The CAOS Camera – Unleashing the Power of Full Spectrum Extreme Linear Dynamic Ranging Imaging

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Abstract—**The CAOS camera invention is described that allows high security full spectrum (350 nm to 2700 nm) extreme linear dynamic range bright target imaging. First time experiments highlight real-time simultaneous tracking of bright visible and infrared laser beams.**

Keywords—Imager, Camera, Digital Micromirror Device

I. INTRODUCTION

Active imaging involves using a bright light source to illuminate a target of interest. Lasers are commonly used as highly directional illuminators of scenes including scenarios of extreme dynamic range (i.e., image contrast) such as in night vision (e.g., fire and rescue) or bright daylight or moonlight conditions with some dark regions (e.g., inside tunnels within a scene) and surrounding bright zones. Depending on the application and scene scattering parameters as well as eye safety concerns, lasers used vary in wavelengths covering a full spectrum from, for example,   355 nm (UV) to visible band (480-680 nm) to NIR (705 - 2000 nm). Under such extreme conditions of full spectrum usage and high contrast, current CMOS/CCD/FPA technology is highly limited for delivering a full spectrum, extreme dynamic range, bright target, optical imaging unit that is also cost effective.

Fig. 1. Shown is Prof. Richard P. Feynman (center), 1965 Physics Nobel Prize, in his 1985 graduate class at Caltech where Prof. Feynman's words many years later inspired N. A. Riza (2nd from left) to invent the CAOS camera.

Recently proposed is a new camera technology called CAOS (Coded Access Optical Sensor) [1-2] that can take on the challenge of active imaging within one camera unit. The CAOS camera operates on the principles of a multiple access Radio Frequency (RF) wireless network that relies on RF coded transmission and electronic Digital Signal Processing (DSP) based data signal recovery. The CAOS camera's inspiration comes from Prof. Richard P. Feynman's words expressed in a graduate class taken by N. A. Riza in 1985 while he was a Masters and Ph.D. student at Caltech (see Fig.1). In this class, Prof. Feynman said something like: There is Radio Moscow in this room, there is Radio Beijing in this room, there is Radio Mexico city in this room; then he paused and said: Aren't we humans fortunate that we can't sense all these signals; if we did we would surely go mad with the massive overload of electromagnetic radiation (radio signals) around us!

Indeed all the radio signals however so weak, that Professor Feynman referred to exist at the same time in space even today, but each are coded with their specific time-frequency domain radio code for its specific radio broadcast channel. Today it is taken for granted that even the weakest of such RF signals can be extracted using a sensitive enough RF receiver that can decode the specific radio code for the transmitted data channel. Indeed that is how today's RF wireless mobile phone network is designed and operated worldwide with ever so sensitive handheld mobile devices empowered with low 1/f noise (f: frequency) electronic processing, DSP gain and noise filtering. CAOS uses this same RF multi-access network design philosophy to create an extreme linear dynamic range, full spectrum, high security optical imager. In the CAOS camera, the chosen multiple pixels of light (called Pixels of Interest or POI) [3] in the scene are time-frequency coded (like RF mobile data signals) that are then extracted after photo-detection via an optical receive antenna. The RF output signal from the optical antenna next undergoes powerful electronic DSP-based decoding that gives extreme and controllable processing gain and noise reduction for high Signal-to-Noise Ratio (SNR) pixel irradiance extraction. Compared to prior-art optical cameras, CAOS's controllable SNR pixel irradiance extraction is a unique feature giving the retrieved image data true robustness. Reliable image data is critical for decision making, e.g., in automotive vision, leading to life savings.

CAOS also features inherent security as POI irradiances can only be decoded if one knows the correct time-frequency codes deployed per POI in the camera. These codes can also be hopped from time-to-time within sequences of POI, adding further security to the camera imaging operations. The CAOS camera design can be optimized for numerous applications requiring its unique features including astronomical observations, biomedical microscopy, industrial machine vision, automotive vision, robotic vision, surveillance, undersea exploration, and aerospace sensor systems [4-5].

