

Pyxis[®] handheld polarimetric imager

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ABSTRACT

The instrumentation for measuring infrared polarization signatures has seen significant advancement over the last decade. Previous work has shown the value of polarimetric imagery for a variety of target detection scenarios including detection of manmade targets in clutter and detection of ground and maritime targets while recent work has shown improvements in contrast for aircraft detection and biometric markers. These data collection activities have generally used laboratory or prototype systems with limitations on the allowable amount of target motion or the sensor platform and usually require an attached computer for data acquisition and processing. Still, performance and sensitivity have been steadily getting better while size, weight, and power requirements have been getting smaller enabling polarimetric imaging for a greater or real world applications.

In this paper, we describe Pyxis[®], a microbolometer based imaging polarimeter that produces live polarimetric video of conventional, polarimetric, and fused image products. A polarization microgrid array integrated in the optical system captures all polarization states simultaneously and makes the system immune to motion artifacts of either the sensor or the scene. The system is battery operated, rugged, and weighs about a quarter pound, and can be helmet mounted or handheld. On board processing of polarization and fused image products enable the operator to see polarimetric signatures in real time. Both analog and digital outputs are possible with sensor control available through a tablet interface. A top level description of Pyxis[®] is given followed by performance characteristics and representative data.

Keywords: Polarization, imaging polarimetry, infrared polarimetry, Stokes vector, remote sensing

1. INTRODUCTION

Infrared polarimetric sensors measure not only the conventional thermal intensity of a target scene but the polarization magnitude and orientation of the plane of polarization as well. By measuring one or more parameters of the polarization ellipse, details can be extracted from a target scene that are not readily apparent when using conventional thermal imagers alone¹. In the past, these measurements have been conducted using large scientific instruments not readily applicable for hand held use. The recent development of un-cooled, infrared sensor arrays has led to a significant reduction in size, weight, power and cost of high-performance polarimetric sensors such as the device shown in Figure 1.

The strength and orientation of an infrared, polarimetric signal relies on surface temperature, orientation, surface roughness, material properties, aspect angle to the sensor, down-welling sky radiance and terrestrial background radiance reflecting from the target. Often times, the polarization signature of a manmade target is different than the surrounding background and most importantly, that difference is often present even when the intensity signature of the target is in thermal equilibrium with the background^{2,3}. In other words, the target can be completely invisible in the standard intensity



Figure 1. A Pyxis[®] camera incorporates a micro filter array mounted in close contact to the COTS FPA.

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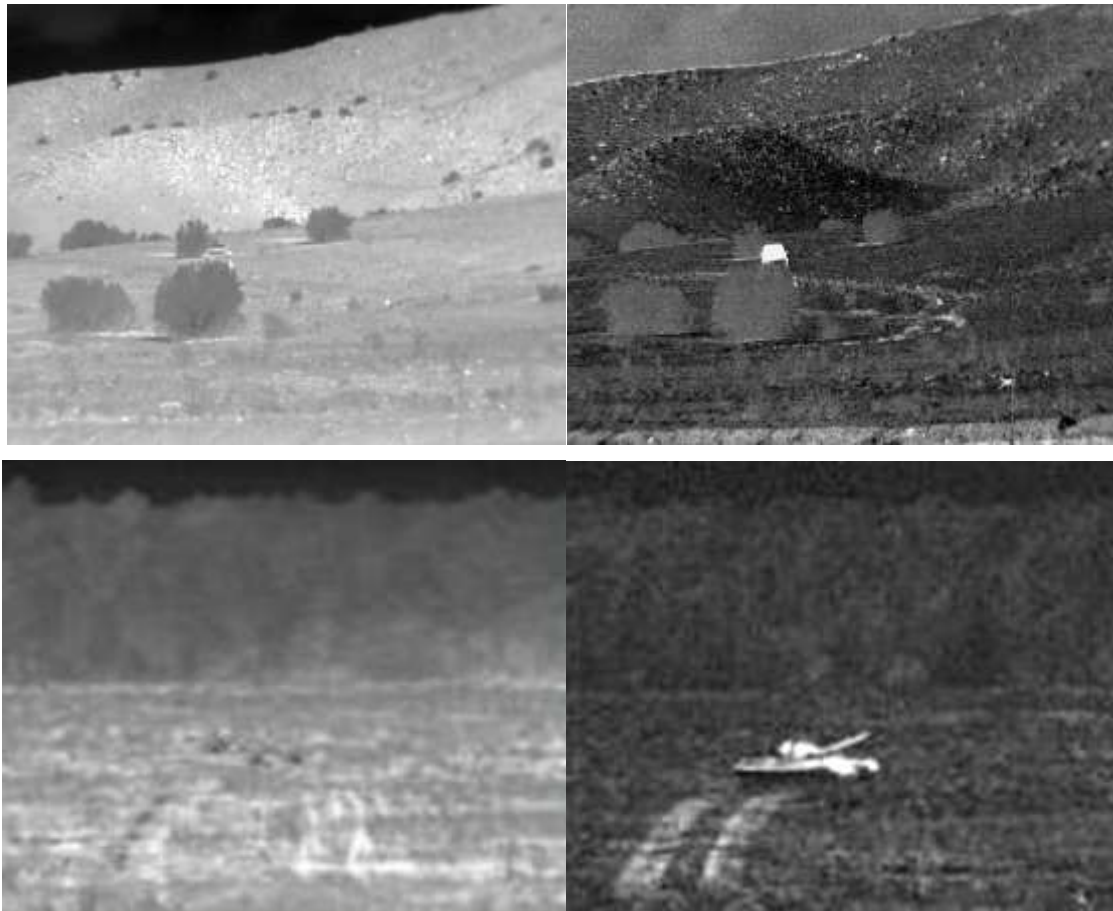


