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Solving Aviation Fuel Complexities through Hyper Spectral Imaging

Optimizing fuel maintenance, eliminating safety hazards and assuring the highest quality

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Introduction

Aviation turbine fuel is used to power the main engines of civil and military aircrafts. It is also used to run auxiliary power units that generate aircraft electrical power. Contaminants in aviation fuel are a serious safety hazard and undoubtedly one of the biggest concerns for the air transportation industry.

Current maintenance procedures required to monitor fuel quality are manual and hence are an operational cost burden for the aircraft operators. Aircraft utilization is affected as they have to be grounded to perform these maintenance procedures; there is also a human element to the integrity of the test results. With increasing fuel costs, airlines and OEMs are looking for ways to optimize the maintenance activities without compromising on safety.

To address the fossil fuel depletion and to reduce the carbon footprint, there is a growing interest in biofuels and experiments are being conducted for adoption of blended fuels. With this change, it is anticipated that there will be a greater need for advanced testing methodologies to ensure that the fuel entering the aircraft is clean, dry and safe.

Air transport is poised for an exponential growth and with airline fuel bills worldwide projected to be USD 216 billion this year (2013) and an overall estimate of 33% of operating cost attributed to fuel; aviation fuel is a big business worldwide[1]. Shell Aviation re-fuels one aircraft every 12 seconds across 800 airports in over 40 countries for about 7000 aircrafts[2].

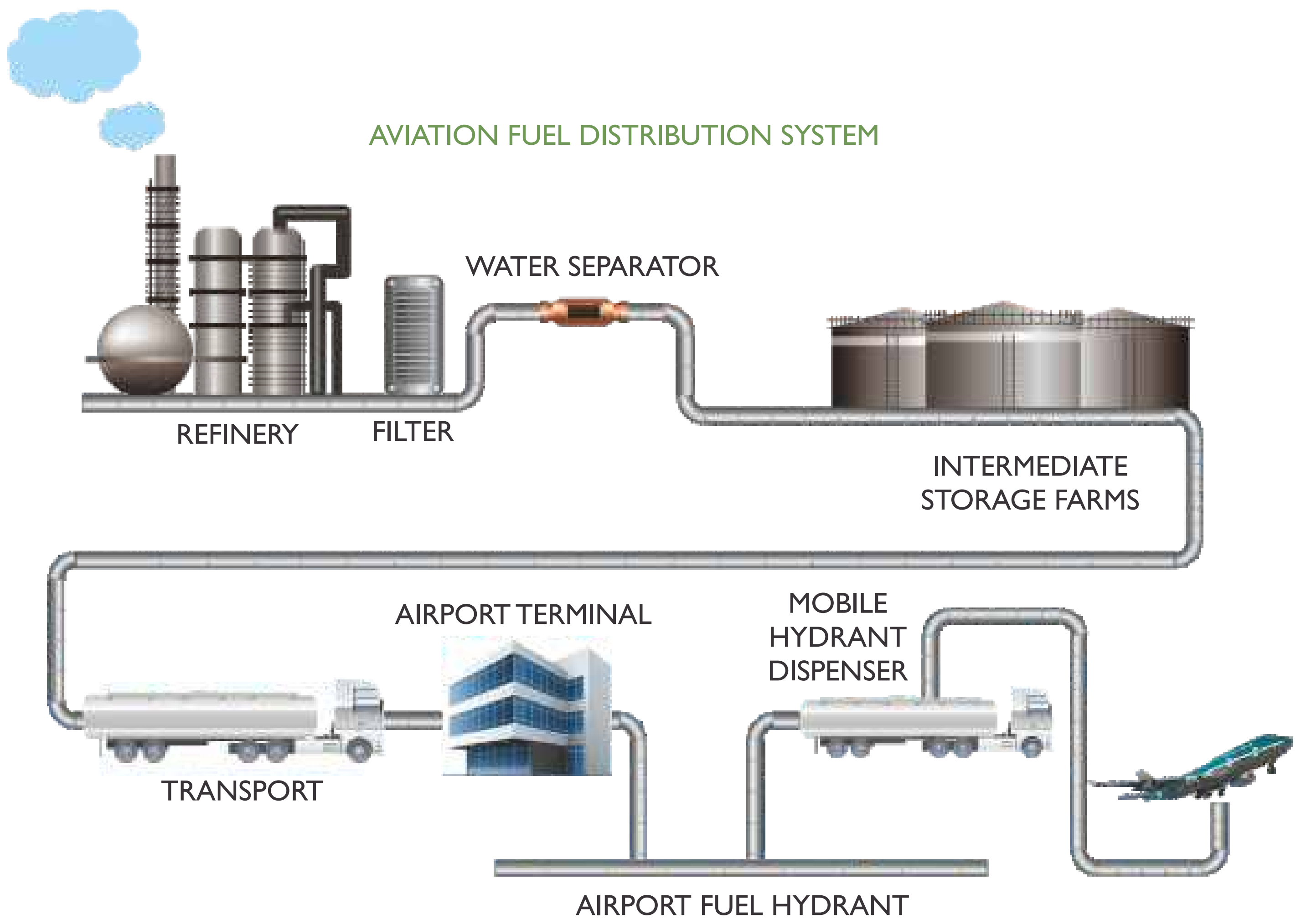
[1] *http://www.livemint.com/Companies/7cefHvK1KcumJfRSImucmI/IATA-raises-profit-outlook-for-worlds-airlines.html*
[2] *http://www.shell.com/global/products-services/solutions-for-businesses/aviation.html*

