Development of a Hand-Held High Resolution Hyperspectral Imaging Camera

Presented by: HinaLea Imaging

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1.0 Abstract

A technical overview of the development of HinaLea Imaging's Fabry-Pérot interferometer (FPI) based proprietary hyperspectral imaging technology is presented. This technology, which was originally developed to read the company's optically-encoded particles, has been adapted to create the first high performance front staring true hyperspectral imaging camera in a handheld, self-contained, ultra-compact form factor.

2.0 Why a Compact Hyperspectral Imaging Camera?

HinaLea Imaging has developed a unique low-cost, high resolution hyperspectral reader platform to read and decode objects labeled with its proprietary microscopic tags. These readers can be readily adapted to a variety of hyperspectral imaging applications offering a unique combination of low cost, compact size, and high spatial and spectral resolution. These instruments will have the greatest impact in the field of sample analysis. Whereby most current instruments analyze the bulk properties of samples, this imager cannot only analyze spectral content with spectral resolutions approaching that of state-of-the-art spectrometers, but can also provide high resolution spatial information, thus making it possible to measure the spectra of sparse particulates and inhomogeneities in the sample.

In their current usage, the readers read and decode the company's nanoparticle silicon dioxide tags which act as edible bar codes that can be sparsely embedded in a wide variety of objects as means of uniquely identifying them. This application posed several distinct challenges for the design of such a reader:

- Detection of microscopic (50µm to 100µm) in diameter, irregularly shaped, largely transparent tags, sparsely distributed over a large field of view *(see Figure 1)*
- Discrimination between adjacent tags. Since no two tags have identical reflectance spectra, adjacent tags, within several tens of microns, must be decoded without cross-talk
- Decoding of tag signals from diverse substrate backgrounds with limited optical isolation from ambient light

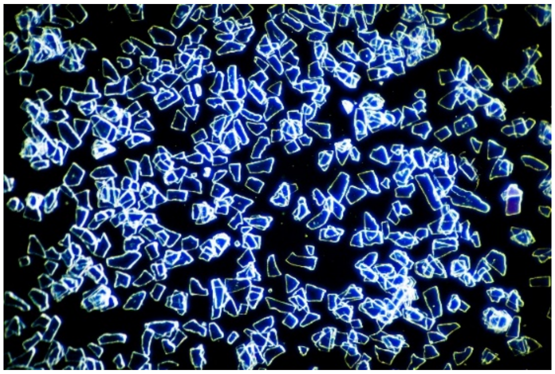

Figure 1: Tags on a flat substrate

Push-broom grating systems were the earliest forms of the hyperspectral cameras, initially developed by NASA, mounted on satellites and airborne platforms for research purposes. Over the past decade there has been growing interest in adapting them for use in agriculture. However, these systems must be mounted on a platform that can move at constant velocity, such as a drone or satellite, as they collect images by scanning one line of a field of view at time [1].

3.0 Hyperspectral Imaging Systems

Typical spot spectrometer systems illuminate a sample with a broadband light source and a scanning grating. This enables accurate spectral measurements of bulk samples but, if the sample is inhomogeneous, the resultant spectrum is a weighted average of the scanned material's spectral components. To resolve the spectral features of individual particulates in solution with adequate spectral resolution, a hyperspectral imaging method must be employed.

Hyperspectral imaging cameras generate 'hyper-cubes' of data, whereby the spectrum at each pixel in the image is collected. Subtle reflected color differences that are not observable by the human eye or even by RGB cameras are immediately identifiable by comparison of spectra between pixels. A variety of spectral imaging technologies exist.

A basic technique for collecting hyperspectral data from an object point source raster-scanning of the field of view. Reflected light is then collected and analyzed in a standard spectrometer. While this scheme results in a good signal-to-noise ratio and thus in excellent read quality, the mechanical motion is slow, stages are expensive and large, and costs involved are relatively high. HinaLea Imaging utilized such an approach in early versions of its reader.

The most common type of hyperspectral imager is the push broom system whereby a line on the object plane generates a 2D pattern on an array sensor. The collection of a complete data cube (2D spatial x 1D spectral) requires mechanical scanning. While the dispersing elements can be made small and each spectrum can be collected in as short as 1ms, the mechanical motion makes these instruments somewhat bulky and prone to misalignment. Furthermore, increased spatial resolution comes at the expense of longer collection times.

Often discussed along with hyperspectral imaging technology, are multispectral systems, the most popular of which are based on patterned filter arrays. These are an extension of color cameras where the typical Bayer or RGB filters overlaid on the image sensor are replaced with an array of 16 or even more color filters. While no user alignment is needed, and imagers can be miniaturized, the spectral resolution is quite limited and comes at the expense of spatial resolution, making this technology inadequate for many critical sample analysis applications.

