Advances in Hybrid Optics Physical Sensors for Extreme Environments

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ABSTRACT

Highlighted are novel innovations in hybrid optical design physical sensors for extreme environments. Various hybrid design compositions are proposed that are suited for a particular sensor application. Examples includes combining freespace (wireless) and fiber-optics (wired) for gas turbine sensing and combining single crystal and sintered Silicon Carbide (SiC) materials for robust extreme environment Coefficent of Thermal Expansion (CTE) matched frontend probe design. Sensor signal processing also includes the hybrid theme where for example Black-Body radiation thermometry (pyrometry) is combined with laser interferometry to provide extreme temperature measurements. The hybrid theme also operates on the optical device level where a digital optical device such as a Digital Micromirror Device (DMD) is combined with an analog optical device such as an Electronically Controlled Variable Focal Length Lens (ECVFL) to deliver a smart and compressive Three Dimensional (3-D) imaging sensor for remote scene and object shape capture including both ambient light (passive) mode and active laser targeting and receive processing. Within a device level, the hybrid theme also operates via combined analog and digital control such as within a wavelength-coded variable optical delay line. These powerful hybrid design optical sensors have numerous applications in engineering and science applications from the military to the commercial/industrial sectors.

Keywords: Optical sensors, temperature sensor, 3-D imaging sensor, extreme environments, liquid level

1. INTRODUCTION

The sensor community is constantly being challenged to provide robust sensor solutions for the extreme conditions of next generation systems including space stations, aircraft and ship propulsion (e.g., jet engines), electric power plants (both nuclear and fossil-fuel), industrial materials production plants (e.g., steel fabrication, corrosive chemical liquid factories), machined parts design and testing platforms, and hostile military target acquisition/recognition systems.

Recently proposed is a hybrid optics approach to robust sensor design that combines the secure signal remoting capability of an optical fiber with the minimally invasive nature of a laser targeted light beam to produce the required optically encoded sensing data. The free-space laser beam provides the required physical isolation between the extreme environment zone and the friendlier signal monitoring zone while standard fiber-optical routing provides the mechanism for secure light delivery and capture for sensing and remote post-processing. Additionally, electronically agile beamforming optics such as an analog-mode ECVFL is added to condition the transmit/receive free-space beam, adding intelligence and robustness to the spatial sensing operations required to measure the remote target sensing data. Depending on the application, these hybrid sensors can use hybrid signal processing methods that can combine methods such as Black-Body (BB) radiation capture, laser interferometry, tunable and broadband optical spectrum analysis, and multi-dimensional spatial light processing. The hybrid theme has also been proposed on the active optical beam controls device level such as for combining digital and analog optical devices to form powerful remote optical sensors for both active (laser) and passive (ambient light/radiation) sensing, including broad spectrum sensing. One feature of the proposed agile lens and DMD sensors is their ability to implement smart and compressive sensing, thus providing direct reduction is sensed data required for image transmission and processing. To date, design and experimental results have been reported on a variety of these remote sensors for measurements of hot [1]-[6] and cold temperature [7], pressure [8]-[10], solid object range [11], liquid level [12]-[13], 2-D optical power irradiance distribution imaging (laser and

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diffused incoherent targets) [14]-[20], 3-D beam parameters [19]-[23] and 3-D solid object shape [24]. The hybrid digital-analog control with a wavelength sensitive delay has also been proposed for delay signal processing applications [25].

2. ALL-SILICON CARBIDE-BASED SENSORS

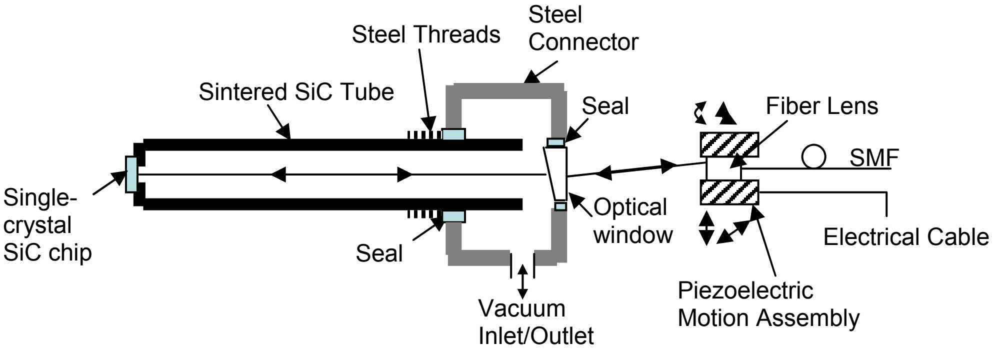


Figure 1. Proposed basic design of the all-passive frontend all-SiC temperature probe with its active motion control back-end. For optimal design, the SiC chip is fully encased in the SiC tube.

As an example, the first hybrid sensor described in this article is an extreme environment temperature sensor. Accuracy, reliability, and long-life times are critical parameters for sensors measuring temperature in gas turbines of clean coal-fired power plants. Greener high efficiency next generation power plants need gas turbines operating at super high temperatures of 1600 ºC where present thermo-couple temperature probe technology fails to operate with reliable and accurate readings over long life-times. To solve this pressing problem, the concept of a new hybrid class of all-Silicon Carbide (SiC) optical sensor has been proposed where a single crystal SiC optical chip is embedded in a sintered SiC tube assembly, forming a Coefficient of Thermal Expansion (CTE) matched all-SiC front-end probe. Because chip and host material are CTE matched, optimal handling of extreme thermal ramps (over 1000 ºC in a few seconds) and temperatures (e.g., 2000 ºC) is possible. Light is routed from the friendly post-processing zone via fiber-optics to the entry point of the gas turbine sensing inlet where a freespace laser beam is generated within the all-SiC frontend sensor probe (see Fig.1).

