2011-03-17

Fiber Optic Sensor Interrogation Advancements for Research and Industrial Use

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Fiber Optic Sensor Interrogation Advancements
for Research and Industrial Use

M. Wesley Kunzler

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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April 2011

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ABSTRACT

Fiber Optic Sensor Interrogation Advancements for Research and Industrial Use

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Master of Science

Spectrally-based fiber optic sensors are a rapidly maturing technology capable of sensing several environmental parameters in environments that are unfitting to electrical sensors. However, the sensor interrogation systems for this type of sensors are not yet fit to replace conventional sensor systems. They lack the speed, compact size, and usability necessary to move into mainstream test and measurement. The Fiber Sensor Integrated Monitor (FSIM) technology leverages rapid optical components and parallel hardware architecture to move these sensors across the research threshold into greater mainstream use.

By dramatically increasing speed, shrinking size, and targeting an interface that can be used in large-scale industrial interrogation systems, spectrally-based fiber optic sensors can now find more widespread use in both research labs and industrial applications. The technology developed in this thesis was demonstrated by producing two advanced interrogators: one that was one half the size of commercially available systems, and one that accelerated live spectral capture by one thousand times – both of which were operated by non-developers with little training.

Keywords: fiber optic sensors, wavelength based optical sensors, FBG, fiber Bragg gratings, micro aerial vehicle, MAV, fiber heating coefficient, structural health monitoring, composite materials, sub-sensor, multi-sensor, temperature, strain, handheld, FBG interrogator
ACKNOWLEDGEMENTS

All beneficial work comes at a cost. These advancements are only brought to light because of the following shoulders I am standing upon:

- the solid expertise, support, and patience of my advisement committee, from Dr. Wirthlin who significantly increased my writing and technical skills, to Dr. Selfridge who lead me on this adventure, to Dr. Schultz who kept my feet on the path,
- a foundational FSIM platform created by Seth W. Lloyd and Jason Newman,
- the additional help of Tyson Lowder, Daniel Wilding, and Zixu Zhu,
- the BYU MAGICC Lab,
- Dr. Kara Peters and her team at the University of North Carolina,
- the financial support of the US government TRMC T&E/S&T program,
- the unique environment of BYU and its excellent ECEn program,
- and finally, the strength of my sweet wife, Marianne – who kept five children alive while this developed.
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1. INTRODUCTION

When wavelength-based fiber optic sensors were developed, a new field was opened where researchers could sense physical stimuli based upon the color of light passing through a fiber optic strand. Several novel transducers have given these sensors a broad suite of capabilities. Interpreting the sensor response requires equipment with the ability to discern the wavelength response of each sensor. Such readout systems interrogate a sensor by illuminating the fiber with specific wavelengths of light, and then use the chromatic response to detect the status or change of the sensor parameter. Spectrometers of this nature have largely limited use of this technology to research labs and government-sponsored experiments. The interrogating systems have been large and slow and difficult to use.

Sensor interrogators are one of the chief hurdles limiting this technology in mainstream industrial and research use (1). Widespread use has been hampered by the youthfulness of the technology. Richer datasets can be obtained in more applications using wavelength-based fiber optic sensors if the interrogator can be made more compact, usable, and able to output higher data rates.

1.1 Potential of Wavelength-based Fiber Optic Sensors

Fiber optic sensors that respond with a wavelength signature have grown from first development in the 1980s to become a $100 million per year market (1), with applications as
diverse as oil and gas, electric energy, structural health monitoring in civil structures and various types of ground vehicles, and aerospace vehicles (2). Compared to conventional sensors such as strain gages, the technology offers vastly simplified wiring (as seen in Figure 1-1), longer range, a nonmetallic body, EMI and corrosion resistance, as well as small size.

Figure 1-1: Equipment required for 400 conventional strain gage sensors (top) vs. 3,000 fiber optic strain sensors (bottom) in a test performed by NASA-Langley (1).
Though these sensors chiefly respond to strain and temperature, ingenious transducers have been developed that make the technology sensitive to other parameters. These sensors have been installed in a broad array of situations by the author and others, including the following list:

- Hot-melted into asphalt to monitor traffic frequency and weight on a freeway
- Adhered to bridges to monitor structural health (3) (4), as seen in Figure 1-2
- Placed in windmill blades and poles
- Used to monitor acoustic emissions that warn of plate failure
- Embedded in composite materials (5) for structural sensing, as seen in Figure 1-3
- Housed in ship lavatories to track humidity
- Buried to assess soil moisture (6)
- Pinned to fighter jet landing gear during landing tests
- Passed down oil wells to measure temperature and pressure
- Immersed in hot salt baths to detect corrosion
- Attached to composite jet engines for NASA shuttles to monitor aging
- Exposed to jet afterburner plumes for temperature monitoring

Each application acquired data for some environmental parameter such as strain, temperature, humidity, chemical content, etc. These parameters are often monitored in the presence of EMI, size constraints, high temperature, or combustible and corrosive environments. In Figure 1-2, the fiber optic structural health monitoring of the two-lane Horsetail Falls Bridge east of Portland Oregon yielded enough sensitivity and dynamic range to capture both heavy traffic and pedestrians.
Figure 1-2: Fiber optic sensor on a 2-lane bridge (top) yielded high sensitivity (bottom).

The composite bottle impact monitoring in Figure 1-3 shows the connectors on the left and some of the fiber ingress into the weave. In this case, the results of impact damage were analyzed using an optical spectrum analyzer.
1.2 Sensor Interrogator Limitations

Despite the various applications of these sensors, they have not gained widespread adoption due to several characteristics that are undeveloped. Some of the key limitations will be described next.

First, interrogation methods are slow, especially for multi-parameter data that comes from the full spectral response of the sensor. Typical methods yield a data rate of a few Hertz, with some interrogators reaching kilohertz rates for very basic sensor data. Kilohertz rates are better suited for vibration and impact monitoring. More comprehensive sensor data could be obtained if entire spectral scans could be acquired at kilohertz rates, providing richer strain information than was possible before. But because spectral response is not well understood, high speed spectral capture is technology that was previously unavailable. An industrial survey of fiber optic sensor (FOS) interrogator speeds is shown in Table 1-1.
Table 1-1: Few fast multiple-sensor interrogators were available on the market before this work.

<table>
<thead>
<tr>
<th>Available FOS Interrogators</th>
<th>One sensor at a time</th>
<th>Several sensors</th>
<th>Hundreds of sensors</th>
<th>Sub-sensor structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low speed (1-100 Hz)</td>
<td>many</td>
<td>many</td>
<td>few</td>
<td>several</td>
</tr>
<tr>
<td>Medium speed (0.1-10 kHz)</td>
<td>several</td>
<td>few</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Speed (10 kHz-10 MHz)</td>
<td>few</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interrogator size is another barrier to many applications. Fiber optic interrogators are typically adapted from large telecom components that are not optimized for small size or the low power consumption requirements of many field studies, particularly in mobile applications.

Interrogator usability problems also hamper proliferation of this young technology. Debugging new installation problems requires significant technique, and spectral sensor data interpretation often requires a high degree of optical expertise. Deeper applications frequently cannot be explained even by specialists, due to the nuances of the spectral response caused by unconstrained sensor stimuli (reviewed in detail in Section 2.1.4, Grating Variations).

Other limitations include the high cost of these interrogators relative to conventional sensors, and tighter constraints of fiber handling that are unfamiliar to new users.

1.3 The Solution: a Fiber Sensor Integrated Monitor

Though applications and sensor packages vary widely, the wavelength discriminating optical interrogator is a common denominator among many sensor systems. This research focuses specifically on improving the interrogator and its proficiency in detecting the reflected color of the optical sensor. A Fiber Sensor Integrated Monitor (FSIM) was designed with the following goals:
a) Smaller: the packaging would be small enough to be used in many other application areas. This includes the size of the power source, since untethered applications – such as flight – must count battery weight as part of the instrumentation size.

b) Faster: not only are faster single-point data rates needed for vibrational and impact testing, faster full-spectrum data plots will reveal a more comprehensive environmental profile of what the sensor is experiencing.

c) More usable: the sensor system needs to be understood by an industrial test foreman to become a mainstream industrial tool. Debugging must not require an advanced degree, and the results need to be standardized enough for to mesh with other sensor data gathered. Many of these details have not matured in fiber optic sensors because of the newness of the field.

Using a novel optical element for spectral interrogation and some of the best of contemporary technology and expertise, the FSIM was designed to be smaller and faster. Extra effort was placed upon usability, and several unique results have precipitated from test applications described in this work. The FSIM was made to be a turn-key solution that was one half the size of the smallest commercial interrogator of its type. Another prototype was accelerated to collect full spectral scans at 1,000 times any other known competitor. Its usability was sufficiently increased that each FSIM prototype was operated by scientists who did not develop the platform, after only minutes of training. These prototypes enabled aerial sensor data to be collected, thermal response measurement, and structural damage assessment to be made that was not previously possible (7) (8) (9) (10).
The impact of this work provides the FOS industry with greater technology for advanced sensor systems. FSIM techniques will allow others to create improved FOS readout units that offer research and industrial users a contact sensor system with more capability than ever before.

1.4 Research Outline

To clearly describe the interrogator developments, one must understand the basics of these sensors and readout systems as related to the fundamentals of the FSIM design and capabilities. This document starts in Chapter 2 by providing a background in fiber optic sensors and interrogators having capabilities the FSIM builds upon. This comparison outlines the need for advancements in wavelength-based readout units and details on the limitations of current FOS interrogation systems. Chapter 2 describes both point sensor and full spectral responses to environmental stimuli.

Chapter 3 walks through the interrogation improvements of FSIM prototype technology. Each development in size, weight, speed, and usability is discussed for the optical hardware, fiber optic packaging, spectral discriminator control, data acquisition, processing, firmware configuration, inter-processor communication, and PC software data manipulation.

Application of this FSIM technology is shown in Chapter 4, detailing the successes and some limitations of the new platform for both single point and full-spectral data acquisition. The technology is applied to small vehicle flight, thermal laser response, and both surface-mounted as well as embedded structural damage detection. Additional description is also given on using full spectrum interrogation techniques and greater application at high speeds. Finally, a summary is presented of what was accomplished beyond the state of technology that existed when the research began. A list of future work completes the thesis.
2. OVERVIEW OF SPECTRALLY-BASED FIBER OPTIC SENSOR SYSTEMS

Since wavelength-based fiber optic sensors are uncommon and function on different principles than standard electrical sensors, a short primer will detail why the FSIM work is valuable. This chapter describes the function, design, and interrogation of spectrally-based fiber optic sensors and their interrogation systems, providing the technical background necessary to understand the advancements described in the rest of this document. It exposes the state of the art of FOS readout systems and unsolved problems which the FSIM technology addresses.

The sensor functionality and fabrication will be described first, followed by sensor variations and perturbations which are sometimes troublesome for most sensor systems. These are explained because the FSIM can interrogate them, which will be shown in later chapters. The readout methods described next include techniques that allow high bandwidth at the cost of multiplexing capacity and vice versa. This chapter finishes with a discussion of the limitations of current FOS readout systems, so that the need for a new design will be clear by Chapter 3. The results in Chapter 4 will show how these limitations have been overcome.

2.1 How Spectral Sensors Work

To measure environmental characteristics, an optical fiber must be modified (11) such that it will change its optical parameters in relationship to the change in the environment. The most common way to create such a sensor today is by making a fiber Bragg grating (FBG).
FBGs respond quasi-linearly to temperature and strain (12). The FBG can be created in an optical fiber either during creation of the fiber or afterwards, then installed in a manner that makes them respond to various environmental characteristics of interest.

2.1.1 Bragg Principle

While there are variations, standard FBGs use the Bragg principle to pass all spectral wavelengths except the wavelength immediate surrounding the Bragg frequency, as shown in Figure 2-1. Light not at the Bragg frequency passes through the FBG spectrally unchanged. As the light passes through these variations, the frequency that resonates with the period of the Bragg grating will be (typically) reflected back towards the light source. In this figure, R represents reflection, and T represents transmission.

![Figure 2-1: A fiber Bragg grating is illuminated by a light source, yet light at the Bragg wavelength is reflected back as a single Gaussian peak.](image)

The Bragg “grating” in the optical fiber consists of periodic variations in the index of refraction of the core of the fiber, as illustrated in Figure 2-2. These grating “lines” create the sensor’s Bragg wavelength at twice the grating period, \( \Lambda \), times the average index \( N \), as given by

\[
\lambda_B = 2N \Lambda. \tag{2-1}
\]
This principle of using periodic index variations has been successfully used in wavelength-selective lenses and mirrors for the free-space realm, as well as in optical fiber to make wavelength-selective mirrors for telecommunications.

![Figure 2-2: A fiber Bragg grating is made of periodic index changes along the core of the fiber.](image)

When the transmitted or reflected optical spectrum is measured, the Bragg wavelength changes ($\Delta \lambda_B$) with the temperature of the FBG and the strain on the FBG as given by

$$\frac{\Delta \lambda_B}{\lambda} = C_s \varepsilon + C_T \Delta T,$$

(2-2)

where the key components are the temperature change $\Delta T$ and the strain (the change in length divided by the total length) $\varepsilon$. The other parameters are the strain coefficient $C_s$ and the temperature coefficient $C_T$ (13). These coefficients include changes in both the effective index of refraction of the guided mode $N$ and the grating period $\Lambda$. The wavelength changes are quasi-linear, at least over traditionally-used ranges.

2.1.2 Manufacturing Process

Fiber Bragg gratings are only useful if they can be manufactured affordably. Grating masks and holographic approaches are used that inscribe multiple index changes simultaneously.
Some fabrication methods rely on chiefly photochemical changes (14), while others mechanically alter the fiber; each has an effect on the tensile strength and thermal life expectancy. Sensor FBGs are commonly between 0.2-1.0 cm from the beginning to the end of the fiber grating (as seen in Figure 2-3), and are a commodity purchase in a 2 meter long fiber.

![Figure 2-3: The dark areas show non-standard coating over some FBGs (1).](image)

To photochemically make an FBG, a fiber doped with Germanium is first loaded with hydrogen to increase its photosensitivity. Then the fiber is exposed to intense laser light at the locations where the index needs to vary – typically UV light through a photomask. Telecom gratings modify the pattern somewhat to flatten the response of the FBG reflection, creating an apodized grating with a flat-topped spectrum like that of Figure 2-4. FBGs are considered more accurate and easier to read in sensing applications when the Gaussian peak is distinct and not saturated. Therefore, sensor FBGs are not typically apodized.
Temperature has a significant effect on FBG sensors. Photochemically induced fibers are currently the easiest to fabricate, and they retain more of their original strength than mechanically etched fibers. They also tend to “erase”, or decrease their reflection intensity, with sufficient time at high temperatures. 300 degrees C for 30 minutes can erase 95% of the intensity of these gratings. Since many fiber coatings degrade at or before this temperature, it is often not a consideration, but high temperature sensing applications are still requesting more margin than chemically induced sensors offer. At least one group has experienced success at higher temperatures with special fiber dopants, though coatings must match the temperature range. Common acrylate coatings lose integrity above 85 degrees Celsius, and polyimide coatings deteriorate above 300 degrees, but gold coatings have successfully protected fiber up to 850 degrees Celsius (16).

Photochemically induced FBGs are most commonly fabricated by stripping the protective coating off a fiber (chemically or mechanically) before writing the grating, then recoating the
fiber. The stripping process can weaken the sensor tensile strength. Recently, draw-tower writing of FBGs has become more common (depicted in the Figure 2-5), with at least two facilities in the US and one in Europe. This allows lower costs and greater sensor strength, since the FBG can be created before the original coating is applied. The process helps make FBG sensors that are affordable enough for industrial use.

Figure 2-5: The manufacture of draw-tower gratings writes the grating as the fiber is created (1).

Mechanically induced gratings, on the other hand, were originally created by etching or damaging the crystal lattice of the optical fiber in a periodic grating shape, thereby fabricating
FBGs that will not erase until the fiber optic material itself began to fail. This enabled some FBGs to exceed 1,000 degrees Celsius, and even higher in sapphire fiber (17).