This paper highlights the safety aspects of aviation fuel and its handling procedures and proposes a solution using hyper spectral imaging to rapidly and accurately detect the presence of contaminants.

Aviation Fuel Supply Chain: A Brief Background

Fuel costs comprise of the bulk of the operational costs for an airline. There is a large ecosystem directly or indirectly connected with aviation fuels:

1. The oil companies and their refineries
2. Distributors
3. Shipping companies (land and waterways)
4. Third party organizations who undertake refueling operations
5. Companies that build refueling vehicles, pipelines, storage systems and filtering units
6. Companies that build laboratory instruments for quality control
7. Aircraft engine manufacturers who perform tests and approve type certification of their engines for a specific fuel
8. Aircraft OEMs
9. Airlines
10. Airports
11. Standards bodies that frame quality control procedures, publish and maintain fuel specifications, undertake incident investigations and serve as an independent body for facility inspection, monitor fuel quality and handling procedures
12. Government controlled regulatory bodies such as FAA (Federal Aviation Administration) and EASA (European Aviation Safety Agency), which create governing policies and also monitor and review various aspects dealing with aviation fuels and grant approvals and certificates



There are several stages in the distribution of aviation fuel from the oil refineries to the airport storage tanks, before it reaches the aircraft wing for re-fueling. Depending on the logistics, the fuel is transported by land in large trucks, railway wagons or by ships (tankers) for transoceanic routes and inland waterways. Distributors may have intermediate storage tank farms for longer routes.

Most of the large airports are connected through pipelines to the main receiving storage tanks at the airport terminal. These are connected by underground pipelines to several fixed fuel hydrants on the tarmac in designated places where aircrafts are parked. Mobile refueling vehicles dispense fuel to the aircrafts from the fixed hydrants. They usually have pumps, monitoring and filtering systems to control the fuel being delivered to aircrafts.

It is of paramount importance for aviation fuel to be clean, dry, and as per specification. International standard bodies publish the standards, specifications as well as accepted quality control procedures. They also continuously monitor and audit fuel handling and storage around the world and report non-conformance.

For large commercial jets, the fuel grades are JET-A and JET-A1. While JET-A is used in North America for domestic as well as international routes, JET-A1 is the predominant fuel used in the rest of the world.