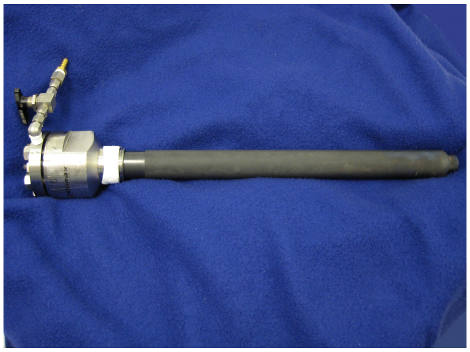


Figure 2. All-SiC temperature frontend probe shown in an assembled fashion.

The tip of the probe sits in the hot gas of the combustion chamber. As shown in Fig.2, the probe consists of three connectable parts. The first part is the long (e.g., 42 cm) probe that is an all-SiC hollow tube with one end open and the other end containing the embedded thick (e.g., 400 microns) SiC optical chip that optically and mechanically responds to the temperature of the gas. The second part is a steel pressure connector that engages with the open end of the probe to form a pressured sealed connection. The third part is a probe window assembly with a vacuum valve to enable a weak vacuum inside the probe cavity. The assembled probe is inserted into the gas turbine combustor inlet via a pressure fitting. A short range (e.g., < 20 cm) optical transceiver module provides the laser beam for SiC chip targeting and the temperature encoded receive beam capture. Note that unlike thermo-couple and optical fiber approaches that require extra protection tubes around the electrical/optical wires, the proposed probe requires no such special protection; hence avoiding the CTE mismatch problems as well as the need for complex long-term packaging of many protection layers.

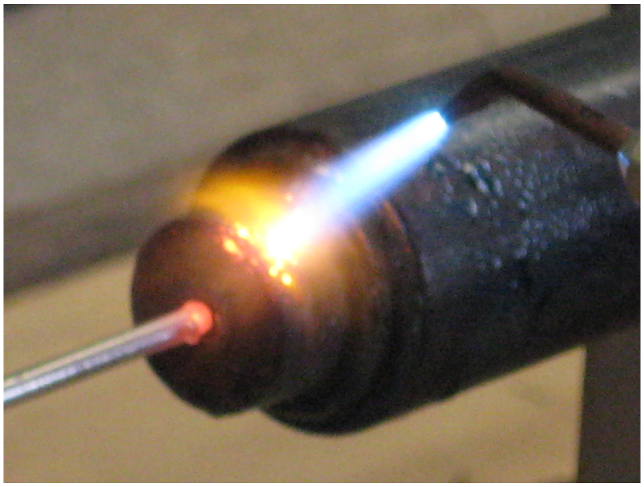


Figure 3. All-SiC probe and High Temperature Thermo-Couple under oxy-acetylene flame thermal and localized thermal ramp joint test with temperatures reaching 1600 ºC.

Recently, a first successful industrial combustor rig test has been completed of the hybrid all-SiC temperature sensor front-end probe indicating demonstrated probe structural robustness to 1600 ºC. Testing was carried out over a one month duration with eight combustor thermal shock tests. Fig.3 shows a mechanical probe structural integrity test conducted with an oxy-acetylene flame where the probe remains intact but the TC melts. In short, the hybrid design encompasses the theme of combined hybrid materials (i.e., sintered and single crystal SiC) and hybrid optics (i.e., wireless plus wired fiber-optics). Further details on the proposed hybrid design sensors theme can be found in the listed references.

2. ANALOG AND DIGITAL DEVICE DESIGN-BASED SENSORS

Figure 4. Electro-Wetting technology liquid lens from Varioptic, France used as the Analog optical beam control ECVFL device in the proposed remote sensors. (From Varioptic Web Site)

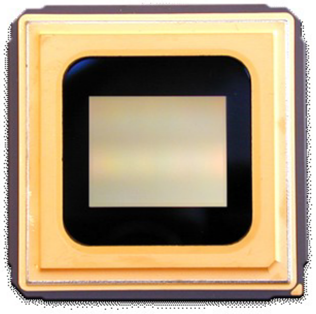


Figure 5. The TI DMD used as a smart mirror digital light control device in the proposed remote sensors.

Analog and digital beam control devices can also be used and combined to form hybrid design optical sensors for remote sensing of extreme environments. The analog optical beam control device deployed is the ECVFL. Specifically, used for experiments is an Electro-Wetting technology liquid lens from Varioptic, France (see Fig.4). The digital light control device used for designs is the TI DMD shown in Fig.5.