II. THE FULL SPECTRUM CAOS CAMERA

The first designs of the *passive mode* CAOS camera [2] have been based on the TI Digital Micro-mirror Device (DMD) [2, 4-9]. The *active-mode* CAOS camera described in ref. 2 uses a time-frequency modulated Light Source Array (LSA) versus the passive-mode where light from the surroundings (e.g., from sunlight, moonlight, LED or laser lighting fixtures) illuminate the target or the target itself is generating light.
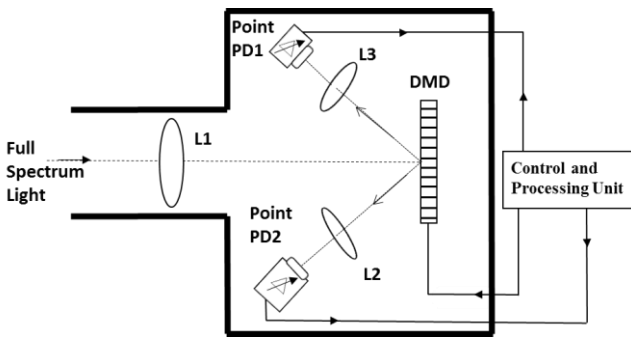

Fig. 2. Full spectrum extreme dynamic range CAOS camera design such as for active imaging using different wavelength bands laser illumination of targets..

Fig.2 shows the design of the full spectrum extreme dynamic range CAOS camera such as for active imaging using laser illumination of targets. L1, L2, and L2 are spherical lenses. L1 is an optional frontend lens that is deployed based on the type of light irradiance map requiring measurement. For example, for direct mapping of laser beam profiles, L1 is not needed. On the other hand, to map an incoherent far-field target scattering illumination light, L1 brings the far-field radiation onto the DMD plane. L2 and L3 image light from the DMD plane onto PD2 and PD3, respectively. Point PD1 and point PD2 can be two different optical material detector assemblies (e.g., Silicon and Germanium) sensitive to two different spectral bands to allow simultaneous full spectrum imaging. The broadband (350 nm to 2700 nm) DMD [10] operates in the time-frequency CAOS mode for the chosen POI required such as for simultaneous visible and IR laser beams target tracking. Importantly, note that the DMD incident CAOS time-frequency modulated light goes to both point PD ports and the AC signals from these PD ports are independently and simultaneously processed via computer based DSP to extract the two different optical bands laser beam irradiance maps. To block light entering the PD from

unwanted wavelength bands, bandpass optical filters can be placed in the PD1 and PD2 paths.

At this point, it is important to state that the origin of the CAOS camera TI DMD optical architecture design shown in Fig.2 is linked to Riza lab's prior work in the late 1990s. Specifically, the DMD agile pixel dual port optical architecture (also called the Agile Pixel Imager) that using agile pixels (e.g., moving apertures like slits, pin-holes, edges, etc.) and deterministic computer computations for image recovery was proposed by the Riza lab in 2001 initially for laser irradiance mapping [11]. This work was based on 1997 DMD optical architecture advancements by Riza lab for aerospace [12] and fiber-telecommunications applications [13]. Riza lab in 2003 also proposed the symmetric dual point detector DMD optical architecture for robust noise tolerant optical imaging [14-15]. All these imaging works used non-random DMD pixel assignments and DC light level point PD generated photo-charge signal capture that was combined with computational image retrieval methods to create viewed optical images. The point PD signal was a DC signal (vs AC signal in CAOS) and no time/frequency domain processing was engaged. The Riza lab also proposed a super-resolution DMD agile pixel imager based on analog-digital micromirror control and sub-micromirror displacement processing [16].

In contrast, it is also relevant and important to point out that the DMD-based compressive imager design reported in 2006 by the Rice University (USA) Baraniuk lab in SPIE Conference Proceedings [17] and later in 2008 in an IEEE Magazine [18] uses the same basic DMD optical architecture imager design earlier published by the Riza lab in OSA Applied Optics in 2002 [11]. The Rice DMD compressive imager uses spatial processing using pseudo-random spatial maps [18] on the DMD with point PD collected DC light levels and iterative compressive sensing algorithms [19] to get an *estimate* of the seen image. The Riza lab *Agile Pixel Imager* does not use random spatial masks and iterative techniques to get image estimates. The CAOS camera also does not use random masks. Specifically, CAOS is based on non-random time-frequency based signal processing with spatial smartness (e.g., via the CMOS sensor or other spatial scan methods) and delivers the *true* image (without estimations). It does not use spatial correlation style processing with compressive algorithms that is used by the Rice group.