A desirable configuration for the reader requirement and many unaddressed hyperspectral imaging applications is to illuminate the whole sample using an economical illumination source and then to use a tunable filter in front of the sensor to select a sequence of narrow spectral bands, thereby quickly and efficiently collecting a hyperspectral cube without having to move the instrument. These "front-staring/band sequential" systems are often not as optically efficient compared to a grating; however, with sufficient input light, such a system can achieve very high spectral and spatial resolutions with fast acquisition times [1].

4.0 The Fabry-Perot Interferometer as a Tunable Filter

An interferometer is a device which causes a light beam to interact with itself forming interference patterns (an interferogram). These can be used for diverse applications, including for selecting specific wavelengths from a wide band input. A simple implementation of an interferometer is the Michelson Interferometer shown in *Figure 2*. The two light rays from a common source combine at the half-silvered mirror to reach the detector. They may either interfere constructively (strengthening in intensity) if their light waves arrive in phase or interfere destructively (weakening in intensity) if they arrive out of phase, depending on the exact distances between the three mirrors.

As the difference in optical path between the two split beams is varied, a coherent, monochromatic light source will show constructive and destructive interference resulting in bright and dark bands in the interferogram, as shown in *Figure 3*.

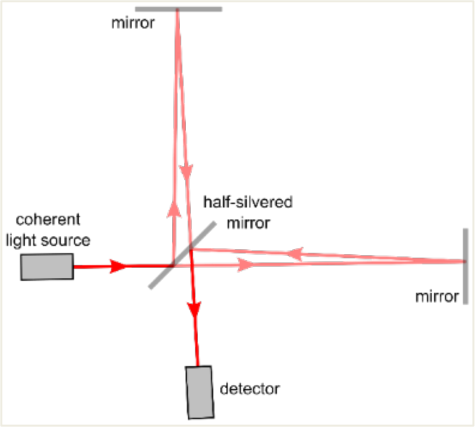

Figure 2: The light path through a Michelson interferometer, (Wikipedia Creative Commons Attribution-Share Alike 4.0 International license)

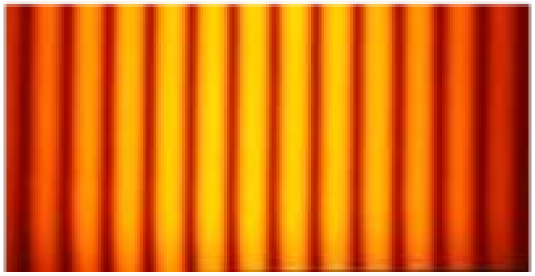

Figure 3: Interference patterns formed by scanning the optical path difference of a monochromatic light in Michelson Interferometer (Wikipedia Creative Commons Attribution-Share Alike 4.0 International license)

Since there is a known relationship between the difference in path lengths and the wavelength of light which constructively interferes (i.e., is transmitted with maximum amplitude), the Michelson Interferometer can be used, in principle, as a tunable filter. However, because the wavelength of visible light is in the sub-micron range, any vibration or motion between the numerous components of the interferometer, will result in spectral errors. Therefore, such a device is not suitable for a handheld reader application.

A related device is the Fabry-Pérot Interferometer. The heart of the Fabry-Pérot interferometer is a pair of partially reflective glass optical flats (an etalon) spaced hundreds of nanometers to centimeters apart, with the reflective surfaces facing each other.

The varying transmission function of an etalon is caused by interference between the multiple reflections of light between the two reflecting surfaces. Constructive interference occurs if the transmitted beams are in phase, and this corresponds to a high-transmission peak of the etalon. If the transmitted beams are out-of-phase, destructive interference occurs and this corresponds to a transmission minimum. Whether the multiply reflected beams are in phase or not depends on the wavelength (λ) of the light, the angle the light travels through the etalon (θ), and the optical path length of light in the etalon (ℓ). If the plates are separated by air, l is also the physical gap between the plates.

The phase difference between each transmitted beam pair (i.e. T2 - T1 in *Figure 4*) is given by δ:

$$\delta = \left(\frac{2\pi}{\lambda}\right) 2n\ell\cos\theta.$$

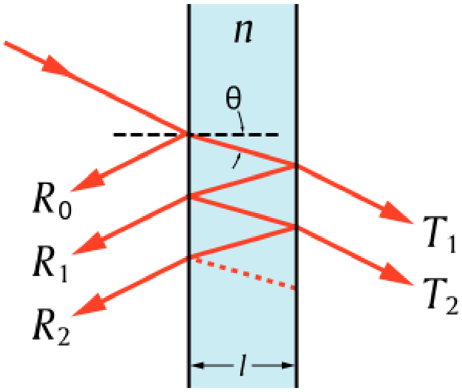

Figure 4: A Fabry-Perot Etalon (Wikipedia Creative Commons Attribution-ShareAlike 3.0 files)

If both surfaces have a reflectance R, the transmittance function of the etalon is given by:

$$T_e = \frac{(1-R)^2}{1+R^2-2R\cos\delta} = \frac{1}{1+F\sin^2(\delta/2)},$$

where

$$F = \frac{4R}{(1-R)^2}$$

is the coefficient of *finesse*.