ASTM (American Society for Testing and Materials), AFWG (Aviation Fuels Working Group) of the IATA (International Air Transport Association) and JIG[3] (Joint Inspection Group) are some of the leading agencies working on standards and specifications.

Aviation Fuel Hazards

On 17 January 2008, a British Airways Flight-BA038 (a Boeing 777-200ER aircraft) from Beijing crashed while landing at the London Heathrow Airport. Investigations revealed that fuel lines had clogged due to ice formation from water present in the fuel and the aircraft's engines could not respond to the thrust demanded by the auto throttle during landing[4].

On 13th April 2010, a Cathay Pacific Flight CPA780 (an Airbus A330-342 aircraft) made an emergency landing at the Hong Kong International airport due to the loss of engine thrust control. Investigations revealed that contaminations in the fuel lines had clogged the fuel valves, immobilizing them. These contaminants possibly originated from the fuel dispensing unit where the aircraft was last re-fueled.

Though the above two incidents can possibly be attributed to design and operational flaws (as reported by AAIB[5] and the Hong Kong Civil Aviation Department), there is no doubt that any kind of fuel contamination is a highly critical safety situation.

Fuel quality checks are mandated and audited at every stage in the distribution, from the time it is taken from the fuel supplier's terminal till it is pumped into the aircraft's fuel tanks. However, despite these quality checks, there is a high possibility of contamination exceeding allowed limits.

Aviation fuel: Effects of Off-Spec and Contamination

Some of the important properties and characteristics of aviation fuel are its specific gravity, viscosity, freezing point, flash point, calorific value/specific energy, composition (hydrocarbons, sulphur etc.) and maximum allowed contaminant concentrations.

Fuels that deviate from the standard specification can cause mishaps. Depending on the extent of the deviation, it also results in suboptimal engine performance such as reduced thrust and efficiency and increased emissions. It can also cause long-term effects on the engine, leading to reduced service life. Fuel contaminations usually result in disastrous consequences. Fuel can be contaminated with water, solid particulate matter and micro-organisms.

Water contamination

Water can enter the system due to the water separator or filter malfunction and non-conformance in the distribution, storage and re-fueling procedures. Dispersed water that enters the aircraft fuel system can cause loss of engine thrust or in the worst case, an engine flameout. As per standards, the threshold limit for water in aviation fuel is 30ppm (at 20°C).

Excess water causes corrosion of the inner walls of the fuel tanks generating rust particles. Prolonged exposure increases the possibility of water ingress into the composite parts of modern aircrafts, endangering its structural properties.

Excess water contamination in the aircraft's fuel tanks is also likely to affect fuel volume estimation (on aircrafts with capacitive sensors). This is

[3]Group with representations from major oil companies | [4]Ice accumulation from precipitated water had clogged the Fuel Oil Heat Exchanger
[5]Air Accidents Investigation Branch

because the dielectric strength of water is significantly different from that of fuel and will cause the sensors to pick up erroneous fuel levels. Calculation of fuel mass is also likely to be erroneous since the fuel density sensors will also be inaccurate for the same reason. On aircrafts with fuel balancing systems, this can lead to inaccurate CG computation and an inefficient flight control trim. Microbial sludge formation can also get entrapped in the sensor assemblies resulting in faulty measurements. Since the aircraft's Flight Management System depends on these sensor measurements, it is obvious that it is a highly critical and safety compromising situation.

Mechanics of Water–Fuel Balance in Aviation Fuel

Being hygroscopic, water is marginally soluble in fuel and the amount of dissolved water depends on temperature. With a dip in fuel temperature, part of the dissolved water precipitates out of the fuel as free water and finally settles at the bottom. Conversely, with a rise in temperature, ambient moisture is absorbed into the fuel till equilibrium is regained. Repeated cycles of temperature variations (caused by frequent altitude changes or flight route through cold regions/polar routes) can result in significant amounts of water accumulation in the aircraft fuel tanks.