Figure 2. The comparison of infrared intensity images (left) and infrared polarimetric images (right) of a target scene clearly demonstrates the enhanced target acquisition capabilities of polarimetric imaging technologies. (Courtesy of Kris Gurton, U.S. Army Research Laboratory)

image while at the same time exhibiting a strong polarimetric signature. This capability for enhanced target acquisition is demonstrated in the images provided in Figure 2.

The images above show application for primarily military use. However, with a handheld sensor with minimal support equipment, the ability to quickly and easily collect data in a variety of different situations has enabled investigations of other applications for infrared imaging polarimetry. These include detection of oil on water, roadway following and road edge detection, and pedestrian and vehicle tracking among others. These will be described in greater detail below.

1.1 Technology Overview

The technology underlying the Pyxis[®] sensor exploits the polarization of light in our environment, a fact that we use every day with our polarized sun glasses to reduce glare off the car in front of us in traffic. When ambient illumination is reflected off of an object, the reflected light becomes polarized. Likewise in the thermal infrared, light is polarized in both emission and reflection. Polarization is one of the fundamental quantities of light along with intensity and wavelength. However, these three quantities are independent of each other so that two beams of light with the same intensity and wavelength (or spectral distribution) can have very different polarization states. An imaging polarimeter measures these polarization states and provides additional information that exploits the polarization differences in the scene that are frequently different from the broadband intensity.

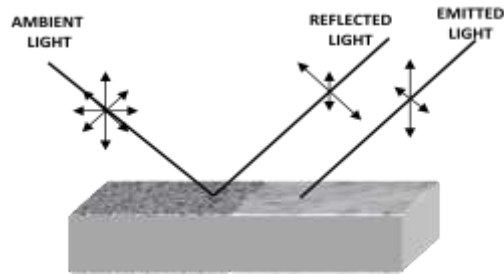


Figure 3. Phenomenology of polarization sensing. Emission and reflection of light from surfaces of different materials at different angles leads to a rich phenomenology for polarized light.

Figure 3 depicts some of the phenomenology that gives rise to polarization signatures in passive polarization imaging. The polarization in the scene depends on the angles of the surface normals relative to the sensor look angle and the surface optical characteristics. The larger the angle between the surface normal and the sensor look angle (the angle of incidence or AOI), the higher the polarization signal from that surface. The surface optical characteristics depend on the materials of the surface and other surface characteristics, such as roughness and presence of dirt and water. As the surface roughness increases, the polarization signal reflected or emitted from the surface decreases. As a result, most manmade objects such as painted metal, glass, or concrete have a significantly stronger polarization signal than natural backgrounds. Though polarization measurement does not require intensity or thermal contrast, any thermal signature that is present is also detected.

Polarization images thus provide additional detail on the geometric and materials features of targets. In situations where contrast is small (i.e. temperatures across scene elements is uniform) strong polarization signatures are possible due to changes in target geometry or surface properties. The primary benefit of the proposed sensor is that it provides a multitude of sensing modalities in a single highly integrated sensor. LWIR thermal and polarization are combined in a single camera so that together the camera provides advantages over conventional thermal imagers in target detection/visualization, camouflage detection, image clutter rejection, and a host of other applications. These advantages positively impact target detection range, target discrimination range, and operator target observation time and situational awareness.