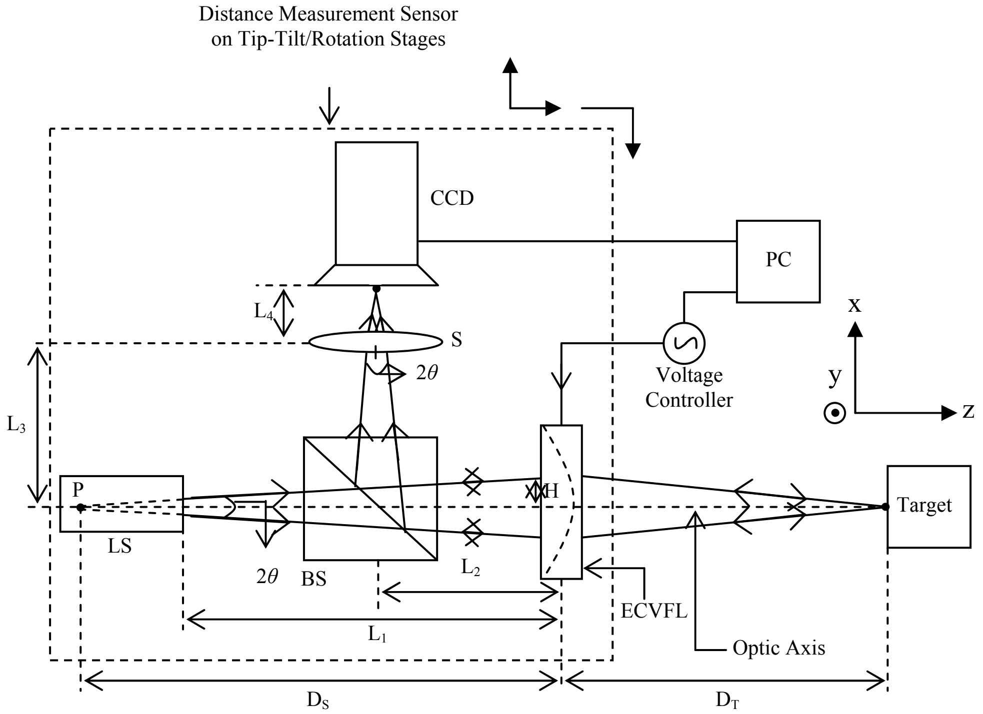


Figure 6. Proposed analog ECVFL-based distance sensor for remote target distance sensing.

As shown in Fig.6, the ECVFL has been used to design a novel distance sensing using spatial signal processing without the use of any EMI sensitive and electronic hardware intensive RF/time signal processing. Early results on distance sensing have been proven as shown in Fig.7 with ~ 1 m distance measurement range that is useful in many industrial applications such as large machine parts testing. With proper ECVFL design, the distance range can be extended or reduced with higher resolutions. In addition, prior-art classic distance measurement techniques can be applied with this spatial processing distance sensor to produce powerful new distance sensors. For example, the Fig.6 distance sensor can engage small angle classic triangulation methods to improve the resolution of the sensor within each coarse distance bin based on ECFVL spatial processing. The Fig.6 distance sensor has been used for liquid level sensing and these results are shown in Fig.8. Levels of cryogenic liquids such as hydrogen and nitrogen in tanks such as for rockets and industrial systems can also be measured by the Fig.6 sensor using no electrical contact. The proposed distance sensor can also realize an all-passive displacement-based pressure sensor.

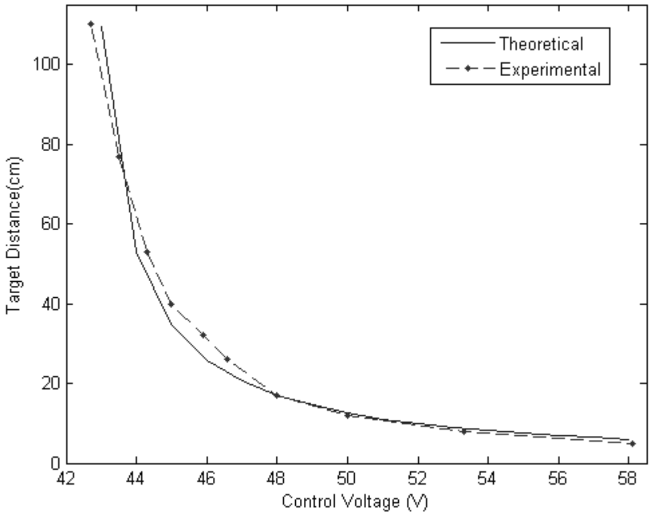


Figure 7. Demonstrated distance sensor theory vs. experimental response for a solid reflective target.

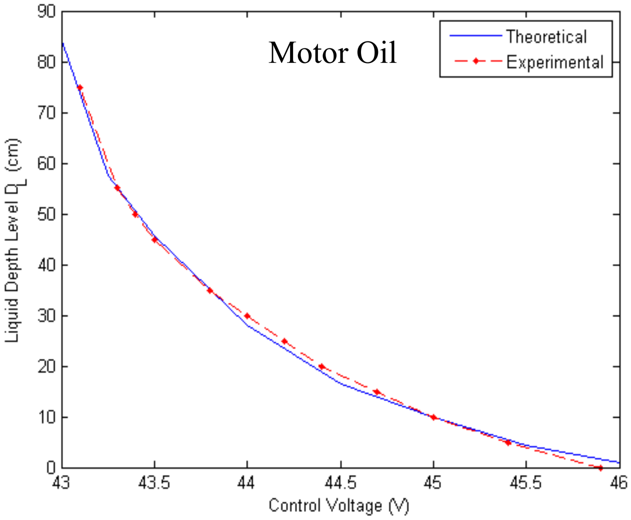


Figure 8. Distance sensor used for motor oil level sensing indicating match between designed theory and experiment.