Free water in the aircraft fuel tanks is a safety hazard and they are periodically drained via a drain plug as part of periodic ground maintenance procedure. Modern aircrafts have water-scavenging systems that remove free water from the tank bottom and discharge them back into the fuel, which is eventually consumed in the engine combustion process. Depending on the ambient temperature, the precipitated free water can also freeze. To prevent ice from clogging the fuel system of the aircraft, they are heated in heat exchangers. Icing inhibitors are also mixed in the fuel as additives.

The aircraft fuel system design features as well as the re-fueling operational procedures described above can take care of trace amounts of dissolved water. However, excess un-dissolved free water entering the aircraft from the re-fueling system is hazardous and prohibited.

Existing Methods for Detection of Dispersed Un-dissolved Water

Of all the contaminants, water is considered to affect airline operations the most. It is vital for quality checks to be mandated at all fuel handling points. The most critical point in the fuel supply chain is when it finally enters the aircraft wing. A safe, reliable, cost-effective and rapid in-line water detection system in the re-fueling vehicle will be a boon for aircraft operators.

There are a few commercial tool kits currently being used, to detect water in aviation fuel. These are manual laboratory procedures applied to a fuel sample drawn from the monitoring point. Traces of finely dispersed waters cannot be detected by visual inspection.

Water Detector – Shell

The water detector unit comprises of a small disposable detector capsule with a filter paper coated with water sensitive chemical inserted into a plastic syringe. Fuel sample is drawn into the syringe for testing. If the color changes from yellow to green, it indicates the presence of 30 ppm[6] of free un-dissolved water.

Hydrokit - Velcon

The Hydrokit consists of an evacuated testing tube with a water sensitive powder, a sample bottle, tubing and needle. The vacuum tube is sealed with a rubber stopper. A sample is taken in the sampling bottle and using the needle attached to the tube a small amount is introduced into the testing tube by piercing the rubber stopper. The change of color to pink indicates presence of 30ppm or more of un-dissolved water. There is a reference color chart for comparison that indicates the quantity of water in ppm.

Metrocator kit

The Metrocator kit consists of a chemical dye in a glass vial and a paper disc under vial cap. Fuel sample is taken into the vial and inverted. The change in color in the paper disc is compared with a reference chart to compute the un-dissolved water concentration.

Solid Particulate Contamination

Suspended solid particulates can be created by corrosion on the inner walls of the aircraft's fuel tanks (caused by excess water in the fuel). They can also enter into the aircraft in the form of rust or microbial sludge formed in the storage tanks and pipelines, dirt, sand or solid particles from the filter unit in the dispensing system.

Solid particulates can block fuel lines, nozzles and filters or result in debris that can damage turbine blades or the engine casing. Restrictions in the fuel feed system can cause loss of engine thrust or flameout.

Microbial Contamination

Excess water promotes the growth of microbes that thrive at the boundary of the fuel – water interface. They feed on the hydrocarbons present in the fuel and oxygen from water and can breed rapidly. There

[6] *parts per million*

are several microbe strains in aviation fuels depending on the ambient temperature profile and the geographic region from where the fuel originates (one of the predominant strain in aviation fuel is reported to be the fungus Hormoconis Resinae).

Remnants of these microbes and their waste products result in acids and sludge formation that can corrode metallic parts and destroy the rubber sealing in the aircraft's fuel feed system. It also restricts fuel flow and can cause water separator and fuel filters to clog. Sub-micron solid particulates resulting from microbial contamination can sometimes remain in a suspended form and enter critical sections of the engine fuel system.