Polaris has demonstrated improved performance for a number of these applications. It is well known that at certain times of day, the apparent temperature of the object of interest can match the apparent temperature of the surrounding background, and the object can be very difficult to see in the thermal image. These events are referred to as thermal cross-over periods and occur twice a day, once after sunrise and again after sunset. Polarization excels in this situation. It also performs well when the target is in thermal shadows. Figure 4 shows a polarization image, a standard thermal image, and the visible image of the scene for reference of two pickup trucks in shade. The trucks are perceptible in the visible, but the visible shadow makes them difficult to see. In the thermal image, only the windshields are visible in reverse contrast – the rest of the trucks' bodies are in near thermal equilibrium with the background. The trucks are visible in the polarization image because polarization is sensitive to the trucks' surface roughness and their surfaces' geometries, which are different than the surrounding background.

Another issue that degrades standard thermal imaging performance with standard thermal cameras is background clutter. The target of interest can often have the same apparent temperature, size and even shape of surrounding background. The image pair in the top of Figure 2 shows a thermal image (left) and a polarization image (right). There is a single vehicle in the image that is of similar size and shape of the surrounding juniper and sage brush. It is very difficult to find the vehicle in the thermal mode. However, in the polarimetric mode, the vehicle is clearly visible. Again, this is because the polarization image is based on surface geometries and roughness, different phenomena than the thermal image. The image pair in the bottom of Figure 2 give a second example of polarimetric detection when the thermal spatial features of the target are very similar to that of the background. The polarization image even shows detection of the tank tracks.

1.2 Polarimeter architectures

The specific configuration of an imaging polarimeter depends on a number of design requirements which, in turn, is dependent on the application and the state-of-the-art technologies available to meet those requirements. The physical configuration can be broken into categories [9] according to the optical path and layout of the electro optical components.