Another application where the ECFVL-based sensor is applied is object shape sensing. Fig.9 shows a proposed design for this shape sensor that has the capability to provide smart and compressed sensing. In this case smart and compressed sensing is provided by two mechanisms. First, based on the object features, the sampling laser spot beam size can be adjusted to use the biggest beam spot size for a given feature on-axis z-distance plane. Thus, optical scanning of target 3-D object uses the smart spot size that produces the least number of spot scans to register the object's feature for later computer processing and data transfer. Second, a beam flooding technique using an expanding beam spot size can be used to define the feature edges/boundary for a given axial distance. Edge effects via optical wavelength exposure can produce clear boundaries for an in-focus (for a given z-plane) image and hence large object features can be rapidly defined and directly captured with many beam spot scans. Thus, direct compressive sensing can be achieved for viewing 3-D objects. The point to note is that beam focus power along the beam propagation direction (or optical axis of system) gives unique compressive sensing powers using a differential optical sensing method with comparative image views for different z-planes. Active sensor implies a laser beam is used to illuminate the target while passive sensor implies that ambient or indirect light is used to observe the target. Another important point to note is that both convex and concave lensing can be implemented via the ECVFL implying that the beam spot size compared to an un-aided laser beam can be decreased or increased in spot size. This feature is indeed important as it implies that super-resolution scanning of the target object/scene can be achieved compared to scanning with a classic expanding (or unaided) laser beam where spot resolution gets worse with increasing target depth ranges. Note that this far-field laser-based smallest spot generation capability of the sensor coupled with x-y mirror beam scanning provides a novel approach to 2-D displays and 2-D image imprinting, micro-fabrication, and optical lithography.

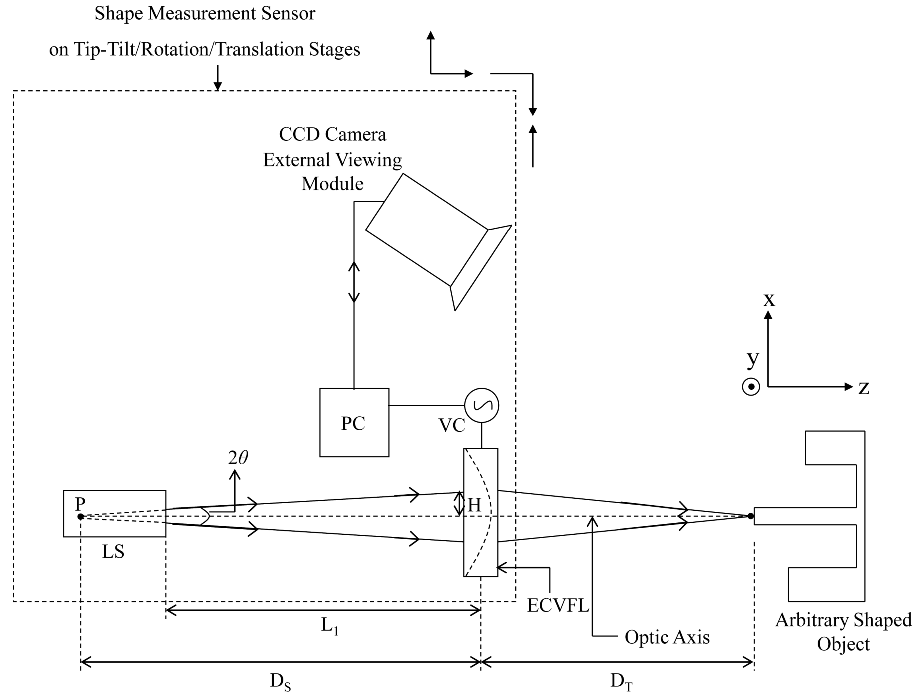


Figure 9. Proposed remote sensor for 3-D shape measurement with smart and compressed sensing features.

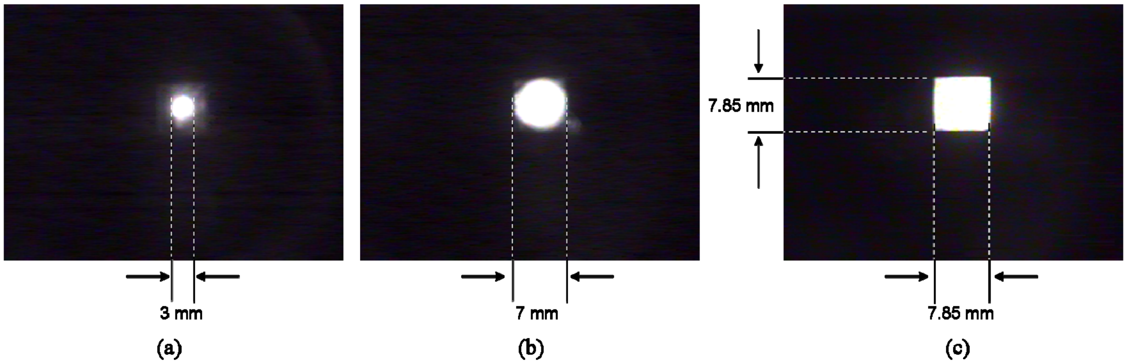


Figure 10. The proposed Fig.9 shape sensor implementing the target feature beam flooding technique that defines the feature boundary via a single laser spot beam. The object feature in this case was a square surface at a given z-plane compared to its surrounding target features, e.g., like a square roof of a mini sky-scraper located within many mini sky-scraper buildings.