Surface Relief FBGs (SR-FBGs) are chemically etched FBGs which have shown promise as a sensor medium. They also last as long as the fiber can optically transmit light, even beyond 1,000 degrees Celsius. They are created using photolithography techniques, similar to microelectronics. They also have the special benefit of allowing sensor designers to replace the core with other compounds that respond to environmental parameters, such as gases and electromagnetic waves (18) (19).

2.1.3 Fiber Bragg Grating Benefits and Challenges

FBGs have many useful characteristics that the FSIM technology makes more applicable; as well as some that make it harder to use. These will be briefly described here to better understand application with the FSIM technology.

Wavelength selective fiber-optic sensors enable special measurement capabilities in environments where conventional sensors do poorly, since the sensing medium is typically standard telecom-type fiber (glass), and the measurement is conducted with photons. This combination makes the sensors dramatically less affected by high energy electrical or mechanical interference, such as external crosstalk, radio frequency interference, or the electromagnetic interference typical of ignition processes and other phenomena. Glass (and the typical polymer or acrylate coatings around fiber) can be used in harsh environments where salt, corrosivity, or explosive gases and liquids preclude the use of electrical sensors. In single mode fiber, they can be interrogated through several kilometers of fiber.

FBGs can be multiplexed to reduce cabling requirements. Figure 2-6 shows an example of FOS wavelength-division multiplexing where each sensor has an exclusive Bragg wavelength.
Dozens of sensors can function without cross-talk along a fiber as long as each maintains a unique wavelength.

Figure 2-6: Multiplexed FBGs along the top produce a reflection spectrum like that on the left. The transmission spectrum is shown in the bottom-right spectral plot (20).

The ability to multiplex becomes critical for large-scale structures, such as bridges, oil wells, wing strain, etc. Figure 1-1 shows the wiring needed for 400 conventional strain gages, whereas a single fiber can house thousands of optical sensors. In health sensing of composite material, the number of ingress points is minimized by the fact that the sensors can be multiplexed in arrays along a single fiber that was embedded during fabrication of the composite material. It should be noted that breakage does affect the single fiber concept much more than conventional sensors, though optical fiber can be interrogated from either end (giving one backup access point per line).

FBGs can be used to detect many different parameters beyond strain and temperature. They have been used to detect humidity by adding a coating to the FBG that swells in the presence of humidity, thereby inducing strain. They have likewise been used to detect soil moisture, electric current, hydrogen levels, and other things via appropriate transducers (21).
However, fiber optic sensor technology does require special considerations compared to the convention sensors with which they compete. Since the fibers are small and thin, care must be taken to protect them, especially at high temperatures when they become brittle. Reconnections are much more difficult than the soldering iron approach to conventional sensors, since the microscopic core of a splice has to be aligned for reconnection. Each transducer or application must isolate the FBG from other parameters that could change the Bragg wavelength; or users must alternately measure the unintended parameter and subtract its effect. This often requires careful packaging or additional sensors – sometimes of other types.

2.1.4 Grating Variations

Gratings that do not have a periodic spacing between each index change behave differently than standard FBGs. Two fiber optic grating variations need to be described for this document, since the FSIM technology increases the ability to use them: asymmetric (non-Gaussian shaped) gratings, and sub-grating strain responses from standard FBGs.

Intensity chirped gratings have an asymmetric, linearly increasing grating spacing along the length of the fiber grating, as well as a linearly increasing intensity of index changes. Figure 2-7 shows the spectral response, resulting in a triangular spectrum. As a point sensor, they are not considered ideal, since they are physically much larger than FBGs, and if part of the grating is changed more than another part is, the resulting spectral waveform is no longer the same shape. Perturbing some of the grating shifts some of the optical energy to a different wavelength, while the rest remains at its original wavelength. These gratings could be used as large sensor arrays, but the technology to convert from spectrum to physical displacement is still being developed, and needs tools like the FSIM technology to quantify partial spectral shifts at high speeds.
Similarly, a standard FBG profile becomes convoluted if some of the “lines” of the grating become non-periodic during sensor interrogation. This commonly occurs when the sensor is embedded – either in the medium of interest (like carbon composites), or in sensor housing – even epoxy. For example, it has been seen that athermal packages will “chirp” a grating while trying to keep it isolated from temperature effects. Special coatings to convert humidity or other parameters can also chirp the grating if they do not apply linear forces – due to the coating response, or due to uneven coating application.

Much interest has been generated in understanding spatial strain gradients, particularly inside composite materials where models are less consistent and structural health estimation is more difficult. FBGs offer the potential of knowing the spatial location of each line of the grating.
that has been embedded. FBGs have also been written into polarization maintaining fiber which allows detection of transverse and axial strain, or axial and temperature separately – but these measurements have been difficult to understand because strain gradients were imposed upon the sensor that were smaller than the grating length, causing irregular grating spacing. Figure 2-8 shows the reflection spectrum when strain is caused by uneven transverse force on the FOS, causing spectral shifts by creating birefringence in the fiber (23). Such irregularity still generates speculation among scientists concerning where strains are applied along the lines of the grating.

![Graph](image)

Figure 2-8: Many spectral variations result from FBGs that are transversely strained in a cured composite weave (24).

Recent interrogation inventions have been able to discern each line of the grating, but only at low speeds (around 10 to about 1 kilohertz (25)). The FSIM technology is needed to open the door for interrogation of sub-grating strain above kilohertz speeds.
2.2 How Fiber Grating Interrogators Work

Without an interrogator, an FBG is just a dark, useless piece of glass. Fiber grating readout systems illuminate the fiber and interrogate the optical properties of the sensor to determine how the environmental parameters are affecting the FBG. Some target absolute accuracy (such as the current room humidity), while others only need to detect relative changes (such as vibrational frequency or relative strain or degree of corrosion). Several sensor interrogation techniques have been developed, but each has been limited to high sensor count at low bandwidth, or high bandwidth for a single sensor. Although many of the sensor interrogation techniques to be described work with any wavelength based sensor such as a fiber Fabry-Perot (FFP) etalon, this technology was developed particularly for laser induced and surface relief fiber Bragg gratings (FBGs).

2.2.1 Fiber Optic Swept Spectrometers

The most common type of FBG interrogator is the swept wavelength interrogator, which has a tunable spectral discriminator that is swept or tuned through various wavelengths in spectrum analysis fashion. The tunable element is either a laser that sweeps through a frequency range, or a wavelength-selective filter, that only allows a narrow portion of a broadband source to pass. In this way, the reflection (or transmission) intensity of each grating can be determined as the tunable element matches the principle sensor wavelength during its sweep. The match results in a convolution of the discriminator and the sensor. To match the convolution peak (or trough) with a known wavelength, the resulting FBG intensity data is then compared to a timestamp or the peak of a calibrated optical reference that is likewise being illuminated by the tunable element.
An example is illustrated in Figure 2-9, where a tunable laser emission is directed down a fiber until it passes through a circulator. On the top-right side of the circulator, it reaches the FBG where it will pass through, relatively unaffected, and emit from the end of the fiber – unless the laser wavelength matches some of the FBG reflection spectrum. The reflected portion returns back through the circulator and is received by the photodiode to have its intensity measured and saved into a processor’s memory of the spectrum. The processor continues to sweep the laser’s wavelength to the end of the spectral range, possibly capturing reflections of other sensors as well, or a reference grating. After the entire spectrum has been scanned, a CPU can process the data and compare the wavelength of the peak of each FBG reflection to that of the previous scan. This peak shift is converted to a strain or temperature or another value, based upon the predetermined conversion parameters.

![Diagram of swept laser FBG interrogator](image)

**Figure 2-9: Swept laser FBG interrogator (26) wherein laser light reflects off each FBG and is detected by the photodiode (PD).**

The speed limitation for swept systems occurs due to the maximum tuning speed of the tunable element, as well as the time required to process several data points to find each sensor...
value. Most competitive commercial systems (like many from Micron Optics) offer a sensor data rate of 100 Hertz, with top version only recently offering data rates in excess of 1,000 Hertz.

### 2.2.2 Other Interrogation Methods

Other interrogator types operate using fixed spectral filtering or optical interference. For example, chirped gratings have been used as fixed spectral filters, using wavelengths that matched the sensor being interrogated. This method of filtering all except a single wavelength range (a single mode) is called demodulation. When a broadband source illuminates the sensor, the reflection must pass through the chirp grating filter before reaching the detector photodiode, as illustrated in Figure 2-10. The overlap of the sensor grating and the filter grating will block the reflection from the sensor, unless it shifts spectrally away from the filter’s wavelength. In other words, any wavelength change to the FBG will move its spectrum into or out of the strongest part of the chirp grating’s reflection mask, therefore changing the optical intensity that reaches the photodiode. The filter grating becomes the spectral discriminator, or “demodulator”. Optionally, the intensity of the sensor’s reflection can also be sampled to ratio out any light intensity fluctuations (shown by the line running into the optical detector without any filtering).

High speed demodulation in this manner requires no moving parts and only a linear equation to convert the intensity into a strain or temperature parameter; therefore, its speed is limited only by the photodiode, amplifiers, and ADC speed – systems using this technique have measured strain at megahertz speeds (27). Unfortunately, only one sensor can be interrogated per discriminator, since two could cause aliasing. It also cannot provide more than one data point per fiber sensor, so chirping or sub-grating strains can cause unexpected results in this kind of system. The discriminator is usually one of the most expensive and complex components, though
some efforts are being made to micro-fabricate them for reduced cost, by companies such as Redondo Optics (28).

Figure 2-10: A high speed demodulation of FBGs can be performed by spectrally filtering any changes (29).

Interference based interrogators encompass a large portion of popular readout devices. They create an optical interference pattern between the grating and a reference. There are diverse means of doing this, but most involve a tunable laser that reflects from both the sensor (that moves with strain or temperature) and a fixed-distance reference, then returns to a receiver where the two light paths create the interference pattern based upon their relative distances. Interference systems typically use mechanical movement to sweep across the optical spectrum, and they also
must reduce a large time-based dataset down to a smaller spectrally-based set. This can result in high accuracy and allows for a high sensor count, but due to optical sweeping challenges and processing requirements, this technology had not provided multi-kilohertz speed for a high sensor count at the time of this work. NASA-Langley and Luna Innovations are leaders in this area.

Array-based interrogators may have the most potential for raw acquisition speed at high sensor count. With this technology, the spectrum reflected from the optical sensors is spread out upon a pixel array from either a camera or specialized photodiodes. Each pixel receives the light intensity for a particular wavelength of light. This allows all or individual pixels to be interrogated using mature CCD or CMOS camera-type methods, providing speedy measurements at multiple sensor wavelengths. Current commercial devices of this type are considered very expensive to fabricate the array and other components, since most camera technology specializes in visible wavelengths, and telecom has chiefly made 1310 and 1550 nm sensor components affordable. High speed CMOS arrays are not yet possible at the higher wavelengths where the other optical components of a sensor system are mature. However, some companies are making steady progress, like Ibsen Technologies, which developed a non-CMOS scanning array interrogator. Like other scanning technologies, optical arrays must trade range for resolution.

2.3 Limitations of Existing Interrogators

Three key limiting factors of FOS interrogators for wide-scale industrial use include the maximum data-rate for multiple sensors, system size and weight, and usability. As each is described here, it should be noted that they are based upon the state of the art before the development of the FSIM.
2.3.1 High Speed with High Sensor Count

Optical sensor interrogators have failed to provide high data-rates for multiple sensors at the same time, particularly for sub-grating spectral information. Many industrial uses for sensor systems require high data-rates from multiple sensors that simultaneously monitor a single event. Consider the following examples:

- Mechanical structures (such as airplane structures) are routinely loaded for strength tests, with hundreds of conventional strain gages monitoring the strain on every fulcrum – watching for a sudden, unexpected loss of stiffness signifying a failure.
- Geophones recreate a wave response from pulses injected into the Earth.
- Researchers capture the directional waves of force and heat created by explosion in order to gain greater control of future detonations.
- By monitoring in real-time the current shape of a “flying wing”, researchers can keep a new type of aircraft aloft.

Since most current FOS interrogators must scan across the spectral band being interrogated before processing that data, interrogators have been limited to the tuning speed of the optical discriminator. Applications like those mentioned above are a stretch for FOS interrogators. Common devices scan at 1-10 Hz, and the bulk of interrogators are scanning in the hundreds of Hertz. As mentioned, the latest high-end commercial devices have just recently passed the 1 kHz boundary for scanning multiple ideal sensors with Gaussian spectral peaks.
2.3.2 Speed Limitations

To obtain multi-kilohertz data, the spectrum must be scanned and processed at rates previously unobtainable. Past interrogators have been limited in three key factors:

1. The spectral discriminator cannot move fast enough to provide high data rates.
2. The raw data passing mechanism has not been set up to pass many thousands of spectra to the processor each second.
3. The CPU cannot process many thousands of spectra per second (along with whatever else is demanded of it).

2.3.3 Compact Size at Low Power

The size of interrogators has also limited industrial use. Lab instruments may be large, heavy, and require careful handling, but field use typically requires something a user can carry or place as a payload on a vessel. Previous interrogators ranged from 4U rack-mounted devices to a 1 Hz device near the size and weight of a small college textbook, like the Spectraleye shown in Figure 2-11. These work for stationary sensing environments, but may add a burden to mobile sensing environments. Robots, autonomous vehicles, and aircraft must expend significantly more energy (and thus reduce deployment times) with increased weight. Though FBG sensors are extremely small, no FBG interrogator available during the start of this research worked well in field tests where they must be deployed on carriers smaller than that of a person. The size and weight of the interrogator was always a limiting factor.

The largest parts of an interrogator typically include the light source, the spectral discriminator, and the processing unit. Optical light sources are not so large themselves, but most use a lot of power and create a lot of heat. The heat usually requires thermoelectric cooling, and the energy consumption requires larger batteries – which contribute to size and weight of FBG
interrogators. Spectral discriminators are traditionally mechanical in nature, requiring more room. Processors typically require more size and battery power as processing capability is increased.

Figure 2-11: The Spectraleye may be the smallest commercial FBG interrogator at 1,270 cubic centimeters, housed with a PDA for processing power (30).

2.3.4 Usability

Many current sensor interrogators are difficult to use. Industrial equipment must be able to complete a task simply enough to allow the user to focus on what is tested instead of the test setup. Further maturity of a technology allows it to fit seamlessly with other tools to accomplish a greater task. Previously developed interrogation systems are becoming standalone devices, mature enough for repeatable tests, but integration into larger tests had not yet occurred.
Fiber optic sensor systems need to increase in user friendliness in order to be relied upon for more research and industrial tasks. A system is “usable” to industry when control is natural to the general test foreman, its status is evident, debugging is not a mystery, and results are standardized to merge their data with the conventional sensors. The most usable tools demonstrate flexibility to be employed in more than one situation. They demonstrate robustness of device and data, which is often the dividing line between a tool and a research project. Conversely, common FOS system frustrations include sensor and system setup complaints, unexplained interface stalls, data misinterpretation, spectral cross-talk from insufficient spectral spacing of sensors, optical power budget limitations, external processing requirements and dedication of external computing power, and interface challenges with supervisory computers.

**2.3.4.1 Nodal Integration with Other Sensor Systems**

The concept of an “autonomous sensor node” is unusual for fiber optic sensor systems. Currently, FBG sensors are typically the only sensors used in a test. Making an FOS system one node in a suite of sensors would allow it to be more usable for industrial applications. Sensor use in industry frequently combines multiple environmental measurements and sensor locations to depict the overall condition of a system, such as knowing the strain, temperature, and humidity in an aircraft structure. This distributed approach requires each sensor to interface with the data logger or supervising processor in a standard fashion, both at the physical interface level and the data transfer level.

Before the FSIM work, interrogators worked in seclusion. Popular physical interfaces were RS-232 and PCI cards (often via a National Instruments DAQ card), though a few interrogators are starting to add point-to-point Ethernet interfaces (31). The data transmitted over the interface was typically raw analog (to be interpreted by PC software), a spreadsheet file, or
optical spectral data, understood only by specialists – but not in a format for strain or temperature sensing in a large-scale or autonomous test. Additionally, a user’s PC was typically required to dedicate its processing to interpreting the data results.