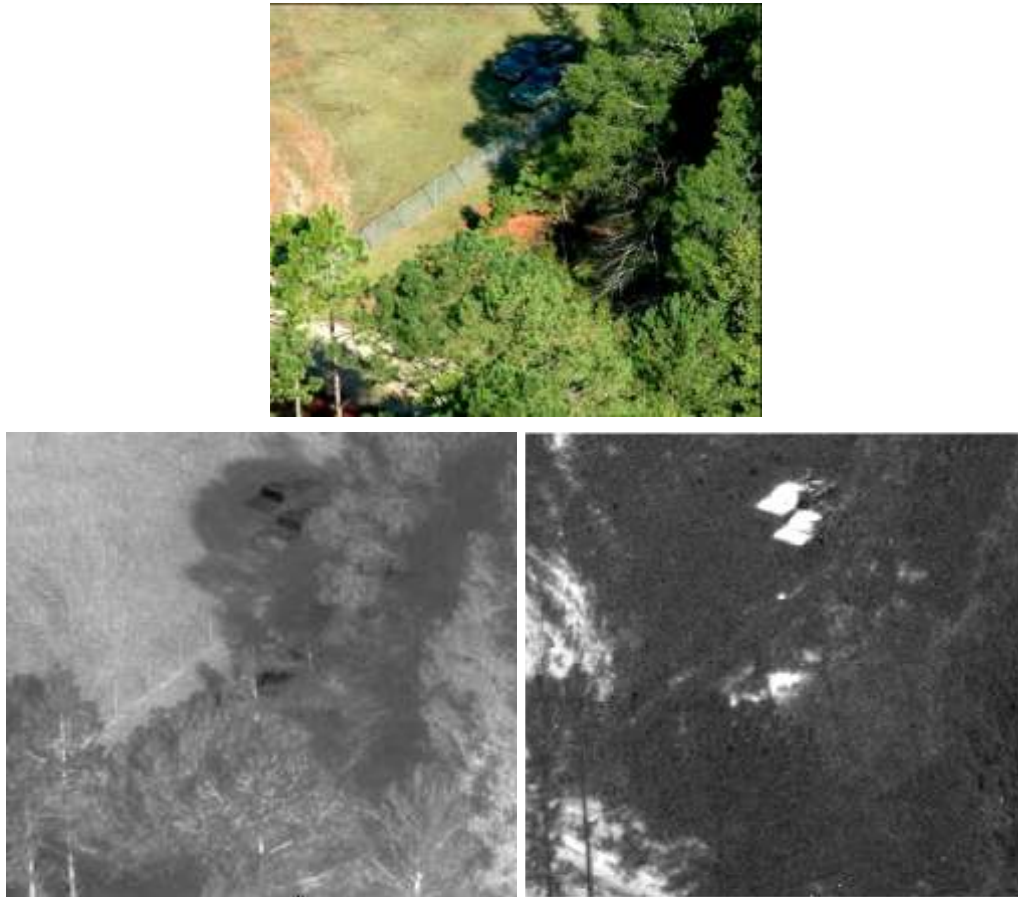


Figure 4. Visible picture of two pickup trucks in shade (top), long-wave IR intensity image (bottom left), and long-wave IR polarization image (bottom right). Strong contrast in the polarization image shows advantages for enhanced target detection using imaging polarimetry.

There are five primary configurations for imaging polarimeters: division of amplitude, division of aperture, rotating element, micro-optic, and channeled instruments.

In a **"Division of Time"** polarimeter, rotating optical elements are employed to measure the polarization states. This approach is attractive in the scientific community because it is relatively straightforward in both system design and data reduction and can provide extremely accurate polarimetric information. An obvious drawback to this design is that both the scene and platform must be stationary to avoid introducing inter-frame motion. In this type of polarimeter, the rotation of the polarization elements causes a time modulation of the polarized light incident on the focal plane from the scene. The data can then be reconstructed using well known Fourier Transform methods. Reducing the data on a pixel-by-pixel basis produces Stokes images that can be used to produce images of the degree-of-linear-polarization, degree-of-circular-polarization, or other derived quantities such as orientation and ellipticity. This design employs a relay lens set so that any wedge in the rotating retarder is not translated into image nutation. With this approach the rotating element can be a polarizer, if only linear polarization states are required. Recent successes with high-speed continuously rotating retarders have minimized artifacts due to sensor platform/scene motion. Nevertheless, image registration is necessary to remove spurious registration artifacts in dynamic scenes.

A **Division of Amplitude** camera consists of two to four separate imaging arrays. Each array is mounted such that a single objective lens is used in combination with a series of polarizing beam splitters and retarders called a polarization beam splitter block. Rigid mechanical mounts are used to precisely align the arrays such that they are facing the cube assembly exit apertures. The arrays capture the polarization images simultaneously, thus eliminating false polarization effects due

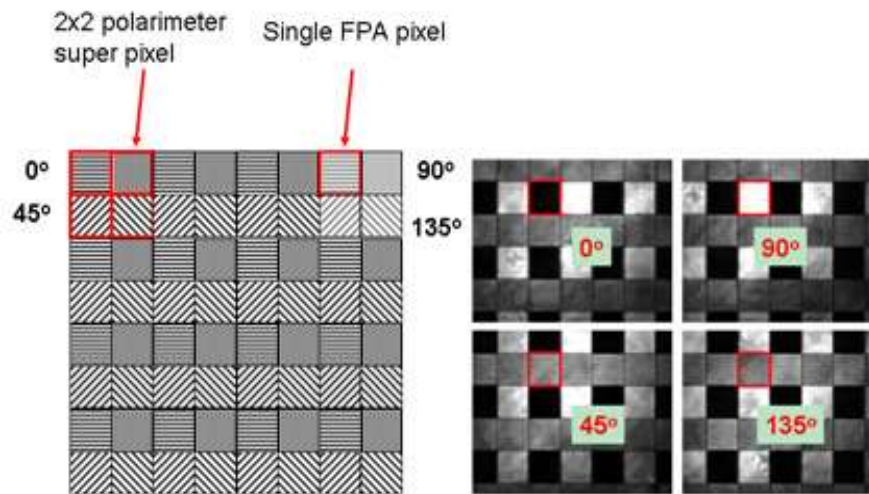


Figure 5. Polarization Elements of a Pixelated Imaging Polarimeter

to scene dynamics during the serial collection process. Each of the four paths through the beam splitter block analyzes a different aspect of the incident polarization. This makes efficient use of the polarized light so that none of the light is absorbed or rejected. [10] Furthermore, the analyzed polarization states are as nearly orthogonal as possible, and evenly span the possible incident polarization states. Special care must be taken in alignment, and in practice mechanical alignment to the required tolerances is not possible. As a result, post-processing is required to co-register the four images to sub-pixel accuracy.