As shown in Fig.11, the DMD digital light control device by TI has been proposed to enable a smart optical irradiance image sensor. Smartness comes from the fact that the DMD has ~ 1 million digital micromirrors that can be rapidly programmed to form various shape, size, and location optical apertures or windows to sample an incident optical irradiance distribution on the DMD chip. The inherent dual tilt nature of the micromirror operation produces two physical separated light capture optical detection ports and this feature leads to irradiance detection with a self-sustained irradiance calibration for each optical reading at the detection ports. Hence, one can have a temporal fluctuation in the overall irradiance pattern, nevertheless, one can produce the final irradiance map that is independent of the irradiance temporal fluctuation. Of course, this assumes that there is no temporal fluctuation during any given single sample zone photo-detection operation.

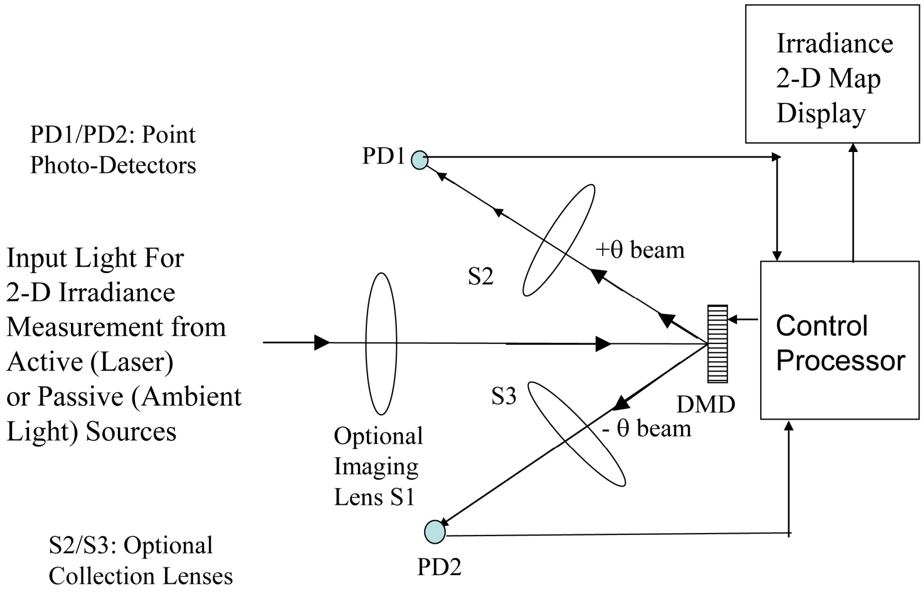


Figure 11. Proposed 2-D optical source irradiance mapping sensor using the DMD spatial sampler.

A number of experiments on optical irradiance imaging for a number of different types of optical sources have been implemented that include a variety of lasers (e,g., Visible, IR, UV wavelengths) and an infrared incoherent target. In addition, a liquid crystal digital-mode light control device has also been used for the irradiance mapping sensor versus the TI DMD. Note that depending on the light source, optional lenses S1, S2, and S3 are deployed for proper projection and collection of source irradiance. The physical size of the point photo-detectors PD1 and PD2 and the focal length of lenses and distance of optical components relative to each other is dependent on light source properties such as spatial and temporal coherence, beam divergence, etc. Note that light attenuation filters can also be placed at the photo-detectors between the DMD and PD1 and PD2 locations to handle high irradiance sources. Also note that the Fig.11 sensor can enable wavelength specific imaging if wavelength sensitive photo-detectors are used in the sensor, giving additional power to remote sensing functions. Fig.12 shows an example Fig.11 sensor application for imaging/profiling a spatially coherent light source, i.e., a laser with a classic Gaussian beam. It is also possible for the incident irradiance distribution to have a non-Gaussian distribution. By using pin-hole sampling, the Fig.11 sensor can image this non-uniform irradiance distribution. Fig.13 shows an example irradiance recovery for a 1-D grating like pattern on the incident irradiance that is correctly recovered by the Fig.11 sensor. Fig.14 shows another test of the Fig.11 sensor for mapping an incoherent IR heart-shaped target.