2.3.4.2 System Status/Feedback

FOS systems have been notorious for their lack of feedback to the user, perhaps because more effort has been placed upon advancement in the optics than upon the user interface. When the interrogators locked up or “hang” to reconfigure, acquire IP addresses, perform calibration, or due to internal errors such as when the wrong sensor count is found, the standard response is “no feedback”, leaving the user wondering what the problem is for a technology that is still considered unproven. Dirty optical connectors, misconnected cables, broken fibers, and dead batteries are only the list of common causes of FOS system problems, and new users have to become optical experts to know what to do next. Many of these problems could be diagnosed by the processor, but these usability features have not been added to most FOS systems.

2.3.5 Flexibility

Usable sensor systems need to do well what they are expected to do, but when they are adaptable to unusual circumstances, they become a tool of choice for those who are advancing technology. FOS systems have two inherent problems that had not been addressed: sensor wavelength crossover, and handling of un-ideal spectra.

Sensor wavelength crossover occurs because each FOS is a reflection of light at a specific wavelength. As mentioned, the sensors in this type of system are multiplexed by using a different nominal wavelength for each sensor. Thereby multiple sensors are discernable by sweeping the entire spectrum – as long as the nominal wavelengths for two adjacent sensors do not move into
one another as the sensor is responding to environmental stimuli. Great pains (and expense) are taken to choose the ideal nominal wavelength so that each sensor will have its own spectral range that will not cross over its neighbor. If estimates are too small, identification of each sensor is lost, and it is unknown which spectral peak represents which sensor, as seen in Figure 2-12. This makes the system unusable for that part of the test.

![Figure 2-12: Model of two FBG profiles crossing one another, such that individual identity begins to be lost.](image)

Another way FOS systems need to be more usable is in how they handle non-ideal spectra, mentioned in the earlier sub-section “Grating Variations”. When a fiber Bragg grating sensor is strained in a non-uniform manner along the length of its grating, the smooth Gaussian peak distorts into odd shapes that are not directly reversible with spectral data alone. This distortion can occur due to stimuli such as uneven sensor mounting methods, packaging forces, or other uneven strain gradients that are smaller than the length of the grating. FOS systems need to have robust enough wavelength discriminators and spectral peak finding algorithms to identify what is really happening with sensor being monitored, and pass relevant information to the user.
As can be seen, the limitations of existing systems includes not only speed and size constraints, but a turn-key usability level to help cope with the various responses of FBG sensors. Because fiber optic sensors use unique properties to measure environmental factors, they need to be interrogated in ways that make them usable with other sensor types so they can become a widespread tool for industrial use. Autonomous nodal integration, user feedback, and flexibility could improve extant FOS interrogators so that the user need not become an optical engineer to employ them.

Fiber optic sensor systems can become a tool to advance scientific discovery, and improve industrial design. But it will require not only continued understanding of the sensor response, but also improved speed for high optical sensor counts. Mobile applications will require lower size and power usage. And perhaps the largest key to widespread adoption of wavelength-based FOS systems will be to improve system usability by advancing the level of autonomy, feedback to the user, and flexibility of the readout system.
3. DESIGN AND INTEGRATION OF THE FSIM

In order to advance fiber optic system systems past the laboratory and into industrial use, developments were needed to increase dynamic performance, reduce size, and improve the usability of the FOS interrogator. The size of the optics and electronics needed to be dropped in half to approach handheld size and thereby significantly increase FBG use in mobile applications. The spectral sweep and data transfer speed needed to be hundreds of times faster to enable spectral capture of vibrational events. And yet the whole system needed to be easier to operate to encourage widespread adoption.

Until now, a fast and small optical filter has limited FBG sensor interrogation. Recently, a novel MEMS tunable optical filter opened the door to higher speeds and smaller size, if only the right components and techniques could be coupled with it to make a new sensor readout system. To increase usability, the Fiber Sensor Integrated Monitor (FSIM) developed from the concept of integrating fiber optic sensor system as a node of a larger test system, rather than as an isolated testing platform. Its distributed nature and contemporary components enabled valuable features that are required for increased industrial and research adoption.

In this chapter, two prototypes will be described: a slower, handheld FSIM, and a high-speed FSIM which is currently in a bench top form factor. A system overview will be given first, before low-level improvements are explored. To accomplish the FSIM goals, these new interrogators required changes in system architecture, optics, electronic hardware, firmware, and
the user interface (software), which will be briefly described wherein significant advancements were made.

Many contemporary techniques were applied that seem absent in other FBG interrogators; they have been included in several appendix entries for the benefit of the reader. Several of the firmware techniques used to accelerate processing speed and increase usability are shown in Appendix B. The processor-peripheral nature of the hardware was typical of embedded design, but required attention to the gain-bandwidth issues of pushing for the smallest and fastest interrogator. These details can be reviewed in Appendix A.

3.1 System Level Design as an Autonomous Node

The FSIM technology excelled beyond other interrogators using a common optical layout with high performance components that were organized in ways previously unexplored. It created a 1 Watt handheld FOS sensor node weighing less than 344 grams, and another prototype capable of acquiring faster sensor array data from impacts than any previous FOS interrogator developed. Each handled its own control and processing needs.

The optical configuration of FSIM prototypes was not unusual for sensor interrogators: a processing unit tuned a discriminating element across a selected wavelength band while reading from a photodiode to obtain sufficient information to ascertain sensor readings. After a full sweep, the FSIM would convert the spectral features to wavelength to determine the response of a wavelength-based sensor.

The FSIM differed from most industry standard packages by moving the processing off a PC into the interrogator, yielding several advantages of increased usability and performance:

- The user’s PC was freed up to perform other tasks.
• The real-time processing avoided PC operating system interruptions that may hinder data collection speed and reliability.

• Creation of a real-time processing interface was easier.

• The processing units were able to be smaller and lower power.

The FSIM was made into a node by being autonomous and easily integrated with other systems (32). All data processing was performed on-board and stored until requested via standard RS-232 or ASCII over Ethernet interfaces. Transforming an FOS interrogator into a sensor node made it more usable by non-optical professionals because it met the criteria listed above.

3.1.1 Handheld System Design

As a handheld prototype, the FSIM was designed from small enough components to be carried in a pocket. This required not only the miniature optical components, but also a much smaller processor than was used in the commercially available PC-based systems. A 16-bit PIC microcontroller was selected to manage the optical filter control, photodiode data acquisition, processing, storage, and RS-232 interface with the outside world (20), with significant room for miniaturization still remaining (which can be seen in Figure 3-1). The resulting processing speed was similar to common FOS systems (dozens to hundreds of Hertz), but the low power target of this unit reduced the size and weight of both processing and battery requirements.

The unit was housed with OEM DC-DC converters to provide the voltage rails needed for the various electronics, and packaged with the carefully wound fiber optic strands needed for proper sensor discrimination. Since the PCB layout was not originally planned for a handheld package, some components were placed at perpendicular angles to the board. To prevent sharp
fiber bends which lose optical power, some components were soldered diagonally in their footprint to improve proper optical fiber routing. Winding techniques for compact fiber packaging can be read in Appendix A.1.

![Component Diagram]

Figure 3-1: The components for the handheld FSIM package fit on a 2.5 x 6” board.

### 3.1.2 High Performance System Design

Reaching for higher data throughput, the most recent FSIM configuration increased performance by maintaining multi-sensor readout speeds in the tens of kilohertz range – more than one thousand times faster than standard optical spectrum analyzers. This advancement was enabled due to higher speed port (100 Mb Ethernet) and the parallel processing available through
pipelining data in a field programmable gate array (FPGA). The FPGA’s parallel logic gates controlled the optical filter, acquired ADC samples at 25 MSPS, and processed each spectral waveform in search of FOS peaks, all simultaneously. It also passed data to an Ethernet-enabled processor upon request, allowing data to be streamed at high speeds across a network into a supervisory host processor or a PC for display. Size and power consumption were increased since standard development boards were used in the prototype, though further development work could shrink the size while maintaining the high increase in usability and speed.

Figure 3-2 shows data from a sensor impact being acquired (top) from one of the spectral grating profiles (shown at bottom) in real-time from an FSIM prototype. This scan was taken at 3 kHz, approximately three times faster than commercial systems of the same time period. This figure depicts the strain response of a plate-mounted FBG sensor during an impact, which is an event that cannot be captured well with a readout unit that provides less than 100 Hz data rates.

Figure 3-2: Kilohertz sensor data rates were obtained from the FSIM prototypes. The top graph shows strain vs. time, and the bottom graph shows the optical spectrum containing 4 FBG sensors interrogated by the FSIM.
The high performance FSIM is shown in Figure 3-3. This prototype was larger since prototyping speed was more important than size. The use of evaluation boards quickly grew the size of this unit.

Figure 3-3: The FPGA board controlled the optical filter DAC, read the optical response ADC, and concurrently passed refined sensor data to the Netburner Ethernet board.
The fast FSIM replaced all its non-optical electronics with much faster components. The FPGA, mounted on a Spartan-3 carrier board from Digilent, Inc., used the DAC to control the optical filter on the amplifier board. This signal directly controlled the scan of the optical filter across the spectrum. The optical response entered the photodiode located on this board, was amplified, and then sampled by the ADC board (bottom-right). The ADC fed its 14 bits into the FPGA. Refined data was passed from the FPGA to the Netburner module on a shared bus via a dual-row header to the memory-mapped I/O of the FPGA. This gave the FSIM Ethernet communication capabilities. The small size of the Netburner module is shown in Figure 3-4.

![Figure 3-4: The Netburner module housed a Freescale microcontroller with peripherals to use the RJ-45 connector visible above (33).](image)

This system, when completed, demonstrated its performance by capturing laser-pulsed heat measurements and the effects of impacts in composite laminates – both at speeds never before possible. These tests will be discussed in Chapter 4.

### 3.2 Optics

The FSIM was capable of high speed and small size because it was based upon a scanning spectral filter originally designed for telecom switching. This high speed filter started
with a broadband source and passed a narrow band of filtered light to an FBG sensor array and an athermally package wavelength-reference grating. As the filter’s wavelength was swept across the usable spectrum from the light source, the reflection at each wavelength was measured by a photodiode and saved in memory to identify the reflected wavelengths of each FBG. This spectral information was time-aligned to match a temperature calibration lookup table for converting timestamps to wavelength, corrected by the wavelength reference. Light only reflected if the filter was tuned to the same wavelength as one of the FBG nominal wavelengths. Figure 3-5 shows a variation of this system, wherein the filter is placed to tune the broadband reflection from the sensor array.

Figure 3-5: The FSIM technology is depicted inside the black box, showing the flow of light and information from left to right.

Industrial use is encouraged when costs are low. The FSIM system configuration targeted the popular telecom 1550 nm wavelength, which allowed the use of components designed for the telecom industry, such as the low cost illuminator, waveguides, and optical receiver. The optical discriminator was a key enabler for significant performance improvements at low cost, since it was a compact and nimble MEMS tunable optical filter.
3.2.1 MEMS Tunable Filter

The most difficult to find component for bringing FOS interrogators into mainstream use was a spectral discriminator with sufficient tuning speed, bandwidth, and resolution to enable spectral capture at vibrational speeds. Fortunately, Nortel Networks had developed a tunable optical filter for C-band telecommunications with unparalleled performance: the MemTune MT-15X-100 (34). The nearest related component with significant capabilities is produced by Axsun Technologies, but requires much higher voltages for tuning inputs and has a lower tuning speed. The Nortel MEMS-based optical filter was designed to tune across 10 nanometers per microsecond, which was over 3 orders of magnitude faster than other filters available at the time of its design. In the Photonics Lab at Brigham Young University, one unit performed at 30 million nanometers per second (but only over wide spectral sweeps; the slowest part of each sweep occurred during the change of scan direction).

Figure 3-6 shows an oscilloscope capture of the light passing through a MemTune device that is sweeping back and forth across 4 gratings, 4 times, at 800 kHz – a phenomenal speed. The intensity (height) of the sensor reflections in the lower trace is arbitrary, based upon the illumination provided. The reflections vary with each scan, probably due to the display resolution limitations of the oscilloscope, or possibly due to low temporal coherence of the superluminescent light source which is illuminating the gratings for only an average of 30 nanoseconds as the filter passes.

The optical filter’s 3dB mechanical roll-off was near 10 kHz, but the unit was usable when scanning at 50 kHz and above if spectral range was able to be compromised. Since the free spectral range was near 100 nanometers (and common broadband sources are 40 nanometers wide), the optical filter was no longer the performance bottleneck in the FSIM design.
The MemTune unit lent itself to size reduction due to its compact nature and low power requirements. In a butterfly package measuring 30 by 13 by 7 mm (although the fiber optic pigtails triple the effective length), the filter raised eyebrows at conferences when placed beside the large free-space optical filters used for spectral discrimination in other interrogators, as shown in Figure 3-7 below.

![Figure 3-6: Oscilloscope capture of the optical filter response as it repeatedly sweeps across 4 FBG sensors at 800 kHz (the driving voltage is the upper trace at 20 Vpp).](image)

The filter’s low power requirements were also a significant factor to be managed in making a compact interrogator, since the need for battery power can counteract component size reduction. The flexible membrane in the MEMS filter required only 100 microamps over its 36 V range. The device has a Peltier thermoelectric cooler (TEC) and internal thermistor, but these
were unused since that would require up to 2 Amps at 2.1 volts to maintain filter temperature. To reduce size further, the filter temperature was allowed to drift, but the tuning wavelength was characterized at one-half degree steps across a 40 degree band; then processing compensated for temperature drift with the resulting look-up table.

Figure 3-7: Size comparison of optical interrogators shows (a) a modern Agilent optical spectrum analyzer, (b) a Micron Optics interrogator, and (c) an FSIM prototype.

3.2.2 Light Source

The broadband light source also had the potential to add significant weight through the battery capacity that could have been required by high power consumption. Popular light sources for FOS interrogators include bright erbium doped fiber amplifiers and super luminescent diodes. Unfortunately, the brighter they are, and the more they illuminate, the hotter they become, requiring thermoelectric cooling (TEC) to maintain. The Exalos 1505-8 superluminescent light emitting diode (SLED) was chosen for the FSIM because of its ability to provide over 100 mW without requiring an additional TEC. It produced 40 nanometers (FWHM) of broadband light for
about 150 mA of current (approximately 250 mW power usage). The SLED came in a standard TOSA package and was reliable across a commercial temperature range.

To increase FSIM usability, two light source power levels were designed for the SLED. This is because a common setup problem users experience with FOS interrogators is one where no data is received. It is left to the user to discover whether sensors are not seen because of dirty optical connections (most common), broken optical fiber, or a damaged or disconnected light source, or a damaged or disconnected photodiode. Under normal operating conditions, the SLED was powered on its rated current level. If the processing unit was unable to detect sensor reflections, the light source was given 10 times its rated power for the brief period required to perform a single spectral scan (approximately 100 microseconds). The single scan at 10-times normal power allows the processor to ascertain and to communicate to the user whether the sensors could be readable with more light, discerning for the user the need to clean the optical connectors or remove microbend losses. Since the chief failure mode of the SLED was due to the melting of internal components, and the thermal mass of the TSOC package is significant, no damage is incurred through this technique, and this brief diagnostic tool increases system usability thanks to the high speed of the optical filter.

3.3 Firmware

The FSIM optics were controlled by firmware algorithms to peculiar to improving size, performance, and usability. Despite the data processing constraints in all FSIM versions, the internal control algorithms had to work in lock-step so that data received would be time-matched to the stimulus. To avoid needing higher-end hardware and greater power consumption, several techniques were employed in the FSIM to facilitate data collection with reduced hardware support while avoiding data bandwidth limitations. Internal calibration reduced the size by
removing a TEC, but this advancement came at the cost of with a significant firmware routine. Large datasets needed to pass through ports with limited bandwidth. The pipelining of these processes made the FSIM into the fastest full spectrum interrogator in the world, but the handheld unit required some special algorithms as well, just to provide a customary data rate.

The firmware that controlled FSIM electronics needed low-bandwidth but human-readable communication, which meant planning control commands to return data or status that could be processed without human intervention but still be comprehended by users. Flexibility was instilled by creating high level commands from basic building block commands in order to enable ease of use – which meant the low level commands needed to be self-contained so that high level commands could rely upon the low level command execution in any order required to accomplish previously unconsidered tasks.