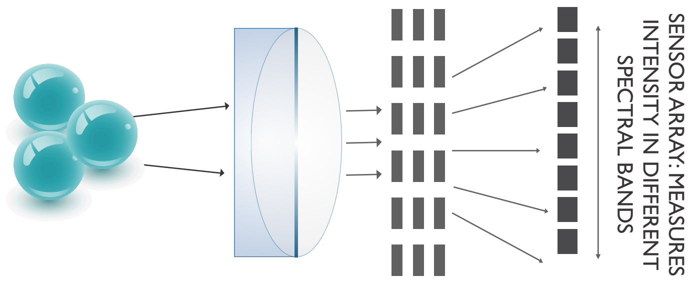
Controlling the spread of microbial activity is done by regular maintenance and use of anti-bacterial chemical agents. However, the safety is subject to the effectiveness of the ground maintenance crew. The anti-bacterial chemical additives can also result in changes in the fuel properties and formation of additional solid particulates and debris build-up that can clog the fuel feed.

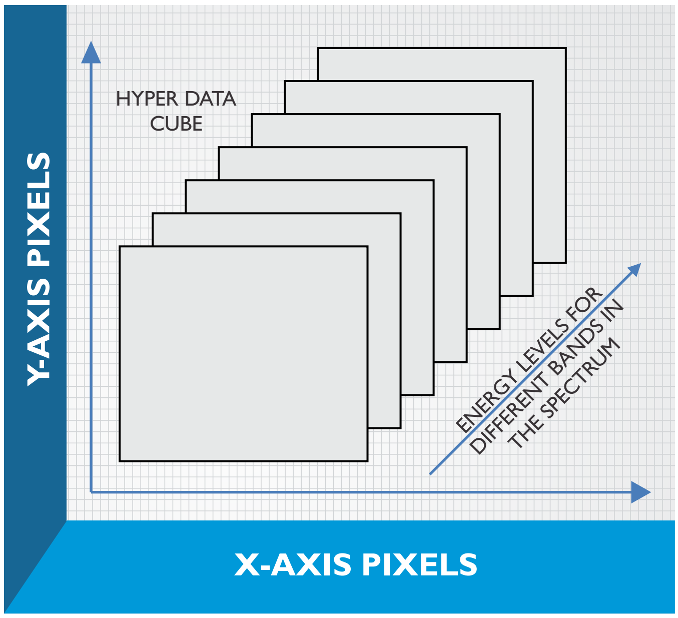
Hyper Spectral Imaging – An Introduction

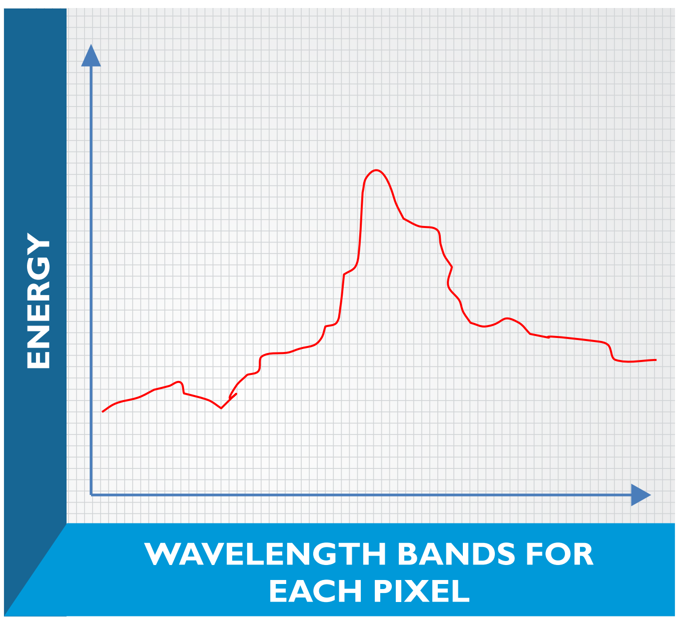
Objects differ in the way they absorb or reflect electromagnetic energies of different wavelengths. A measurement of energy levels in a specific range of spectral bands is termed as the spectral signature of the object at that point. The spectral signatures can be used to identify a particular object and elemental composition of a substance by comparing it against a reference. It can also be used to detect deviations and non–conformance in a particular sample.