There is no relationship between the CAOS camera and the 2006 Rice compressive imager called by many as a *Single Pixel Camera*. It is important to note that the CAOS camera can also choose to deploy compressive and other image processing methods if needed to improve operational efficiency and speed and also continue to deliver high linear DR imaging. Spatial positions of time-frequency coded CAOS pixels on the DMD are not correlated in space and require no spatial correlation properties. CAOS pixel time-frequency codes assigned to pixels in the image space need to show good zero cross-correlation and/or non-overlapping spectral outputs in the time-frequency (i.e., Hz) domain for best multiple access image pixels recovery.

III. EXPERIMENTS

The Fig.2 full spectrum CAOS camera design is experimentally setup in the laboratory. The setup is based on the Vialux V-7001 DMD board with a 13.68 μm micro-mirror size. PD1 is a Thorlabs switchable gain silicon detector model PDA100A2 and PD2 is a Thorlabs switchable gain germanium detector model PDA50B. PD1 covers the spectral range from 320 nm to 1100 nm whereas PD2 covers 800 nm to 1800 nm. The deployed visible band color filter is Thorlabs model FGS900M with band specifications of 315 nm to 710 nm. The deployed IR band filter is a long-pass Thorlabs model FEL0800 with a filter pass-edge of 800 nm. The visible test laser used is a 13.7 mW Melles Griot He-Ne 05-LHP-991 laser. The eye safe 1550 nm test laser used is a 50 mW model S4FC1550 Single Mode Fibre (SMF) connected Fabry-Perot diode laser set to 15.3 mW. This laser feeds a SMF cable with a fiber lens at the end of the cable. The plano-convex lenses L1, L2 and L3 have focal lengths of 12.5 cm, 7.5 cm and 7.5 cm, respectively. Distances are: L1 to DMD: 14.5 cm, DMD to L2: 16.5 cm, DMD to L3: 17 cm, L3 to Si Point PD1: 13.4 cm, L2 to point Ge PD2: 13.75 cm, fiber lens to L1: 37.5 cm, and He-Ne laser to L1: 112.5 cm. The control and processing unit consists of a NI-6366 8 channel Data Acquisition (DAQ) card with a maximum sampling rate of 2 Mega-samples/sec and a DELL i7 laptop with a processor clock of 2.80 GHz.

The CAOS camera system has undergone automation for near real-time imaging. Specifically, CAOS pixel time-frequency encoding operations that includes code generation via software and DMD control, again via software has been implemented using a high speed Dell laptop. Depending on the initial scene intelligence gathered by the CAOS camera operating in an aperture scan mode such as TDMA mode gives a DC signal-based scene initial irradiance map. A CMOS camera can also provide this intelligence which is used to decide which CAOS-mode (e.g., CDMA, FM CDMA, FDMA, etc) [9] is used to encode the selected POI map. Once CAOS camera is reconfigured for time-frequency encoding, the POI irradiance map capture starts generating an AC signal from the point PDs that are fed to independent channels of a multi-channel DAC board operating at 16-bits digitization with a software chosen DAC voltage range as well as sampling bit rate. The digital DAC data is stored in the laptop and decoding processing takes place to generate a CAOS POI irradiance map for the given CAOS encoding capture interval. This encoding and decoding process starts again for the same POI capture and irradiance generation, producing a sequence of viewed POI images for near real-time imaging operations. To test these near real-time operations, a 13.7 mW He-Ne laser beam is passed through a centre-offset electronically variable focal length liquid lens that has its focal length modulated at a 0.3 Hz rate. This liquid lens modulation generates both a focal length change plus a tilt prism affect. The combined effect is a translating laser beam with a changing beam spot diameter. In this experiment, L1 is removed as the laser beam directly strikes the DMD plane.
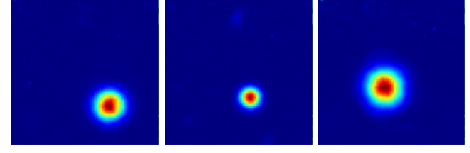

Fig. 3 Near real-time video frames (12 POI frames/second) of a scanning and focal length changing 633 nm laser beam imaged by the CAOS camera.