3.3.1 Spectral Sweep, Windowing, and Hopping

Interrogators gather sensor data by sweeping a discriminator across the optical spectrum, then analyzing the resultant waveform for the wavelength location of peaks or troughs that represent sensor data. The microcontroller-based FSIM could not gather and process data fast enough to analyze the full sensor range at more than 0.4 Hertz for high accuracy levels.

To circumvent this data quantity problem, a windowing technique was employed, reducing the data that needed to be processed. This was accomplished by only scanning the part of the optical spectrum where sensors were expected to provide information, and skipping spectral bands in between those sensors (35). The procedure is described here, and shown in Figure 3-8:

1. First, the entire spectrum was scanned to find the initial wavelength location and number of the sensors attached.
2. In subsequent scans, the fast optical filter “hopped” across unused portions of the optical spectrum to reach the (previously discovered) next grating profile, using the sensor reading from the previous sweep as its basis. In other words, the optical filter was tuned as fast as possible to across unused spectral bandwidth.

3. Then the filter would scan across the grating, saving data that would later reveal the center or peak of the grating.

4. The filter then hopped to the nearest edge of the next grating profile to repeat the process.

5. When all of the occupied wavelength spaces had been scanned, the processor would find the peak in each scanned section to identify sensor spectral changes.

This algorithm was critical to the functionality of the handheld unit, often reducing the processing required by a factor of ten or more so that a low-power microcontroller could process it with sub-second data rates. The window for each sensor was adjusted with each scan to prevent the sensor from drifting out of the next scan. Obviously, the size of the window needed to incorporate the maximum expected sensor change from one scan to the next, so that the window adjustments could keep up. As a usability precaution against unexpected events wherein the sensor did exceed the expected scan bandwidth, the following self-correction was added: if a peak was not found in each of the scanned sections, the initial “full scan” would be repeated, to re-establish the windowed scan area around each sensor peak. Thus, compactness was obtained, and usability was maintained. A future improvement could selectively choose portions of the spectrum to rescan, preventing a long rescan of the entire spectrum.
3.3.2 Spectral Compression

The combination of usability and high performance required the addition of sensor data compression. Passing data to a PC or other host processor has long been problematic when the bandwidth of the data is close to the maximum port bandwidth. The handheld unit used an RS-232 port at 115K baud, which was the maximum that most PCs supported, and generally had enough bandwidth to send the center wavelength, temperature, or strain of each sensor at dozens
or hundreds of Hertz. No packet splitting was necessary for small data segments, such as sensor peak data from a single sensor array. However, when entire spectral waveforms began to be transmitted, the interface suffered from alignment issues related to occasional lost serial bits, complexities due to variations in spectral scan sizes and the number of sensors, and generally, the inability to keep up with the large quantities of data being acquired in changing test cases. Spectral data could be captured in memory, and then sent across the port for post-analysis; however, a higher degree of performance was being masked by the low usability inherent in the RS-232 bottleneck.

Replacing the RS-232 interface with a 100 megabit Ethernet port was not enough. By adding a 100 megabit Ethernet interface, the bandwidth was significantly increased (Internet forum users suggested 3-4 MB/sec data transfer was about the maximum obtainable using state-of-the-art microcontrollers). Unfortunately, the new tool we were developing needed 100 two-byte data points per nanometer and at least 20 nanometer scans at 1000 Hertz or better (which multiplies to 4 million bytes). With roughly 4 MB of data points to send, some additional time was consumed by the overhead of headers, error correction, and the splitting and reassembly of packets, just on the application level (in addition to the low level IP processing and slow-downs from slower computer bottlenecks). The Netburner would not likely be able to transmit all this data unhindered, and faster speeds were desired.

Compressing the spectrum was again a performance booster, by “windowing” the spectrum such that only the data containing useful spectral information was passed across the network cable. This typically means cropping all data below an optical intensity threshold. The host processor could turn this feature off if it was not fast enough or was not programmed for
reassemble of the spectral pieces. In such cases, it is more typical that only the sensor peak
wavelength would be requested anyway.

Further investigation should also be given to greater compression schemes such as those
used for speech compression. FOS waveforms have a limited range of comprehensible
permutations, so speech compression may be an excellent method of passing the same
information with smaller packets. Additionally, the large number of sampling bits in
interrogators is chiefly to maximize the SNR, not for high resolution of the peak intensity. The
spectrum could potentially be reshaped quasi-logarithmically without loss of information, and
then resampled as an 8-bit data stream for further compression.

3.3.3 Peak Tracking and Crossover Compensation

A common usability problem in FOS systems occurs when a sensor exceeds its expected
range and reflects at the same wavelength as another sensor. Spectrally, the two sensors merge
together and become indistinguishable. Worse yet is that when they re-emerge, it is unknown
whether the rogue sensor has continued to move out of its designated band, or is returning to its
band. It is also difficult to discern whether there has been movement of the victim sensor peak.
This loss of sensor identification causes complete swapping of stored information from the
crossover point forward, creating in-fiber crosstalk between sensors. This can make the data
unusable or at least extremely hard to correct, especially for one untrained in spectral processing.

Two mitigating techniques were considered for this problem: identify the sensors using
momentum and using wave-shape. Wave-shape can often identify a sensor due to the
perturbations along the otherwise Gaussian waveform of each grating sensor. Perturbations often
come from fabrication anomalies or mounting imperfections, but artifacts such as a chirp could
also be designed into fibers for identification purposes. If sufficient processing power is
available, the two overlapping sensor gratings could be distinguished by a pattern match of their waveform, particularly if the two are not similar in overall shape.

The other option considered to increase usability during sensor crossover was spectral momentum tracking. This concept was employed in the FSIM, though not thoroughly tested. It tracked the rate of change of each sensor peak as a means of estimating its next movement. If two sensor peaks were within close proximity of one another, the sensor order was allowed to switch places based upon which sensor peak had sufficient “momentum” to have moved into each position, using the derivative of its recent spectral changes. Obviously, this is not fool-proof, and accuracy would decline if both sensors in question had low momentum values; but this is an example of how the interrogator can increase usability in difficult circumstances that would otherwise be hopeless.

3.4 Host-side Development

Usability and high performance features were enabled in the FSIM user-interface PC by creating a data collection suite that gave priority to high speed data collection and user-discoverable capabilities. The status of the interrogator had to be apparent; control needed to be intuitive and responsive; and no features should sacrifice data-throughput performance.

For ease of use and rapid code deployment, the host interface was designed in a LabVIEW programming environment from National Instruments. It provided UDP transmit and receive drivers in the PC, PDA deployment add-ons, and quickly accessible plotting and data saving tools – as well as popular controls that needed no user instruction. The software was designed to be a user-accessible extension of the tools created in the FSIM firmware, and in every instance provided feedback about status using the FSIM commands provided. A scrollable
log of the last several FSIM responses rounded out the user’s transparency into the status of the interrogator. One view of this is shown in Figure 3-9, shown before FSIM startup.

Figure 3-9: The PC interface for high performance FSIM tracked status, history, and allowed easy access to high and low level commands.
3.4.1 Maintaining Speed in the User Interface Software

To maintain the high throughput of the FSIM, care had to be taken to employ low-overhead software architecture and signaling model and a low-overhead data management method. Several “best practices” of programming were employable, even in a dataflow language like LabVIEW. Optimally-sized data chunks were used, with references instead of multiple copies of large arrays, and subVI calls were avoided or made re-entrant to reduce loading time. Since "Autoscale" consumes processing for each data point, it was only actuated at the beginning of the dataset or by button for subsequent updating. Primitives were chosen over turn-key function calls. Though ease-of-use was remembered, the first goal was to optimize data processing speed. More details about increasing software throughput are available in Appendix B.6.

3.4.2 Data Management

High throughput was also preserved by minimizing the creation, resizing, and destruction of data structures in LabVIEW. As new data was received, it sometimes came broken into packets and needed to be reconnected and processed. Rather than resizing the array for each receipt or processing action upon part of the incoming data, a FIFO data structure was developed as a LabVIEW subVI. High throughput was obtained by starting with a large circular array for incoming characters, actuated by moving array pointers within the array as each small piece was read and processed – instead of rewriting the entire array as each portion was processed. Flags were arranged for buffer overruns.

To make the FSIM ready for mainstream industrial use, post analysis of spectral data needed to be straightforward. Peak data was saved in a spreadsheet format (similar to conventional sensor systems), but full spectral data was typically far too large to be viewed with
typical office spreadsheet programs. Since writing spectral data to file was up to 20 times faster in binary format than when converted to “spreadsheet format”, a binary data viewer was created.

The waveform viewer was developed to visualize the spectral waveforms that now could be captured in thousands per second. Often such large datasets overwhelm PC resources and slow data analysis. To give the user flexibility according to the processing power available, the spectral viewer allowed users to choose how many of the data files to import into memory, what portion of the spectrum to display, and even to open one waveform out of every fixed set size or hand-entered selections, giving an overall view of the data with less data memory reading overhead. As Figure 3-10 shows, all plots could be seen in comparison, showing the progression of sensor data over time.

![Figure 3-10: FSIM Data “Spectral Viewer” quickly reviewed a set of captured strain waveforms.](image)

The most challenging part about design of this viewer was that it could not host every possible view type desired by users. So, time decimating features allowed datasets to be
simplified and exported in tab delimited file format for analysis with other tools. This data reduction method became the most frequently used feature of the Spectral Viewer, facilitating the data processing for these large quantities of optical spectra.

Surveying these details of FSIM design and fabrication shows the attention to detail required to make the fastest, smallest, and most usable spectrometer of the decade. By using the best components, skillfully integrated, several of the drawbacks have been mitigated for fiber optic sensor interrogators, pushing the technology closer to industrial usability.
4. RESULTING CAPABILITIES OF THE FSIM DESIGN

Every prototype needs to be tested to explore its capabilities and prove its features. To show how the interrogator improvements of size, speed, and usability could really push FOS technology into greater research and industrial use, the FSIM was used in several laboratory and field tests to stress each part of the new interrogator capabilities.

This chapter shows the setup and results of several FSIM tests, starting by exploiting the benefits of the smallest prototype, then progressing to the higher speed prototype and increasing DataStream complexity. The first half of the chapter shows how the FSIM matches past technology by monitoring each sensor as a single point in two novel tests demonstrating size and speed.

Demonstrating “basic” use as an FOS sensor interrogator required the FSIM to produce data from multiple FOS points simultaneously, which it did via RS-232 and via a Bluetooth adaptor to a PDA (see Figure 4-1), as well as while riding on a an autonomous micro-air-vehicle (MAV). This was a field test only possible due to the FSIM’s unusually small size and weight. Additionally, neither PDA nor MAV interface would have fit into the time budget if the data interface had required more than a few afternoons of interface coding, showing the benefits of focusing on usability.
The last half of the chapter investigates sub-grating strain by explaining the unfamiliar principles of interpretation, and then using the FSIM to interrogate it in three high speed tests. The FSIM moved beyond “basic FOS interrogation capabilities” using speed advancements in scanning and data processing. It captured and displayed optical spectra at vibrational speeds, which has not previously been possible in real-time. Using this unique “full spectral view”, the high-speed FSIM revealed the sub-second effects of heating an FBG using a CO2 laser. This enabled analysis of the maximum thermal response of an optical fiber, as well as its thermal conductivity (9). The FSIM did this by exploiting a special, emerging functionality of fiber optic sensors: capturing multiple pieces of spectral information from a single sensor at high speeds, as the laser heat pulse moved through each portion of the grating. This same spectral capture capability later demonstrated the ability to capture non-repetitive strain perturbations at vibration and impact speeds, exposing inherent flaws (8) as well as damage propagation in structural materials (36). These tests will each be described next.
4.1 Point-Sensor Data Acquisition

Since most FOS sensor applications need to interrogate the peak wavelength of multiple sensors simultaneously, the FSIM first needed to verify it could match this technology. The FSIM did this in a light weight flight test of Section 4.1.1, which also helped prove that FOS technology could be made more usable by interrogating a sensor array as an autonomous node. The FSIM was next accelerated sufficiently to monitor the response of the sensor itself to the beam of a high-powered CO2 laser, which will be described in Section 4.1.4.

4.1.1 Application: Mini-UAV Flight

The first major application capitalized on the new size and weight of the FOS technology. It allowed optical sensing of both flight temperature and wing strain on-board an MAV designed by the BYU Multiple-AGent Intelligent Coordination and Control (MAGICC) Laboratory. The flight test had the following goals:

- Ascertain whether the motor is in danger of overheating during flight.
- Monitor the severity of winglet-strain during flight.
- Interface with the MAV microcontroller within the 3 days budgeted.
- Avoid impeding MAV flight.

Within a few days from idea inception, the FSIM system became a self-contained, self-powered, and compact on-board telemetry system: allowing normal MAV flight, handling its own processing needs, and passing sensor data to the MAV “autopilot” for wireless transmission during the flight. Never before flown on such a small platform, this miniature FBG readout unit verified through flight tests that the FSIM technology had advanced the usability and compactness of FOS interrogation.
4.1.2 Test Bed: Vehicle and Sensor Mount

The MAV chosen used a 152 cm wingspan, a fuselage length of 58 cm, and a 12 cm body thickness, with just enough leftover thrust to carry the handheld FSIM. The MAV weighed 1.1 kg unloaded, and strained noticeably when the FSIM added another 25% to its total take-off weight. Fueled by three multi-cell lithium polymer batteries, the MAV was propelled by a brushless electric motor that employed an electronic PWM speed control. Figure 4-2 shows the interface for the MAV with its integral Kestrel autopilot controller board, which is embedded in the MAV. The MAV also contains a 16 channel U-Blox GPS receiver and a 1 Watt, 900 MHz radio modem (which wreaked havoc on the data integrity of the originally unshielded FSIM).

Figure 4-2: The MAV test bed consisted of the Kestrel autopilot board that controlled the MAV (right), the MAV (center), and the optional remote interface (left).

Though this description explains how the small size and weight of the FSIM technology was critical to successful MAV take-off, another key to making this test successful was that air-time would not have been possible without rapid ability to interface with the MAV processor. The FSIM’s standard RS-232 port and straightforward data format were interfaced to the MAV by an undergraduate student to gather sensor data to be sent wirelessly to the MAV ground station. Testing began within a few days in a nearby field.
As shown in Figure 4-3, the FSIM was mounted on top of the MAV. This mounting location was not ideal for the MAV aerodynamics, but was meant to shield the FSIM optics from impact during landing (since the plane has no landing gear). The lower two figures show the FBG sensors mounted to the wing and to the speed control circuit with polyimide tape.

Sensor mounting was given special care to prevent bending the 125 micron fiber beyond its critical angle to maintain the FSIM’s power budget. The sensor mounted to the speed controller was sandwich between two layers of 2 mil polyimide tape and attached to the largest mass. The unjacketed fiber leading to it was likewise protected between two pieces of polyimide tape to exit the fuselage compartment and fastened every 4-6 inches to the plane. Extra fiber length was coiled and taped to the Styrofoam fuselage.
The wing strain sensor was mounted with careful technique as well: the end was fastened to the winglet by several pieces of tape to minimize slippage. Since FOS strain sensors do not compress consistently unless they are embedded (being difficult to push, like a string), the sensor was held in a slightly strained state to add pre-strain while each side was likewise fastened securely to the alcohol-cleaned surface. The extra fiber line leading back to the connector was spooled on the wing and protected as before mentioned, being cautious to avoid sharp bends that would lose light from the fiber or areas likely to snag the fiber.

4.1.3 Sensor Flight and Results

Before flight, the designers hypothesized what sensor results were anticipated: wing strain was expected to vary with turns and speed. This strain sensor was also susceptible to temperature, so better results may require subtracting the temperature sensor data. The temperature of the speed controller was expected to rise as the engine started, and increase further as the MAV reached full throttle.

Flight testing did not proceed as expected. Take-off failed for the first dozen or more attempts. Ironically, these crashes actually helped demonstrate that the FSIM technology is robust enough to be usable in non-lab settings. Since the MAV is hand-launched for every take-off, FSIM sustained crashes on several sides: fortunately, without failure. After a loose motor mount was discovered and repaired, subsequent launches were successful.

The sensor data broadcast down from the MAV showed rapid response in temperature and wing strain, shown in Figure 4-6, Figure 4-4, and the close-up in Figure 4-5.
Figure 4-4: Winglet strain was seen to generally match airspeed.

