**Figure 4.9.** Water-Oil experiment Image to image registration

Image to image registration shows 8.996 pixels as the total RMS error. The corners used in the images registration were the corners of the bucket where the upper level of water reaches. This is not practical for a real world disaster because there might be no objects around the spill or there are some features not distributed on site in a way makes no use of it. Therefore, some objects should be distributed around the spill or the best scenario is using a better thermal sensor that provides better imaging than the Lepton (RGB + Thermal in one product), but costs will be higher.



**Figure 4.10.** Fused image of the water-oil experiment

In the fused image, the reddish color represents higher temperatures and green is cooler. The oil, shown in red (Fig 4.10) has a reddish color as well as the plastic water container containing the oil because plastic absorbs thermal energy more than water so the areas of water looks green because its much cooler than the oil patch or the plastic.

Next step is running a supervised classification algorithm using ERDAS Imagine software for both the RGB image and the fused image to see how having the thermal image replacing the red band in the RGB image impacts the results. The images were clipped to an area of interest before running the classification process to minimize the confusion of the temperature variances of the plastic container. We used three training signatures for each class (water and oil).



**Figure 4.11.** RGB image classification where red is water and black is oil



**Figure 4.12.** Fused image classification where yellow is water and blue is oil

## 4.2 Conclusion

The inexpensive Lepton thermal sensor used in this research showed that it is capable of being used for oil spill detection, it helps in the visualization of oil spills for disaster management purposes. Calculating oil spill surface area is feasible; however, volume is not because depth cannot be measured with thermal sensors unlike laser sensors. Lepton thermal sensor has shown great results when having only two mediums. In the second experiment, it reflected very close results to what the RGB image, given that the RGB imaging system is not practical in night operations. Therefore, Lepton thermal sensor is able to produce great results for the different temperatures of oil and water (which is a typical application scenario with oil spills) but for limited altitudes due to fisheye effect as images gets more distortions. Other thermal sensors manufacturers has provided limitations for the maximum altitudes to work with.

Working with oil slicks offshore is kind of a tricky situation for environmental treatment due to the oil spread and the movement of water due to tides or in the case of rivers, a flowing water. The environmental cleanup after an oil spill disaster in water bodies is accomplished by identifying the thickest oil patches and skimming the surface. Skimming can only be accomplished in calm water by containing the oil using collection booms. Other treatment scenarios are either burning or chemically dispersing the oil unless the spill is near shore, then only skimming is allowed (NOAA, 2018). For all the previously mentioned oil spill conditions, it is always better to start with the thick oil patches soon after the spill, clean it up before it spreads and becomes more difficult, and time consuming. In the water-oil experiment, the target was used engine oil because crude oil was unavailable. In thermal imaging offshore, oil is shown as a hotter area in the daytime and cooler than water during nighttime because oil tends to absorb the thermal energy faster than water during the daytime and cools down faster than water during nighttime, depending on oil layers thickness. Thicker patches absorbs more heat during the

daytime (M. Fingas, 2016). Therefore, crude oil could have more temperature variances than the used engine oil. This would enable better thermal sensor detection. In addition, the sensitivity of thermal sensors is an important factor in the detection of variant temperatures.

To compare using a UAS thermal sensor to common methods using a manned aircraft, a Lepton sensor mounted on a quadcopter UAS system could minimize the field exposure, risks and costs involved. However, using UAS systems depends on many factors that must be considered first such as budget, sensors and drone capability, area size needs to be covered and takeoff/landing space required.

Challenges to consider when working with Lepton thermal sensor for oil spill detection and monitoring:

- Fisheye effect if the Lepton sensor flown over a high altitude.
- Different angles of the Lepton and the drone system camera may result in misleading results if bands fusion needed.
- Field of view
- Lepton output needed to be georeferenced to the RGB image to execute the classification because it gives more understanding for the area than just a classification for the thermal image where features are hardly identified. The image-to-image registration is not practical when working offshore because fixed objects are not easy to establish, and in onshore scenarios, it is not very precise.
- The need to resize the thermal images due to the smaller pixel array to match the size of RGB images if the job requires a data fusion.
- Lepton thermal sensor does not have a built-in GPS.

Better devices are available in the market but the cost is much higher than a Lepton thermal sensor. For example, FLIR DUO Pro Radiometric Sensor cost around 5200\$ and it has great features including the capability of visible imaging, thermal

and IR in visible imaging which saves time and minimizes human errors by terminating the need to register images one to the other for the visualization. FLIR DUO sensor has a gyroscope, remote controller. It has a built-in GPS and the thermal sensitivity for Lepton and FLIR DUO Pro is the same  $<50 \text{ mK}$  ( $0.050^\circ\text{C}$ ) (FLIR Duo Pro R Overview, 2017) (Lepton® LWIR Camera Modules, 2015).

Such systems like the FLIR DUO Pro Radiometer saves time also in its operation, much more accurate observations and easier than mounting a Lepton sensor on a UAS as it comes with mounting features. Also depending on the availability of sufficient takeoff/landing space and budget, oil spills detection could be better mapped using more expensive UAS such as the ebee system. The ebee (senseFly drone system) is capable of covering 4.6 square miles area in a single automated flight. Also having different types of sensors on board (RGB, Multispectral and Thermal). eBee system costs roughly around 25000\$ at the moment (supplied with only the RGB sensor) and comes with a processing software.

It is important to mention the challenge in working with thermal sensors for offshore operations; it is very challenging to tie images together in open water cases. However, it is a good option to work with it for oil spill cases in rivers or small lakes where the shorelines are seen in the images, which help in identifying control points.

A Lepton sensor can still be used for less environmental threatening jobs like smaller spills from a pipeline break onshore when there is only oil and soil for example or a small spill in a marsh or a lake. In such condition, a UAS system helps very much in the planning for controlling the spill directions by flying the UAS and easily extracting a preliminary data to know the area elevations / slopes for onshore cases and areas size of spills but it will consume a little bit of time.

### **4.3 Recommendations**

Users interested in mobile applications should explore options other than the DJI go application such as Drone Deploy or precision mapper for example because These applications gives the ability to better control the UAS and automate the flight. In this case, even if using Lepton sensor, the drone could be sent to exactly the same point and the same altitude better than doing this manually and ending up with oblique or shifted images. Also DJI go doesn't offer data processing (Mosaicking). If larger areas needs to be covered drone deploy app for example is capable of processing the images captured and produce a 2D or 3D map and also gives the ability to measure distances on created maps.

My recommendations for thermal sensor for oil detection is to use a one piece sensor that is capable of capturing images with visible + IR bands as explained earlier in the conclusions. It minimizes human input and the time consumed for processing in situations where time worth a lot, this way makes it much more practical to calculate areas of contamination by having one sensor mounted and GPS supported.



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