Hyper spectral imaging refers to the measurement of the spectral signature of an object in the spatial and the spectral dimension. Spectral information (energy level) is captured for each pixel for a specific range of wavelengths (typically hundreds of wavelengths spaced nanometers apart) and the resulting data is in the form of a data cube, as illustrated below, is usually large.

Hyper spectral imaging has been there for several years. Though this has been predominantly used in remote sensing applications and satellite imagery with expensive and bulky equipment, there have been many advances in the recent past and low-cost handheld equipments are being designed for application in several industry segments.







LED light sources have high electro-luminance conversion efficiency, the ability to control distribution of spectral power emitted and with a limited wavelength band can be used for multi-spectral analysis as an alternative. The result is a lower complexity of the system and cost.

Line Scan Imaging

Typical hyper spectral cameras perform a line scan of the image, extracting spectral information. Scanning operation takes time for acquisition of a complete data set. This requires the object to be static or slow moving. The camera mounting can also move to arrest relative movement during exposure.

Snapshot Imaging

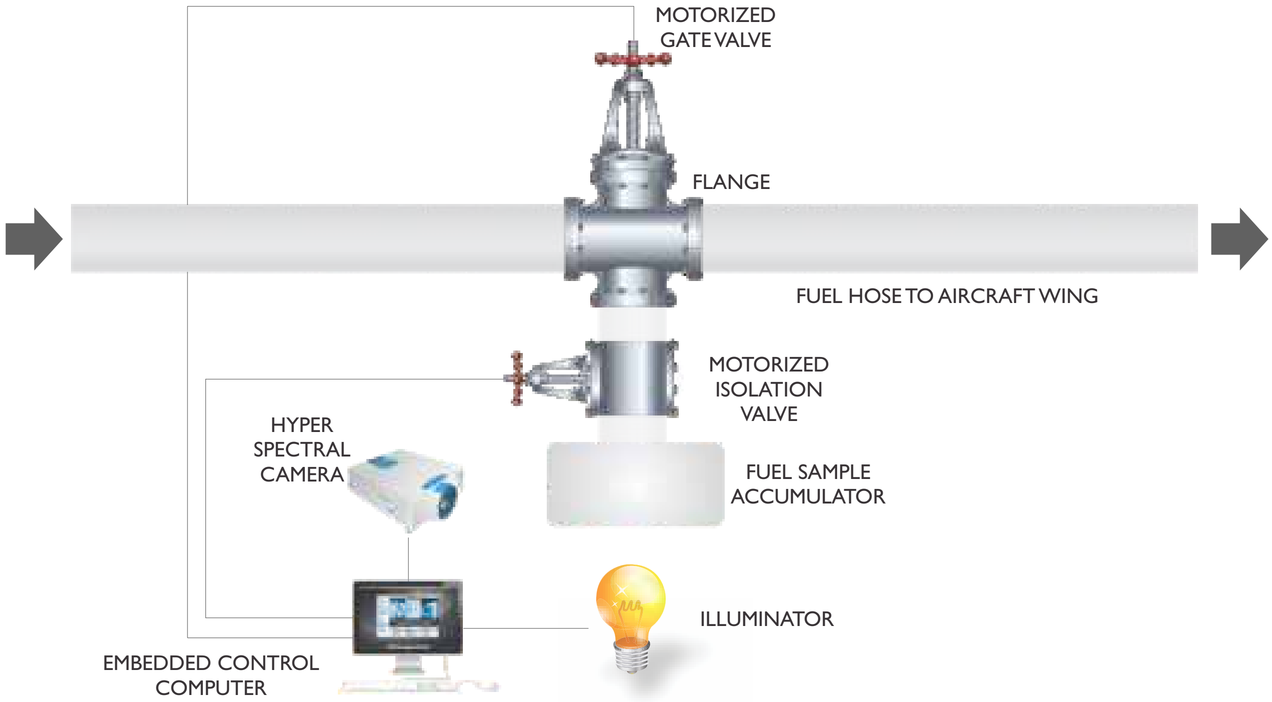
Recent advances in high performance hardware, nano electronics, parallel algorithms and advanced optics have resulted in the development of single shot cameras that can obtain a snapshot of the object and extract the entire spectrum from the sample at one discrete point in time These equipments will not require long exposure times and can be deployed for in-line analysis of fast moving objects in an industrial environment. This year (2013), IMEC has announced prototype that can perform snapshot capture[7] of a 256x256 hyper cube having 32 bands in the 600-1000nm range.