A **"Division of Aperture"** polarimeter uses re-imaging optics to project multiple images onto a single focal plane array. This architecture acquires all of the polarization data simultaneously and ensures that the fields-of-view of all of the polarization channels are co-boresighted. It has the advantage that only a single FPA is required and once the optics are mechanically fixed, the alignment remains very stable over time. Two disadvantages of the "Division of Aperture" approach are loss of spatial resolution (a factor of two in each linear dimension) and an increase in volume and weight for the re-imaging optics. In addition, matching transmission, apodization, magnification, and distortion between the channels is difficult, but can be accomplished. It should also be noted that this strategy is more difficult to employ with coherent illumination due to coherent scattering and interference.

The **"Channeled Instrument"** technique involves the use of birefringent wedges and/or diffractive optics placed in an intermediate image plane. The wedges and/or diffractive optics encode the polarization content of the image onto spatial carrier frequencies. The image is therefore a mix of spatial frequencies from the target and spatial frequencies with polarization information. This configuration has the advantage that all of the information is contained on a single FPA and no moving parts are involved. The disadvantage is that significant cross-talk between target spatial frequencies and polarization frequencies can occur.

The final configuration is the one used for the Pyxis® handheld polarimeter. Recent advances in micro-optics manufacturing have allowed the integration of micro-optical polarization elements directly onto a focal-plane-array (FPA), thus creating a **"Division of Focal Plane"** (DoFP) polarimeter. In this configuration, pixelated linear polarization elements are attached directly to the FPA. Several systems operating in the visible, SWIR, and LWIR waveband have been built using this technology. Most DoFP systems use interlaced polarization super-pixels as shown in Figure 5. A typical system must compute the Stokes vector at interpolation points on the FPA, thus DoFP systems must trade-off spatial resolution for polarimetric information. It should be noted that the intensity information is still collected at the full resolution of the FPA. DoFP systems have some significant advantages. All polarization measurements are made simultaneously for every pixel in the scene and it uses a single FPA with no added complications to the optical train. The architecture is very similar to commercial color cameras that use a Bayer color filter overlay on the FPA.

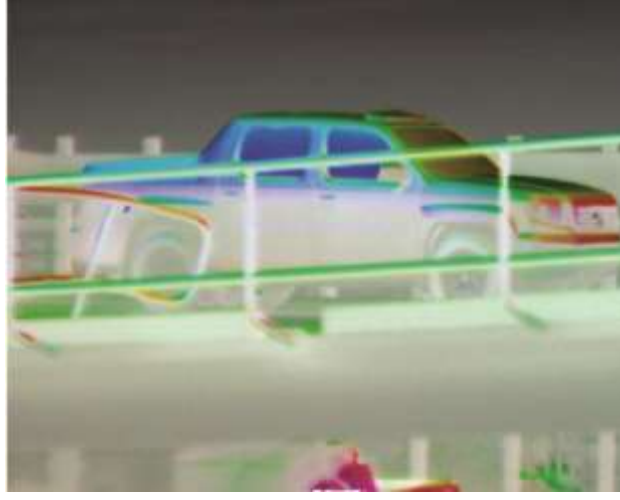


Figure 6. LWIR color fused image of a truck.

The polarization imagery is represented as Stokes images

$$s_0 = \frac{1}{2}(I_H + I_V)$$

$$s_1 = I_H - I_V$$

$$s_2 = I_{45} - I_{135}$$

where $I_H, I_V, I_{45}, I_{135}$ are images linearly polarized in the Horizontal, Vertical, 45° and 135° orientations. Note that the s_0 image is simply the standard thermal image. The s_1 and s_2 images are often useful data products in and of themselves to view. However, additional data products derived from these three are often selected. For example, the degree of linear polarization (DOLP) image is often used to suppress background to detect an object. DOLP is given by,

$$DOLP = \sqrt{s_1^2 + s_2^2}.$$

Finally, data fusion is possible exploiting both the thermal and polarization data products. The imagery can be viewed independently or fused images can be formed from combinations. Data fusion captures all of the information and displays it in a single imager, giving the operator a more intuitive view of the scene. One of the preferred methods for displaying thermal and polarization together is called color fusion. Figure 6 shows a color-fused image taken with the Polaris Pyxis LWIR imaging polarimeter. In the color fused image, the un-polarized thermal image is displayed as normal grey scale. The polarization is displayed in color from a user defined threshold. A typical threshold is 1% DOLP. When a pixel exceeds 1% DOLP, the pixel is colored based on the orientation of linear polarization. The saturation of the color increases with increasing DOLP. Surfaces of the same orientation, which is another data product derived from the Stokes images, will have the orientation or angle of polarization (AoP). For example in Figure 6, the color of the structures in the foreground is the same as the horizontal surfaces of the car hood, adding to scene perception and situational awareness. This additional orientation information can assist in determining target pose direction.