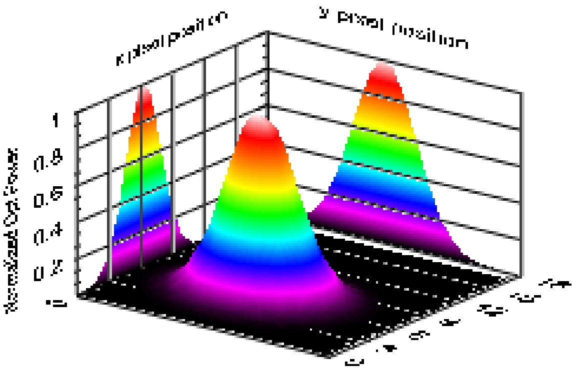
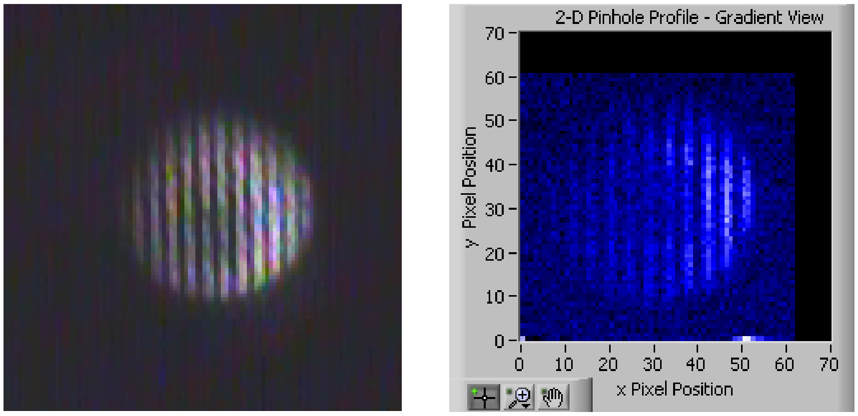
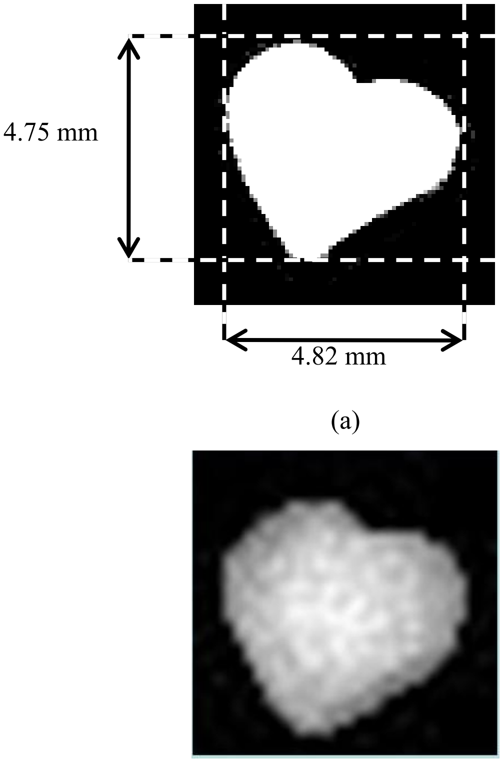


Figure 12. Optical irradiance 2-D mapping of a coherent light source (classic Gaussian beam irradiance distribution laser) using the Fig.11 sensor. Note that a UV 337 nm laser was used for this sensor test.



(a) (b)

Figure 13. Optical irradiance 2-D mapping of a non-uniform irradiance distribution using the Fig.11 sensor. The pattern is a 1-D grating produced using spatial modulation of a laser beam. (a) The irradiance pattern seen by a CCD. (b) The irradiance pattern mapped by the proposed Fig.11 sensor.



(a)

(b)

Figure 14. Optical irradiance 2-D mapping of an incoherent light source (an IR heart shaped target) using the Fig.11 sensor. (a) IR heart object image captured by an IR CCD. (b) Heart image formed using the Fig.11 sensor.

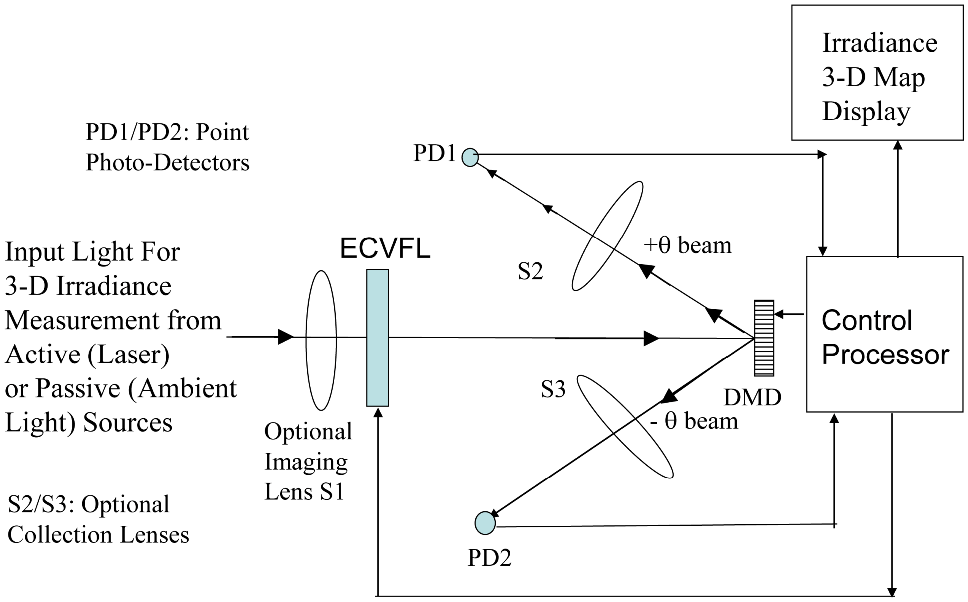


Figure 15. Proposed optical source 3-D (x,y,z) irradiance mapping hybrid sensor using the DMD spatial sampler with ECVFL focus control.