Figure 4-5: Winglet strain during take-off and early flight was compared with height and airspeed.
The results were more extreme than anticipated. The winglets did bend as the MAV turned or fought the wind – or during some crashes, such as at the 565 second mark. The data in the graph shows that the wings flex twice as the MAV was hurled into the air, and then begins to power itself, with the strain changes 90 degrees ahead of the height above ground. Winglet strain also tracks airspeed more closely than height above ground, as would be expected.

The response of the temperature sensor did not match the hypothesis; it showed an inverse relationship to speed rather than a heating relationship to the higher current flow, seen in Figure 4-6. Though questioning the validity of the sensor at first, the investigators finally realized that the sensor was showing the effect of airspeed on temperature. Greater speed increased airflow, leading to a greater cooling effect (7).

![Graph of Airspeed vs. FOS Temperature](image)

**Figure 4-6:** Temperature sensor data was compared with airspeed.
Sensor data was successfully retrieved from the FSIM during this test; however, flight troubles brought attention to the following lessons learned:

- The speed controller had no overheating concerns during flight.
- Improved winglets may potentially be designed based upon the strain profile during launch. The data gathered could be used to shore up winglet response.
- Unshielded amplifiers are not prepared for industrial applications with antennae.
- The long FSIM package reduced mounting options (it could not fit in the MAV’s payload bay). It was helpful, that the FSIM was not long in more than one dimension.

Overall, the success of the handheld FSIM met the flight goals and showed that a wavelength-based fiber-optic sensor system could be made smaller than ever before, and used in physically rough environments. The low weight and power requirements of the FSIM allowed unprecedented application and gathered useful data.

4.1.4 Application: Fiber Optic Thermal Response to a CO2 Laser

Using higher speed FSIM technology, the interrogator captured the heating rate of a surface relief FBG that was exposed to a hot pulse of CO2 laser energy. Multiple cycles of heating and cooling allowed the acquisition of the heating rate of the fiber sensor itself (9). This unique test demonstrated interrogator usability and speed.

The FSIM interrogator was set to sample at 1 KSPS to provide 1 millisecond time points. Drs. Richard Selfridge and Stephen Schultz led the creation of a D fiber, surface-relief FBG fabricated in BYU’s Electro-Optics laboratory, which was placed in a carefully controlled laser path as seen Figure 4-7 to evenly heat the entire grating.
Figure 4-7: The CO2 laser was setup to heat the FBG evenly.

Because the FOS is only 125 microns thick in one dimension, with no coating, the thermal mass of the fiber was very small, allowing rapid heating of the actual measurement device. The thermal mass contributed to a heating time constant of 77 ±3 ms and a cooling time constant of 143 ±10 ms that was consistent for any heating target up to 1200ºC, as seen in Figure 4-8.

This round of testing also showed that the D shaped fiber heating varied depending upon the angle of incidence, with the rounded side of the fiber exhibiting a heating time constant of 116 ms.

A unique advantage of the FSIM was its ability to gather spectral width simultaneously. Broadening of the sensor’s spectral peak would indicate uneven heating along the length of the grating; but the data in Figure 4-9 shows that the full width half maximum (FWHM) stayed constant during the test.
Figure 4-8: Heating and cooling response of the FBG is shown up to nearly 1200 degrees Celsius.

Figure 4-9: Constant spectral width shows even laser heating.

The FSIM technology was fast enough to analyze the maximum heating characteristics of the fiber optic sensor itself, and verify that the test was correctly applied.
4.2 Sub-Grating Changes: Pseudo-continuous Sensor Array

Moving beyond point sensing, we hypothesized that continuous spectral scanning combined with higher speeds was the key that could unlock the power of using a single FBG sensor as a continuous sensor array in dynamic measurement systems. Such an expansion would be valuable in obtaining more information from each sensor, and in salvaging data from point sensors that experienced unexpected sub-grating strain gradients like those shown in Figure 4-10. This section describes how the phenomenon of a “FOS sensor array” can occur and how the high speed and usability of the FSIM can enable the technique to be used for measurements previously unobtainable with FOS sensors. The concept is then demonstrated with additional laser heating data, followed by two cases of capturing impact data.

Figure 4-10: If the triangular wedge in the bottom image were flexed, the strain along the length of the FBG would be nonlinear, as shown above.
As illustrated in Figure 4-10, using an optical spectrum analyzer as a sensor interrogator has a limitation if the grating is strained nonlinearly along its length. These sub-grating strain gradients create non-Gaussian spectral profiles that are interpreted differently by each spectral interrogator, which may determine the sensor value based upon algorithms such as the following:

- The first peak found above the noise threshold.
- The highest local peak within a set spectral window.
- The centroid of the spectrum within a spectral window.
- A Gaussian or similar curve-fit.
- A zero-crossing of the derivative (best after spectral convolution to smooth the spectrum).

As expected, each algorithm will produce a different result, contributing to measurement discrepancy. Sometimes an algorithm also creates “ghost sensors” which appear when the spectral peak splits sufficiently to be considered two separate sensors. If the interrogator collects sensor values from the spectral peaks it finds as it sweeps, the introduction of another sensor causes havoc to the resulting data array.

### 4.2.1 Interpreting Sub-grating Changes

Algorithms may be developed to ignore or minimize the ghost sensor effect; but a more informative choice would be to interpret that phenomenon. These phantom sensor peaks actually represent useful information representing physical stimuli. Interpretation has been difficult using only spectral information, because the same spectral response can be created by multiple different stimuli. One cannot tell from a spectral scan alone which part of the FBG is being strained more than another. However, if the stimuli can be constrained, some valuable
information can be interpreted from the optical spectrum of an FBG experiencing sub-grating strain gradients. Our findings on this subject will be described in this section.

Most researchers avoid sub-grating strain problems by insulating the sensor from multiple stimuli. For example, it is well known that an axially strained FBG with no adhesive close to the FBG (only mounting points far from the FBG) will certainly have no biaxial strain. However, when the FBG needs to be fully adhered to the object under test, epoxy can cause transverse strain if it is too thick; so care must be used to limit epoxy thickness to the thickness of the fiber. Despite careful technique, embedded applications and small surfaces will inherently have sub-grating strain to work around because the forces have gradients smaller than the sensor length.

On the other hand, by constraining the possible stimuli and knowing common spectral responses, the number of interpretations decreases. The following techniques can be used to obtain information from spectra that do not match the ideal, when some stimuli are able to be constrained:

1. Use sensor mean and variance for sub-grating sensing variations.
2. Split a FBG grating into 2 or more sensing regions.
3. Consider the FBG to be a sensor array for interpretation.

These concepts will be described in detail, in preparation for seeing their application in FSIM testing.

4.2.1.1 Technique 1: Use Sensor Mean and Variance

If axial strain-induced splitting occurs (and transverse strain can be ruled out due to mounting considerations), sensor stimulus can be interpreted by viewing the FBG as a series of sensor gratings that are immediately adjacent to on another on the fiber – hitherto referred to as
sub-sensors. If one sub-sensor is strained more than another is, a smaller spectral peak will break free from the main body and reveal the strain on that portion. Thus, the mean wavelength of all the spectral response near that “wavelength area” represents the average strain of the FBG. To get more resolution, note that localized strain along the length of the grating can be identified by the peaks that act independent of the average. Because all FBG responses are at the same wavelength, it cannot be discerned which sub-sensor is experiencing which strain level using the spectrometer approach. If they all reflect at the same wavelength, the spectral intensity of that wavelength is at a maximum. However, in the case where the sub-sections of the grating are strained individually, the area under the curve of each peak does represent the amount of sub-sensors that are affected. This is illustrated in Figure 4-11, where the sensor is split by nonlinear strain into two sub-sensors of unequal lengths.

![FBG Response to Strain Gradient](image)

**Figure 4-11**: An FBG spectral profile (thick blue line) and an FBG with part of its length strained more than another part (thin red line) appears as two sensors that are combining their spectral profile.

Thus, the area under the curve will indicate the strain in the vicinity of the sensor, and the width or variance of the group of spectral peaks indicates the variation of strain in the vicinity. In
Figure 4-11, the difference between the left and right sides of the non-linear strain waveform (minus the FWHM of the no-strain peak) represent the strain variation along the sensor. This does not describe every grating line clearly, but it narrows down the possible stimuli. Dramatic changes along a fiber sensor can indicate the nature of the strain of a beam or frame. Since the FSIM gathers all the spectral profile, algorithms can be adjusted to use all the spectral area under the curve. This was tested with the FSIM, and applications will be described later in this section.

4.2.1.2 Technique 2: Use a FBG as 2 or More Multi-Sensing Regions

Using a multi-sensor concept, two or more parameters can be sensed in the same general physical location by intentionally changing the coupling of each sub-sensor. It is common for users to co-locate FBGs to know strain and temperature at a node, so that temperature could be subtracted from the strain sensor. Instead, the sensing area can be constrained such that only half of a single FBG is adhered to the strain location. The unfastened sub-sensor could be decoupled from the strain and act as a temperature sensor of the area near the strain sensor.

Such a “multi-sensor” can be spectrally identified if the sensor is pre-strained before the strain sensor portion is adhered. After the adhesive dries, and the pre-strain is released, the unfastened temperature sub-sensor will relax to a lower center wavelength, showing two distinct spectral peaks from a single FBG. An example will be shown later in section 4.2.3. As another example, FBG humidity sensors could likewise be designed with only part of the sensor coated to respond to humidity.

4.2.1.3 Technique 3: Creating a Sub-Sensor Array

Since FBGs are a compilation of many grating lines, each part of the reflected spectrum contains information about the stimuli on the sensor that the FSIM can capture at kilohertz
speeds. The effects of these can overlap in indistinguishable ways; yet the following constraints assist in understanding sub-grating strain spectral profiles:

- Sensor strain and/or temperature is isolated by mechanical means or by bandwidth
- The setup constrains the transverse and axial strain to be mutually exclusive or isolated based upon test sequence (e.g. a sensor is placed along a neutral axis)
- The gratings are weak enough in reflection that full saturation is unlikely with any combination of strain, which could prevent some grating lines from being manifest
- Portions of the grating are known to have certain types of force

When the principles of FBG spectral response are understood, many details become clear if enough is known about the application to constrain the possible stimuli. The basic spectral response concepts will be described here, and then applied in Section 4.2.4 on composite structural health monitoring. The principles include wavelength shift, peak splitting, peak chirping, end face reflection, and interference effects. The focus here will be on strain gradients, though the next example of uneven heating from the CO2 laser will show that other temperature-induced applications can occur.

As mentioned, axial strain causes a shift to higher wavelengths, and compression shifts to lower wavelengths – though compression is usually difficult unless the sensor is embedded. Partial strain on a grating will cause part of the optical spectrum to move to higher wavelengths, causing peak splitting. These are illustrated in Figure 4-12.
Figure 4-12: Axial strain as shown (top-left) causes spectral shift to higher wavelengths (bottom-left); partial grating strain (top-right) splits spectral peaks (bottom-right).

Transverse strain can also cause peak splitting: as multiple preferred modes or path lengths are created in the fiber, two separate peaks emerge. The peak at the higher wavelength represents the biaxial strain, and the distance between the two peaks quantifies the strain. It should be noted that a small amount of shifting in the left peak occurs from biaxial strain due to the elongation of Poisson’s ratio. If only part of the grating receives transverse force, it creates an additional smaller peak from the larger peak created by the transverse strain, as illustrated Figure 4-13. Numerous axial and transverse forces can greatly multiply the spectral features.

During the emerging process for transverse peak splitting, the combined intensity of the two peaks can cause a center lobe as seen Figure 4-14. These spectral profiles are frequent in sub-grating strain responses that are loaded with transverse strain, and may be due to interference effects between the two emerging peaks. Interference often has a sinusoidal effect.
Figure 4-13: Strain transverse to the fiber (top-left) causes spectral peak splitting (bottom-left); varying transverse strain (top-right) causes sub-peak splitting (bottom-right).

Figure 4-14: Partial peak splitting combines the intensity of two peaks into a center lobe.

If a fiber breaks, the end-face may exhibit a broadband reflection, as seen in Figure 4-15. This back-reflection spectrally rolls off proportionally to the light source. It reduces SNR and is often overcome by crushing the end-face or by adding an optically transmissive material to the breakpoint.
Using these foundational concepts, compounded strain stimuli can be interpreted, as is done in the last section of this chapter, Section 4.2.4.

### 4.2.2 Application: Laser Temperature Gradients

Applying the sensor array concept, the CO2 laser was used to heat only a portion of an FBG sensor, and the response was tracked at high speeds that only the FSIM could show in real time. This gleaned information about the low thermal conduction of fiber optic strands as it effectively peeled away subsections from the main grating.

A 2 mm long grating was placed partly into the CO2 laser path, and the laser was turned on for less than 1 second. Figure 4-16 shows a sequence of spectral profiles by the FSIM as the sensor heating progressed. The heating profile across the grating varied (it was not quite a step function), with the center line of the grating receiving much less laser radiation than the sensor edge that was directly in the laser beam. Notice how each subsection of the FBG was pushed into
a higher reflection band as the lines of the grating thermally expanded. The resulting chirped shape was similar to the chirped grating produced by linearly increasing the grating line intensity and spacing along an FBG as in Figure 2-7.

![Figure 4-16: Nine sequential spectral images are shown of CO2 laser heating for only part of the FBG.](image)

The thermal conductivity of the medium (glass) is shown here, where the response holds for a finite time before the entire waveform would shift with the leading edge. Some shift is detectable, and some of the chirping is likely due to thermal conduction.

This experimental setup hints at a useful tool FBG research. Future grating investigation could be performed with the FSIM technology, using multiple lasers along the fiber to create short-term FBG etalons and other effects. Perhaps such a tool may be useful in confirming a calculated response before fabricating a specialty grating.
4.2.3 Application: Strain Gradients to Reveal Damage (Holes or Debonding)

Exposing the sensor array to strain, the FSIM detected an artificial defect in a cantilever beam during an impact. This defect likely would have been hidden from a standard point sensor or traditional interrogators. The measured result shows a signature effect that can only be acquired with the FSIM concepts developed (8; 8).

The aluminum panel in the expanded illustration of Figure 4-17 shows the setup for this test. An FBG was adhered to the panel near a defect of 1.8 mm diameter. To illustrate the sub-sensor concept, the FBG was placed so that the defect would induce nonlinear strain along the grating. Note also that part of the FBG was purposefully not adhered (the yellow oval represents the cyano-acrylate adhesive). As in the common technique described earlier, the fiber was strained as the adhesive was applied, so that the relaxed fiber split into two spectral peaks.

Figure 4-17: Illustration of a cantilever aluminum beam with a fiber optic sensor mounted near a 1.8 mm manufactured defect (hole).
As seen Figure 4-18, small panel vibrations were monitored with the FSIM starting at time $t_0$, but the defect was not detectable in the spectra. Notice also the small peak in the left-hand side of the spectral profiles at 1550 nm. It may appear like a standard FBG side lobe, but it does not move with the center lobe because it is a second sensor created by partial grating adherence. This sub-sensor responds to temperature, but is decoupled from the panel strain.

Another provocative application of this sub-sensor is as a local wavelength reference. This is because scanning interrogators cost more if they provide absolute wavelength accuracy by including reliable wavelength references to compensate for the jitter, scan nonlinearity, and drift of the scanning mechanism. This part of the multi-sensor is stable in the short-term, and may be sufficient to improve wavelength accuracy of the other nearby multi-sensors in applications where relative spectral shift is the characteristic of interest.

Figure 4-18: Vibration of the cantilever beam caused spectral movement shown here. The sub-sensor peak at 1550 nm was isolated from vibration.
When the panel received an impact, the nonlinear strain induced by the defect caused the FBG to chirp, as expected. This chirped profile lasted only 3 ms, and the defect would be missed if one of the single point algorithms were used. Nevertheless, the spectral width and structure reveal to the FSIM a strain gradient that only a rapid spectral interrogator could capture. This is shown in Figure 4-19.

This data was rapidly reviewed and the most notable spectra were quickly identified using the Spectral Viewer, which brought up the following image of Figure 4-20. This view was setup to place earlier waveforms (t0-t3) lower in the plot, and lower voltages equated to higher wavelengths (the spectral data was not converted to wavelength for this test).