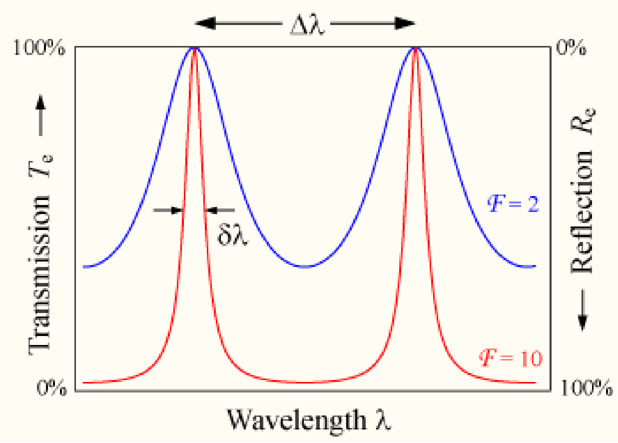

Figure 5: The transmission of an etalon as a function of wavelength. A high-finesse etalon (red line) shows sharper peaks and lower transmission minima than a low-finesse etalon (blue) (English Wikipedia user DrBob)

Maximum transmission (Te=1) occurs when the optical path length difference between each transmitted beam is an integer multiple of the wavelength. In the absence of absorption, the reflectance of the etalon Re is the complement of the transmittance, such that Te+Re=1. The maximum reflectivity is given by:

$$R_{\max} = 1 - \frac{1}{1+F} = \frac{4R}{(1+R)^2}$$

and this occurs when the path-length difference is equal to half an odd multiple of the wavelength.

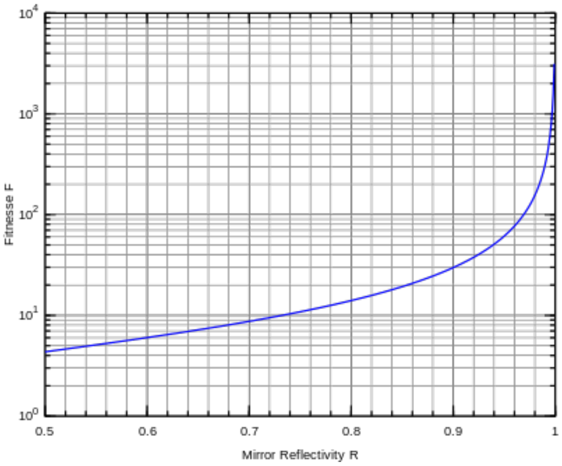

Figure 6: Finesse as a function of reflectivity. Very high finesse factors require highly reflective mirrors (Wikipedia Creative Commons Attribution-ShareAlike 3.0 files)

The wavelength separation between adjacent transmission peaks is called the free spectral range (FSR) of the etalon, Δλ, and is given by:

$$\Delta\lambda = \frac{\lambda_0^2}{2n\ell\cos\theta + \lambda_0} \approx \frac{\lambda_0^2}{2n\ell\cos\theta}$$

where λ0 is the central wavelength of the nearest transmission peak. The FSR is related to the full-width half-maximum, δλ, of any one transmission band by a quantity known as the finesse:

$$\mathcal{F} = \frac{\Delta\lambda}{\delta\lambda} = \frac{\pi}{2\arcsin(1/\sqrt{F})}$$

Etalons with high finesses show sharper transmission peaks with lower minimum transmission coefficients.

A Fabry-Pérot interferometer (FPI) differs from a Fabry-Pérot etalon in the fact that the distance ℓ between the plates can be tuned in order to change the wavelengths at which transmission peaks occur in the interferometer.

Unlike the other technologies mentioned above, the spatial resolution of hyperspectral imagers based on FPIs is only limited by the quality of the optics and the light throughput. This enables spatial resolutions of greater than 10 MP to be achieved without compromising acquisition time, and system complexity.

Furthermore, off-the-shelf image sensors can be used to collect the hyperspectral data cube, thus reducing system cost and facilitating continuous improvement in resolutions as CMOS image sensors advance.

FPIs typically have a limited spectral range which is related to their Free Spectral Range (FSR) and spectral resolution (FWHM).