2. SENSOR HARDWARE

2.1 Pyxis® description

Measurement of this polarimetric phenomenology requires capturing images with polarization filters. The approach chosen here is based on the Division of Focal Plane (DoFP) polarimetric architecture for imaging polarimeters. In this architecture, a pixelated polarizer array is attached to the FPA just above the sensing plane of the FPA (within a few microns). For infrared applications, the pixelated polarizer array uses an IR substrate such as silicon, germanium, or zinc selenide. A metal layer is deposited on the substrate and then the wire grid pattern is etched in to the metal layer using standard semiconductor processing techniques creating the wire grid pattern. For the Pyxis®, the substrate is silicon and the metal wires are aluminum. The polarizers are oriented at 0° and 90°, 45° and 135°, (left to right, top to bottom). Figure 6 (left) shows

Table 1. Pyxis® Specifications

Detector	Uncooled VOx Microbolometer Array
Waveband (microns)	7.5-13.5
Pixel Pitch (microns)	17
Resolution (H x V pixels)	640 x 512
Camera Frame Rate (Hz)	7.5 or 30 Hz
Full Frame Pixel Operability	99.9%
Image products (from analog output, -A model only)	Radiance, S1, S2, DoLP, Orientation, ColorFuse, 14-bit raw
NEDT @ f/0.85	< 50 mK
NeDoLP @ f/0.85	< 0.5%
Size w/o lens (LxWxH in inches)	1.79 x 1.75 x 1.79
Weight w/o lens (g)	83
Input voltage (DC)	5
Steady state power @ 23° C (watts)	4
Peak power @ 23° C (watts)	5.3
Data interface	NTSC and 14-bit Camera Link standard GigE or LVDS optional
Lens Options (focal length, f/#)	20 mm, f/0.85 25 mm, f/0.86 50 mm, f/0.86

a schematic of the pixelated polarizer array. The pixels in different polarization states in a DoFP imaging polarimeter are combined to determine the polarization state of each pixel. A super-pixel is comprised of a 2x2 array of pixels. Figure 6 (right) shows the response of a larger segment of the pixelated polarizer array to vertically linearly polarized light. With vertically polarized light (90° orientation) incident, the horizontally polarized pixel is dark, the vertically polarized pixel is light and the 45° and 135° polarized pixels are gray. The measured incident polarization state is determined based on a weighted sum of interpolated pixels. It is important to note that both thermal and polarization images are captured at the full resolution of the array – spatial resolution is not lost. DoFP systems have the significant advantage that all polarization measurements are made simultaneously for every pixel in the scene. In addition, since the polarization sensitivity is integrated on the FPA, no additional optics are added to the optical train and the system is no larger and is equally rugged as a conventional camera.

One important measure of performance for a polarimeter is the Noise Equivalent Degree of Linear Polarization or NeDOLP. The NeDOLP is the rms noise of the reported degree of linear polarization for an un-polarized scene averaged across all operating pixels of an imaging polarimeter. It gives an indication as to what level of polarization signature is detectable by a polarimeter. Cooled LWIR polarimetric sensors can achieve below 0.1%. The Pyxis® typical NeDOLP is around 0.3%.

The specifications for Pyxis® are given in Table 1. Note that the noise equivalent noise parameters assume an f/0.85 lens, a faster lens than is usually used for microbolometer performance. Since the polarizer has lower throughput for unpolarized light, the loss of light is made up for through the use of a faster lens. However, with the faster lens, the sensor performance for the S₀ or radiometric imagery is similar to that of a (non-polarimetric) microbolometer.