![Figure 4-19: An impact caused nonlinear strain in the vicinity of the defect, causing nonlinear strain seen by the chirped spectral profiles shown.](image-url)
The ability for the FSIM technology to capture multiple parameters per FOS at kilohertz speeds provides a useful tool for research and industry for structural health monitoring.

4.2.4 Application: Composite Structural Health Monitoring

The FSIM technology was also used to monitor the real-time impact damage and failure of a composite beam embedded with a fiber optic sensor. Researchers like Dr. Kara Peters at the University of North Carolina have been expanding the forefront of spectral interpretation for FOS in composite materials using standard spectrometers, and used their expertise to set up a drop tower test wherein the FSIM could watch impacts at high speed.

FBGs have been favored in composite laminates because the material properties and size of optical fiber and fiber reinforced polymer are similar, and embedded fibers do not significantly weaken the weave (10). An FBG embedded in composite material is shown in
Figure 4-21. Peters and associates have interrogated previous instrumented test coupons using slower interrogators (37) but found that the data obtained by the FSIM reduced the sensor types necessary for interpretation of damage states.

Figure 4-21: A fiber optic end-face embedded in carbon fiber reinforced polymer composite for a Daimler-Chrysler test.

This test was setup by sandwiching an FBG along the expected neutral axis of a composite plate, as seen in Figure 4-22. The FBG was interrogated before the test began to obtain baseline measurements and the tests were conducted at 534 Hertz across a 14.9 nanometer spectral bandwidth. The test was conducted by users unfamiliar with the FSIM platform that had only been given a 15-30 minute user overview, days before the trip to the test site. Testing ran without complications – although the slow laptop chosen to save the spectral waveforms significantly limited the scan bandwidth. Since spectral compression was not enabled for the test so that no potentially valuable sub-threshold data would be lost, spectral compression was not a benefit. This usability feature was countered by concern that the feature would reduce resolution.
A drop tower at the University of North Carolina was created to ram 19 mm diameter impact probe at velocities of 2.0 m/s onto the composite coupon. Part failure was defined as complete perforation of the coupon. The drop tower is shown in Figure 4-23.
Figure 4-23: The ram setup of the drop tower, which impacted the test coupon with energies between 11 and 14 Joules but arrested any bounce.

4.2.5 Composite Impact Data Analysis

The embedded sensor started with a typical Gaussian profile, but rapidly changed as damage progressed through the coupon. Figure 4-24 shows 8 of the scans captured during an impact, which started at scan 2. Since these scans are from strike 70 of 82, note how the sensor has significant peak splitting from the compression of the carbon fibers being compacted with each blow. The ripple along the edges is likely due to an etalon effect, which comes from portions of the grating spaced such that an interferometric spectral ripple is created. It is also possible that a ground loop or other noise source is adding these fine features across the peaks.
and empty parts of the spectra. If so, troubleshooting that issue that may need to be added to the automated compensation and troubleshooting routines.

Figure 4-24: Eight spectra during impact 70 show transverse strain, relaxation, and strain reapplication.

Since the author believes axial strain is constrained to be mostly homogeneous due to the mechanical setup, several details are inferable based on the peak splitting being caused chiefly from transverse strain. Note how in scan 3 (partially obscured), some general shift to the right occurs, showing axial strain; but even more widening occurs between the split peaks, which is evidence of high transverse strain. By scan 7, the sensor has returned to its original (general) shape. However, notice that scan 6 actually shows a reduction in transverse strain, as if a bounce is releasing transverse pressure momentarily.
To view several impacts at once, a false color view was used (38). It could be seen as a top-view of the spectrum, where high intensity was given a warmer color, as in the example Figure 4-25.

Figure 4-25: False color images (below) represent the spectral profile (above) with red for high intensity, yellow for moderate, and blue for low intensity.

Figure 4-26 shows the maximum contact force (squares) and dissipated energy (circles) per strike taken from impactor position and acceleration sensors on the drop tower. Note the continual decrease of contact force, with sharp changes during the first and last several impacts. Previous theories suggested that vibration noticed during some impacts was an indicator of structural health, but the investigators noted that they appear throughout the test (shown by the arrows). The FOS spectral data allowed the structural health to be divided into 5 levels of damage progression (shown in the figure), which were identifiable by FSIM data alone.

FSIM spectral data from five impacts are shown Figure 4-27 that were typical of the 82 impacts scanned before coupon failure. Note in the first section how the yellow, representing the sensor peak, moves to the left of the general trend during impact, showing axial compression during while the coupon is in new condition. The direction of this strain shifts in the second
section, where impacts cause a tensile strain, suggesting that sufficient damage has been caused to move the central axis of the coupon upward. This hints that the bottom of the coupon is stretching and failing.

Figure 4-26: Maximum contact force (squares) and energy dispersion (circles) measured on the coupon by conventional drop tower sensors during the 82 impacts (36).

The third section shows movement in both directions, indicative of more play in the test coupon. The nominal peak has now split into two, suggesting a progressive transverse strain on the sensor, which increases by the fourth section. Another key indicator is that the duration of the dynamic strain increased – a strong indicator of decreased mechanical thickness as the resonant frequency has decreased.

A last key to note is that the peak splitting almost completely disappeared by impact 81, the last impact before failure. This transverse relaxation is likely due to delamination of the plies that compressed the sensor. This can be seen in the last section of Figure 4-27, where the sensor
response of test coupon reveals severe movement with each impact, with a large increase in dissipated strike energy. The sensor still functioned after failure.

Figure 4-27: The spectral response is shown during five impacts representing the strain progression through the test.

This test showed that valuable structural health information could be obtained by using FSIM technology to capture high speed, full spectral waveforms during impact testing. Previously, intermittently sampled data needed acceleration and other data to know damage
status, but the sensor array nature of this test gathered a revealing picture of health and the progression towards failure.

The FSIM is still a prototype with shortcomings, but it successfully captured data in several tests that were not possible with any other FOS system. Flying on a small MOV with a few days of interface time, sampling impacts under the hands of those who did not design it, and capturing rapid, complex laser pulse heating affects or defect damage of a plate during impact – each required a higher level of compactness, speed, and usability than previously existed for FBG interrogators.
5. CONCLUSIONS

To push fiber optic sensor technology into the mainstream of industrial and research use, the FSIM technology has improved sensor interrogation by introducing a small, faster, and more usable sensor readout system than was previously available. The new technology can travel in more size-constrained applications, produce full-spectral readout of fiber Bragg grating sensors, and interface rapidly to new users and test interfaces.

Wavelength-based sensors still have hurdles to overcome for widespread adoption. The interrogator technology still needs to be made more robust and be tested for accuracy despite temperature drift and interference, as well as several other common parameters typically accomplished in a commercialization endeavor. The sensor bonding, splicing, and strain range selection continue to be a challenge requiring a high degree of expertise. The lack of standards in the industry creates a variety of opinions of what system requirements are valuable, though the merit of past tests can project future potential.

5.1 Means of Improvement

The advancements that came from this research can push the FOS field significantly closer to widespread adoption. The FSIM technology found that ideal optical components and hardware configurations dramatically shrink the size and weight of the interrogator. Data throughput dramatically increased with fast optical and electronic hardware, which was
maintained by carefully pipelined FPGA processing and Ethernet bandwidths. Usability increased when effort was placed on feedback to the user and circumventing common challenges, as well as facilitating common tasks of data acquisition and data review.

In this work, significant size reduction was obtained by several methods. Using greater amplification instead of a large light source reduced the thermal budget sufficiently to drop below the need for a large and energy-hungry thermoelectric cooler. A MEMS scanning etalon dramatically reduced the size and power budget for the wavelength discriminator. Careful optical fiber routing and rapid processing kept the remaining storage and other microelectronics small enough to make the FSIM a handheld device, one half the size of any commercial autonomous device.

Focusing on greater speed, the etalon sweep was captured by the latest ADC technology and rapidly processed by a pipelined architecture in an FPGA to obtain key sensor information. FPGA memory mapping and DMA transfer through an ARM processor pushed the data across a 100 MB Ethernet connection where LabVIEW software used circular buffering to capture and save entire waveforms or simply refined spectral peak sensor data, enabling thousands of spectral scans per second across the optical sensor range. The result was a spectrometer capable of monitoring many FBGs at multi-kilohertz speeds.

To make the system more usable, common bottlenecks were discussed and planned for regarding system connection, sensor interface, and data handling. A model-view-controller technique was used to decouple the PC video from the data acquisition, giving priority to data retrieval. The interface was documented and standardized for interface with larger sensor networks, so that the Fiber Sensor Integrated Monitor could function as an independent node, gathering data without burdening other processors. Common debugging techniques were coded
in as controllable timeout options for new users, yet low level access was given to allow advanced users macro access to novel techniques. Saved data was catalogued for rapid viewing; and finally, a spectral viewer was created for rapid review and exporting of any portion of large datasets. The systems were rapidly interfaced and put to use by non-FSIM developers, and used to gather data for several published research papers.

5.2 Applications

These advancements were verified by applications in laboratory and field use, including rapid CO2 laser heating of an optical fiber, damage detection of an aluminum and a composite plate, and a micro air vehicle flight. Each demonstrated a new capability of the FSIM technology, and interpretation of spectral sensor waveforms was described in concise detail.

The flight test required a low-weight payload, including operating energy, which only the FSIM could accomplish of any FBG interrogator. The FSIM accurately acquired winglet strain and speed-controller temperature during flight, which were broadcast by the flight controller to the ground and stored on-board the FSIM for later viewing. The throughput was low and shielding was eventually required to obtain a decent signal to noise ratio, but the FSIM gathered all expected data even after dozens of flight crashes due to an unnoticed loose propeller.

Capturing the heating time constant of the heating of an optical fiber with a CO2 laser required high data throughput and the ability to place the sensing medium into the fiber itself (a surface relief FBG). This revealed the heating and cooling characteristics of radiating the D fiber at different angles and showed signature spectral responses thanks to the low thermal conduction of the fiber. Verification of heating uniformity was also extracted due to the high speed spectral capabilities of the FSIM.
Though conventional FBG interrogators obtain one-dimensional data (the spectral peak) from fiber optic sensors, using each sensor as an array enabled damage detection caused by nonlinear strain gradients in an aluminum plate that were only visible in the full-spectral output of the FSIM during an impact. Additionally, the FBG was made into a multi-sensor by choosing to leave part of the FBG detached to act as a wavelength or temperature reference – a principle that could multiply FBG uses and simplify future interrogators.

When embedded in a fiber-reinforced composite material, an FBG response can become meaningless to typical FBG interrogators. The FSIM enabled kilohertz acquisition of spectral profiles that distinctly identified damage progression during a drop test at the University of North Carolina – a task usually left to tedious eddy current, x-ray, or similar methods. The FSIM technology was usable enough to allow the test to be conducted by non-designers with only minutes of training, enabling them to publish multiple research papers using the data.

5.3 Future Work

Future work could potentially improve the size, speed, and usability further: due to slew rate limitations of the photodiode amplifier, the high speed FSIM required a large, high power optical amplifier to provide sufficient light for the system. This enabled the photodiode receiving amplifier to focus on bandwidth instead of gain, thus maintaining spectral features at high scan rates. Newer op-amps with a higher gain-bandwidth product would enable the high speed FSIM to be compact, especially if Ethernet were incorporated into the FPGA. More focus on data compression could significantly reduce the data handling bandwidth required, which would fit more data through the Ethernet and receiving PC’s hard drive, yielding greater spectral speed. It is also easy to perceive adding algorithms to the FSIM that would extract damage states and strain vectors from the spectral data; algorithms that would process in parallel FPGA fabric
without burdening external processing. This would reduce required bandwidth, resulting in higher speed, and potentially enable autonomous damage detection that does not require human interpretation.

The FSIM technology successfully enabled designers to increase the toolbox for research and industrial applications that require compactness, greater sensor array speed, and ease-of-use. This work advanced wavelength-based fiber optic sensor systems, enabling researchers and test foremen to focus on the sensor data instead of the readout unit.
6. **BIBLIOGRAPHY**


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APPENDIX A. HARDWARE DESIGN DETAILS

The FSIM would not have met its goals without careful assembly. The development details are included in this section.

A.1 Component Configuration and Fiber Winding

The original microcontroller-based prototype became a small-sized unit only after careful planning of the routing for the optical fibers. Exceeding the minimum recommended fiber bend radius of 32 mm contributed to loss of sensor resolution, so the fiber for the entire optical system diagram had to be routed carefully to minimize light loss yet allow investigation and modification. It needed to provide pigtail strain relief while lining up the splices in a shock-resistant way. Yet it still needed to minimize the overall footprint. The key principles used for compact fiber optic routing are as follows:

1. Monitor the power budget as fibers are spliced together and routed. Estimate appropriate light levels before-hand and resplice as necessary. Visible “fault-locator” lasers work to show light loss until they reach beamsplitters, which are designed only for the infrared range (they will not pass visible light with the expected 50/50 ratio).

2. Designers should plan component placement to point all fiber pigtailed along a single dimension. This minimizes the unused space of the final assembly. Component misalignment in the original handheld FSIM design created significant extra caution and part movement effort when the FSIM was packaged, as seen in Figure A-1.
3. Routing fibers between layered circuit boards is precarious, since fiber cannot be bent around corners as wire can. Routing fibers between layered boards of the assembly can work best if the fiber begins near the corner of the board and crosses down to the other board while running nearly parallel to the board’s plane, as seen in Figure A-1.

4. Careful routing of the optics not only made the handheld FSIM compact, but preserved it from any damage despite it being involved in over 20 crashes aboard a micro air vehicle during later field testing.

Figure A-1: The handheld FSIM after packaging was about 580 cubic centimeters.
Proper integration and high quality optical components significantly improved the FSIM technology. They enabled higher performance, smaller size, and more easily used interrogation than was previously available.

A.2 FSIM Electronics

To obtain high performance and usability in a small package, the FSIM electronics had to be carefully tailored to the distinctive requirements of the optical components, as well as the algorithms needed to produce FOS data. The following electronic tasks were required:

- The entire system needed to perform both optical filter control and processing of acquired data autonomously to minimize the additional burdens on a user’s PC.
- The MEMS optical filter required an unusual 0-36 volt tuning range.
- The disadvantage of the low power light source needed to be compensated with significant electrical amplification of the received signal.
- Communication with a host processor or PC must occur without compromising the data stream through a finite bandwidth.

To accomplish its objectives of size, speed, and usability, the FSIM technology designed these mixed-signal circuits with nuances atypical to other optical interrogators.

A.2.1 Electronic Architecture Overview

The handheld and the high performance versions of the FSIM attained their accomplishments using the same general block components. They are labeled in Figure A-2 to identify the following functional blocks:
1. The “node controller/processing unit” was upgraded from the 16-bit PIC processor in the handheld incarnation to a 200,000 gate Spartan 3 FPGA in the high speed interrogator.

2. Upstream communication was sent through an RS-232 interface for the handheld prototype, but an Ethernet port was used in the high speed FSIM.

3. The DAC was as an I2C controlled device for the smallest prototype, and a 12-bit, 200 MSPS DAC from Analog Devices for the FSIM with high scanning speeds.

4. The analog to digital sampling was performed by a 50 KSPS internal ADC on the PIC microcontroller, and a 100 MSPS, 14-bit ADC for the high performance FSIM.

The analog and digital cooperation in this system may be typical of a sensor system. But the peculiarities of a spectrometer at high speed or small size are worth further description in the next two subsections.

Figure A-2: The major components used in the FSIM prototypes guided the control and flow of sensor information.
A.2.2 Analog Control and Amplification

A usable spectral interrogator relies upon both low-noise analog tuning and amplification of the response. Due to the low optical power budget of the FSIM and the unusual tuning range of the optical filter, these two circuits required significant gain as well as high bandwidth.

In the high performance prototype, the analog amplification of the filter control also required conversion of current to a voltage. The fast DAC emitted 2 mA maximum, which needed almost 20,000 times amplification to meet the 36 volt control range of the optical filter. High sweeping speeds over a large voltage range require an output op-amp with both high slew rate and a wide voltage range. Since this was no longer considered small-signal amplification, the slew rate of the amplifiers required two stages as well. The 17-34 volt part of that range correlated to the telecom C band, so amplification was needed at higher voltages to match the light source selected.