A more advanced hybrid design sensor has been proposed and is shown in Fig.15 that uses both an ECVFL and DMD. This sensor has the capability to produce 3-D irradiance maps of the incident light irradiance with DMD spatial sampling providing the 2-D irradiance maps for a given ECVFL focal length setting. Specifically, irradiance variation along the optical propagation direction can be mapped by tuning the ECVFL and using the DMD-based sensor to pin-hole sample the incident light irradiance for a given image focus plane. Again, use of S1, S2, and S3 depends on the light source properties. Recently, the Fig.15 hybrid sensor has been used to analyze the divergence properties of a Gaussian laser beam. Specifically, part of these results of measuring single mode Gaussian beam minimum waist and its location is shown in Fig.16. The Fig.15 sensor can also be programmed to implement Hybrid Differential Optical Sensing (H-DOS) that can measure irradiance changes with the 3-D (or x,y,z) coordinate frame that can lead to compressive sensing via boundary detection. Note that due to the reciprocity of optical components, the same sensor functions as a 3-D display or a laser-based 3-D machining/imprinting tool.

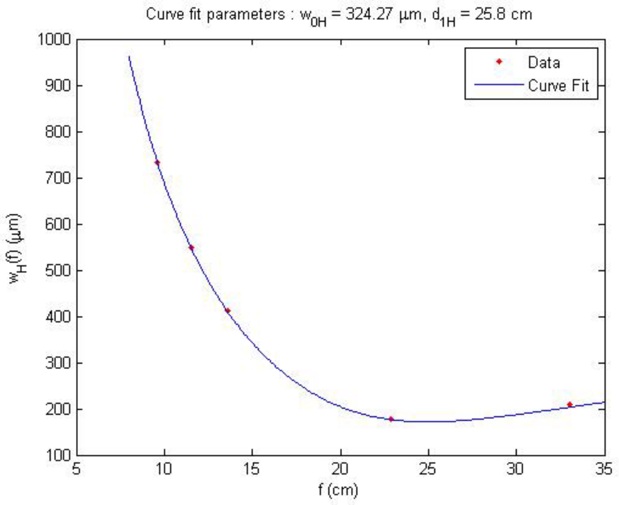


Figure 16. A least squares curve fit determined the test single mode Gaussian laser beam waist parameter in the horizontal direction and its relative location using the Fig.15 hybrid sensor.

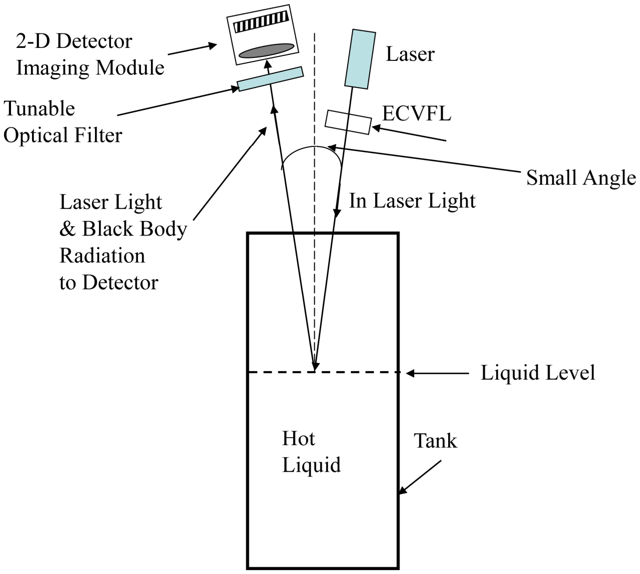


Figure 17. Hybrid design sensor for distance/liquid level and temperature measurement for a hot liquid (e.g., steel) sensing application. This sensor uses two wavelength pyrometry and distance sensing using spatial processing.

Following the hybrid theme, it is also possible to design a novel combined distance-temperature sensor for extreme environments that is shown in Fig.17. For example, one industrial application is measurement of both the temperature and liquid level of molten steel typically in the 1500 °C range. The Fig.17 hybrid sensor design combines the distance (like Fig.6) and liquid level sensor of refs. 11-13 with the 2-wavelength pyrometer such as demonstrated in ref.4 to form a dual function sensor using minimal components. The laser is aligned close to normal incidence with the liquid/hot surface with the angle small enough so the transmit and receive light hardware are physically separated. Given the laser beam size is small and the distance from the surface is sufficiently large (i.e., entry window is designed to be far away from the hot body under evaluation), the small angle approximation holds. The 2-D detector functions to capture the laser beam spot reflected off the hot surface to enable liquid level distance sensing. The detector also images the radiation coming from the hot surface to implement 2-wavelength pyrometry. The detector will deploy a tunable optical filter that is tuned for the laser wavelength and two different Black-Body radiation spectral bands. Recall that the ECVFL is tuned to produce that smallest laser spot on the hot surface. Apart from the liquid lens, the choice for the ECVFL technology is diverse and can include mechanical motion-based bulk lenses, MEMS and Deformable Membrane (DM) technology based reflective mirrors/lenses, and liquid crystal-based transmissive and reflective lenses. The type of ECVFL technology used to design the sensor is highly dependent on the application requirements that relate to lens reset speed, aperture, wavelengths of operation, optical power handling, electrical power budget. Note that use a hybrid lens design combining a variety of ECVFL lens technologies may be the optimal balanced approach for a given application.