2.2 Sensor configurations

The Pyxis® “core” is the sensor focal plane with an LVDS output and serial communications for setting sensor parameters. The Pyxis® 640-G version has a back panel with only an RJ-45 connector. Camera output and control are achieved over a Gigabit Ethernet connection. Power can be provided as Power Over Ethernet (POE). No analog polarization data products are available as output directly from the camera. A primary advantage of this configuration is that the camera can be remotely located, up to 100 meters away, from the controlling laptop. The software is described in the next section. A 5 volt DC power connector consisting of a mini-USB jack enables the use of battery packs used for cell phones at the camera location in addition to the POE. Environmentally ruggedized and drone kit versions are also available

2.3 Software

All versions of the camera interface to a computer (or tablet) and use the Pyxis® Vision Science (PVS) software framework developed by Polaris for commercial applications. PVS provides the ability to control the sensor, view the raw and

processed sensor data, and record data for future processing. An example of the PVS application user interface is shown in Figure 9. Note that the user interface provides a suite of standard color palettes, as well as toolbar buttons for selecting standard output imagery products. PVS gives the operator easy access to intensity data (temperature and radiance) as well as Stokes Vector polarimetry and degree of linear polarization (DoLP). The user has the ability to measure the value of a specific pixel, or to create a histogram or strip chart which displays the values for regions of interest within the image.

PVS is a software framework which provides certain standard functionalities such as display and data recording, with customization for user control of sensor specific operational parameters such as sensor calibration parameters such as non-uniformity correction (NUC) data calibration, and custom processing of sensor raw data for display and analysis. This architecture allows for rapid development of new custom sensor architectures by utilizing standard software components that are well tested, and applying customization for new sensors through the use of well-known software interfaces and efficient compiled data reduction software.



Figure 9. The Pyxis® Vision Science user interface main window. The first row of buttons below the menu are tools to manipulate the image. The second row of buttons select the quantity displayed: radiance, Stokes vector elements S1 and S2, degree of linear polarization, orientation, and ColorFuse data. ColorFuse display of polarization is shown.

Normal operation of the PVS software can be divided into two basic functionalities: sensor operation, and data reduction. The operator is able to display the current video imagery being returned by the sensor when operating either way, but the focus of the sensor operation mode is in configuring the sensor for the task at hand, calibrating the sensor, and collecting the raw data of the event of interest. Processing priority is given to receipt and recording of the raw data frames, and display update rate is given less priority in order to ensure that all raw data is safely stored on the host computer. PVS allows the user to determine the method of data recording. Raw data may be streamed to the disk by the user manually using the graphical data recorder interface. The user may also choose to use the scripted Periodic & Event Recorder which allows for a great deal of flexibility in how data is recorded. Using the Periodic & Event Recorder the user defines a sequence of Record Windows. These Record Windows define the frame rate and number of frames to record. The Periodic & Event Recorder will execute these windows periodically or at user specified times. The Periodic & Event Recorder allows the user to collect only that data that is of critical importance without having to store terabytes of data or having to be present with the sensor to manually record the event.

In data reduction mode the user loads a raw data file, and is able to play back the data for visual analysis, or to process the raw data into polarimetric or hybrid thermal/polarimetric data files. This processing can be performed on entire data sets,

or, if the raw data files are large, can be performed on a subset of the raw data file which contains features or events of interest. These processed data files can be stored in numerical format for further analysis using external tools, or can be exported to standard video file format. Processing of the raw data can be performed as an offline activity after the data collection effort is complete. The algorithms which are used to compute the processed data files are coded in the C++ programming language as a library, and linked with the PVS software.