Solution Architecture to Detect Contaminants in Aviation Turbine Fuel

The mobile hydrant dispenser is the equipment at the very end of the re-fueling chain, before the fuel enters the aircraft wing. Performing an in-line monitoring of the fuel at the dispenser for contaminants while re-fueling is in progress would be the most effective solution. This would be the last defense for all contaminants from downstream equipments and distribution system. Automatic shut off systems can also be built around this solution if the detected contaminant concentration exceeds a threshold level.

Through hyper spectral imaging, we will observe that the traces of water molecules dispersed in the fuel (which is otherwise invisible to the naked eye) will disperse the incident light of different wavelengths. To prevent fire hazards, fuel should not be exposed to the atmosphere while re-fueling is in progress.

Below is an illustration of a high-level view (representative) of an instrumentation to sample the fuel in-line, while it is being delivered to the aircraft. It is proposed to be installed in the mobile hydrant dispenser. It should be possible to be used anywhere else in the fuel distribution system.



PROPOSED SOLUTION ARCHITECTURE

[7] *http://www2.imec.be/be_en/press/imecnews/imechyperspectralcamera2013.html*

Fuel transfer rates usually are fairly high, to minimize the time taken to re-fuel an aircraft. Typical fueling rates at the re-fueling hydrant dispensers are 1000 to 4000 liters per minute using 2.5 inch re-fueling hoses. This equates to a fuel velocity of about 5.2 meters per second at 1000lpm.

To account for the fuel velocity, a fuel accumulator mechanism (as illustrated in the previous page) can be designed with a motorized isolation valve to hold the fuel in the accumulator steady till a measurement is taken. With the hyper spectral camera with snapshot capability, it would be possible (with the suitable design) to obtain data for moving fuel flow, in a single discrete point in time.

Real-time Hyper Spectral Image Processing

Since the size of the data captured by the sensors is large, it will need special processing steps to achieve real time performance. Evolving multi-core and multi-processor hardware, vector processors, GPGPUs as well as parallel programming models OpenCL, CUDA, MPI etc. can be exploited to speed up algorithm processing.

Dispersed water molecules uniformly distributed in the sample is expected to show an overall shift in the spectral signature and can be detected by a comparison with the spectral signature of reference dry fuel. Other contaminants such as micro particulates and bacterial contaminants are expected to be sparsely populated in the sample and hence their presence is likely to exhibit an anomaly - a different spectral signature compared to that of surrounding neighboring pixels. These can be addressed by anomaly detection – classification of pixels whose spectral signature differs from the background by a threshold margin.

The processing of hyper spectral images involves several stages and requires efficient and fast data acquisition to extract the pixel spectral energy distribution, implementation of signal processing algorithms for classification, matching and anomaly detection as well as computation of the results subject to thresholds, for higher accuracy and reduced probability of false alarms.

Hyper spectral imaging provides a safe mechanism to rapidly and accurately detect the presence of contaminants, while meeting the regulatory norms - thereby preventing accidents, providing longer lifecycle to the aircraft components and reducing the burden of operational cost.

[8] www.imec.be
[9] http://www.arise-labs.com/News.html

About the Author

Bhaskar Chandrasekhar is solutions head of aerospace & defense practice of Wipro's product engineering solutions division. He has worked in several technology areas and currently leads solutions development.

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