For a given plate separation, multiple wavelengths will be transmitted through the device. For a given finesse, as we increase the wavelength resolution, the FSR decreases. Therefore, many of the commercial FPI's have a very limited spectral range.

However, HinaLea Imaging has implemented a patented solution to this limitation, which enables real-time extraction of the spectrum on a low-cost embedded processor. This scheme enables the reader to scan from 400 nm to 1,000 nm, with a FWHM of 4 nm. Moreover, using MEMs scale technologies and semiconductor production techniques, a device which is not subject to spectral errors due to vibration or motion between its elements has been created.

The technology can easily be configured into form factors and configurations suitable for laboratory bench-top investigations or production line testing. Such an implementation has not been possible for other band sequential techniques (i.e. AOTFs, liquid crystal tunable filters) due to reproducibility issues, and environmental and power restrictions.

5.0 Building an FPI Based Hyperspectral Imager

To attain a sufficiently high finesse across the whole visible spectrum, the following conditions must be met:

1. A highly-reflective metallic coating with a flat response from 400 nm – 1,000 nm must be used on the mirrors.
2. The flatness of the mirrors must be maintained to within a fraction of a wavelength.
3. The coplanarity of the mirrors must be maintained with a fraction of a wavelength.
4. The absolute gap between the mirrors must be known to within a few hundred nanometers and then needs to be scanned across hundreds of gaps while maintaining this coplanarity.
5. For 400 spectral gaps to be acquired in less than 4 seconds, a scan rate of >100 gaps/second is required, which includes the settling time of the mirrors.

With 10mm diameter mirrors having a nominal gap of 1µm and coplanarity of 1nm, these requirements are akin to taking two football fields, placing them 10mm apart, and ensuring that the gap between their two-end zones are different by no more than 10µm, then proceeding to change that gap in steps of 10µm, 100 times per second, all miniaturized by a factor of 10,000 in a cost-effective, handheld and battery-operated device.

To make this device manufacturable and cost-effective, HinaLea Imaging developed a patent-pending manufacturing process which addresses these challenges. This process includes custom mechanics, electronics and optical stations, as well as a custom inline QC process which ensures that all devices shipped to customers meet all specifications. A custom wafer manufacturing process is utilized to manufacture the mirrors. An optical design which optimizes light collection from the tags while maintaining high spectral resolution has been implemented with an off-the-shelf 2.3 MP CMOS image sensor.

6.0 HinaLea Imaging's Hand-held Hyperspectral Camera

As a result, HinaLea Imaging developed the Model 4100 handheld hyperspectral imager *(see Figure 7)* which features:

- Dynamically tunable wavelength range between 400 nm – 1,000 nm
- Spectral resolution of 4 nm to 15 nm
- < 5 seconds elapsed time from acquisition start to answer
- Compact packaging
- Lower cost relative to state-of-the art hyperspectral imagers
- Robust design
- Long battery life (100 scans, 4 hours)
- Cloud-connected for dynamic database updates

HinaLea Imaging has developed two generations of tag hyperspectral readers based on the FPI technology described above, as well as a portfolio of IP covering the design, manufacturing, calibration, and processing algorithms. The critical components of the readers are manufactured in a custom manufacturing line with a capacity to manufacture thousands of devices per month, as well as to assemble the complete reader.

At the heart of the imager is an optical engine using HinaLea Imaging's proprietary technology which has been adapted from satellite imaging into a mass-manufacturable solution. This optical engine can be adapted to other applications and instruments. HinaLea Imaging is currently collaborating with and is looking for new collaboration partners for harnessing the power of this technology to new application areas [2].

Figure 6: HinaLea Imaging Model 4100

7.0 References

1. C. H., Poole, G. H. , Parker, P. E. and Gottwald, T. R.(2010) 'Plant Disease Severity Estimated Visually, by Digital Photography and Image Analysis, and by Hyperspectral Imaging', Critical Reviews in Plant Sciences, 29: 2, 59 — 107, DOI: 10.1080/07352681003617285, http://dx.doi.org/10.1080/07352681003617285
2. Hod Finkelstein, Ron R. Nissim and Mark J. Hsu, TruTag Technologies Inc., "Next-generation intelligent hyperspectral imagers".

THANK YOU.

For more information contact:
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HinaLea Imaging, a division of TruTag Technologies, Inc., is a technology solutions provider that develops complete hyperspectral imaging solutions both directly and on behalf of strategic partners to address specific problems across a variety of industries, including medical diagnostics, precision agriculture and the quality assurance of food and consumer goods. As part of its solution offering, HinaLea developed the world's first high-resolution, handheld autonomous hyperspectral camera, which was awarded the SPIE Best Camera and Imager Prism Award in 2017.