If 36 volt op-amps were unavailable at the slew rate needed (a likely case for further FSIM acceleration), the control electronics can be simplified and still meet the range of the filter using a fixed-negative rail technique. The filter common can be connected to the -17V rail, then filter can be driven by the DAC’s output op-amp operated using a +17V volt single supply. This method provides sweeping across only the higher voltage C band. The method also cuts the sweep range in half, but better matches the low cost C-band SLED. Future use of only L band components would further decrease the supply voltages needed.

To meet the system performance requirements with a filter that only passes a fraction of its broadband light source (typically 1/40th), significant amplification was used to detect the filtered light reflections from the optical sensors. Without adding an external optical amplification, the photodiode peak input power was approximately 25 nW in the handheld unit,
which translated to approximately 20 nA coming from the photodiode anode. Two op-amp stages amplified the received portion of the optical spectrum by nearly 200 million times. Using an OPA2380 set up as a transimpedance amplifier (TIA) followed by an OPA 2301 resulted in approximately 4 volts peak output for the ADC to capture.

The handheld unit obtained high quality spectral scans with this configuration for up to 20 scans per second, but experienced significant loss of accuracy near 100 Hertz on a typical sweep. To increase the data rate, the high performance unit used a 10 mW, bench top, Erbium-doped fiber amplifier (EDFA), yielding 100 times more light from the broadband source. To avoid this size increase would require an op-amp with a 2 GHz or higher gain-bandwidth product and high stability at high gains, which was not yet available. The high speed FSIM compensated with more optical power and the gain of the TIA was reduced, enabling amplification at much higher bandwidths for the sweeping spectrometer.

Such high gain was not immune from incident EMI noise, however. To maintain noise-free scanning required the handheld FSIM packaging to be internally lined with aluminum, which greatly increased radiated immunity. This proved necessary in the presence of wireless video broadcasts during test flights with the sensor system.

Sufficient data resolution at high speeds was arranged by choosing a faster ADC to sample the amplified sensor response. When the 50 KSPS I2C ADC was upgraded, the faster ADC was run at 25 MSPS. This ADC bandwidth could deliver an unprecedented FOS data rate, where a minimum 10 samples per nanometer are used across a 25 nm bandwidth. This can be calculated as follows:

\[
10 \frac{\text{samples}}{\text{nm}} \times 50 \frac{\text{nm}}{\text{scan}} = 500 \frac{\text{samples}}{\text{scan}}.
\]

These 500 samples would still allow
while staying above Nyquist sampling rate (if the system acquired two data points per scan, while scanning both right and left). In other words, this ADC could be sufficient to monitor over 50 of the 0.2-nanometer wide sensor gratings at an unusually high 50 kHz. In common practice, users often choose to have more range per sensor, which requires that fewer sensors be monitored simultaneously. Some spectral measurements are more accurate with more data points per sensor peak than that calculated above. The optical filter scan range may also be decreased at that frequency due to the roll-off of the scan response unless control theory techniques were employed.

A.2.3 Processing

Dedicated processing harnessed these electronics and christened the FSIM node as an autonomous measurement tool. A low power microcontroller with broad capabilities was a key to making the smallest FOS interrogator in the world. Similarly, it was felt that an FPGA was instrumental to control and process all the details needed to make the fastest interrogator in the world, since there were so many I/O and processing tasks that needed to be completed in parallel.

Using a PC with add-on cards has been standard fare for FOS interrogators. But the FSIM differed by implementing the following requirements to create an autonomous sensor system using the PIC 18F2680 microcontroller:

- Ability to control an analog output: the PIC has a Master Synchronous Serial Port (MSSP) which communicated across an I2C port to a low power DAC8571 (from TI) to provide optical filter tuning.
- Ability to acquire sensor system data: a built-in ADC channel acquired photodiode and thermistor data at 50 KSPS.
- Dedicated, prioritized processing: the unit ran on an 8 MHz clock (scalable to 40 MHz), using prioritized interrupts for acquisition or host serial port communications.

The low power processing and sleep modes of the PIC were also employed to reduce battery drain, so that smaller batteries could be used. The high performance FPGA increased processing throughput using a Spartan 3 FPGA on a development board from Digilent Inc. (39). This board provided three 16-bit DIO ports as interfaces to the high speed DAC, ADC, and SRAM memory. The SRAM was used for sensor data storage. Since FPGAs consist of many independent logic units, the FPGA was able to organize these logic units into parallel, dedicated processing units. They were configured to control the optical filter, acquire photodiode data, process spectra to acquire peak locations, convert the peaks into wavelength information, and send refined data upstream as requested by a host processor.

Careful, iterative refinement of the analog and digital hardware enabled the eventual development of the handheld and high performance FSIM technology. Selecting compact and agile optics, a low power autonomous microprocessor, and avoiding thermoelectric cooling gave the FSIM significant size and performance advantages. The parallel processing power of an FPGA and 100 Mbps Ethernet interface were requisite in control, processing, and passing data out of the system quickly enough to be used for high speed impacts and sub-sensor array studies. Appropriate matching of amplifiers, mixed signal chips, and power supplies enabled capabilities that increased usability, performance, and compactness for future industrial use of FOS interrogators.
B.1 Overview and Pipelining

Whereas many commercial interrogators require a user’s PC to control filters and process spectral responses, the FSIM completed all these tasks internally as an independent node. The autonomy of the FSIM is shown by the comprehensive processing shown in the following diagram of Figure B-1:

![Diagram of FSIM firmware techniques](image)

**Figure B-1:** The firmware algorithms were ideal for data pipelining due to their assembly line-like relationship.

The command interpreter on the far left of this diagram is a processor directing each task. The microcontroller-based FSIM dealt with each of these tasks sequentially, as fast as it was able. The FPGA-based FSIM interpreted commands using a soft-core processor replicated inside the FPGA fabric. It followed a simple routine to read commands from the upstream I/O memory.
mappings, and set up basic parameters of the scanning or data acquisition process. All the acquisition and data reduction beyond command processing was pipelined in the FPGA fabric, enabling a drastic increase in measurement speed. This included acquiring raw data, finding spectral peaks that represented sensor data, organizing them, and converting intermediate data into wavelength values to be stored for access at the memory-mapped I/O.

B.2 Control Algorithms

To maximize processing speed, the overall algorithm governing the FSIM was kept as tight as possible. Nevertheless, usability is increased if attention is also given to user control (to avoid the industry-common unresponsiveness to readout requests). To meet both needs, two threads were used in the high performance interrogator. The first thread acquired new commands and returned system STATUS or redirected FSIM processing upon request, allowing instantaneous user control and eliminating the unresponsiveness seen in many interrogators. The second thread interpreted and processed the user commands in its queue. The outline below shows two of the main branches of this algorithm:

FSIM START:
1) Cold initialization (after reboot) – start THREAD 1: Ethernet receive thread
2) THREAD 2: Warm initialization (performed after settings clear)
3) Idle: Process any incoming commands
   a) If data request:
      i) Send data to host as requested, low priority
   b) If scan command:
      i) Go to range
      ii) Initiate a scan and the ADC pipelined collection process
      iii) As data arrives, begin processing
         1) Find peaks
         2) Convert them to wavelength
         3) Store them
         4) Repeat until # scans requested is fulfilled
   c) Return to idle (step 3)
Ease of use was increased by adding other branches to this algorithm, including adjusting ranges or related scan settings, repeating the last command, debug commands, resetting the unit or restoring default settings, and various versions of data acquisition. Time-critical operations (like acquisition) were placed higher in the comparison list to reduce the comparison time of the case statement. An abort flag was checked in every operation containing a loop to allow rapid return of attention upon user demand. The result was a speedy, flexible interface that kept control in the hands of the user.

B.3 Calibration

As mentioned, the power (and therefore system size) of the FSIM was reduced by eliminating the TEC of the optical filter. The optical filter exhibits a temperature response of +/-100 picometers over a 40 degree operating range, which equates to nearly 10 degrees Celsius or 115 microstrain of sensor error. Processing redeemed the data accuracy by using a temperature look-up table to adjust measurements for both the temperature response of the optical filter and its pseudo-linear response, seen in Figure B-2.

Since the calibration process was fundamental to size reduction in the FSIM, it should be detailed for others to follow and adapt. These are the steps used to create temperature stability without a TEC:

1. The filter was first characterized over the FSIM’s full temperature range to create a temperature-based lookup table.
2. An athermally packaged reference grating was built-in to the FSIM.
3. The FSIM was designed to use the position of this reference FBG to identify the current optical filter temperature from the table.

4. Once the temperature was known, the table was also used to convert each tuning voltage of interest (representing sensor features) into a wavelength.

5. Interpolation between table data points finished the conversion with added accuracy.

Creating the calibration table was straightforward, though tedious. The FSIM temperature compensation lookup table was created by injecting a tunable laser into the sensor input at a known wavelength. The FSIM optical filter interrogates the laser as if a sensor, and the tuning voltage at the laser’s center wavelength was recorded in the lookup table. The table’s column for that temperature is filled as the tunable laser wavelength is incremented and the process is repeated. The optical filter was held at a known temperature using its TEC and an external, bench top TEC controller. After the entire FSIM range was mapped, the TEC controller was adjusted 0.5 degrees to a new temperature and the process was repeated to fill in another column of the lookup table (35). Part of this table is plotted in Figure B-2. Notice that each curve represents the tuning voltage for each wavelength at the temperature shown in the legend.

An athermally packaged reference grating was added to the low-side of the sensor scan range, which served as an indicator of the current temperature of the optical filter. Other means are certainly possible to identify the system temperature (such as the internal thermistor), but the athermal grating was considered to be the most accurate option that did not require additional ADC or other hardware to acquire temperature data. The grating wavelength was chosen to reside in the lower wavelengths since lower wavelengths generally experience less cross-over. This is because most common FOS measurements are of increasing strain and increasing
temperature, both of which push the FOS into higher wavelengths. Two drawbacks to this method include the need to include the reference grating in the scan range, and the possibility of a sensor peak crossing over the reference peak.

Scan by scan use of the calibration table involved the following process:

1. **Identify the points of interest in the scan**: acquire an optical spectrum including the reference grating, and identify the tuning voltage that corresponded to the reference grating and each of the other sensor peaks in the spectrum.

2. **Calculate the system temperature**: using the row of the table that corresponds to the known wavelength of the reference grating, identify the column of the two tuning voltages nearest to the voltage that was measured for the reference grating. The

Figure B-2: Cooling energy was saved by creating this calibration table. The legend shows the temperature in Celsius of each response curve for the MEMS tunable optical filter.
column temperature headings bound the temperature of the current spectral scan. Interpolate between the two temperature bounds using the reference grating tuning voltage to obtain the accurate FSIM temperature.

3. **Convert filter tuning voltages to wavelength for the selected temperature column:** using these selected temperature columns, locate the tuning voltages bounding each tuning voltage of interest (interest typically meant “all sensor peaks”). The heading of the selected rows will bound the wavelength of the point of interest for this scan. For each tuning voltage of interest, use the FSIM temperature to interpolate between the two “wavelength boundaries” to identify the correlated wavelength.

The details of this calibration process were tedious, but not surprising. The table was stored in the FPGA’s internal Block RAMs (BRAMs) so that non-volatile hardware RAM was not required. This memory was limited to two simultaneous outputs per BRAM, preventing concurrent comparison of lookup table values – thus lengthening the process. Perhaps more FPGA fabric would enable multiple BRAMs and more simultaneous comparison. The interpolations were not a simple task – particularly in an FPGA, since two divisions are required. A Cordic algorithm was employed to limit the division process to a fixed number of cycles.

Such calibration required significant non-recurring engineering (though it can be automated by the same processor that performs the interrogation) and proved worthwhile to preserve performance while shrinking size and power consumption.

### B.4 Memory-Mapped Interface

One engineering feature that simplified high performance data transmission was the FPGA’s memory-mapped interface. This is not a built-in feature of FPGAs, but rather the FPGA coded to behave like a memory chip for both command entry and data retrieval. As detailed in
the FSIM Memory Map in Appendix C.1, the number of scans to perform was placed in a certain FPGA memory location across its GPIO bus, and the data was soon available to be read serially from another memory location that automatically incremented with each read operation. Even the number of sensor peaks found and the number of data points available in the full spectrum scan were available at a known memory location, all handled seamlessly by an FPGA HDL entity.

This memory-mapped interface allowed for easy porting of interface algorithms. When the microprocessor was traded for a soft-processor inside the FPGA, the FPGA processing algorithms were still obeying serial port commands placed into the memory-mapped interface. Again, when the serial port was augmented with the Ethernet interface (actually an external ARM processor), the Ethernet interface simply wrote or read the data from “memory locations” as seamlessly as if the “FSIM memory” were internal to the processor.

B.5 High Performance External Interface

To improve usability and avoid another bottleneck in data throughput, significant effort was employed to maximize the data interface throughput from the high performance FSIM to its host. A PC was typically used as a host controller, requesting data and compiling refined data for users to view. Its initial connection was via an RS-232 port, usually opened by a LabVIEW program. Later it became a TCP/IP connection sending data via bulk UDP packets. TCP packets and a WWW interface were also available through the Netburner drivers, and were experimented with but not yet deployed.

The novel usability and speed features created by this interface are worth special description so they may be replicated:
• The simplified, ASCII format of the communication eased interface efforts, with both high level commands for new users coming up to speed, and low level commands for scientists commanding the FSIM to perform complex research operations.

• The command buffer increased usability by stockpiling consecutive commands, easing the host programming effort by removing hand-shaking requirements.

• Each response to the standardized ASCII commands was a tailored error message understandable by humans and machines.

• Individual sensor identification was employed, allowing each sensor to be named and loaded with calibration parameters inside the FSIM node.

• Other helpful troubleshooting methods included optical power boosting and the ability to get status information or interrupt processing at any moment.

Some of these features increase speed and usability enough to merit the following more detailed description.

B.6 ASCII over UDP Interface

Several protocol requirements existed for speed and usability. The interface between a host processor and the FSIM needed to be fast enough to pass all the sensor data the FSIM could create. The protocol needed to be standardized so that its user base could connect using common tools; it also needed to be easily comprehended to reduce the complexity that exists with many commercial FOS interrogators that are not ready for non-optical engineers to use.

The foundation of this interface was a UDP message using an ASCII protocol, written in C and C++. A simplified ASCII format was chosen for various usability reasons:
- It is human readable, accelerating debug and the initial interface of the node into larger sensing schemes.
- It is used in various industries.
- It works over various mediums, such as the RS-232 and Ethernet interfaces mentioned. The standard output stream is simply piped through one medium or the other.
- It commonly has a short version (3 characters for each command) and can be easily machine-interpreted by both ends of the communication.

Each of these motivations did help in the development of the FSIM technology; however, the highest data rates were bogged down by the conversion of the spectral data into text decimal format; so to preserve high data throughput, binary data was sent in between ASCII header data during full-spectrum transmissions.

Because many Ethernet systems fall short in usability as the operator struggles to connect them across their network, the FSIM was set to broadcast its boot-up message and IP address to the entire network, on a specific port the host PC can check. This makes connection trivial if the host program is watching for the announcement. Password protection and encryption were not yet implemented.

B.6.1 Command Buffer and System Status

The basic command/response interface of the FSIM significantly increased the usability of the FSIM. The high performance FSIM received all requests into a command buffer; and then returned a standard response that included the last command that succeeded, and what the FSIM was doing at the moment.
The command buffer added all received text to a FIFO memory array for subsequent parsing and processing. To prevent processor lag from cleaning up an array that was near the end of its allocated memory, the buffer was made to be circular (its entry pointer automatically rolled-over to zero if the command there had already been processed). Another pointer kept track of the next text to be parsed. If the entry pointer wrapped around and met the pointer of data yet to be parsed, the buffer would be considered full and an error message created to note the problem. This circular FIFO command buffer allowed scores of commands to be sent, but was light and fast because it did not need to be “cleaned up” and recreated when it was almost full of used commands.