3. APPLICATIONS AND SAMPLE IMAGERY

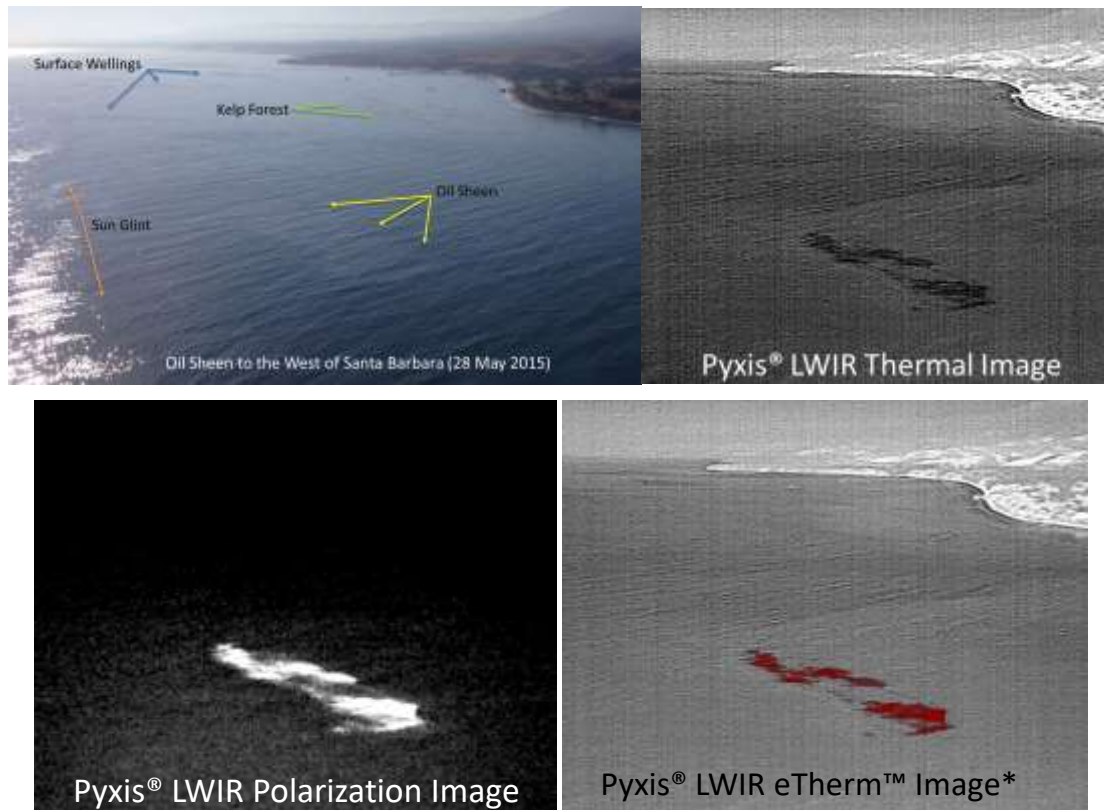


Figure 10. Imagery from oil spill off the coast of Santa Barbara in May of 2015. Visible imagery with potential confounding scene elements (top left), thermal image (top right), degree of linear polarization image (bottom left), and ColorFuse image also called eTherm (bottom right).

PVS has been ported to a Windows based tablet for ease of use and for mobile data collection and as a consequence, several applications have been developed for IR polarimetric imaging. As the first example, detection of oil on water has been demonstrated with the Pyxis®. In May of 2015, a pipeline near Santa Barbara, CA ruptured and released approximately 20 thousand gallos of oil in to the sound off the coast. Nine days later, IR polarimetric imagery using Pyxis® was collected from a helicopter of the ocean's surface in the area of the spill. Figure 10 shows the visible image, the thermal image, the polarimetric image, and the ColorFuse image of the spill. The strong detection afforded by polarization greatly reduces the false alarms by other elements in the scene.

The ability of Pyxis® imagery to find road edges is shown in Figure 11. Based on the thermal image alone, a simple algorithm would be hard pressed to find the real road edge and not be confused by the thermal shadows. This capability is needed for autonomous vehicle navigation.



Figure 12. Visible (left), thermal infrared (center), and IR Polarimetric images (right). The polarimetric image shows detail around the eyes, nose, and mouth with clarity approaching that of the visible image. This imagery was taken with a cooled thermal camera.

Finally, recent results in the area of polarimetric imaging for facial recognition^{4,5} are very promising for non-cooperative biometric identification using uncooled sensors. Figure 12 shows data taken with a cooled sensor that demonstrates the substantial improvement in detail possible with IR polarimetry. Improvements in sensitivity with Pyxis® will enable convenient facial recognition capability without the need for control of external illumination or indeed any external illumination at all. The level of detail possible with the polarimetric image also enables the possibility of cross-spectrum matching, meaning thermal to visible matching, without the need for re-registering subjects in the thermal. This will make this capability much more immediately viable and useful.

4. SUMMARY

In this paper we have described the Pyxis® handheld imager, an infrared imaging polarimeter using a pixelated polarizer filter array working in conjunction with an uncooled microbolometer. The small size and ease of operation is enabling exploration of a whole new class of applications for infrared polarimetric imaging. Improving sensitivity to below 0.3% NeDOLP and expanding the range of lens options available are areas for future work. Polaris is continuing to explore applications that can benefit from the added contrast enhancement provided by infrared polarization as well as to expand this capability into other parts of the optical spectrum.

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