Within a device level, the hybrid theme also operates via combined analog and digital control such as within a wavelength-coded variable optical delay line shown in Fig.18 shown deployed within a proposed coherent distance sensor. The electronically set wavelength of the laser selects the reference delay in the hybrid wavelength coded optical delay line. Details of the delay line are in ref.25. An extra length bias fiber is added to the reference delay path to bias the distance sensor for its starting range position for distance sensing. For optimal receive signal detection, the received RF signal pulse and the reference RF signal pulse, both riding on the selected optical wavelength carrier must overlap in time for optical coherent (interferometric) detection. PD1 and PD2 provide the 180 degree out-of-phase RF signals that can be subtracted for optimal RF signal detection and processing. As a laser can be tuned rapidly (e.g., 1 ns), the Fig.18 distance sensor can swiftly interrogate the designed target distance range to locate targets beginning with the start range position and scanning all other distance range coded positions for their specified wavelengths. Coherent optical detection provides high gain for the otherwise weak target reflected optical signal as a sufficient power coherent laser power is provided via the wavelength coded delay line.

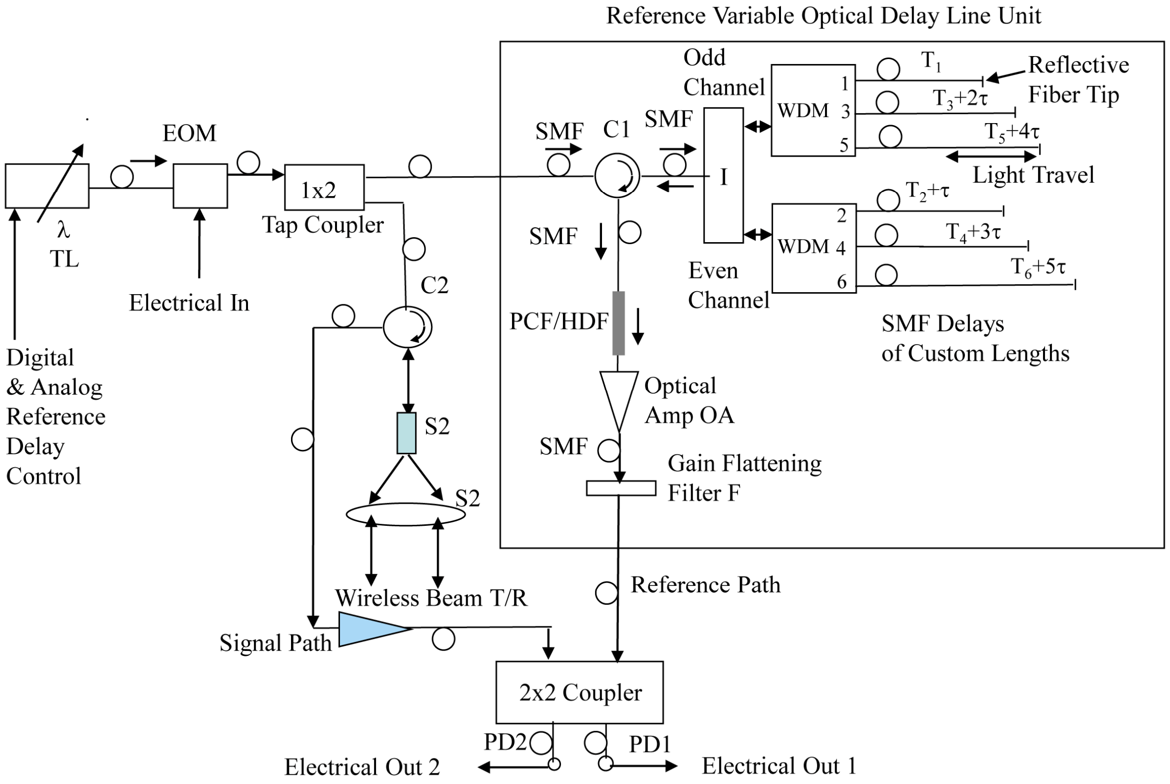


Figure 18. Coherent wavelength coded distance sensor using hybrid design variable delay line.

3. CONCLUSION

In summary, a number of separate innovations come together to deliver the powers of the hybrid sensor design that couples some of the best feature of fiber-optics, free-space optics, analog-mode spatial light distribution control devices, digital-mode light spatial control devices, lasers, thermal radiation, spectral content, optical refractive index changes, imaging and focusing bulk optics, mechanical deformations, spatial processing, and wavelength coding to deliver robust sensors suited for a variety of extreme environment sensing applications. Furthermore, the synergy of sound hybrid design optical sensor engineering and direct compressive sensing and signal processing can indeed promise a better future for the challenging sensing demands of the 21st century. Applications for these proposed hybrid design optical sensor are diverse and includes laser radar and TeraHertz (THz) antenna controls, hyper-spectral imaging systems (e.g., visible, NIR, SWIR), Non-Destructive Testing (NDT) and inspection of RF sensors (e.g., for measurement of antenna (array) structures physical shape, size, location, temperature, stress, pressure), material characterization and fabrication equipment (e.g., sensing temperature, pressure, distance, wafer shape), displays and micro-fabrication/machining, 3-D virtual reality, warfare simulation, & 3-D animation, and controls parameter sensing in aircraft and ship/maritime engines, nuclear reactors, rocket fuel tanks, and power production gas turbines.

4. ACKNOWLEDGEMENTS

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