The command buffer allowed the host to send multiple commands all at once, without waiting for responses. For instance, the following list was sent from the user before a test, to check that a connection was ready and configure the FSIM for optimal settings based upon previous testing of that set of sensors. The # sign bypassed command parsing for comments:

```
hi
wavelengths off
put 53 0
put 52 255
set_range 8200 12200
#check #connection
#spectral #filter #off
#threshold
#scanrange
```

To keep the user aware of system status, this feedback was employed: if a command could not be completed, was misinterpreted, or overflowed the (large) command buffer, a status message was returned – describing the last command that succeeded and the command that had problems. The status message was standardized enough to be computer readable, but included explanation targeted for the understanding of a test operator. A few examples of the status
message are shown below, one where the FSIM is commanded to reboot, and one where scan delay is set to a negative amount of time (an invalid command):

Table B-1: FSIM Status Messages are shown below.

Status Message - Typical Format

```
status: idle   last_command: reboot
scans: 1      scan_delay: 0
sets: 1       set_delay: 0
sensor parameters: none
compensation settings: none
ethernet_address: 10.2.117.24
```

Status Message – Error

```
status: idle   last_command: scan delay -1 ### Error out of range.
Warp speed not available on this unit. End error.
scans: 1      scan_delay: 0
sets: 1       set_delay: 0
sensor parameters: none
compensation settings: none
ethernet_address: 10.2.117.24
```

The error message started and ended with easily parsed tokens to facilitate automation yet still allow flexibility in description. Standard I/O C++ commands were used so that the error information, input commands, and the output data stream could pass through any interface attached (RS-232 and Ethernet were tested), and these were dynamically controllable by ASCII command settings.
Another key component of FSIM usability was to create two FSIM “Priority Commands” that were not placed into the command buffer. They provided immediate response in an independent thread of the FSIM (to prevent the “locked up device” problem common in sensor systems). The first character of each transmission received was quickly inspected for a ‘?’ or a ‘!’ character. Finding one of these interruption characters, the FSIM would immediately return the current status of the device (?), then continue processing commands; or immediately interrupt the device (!), pulling it out of any potential lock-up condition and returning a status message. Contrary to many other FOS interrogators tested, this feature gave users control and clairvoyance into the current workings of the FSIM – instead of the “hourglass” symbol found in other applications.

Each of the FSIM commands were eventually controlled by a PC graphical user interface, which provided more intuitive feature availability, while still offering the flexibility to use lower level commands as well.

B.6.2 Command Structure

The FSIM design efforts culminated in the highest performing and most usable FOS interrogator when the command structure was created to be categorized into high level and low level commands, giving ease to the novice and control to the researcher. The FSIM commands are described more fully in the “User Level Command Description” in Appendix C.2. Below is a summary of the most useful commands for an FOS system. The low-level commands are based upon the FPGA memory map, which can be seen in the FPGA memory map in Appendix C.1.

1. High Level—Settings:
   a. Set_sensor_parameters (included calibration parameters)
   b. Set_number_of_scans
   c. Set_delay
d. Reset_scan_parameters (quick usability if functionality errs)

2. High Level—Data related:
   a. Get_sensor_peaks
   b. Get_waveform_data
   c. Get_all_sensor_data (provides a complete picture of what the sensor system sees and how it interprets it)

3. High Level—Management commands
   a. Status
   b. Help (all commands described)
   c. Confirmation on/off (verbose or terse messaging)

4. Low Level—direct FPGA interface and control
   a. Memory_map (shows entire FPGA interface status)
   b. Get (individual memory map data)
   c. Put (values into the memory map for scan location, number of scans, sweep range, etc.)

Categorizing the commands in this way, the FSIM could operate easily, or perform some tasks its designers never anticipated. It could start scanning FOS gratings upon receipt of just a few characters. Then in the next processing interval, the FSIM could lock the optical filter to the edge of a single sensor and become a MSPS interrogator, returning any slight movement in the sensor, as fast as the data could be sampled and passed through the Ethernet port. With this command structure admitting access to the basic building blocks of the interrogation process, the FSIM became not only a highly usable tool, but also very powerful and flexible tool.

B.6.3 Sensor Identification

Identification of each sensor brought the benefits of on-board calibration of temperature and strain (etc.) constants, as well as the possibility of tracking grating crossover and location by name. The FSIM interface processor created an internal database to track user and FSIM entered parameters about each sensor, so that a well conducted test could return refined data, with less need for post processing.
For example, after a temperature monitoring test at the UTSI Space Institutes Jet Engine Test Bed, where the FSIM monitored the temperature of a new water-cooled test fixture that was placed into the jet stream of an afterburner, the contract monitor closed his remarks by saying that he “couldn’t wait to see the data after it was compiled”. Yet the FSIM was ready to show the temperature response at that very moment, without going home to post-process. Comparing it to the electric thermocouple data, leaving the facility, revealed that both types of temperature sensors had been kept at a cool temperature within the new fixture.

B.6.4 Compensation: Optical Boost and Full Sweep

To round off the firmware features, meditative compensation methods were introduced to facilitate FOS testing for novice testers. The optical boost was added to automatically search for grating sensors beyond dirty connectors or bent fiber by pulsing the light source to ten times its normal strength, scanning the gratings in a fraction of a second, and then return the light source back to safe level. The FSIM could also perform a full sweep of the entire spectrum to acquire initial sensor and scan parameters or if a sensor was lost, before returning back to its user-selected range. Thresholds could be adjusted automatically to search for sensors in the noise. These algorithms could be scripted using low-level commands quickly, rapidly tested without recompilation, and easily disabled if they became too presumptive.

B.6 Software Architecture for High Throughput

A model-view-controller scheme was adapted for a LabVIEW virtual instrument (VI) program, allowing a passive model to update the view as an observer through a publish/subscribe method (40). The model updater was given the highest priority to capture incoming data; the
controller was given medium priority to fetch user requests; the view updated as time permitted. Such signaling scales performance with the capabilities of the host computer.

In LabVIEW, a straightforward way to accomplish this priority structure was to run a separate thread (parallel operation structures) for each of the three code partitions, and prepare each independent loop structure to delay unless the higher priority structure can spare the processing power (with a case structure). This message can be passed with a local variable flag indicating data has been captured for viewing. Nevertheless, to preserve user-friendliness, it is imperative that some feedback be given to the user when the viewer is being delayed, or the user may think that the program has locked up when in fact, it is still collecting data at the highest speed the CPU can provide. This feedback is readily given with a loop count indicator or toggling “LED”. If the “event structure” in LabVIEW is used to facilitate the capture of user input for the controller loop, a well prioritized architecture should add a wait flag (or at least a delay) after the event structure. This flag passes more processing power to the model updating thread, as seen the example of Figure B-3. Without this type of prioritization, data throughput would have been severely limited for the FSIM.

For obtaining the highest speed that the PC’s CPU can deliver, the view and controller processes may need to be blocked indefinitely as the model is updated at the highest transmission rate possible. This was implemented for capturing full spectra from the FSIM at multi-kiloherz speeds. A data-saving subVI was created and given high CPU priority. All other threads block completely, but feedback is still given to the user by showing an update of how much data has been saved each half second. Fortunately, the LabVIEW graphical structure makes it easy to identify potential deadlocks by highlighting the active blocks of the code diagram.
Figure B-3: Model-View-Controller example in LabVIEW; also example of using delays and a flag to prioritize processing in LabVIEW.
### APPENDIX C. LOW LEVEL FSIM DETAILS

#### C.1 The FSIM Memory Map for Rapid Interface Integration

<table>
<thead>
<tr>
<th>Hex</th>
<th>I/O</th>
<th>Description</th>
<th>Default</th>
<th>#Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00</td>
<td>O</td>
<td>ADC Module Status [0-7]</td>
<td>x</td>
<td>8</td>
</tr>
<tr>
<td>0x01</td>
<td>O</td>
<td>DAC Module Status [8-15]</td>
<td>x</td>
<td>8</td>
</tr>
<tr>
<td>0x02</td>
<td>O</td>
<td>Wavelength Calculator Status [0-7]</td>
<td>x</td>
<td>8</td>
</tr>
<tr>
<td>0x03</td>
<td>O</td>
<td>FIFO Status [8-15]</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>0x04</td>
<td>I/O</td>
<td>Scan [0 - Stop / 255 - Continuous / 1 - Single]</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>0x05</td>
<td>I/O</td>
<td>Scan Direction [0 - Up / 1 - Down *]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0x06</td>
<td>I/O</td>
<td>Use Peak Averager [0 - Off / 1 - On]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0x07</td>
<td>I/O</td>
<td>Reference Grating Peak # [0 - First/ 255 -Last]</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>0x08</td>
<td>I/O</td>
<td>High scanning voltage limit [0-7]</td>
<td>13824</td>
<td>16</td>
</tr>
<tr>
<td>0x09</td>
<td>I/O</td>
<td>High scanning voltage limit [8-13]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x0A</td>
<td>I/O</td>
<td>Low scanning voltage limit [0-7]</td>
<td>8960</td>
<td>16</td>
</tr>
<tr>
<td>0x0B</td>
<td>I/O</td>
<td>Low scanning voltage limit [8-13]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x0C</td>
<td>I/O</td>
<td>Enabled Wavelength Calculator [0 - Off/ 1 - On *]</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>0x0D</td>
<td>I/O</td>
<td>Spectral Data -- [Memory Location [5bits]]</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>0x0E</td>
<td>O</td>
<td>Current ADC Value [0-7]</td>
<td>x</td>
<td>16</td>
</tr>
<tr>
<td>0x0F</td>
<td>O</td>
<td>Current ADC Value [8-9]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x10</td>
<td>I/O</td>
<td>Spectral Data Location [0-7]</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>0x11</td>
<td>I/O</td>
<td>Spectral Data Location [8-13]</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x12</td>
<td>O</td>
<td>Spectral Data Power [0-7]</td>
<td>x</td>
<td>16</td>
</tr>
<tr>
<td>0x13</td>
<td>O</td>
<td>Spectral Data Power [8-9]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x14</td>
<td>O</td>
<td>Scan # of pk in FIFO--a write incr.s peak FIFO</td>
<td>0</td>
<td>8/16</td>
</tr>
<tr>
<td>0x15</td>
<td>O</td>
<td>&quot;000000000&quot;</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x16</td>
<td>O</td>
<td>Peak Number</td>
<td>x</td>
<td>8/16</td>
</tr>
<tr>
<td>0x17</td>
<td>O</td>
<td>&quot;000000000&quot;</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x18</td>
<td>O</td>
<td>Voltage [0-7]</td>
<td>x</td>
<td>16</td>
</tr>
<tr>
<td>0x19</td>
<td>O</td>
<td>Voltage [8-13]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x1A</td>
<td>O</td>
<td>Power [0-7]</td>
<td>x</td>
<td>16</td>
</tr>
<tr>
<td>0x1B</td>
<td>O</td>
<td>Power [8-9]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x1C</td>
<td>O</td>
<td>Wavelength [0-7]</td>
<td>x</td>
<td>24/32</td>
</tr>
<tr>
<td>0x1D</td>
<td>O</td>
<td>Wavelength [8-15]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x1E</td>
<td>O</td>
<td>Wavelength [16-23]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x1F</td>
<td>O</td>
<td>&quot;000000000&quot;</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x20</td>
<td>O</td>
<td>Future Timestamp [0-7]</td>
<td>x</td>
<td>32</td>
</tr>
<tr>
<td>0x21</td>
<td>O</td>
<td>Future Timestamp [8-15]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x22</td>
<td>O</td>
<td>Future Timestamp [16-23]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>Future Timestamp [24-31]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>---------</td>
<td>--------------------------</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>0x23</td>
<td>O</td>
<td>Future Timestamp [24-31]</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>0x24</td>
<td>O</td>
<td>Test Read Reg 1 - &quot;0x5E&quot; (94d or 58718w)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x25</td>
<td>O</td>
<td>Test Read Reg 2 - &quot;0xE5&quot; (229d)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x26</td>
<td>O</td>
<td>Test Read Reg 3 - Increments on read</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x27</td>
<td>O</td>
<td>Test Read Reg 4 - Increments on read</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x28</td>
<td>O</td>
<td>Test Read Reg 5 - Increments on read</td>
<td>0 8</td>
<td></td>
</tr>
<tr>
<td>0x29</td>
<td>O</td>
<td>Test Read Reg 6 - Increments on read</td>
<td>0 8</td>
<td></td>
</tr>
<tr>
<td>0x2A</td>
<td>O</td>
<td>Test Read Reg 7 - Increments word on read</td>
<td>0 16</td>
<td></td>
</tr>
<tr>
<td>0x2B</td>
<td>O</td>
<td>Test Read Reg 8 - Part of word for Test Reg 7</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0x2C</td>
<td>O</td>
<td>Test Read Reg 9 - Mirrors 28, doesn't increment</td>
<td>0 8</td>
<td></td>
</tr>
<tr>
<td>0x2D</td>
<td>O</td>
<td>Test Read Reg 10 - Mirrors 29, doesn't increment</td>
<td>0 8</td>
<td></td>
</tr>
<tr>
<td>0x2E</td>
<td>O</td>
<td>Test Read Reg 11 - Mirrors 2A, doesn't increment</td>
<td>0 16</td>
<td></td>
</tr>
<tr>
<td>0x2F</td>
<td>O</td>
<td>Test Read Reg 12 - Mirrors 2B, doesn't increment</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

0x30 | I/O     | Manually Set Voltage (0-7) | 0 16 |
0x31 | I/O     | Manually Set Voltage (8-15) | 0 |
0x32 | I/O     | mS to wait between scans[0-7] | 0 16 |
0x33 | I/O     | mS to wait between scans[15-8] | 0 |
0x34 | I/O     | Minimum Peak Height / 2 | 20(*act.60) 8 |
0x35 | I/O     | Filter Scan Data (0 - Off/ 1 - On*) | 1 8 |
0x36 | O       | Current Scan Number | X 8 |
0x37 | O       | IO_pin A1:4 (trigger) | X 8 |
0x38 | I/O     | BRAM hash | 32 |

**Default Setup Parameters for Optimal Performance:**

```
hi                          #checks #for #Ready
wavelengths off
put 53 0                    #spectral #filter #off
put 52 255                   #threshold
set_range 8200 12200         #spectral #range
```

COMMAND REFERENCE SHEET

**Priority Commands**

! Aborts current command, clears command file, and returns system status.

? Pauses current command to return system status, then continues wherever it left off

**Data Commands**

get_sensor_data
Scan for scalar sensor values (from waveform peaks)

get_waveform
Scans for spectral waveform array

get_all_sensor_data
Scans for both (scalar and spectral array data)

**Management Commands**

status or ?
Returns a Status Message

help
Returns a command reference help message

confirmation <on or off>
Enables or disables confirmation for most future commands

compensate <mode>
System will attempt to improve data quality

reset_scan_settings
Resets all scan-related settings to default values

reboot
Soft resets for all hardware and software

**Settings Commands**

set_sensor_parameters
Sets calibration parameters for all sensors.

sensor 1 <wavelength> <calibration parameter second order>
<calibration parameter first order> <calibration parameter offset>

sensor 2 <wavelength> <calibration parameter second order> ...

number_of_scans <number of scans per set or infinite>
Sets the number of scans in each set of scans.

scan_delay <millisecond delay between scans>
Sets the delay (in milliseconds) between scans within the same set.
All are rounded up to 0, 1, 2, 3, 9, 10, 20, 30, 90, 100, 200, 300, 900, 1000, or 3000

number_of_sets <number of sets or infinite>
Adjusts the number of sets to execute.

set_delay <millisecond delay between sets>
Adjusts the delay between sets of scans.

**Data Messages - Typical Format**

```
waveform timestamp: 59.760 scan num: 3 peaks found: 2
sensor number: 1 temperature: 23.2 wavelength: 1550 power: 1023 voltage: 12312
sensor number: 2 temperature: 123.2 wavelength: 1560 power: 401 voltage: 16098
waveform start: 12000
waveform length: 23060
waveform: 234 234 324 344 234 242 234 234 158 93 208 680 682 976 206 206 876
```

**Status Messages - Typical Format**

```
Status: idle Last command: reboot
Scans: 1 Scan_delay: 0
Sets: 1 Set_delay: 0
Sensor parameters: none
Compensation settings: none
Ethernet_address: 10.2.117.24
```