Fig.3 indeed shows this beamforming effect with the laser beam moving and also changing in focal spot size. To generate this near real-time video of a scanning and focus changing laser beam, the Code Division Multiple Access (CDMA) mode for CAOS is used with 3600 pixels (a 60 x 60 CAOS pixels grid, i.e., POI is 3600 pixels) encoded using 4096 bits Walsh code sequences. Each CAOS pixel is designed to be one micromirror. The video POI 3 frames shown in Fig.3 operate at 12 POI frames/second that is adequate to track the 0.3 Hz modulation rate of the camera impinging 633 nm laser beam passing through the electronically controlled liquid lens. A faster POI update rate can be achieved using a faster DMD micromirror digital modulation rate in excess of the 50 KHz bit rate used or a smaller POI count with a shorter code sequence can be deployed. With improvements in faster frame rate Spatial Light Modulators (SLMs) or use of very fast modulation rate LSAs for active CAOS, much faster POI update rates (e.g., > MHz range) can be achieved.
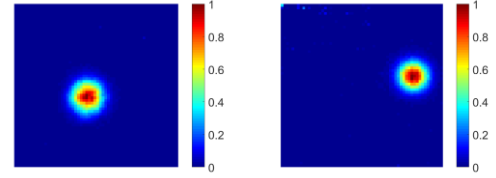

Fig. 4. (left) Visible 633 nm laser beam captured via point PD1 in the CAOS camera. (Right) IR 1550 nm laser beam captured via point PD2.

To start simultaneous visible and eye safe IR beam laser imaging using the CAOS camera setup in the lab, the DMD is again programmed to implement the CDMA CAOS mode. Both laser beams are incident on the DMD plane and are imaged using 3600 CDMA-mode CAOS pixels with a square POI grid: 60×60 pixels, where this time each CAOS pixel is 3 × 3 micro-mirrors. The non-POI region has a static on-off pattern. Each CAOS pixel is assigned a unique 4096 bit long Walsh time code. A 50 KHz DMD modulation bit rate is used with DAC set to a 10 V range setting and a 500 Ksps sampling rate. Light from all the 3600 pixels falls on point PD1 and point PD2 to generate two RF wireless style spread spectrum signals that are simultaneously digitized by two independent channels of the DAQ card. The digitized signal from Si PD1 provides the CAOS-coded signal data for reconstruction of the visible laser beam shown in Fig.4 (left photo). In contrast, the digitized signal from Ge PD2 provides the CAOS-coded signal data for reconstruction of the IR laser beam (Fig.4: right photo). The digitized PD signals are sent to the laptop for time-correlation processing based decoding to allow

normalized pixel irradiance recovery and beam irradiance image reconstruction.

A critical and novel aspect of the proposed Fig.2 CAOS camera design using CDMA-mode dual PD operations is explained next. A "1" bit encoding of a CAOS pixel on the DMD means light from the pixel (micromirrors) goes to the visible point PD1. This simultaneously also means that a "0" bit encoding has occurred for the same CAOS pixel when using the AC signal from the IR point PD2. To demonstrate a simple example of Walsh function based encoding and decoding of a CAOS pixel in CDMA-mode, consider the case of P=15 CAOS pixels using a N=16 bits code design with a specific j^{th} pixel encoding time sequence (vector) $\boldsymbol{a}_j^E$ of [1   0   0   1   1   0   0   1   0   1   1   0   0   1   1   0] and a jth pixel decoding time sequence (vector) $\boldsymbol{a}_j^D$ of [1   -1   -1   1   1   -1   -1   1   -1   1   1   -1   -1   1   1   -1]. This encoding sequence of the jth pixel correctly shows up at visible point PD1 for the stated Fig.2 design and the correct visible pixel irradiance can be recovered via autocorrelation processing (see Fig.4) using its stated $\boldsymbol{a}_j^D$ decoding sequence. On the contrary, a complementary and incorrect encoding sequence of [0   1   1   0   0   1   1   0   1   0   0   1   1   0   0   1] gets detected and produced by the IR point PD2 and its autocorrelation processing fails to produce the IR light CAOS pixel irradiance. A unique solution to this dilemma is to have the IR point PD2 produce an AC signal that after software processing can produce the correct non-complementary encoding, i.e., specific j^{th} pixel encoding time sequence (vector) $\boldsymbol{a}_j^E$ of [1   0   0   1   1   0   0   1   0   1   1   0   0   1   1   0]. Specifically at point PD2, subtracting of a "0" bit from a "1" bit gives the correct "1" encoding bit (i.e., 1-0=1) and subtracting of a "1" bit from a "1" bit (i.e., 1-1=0) gives the correct "0" encoding bit. To determine the AC signal value of the "1" bit at point PD2 for a jth pixel to implement the software-based subtraction, an Error Correction (EC) calibration "0" value bit (for PD1 detection that is equivalently a 1 value bit at PD2) is added at the start of each DMD controlled CDMA N-bit encoding time sequence. For the PD1 DAC output, this EC calibrating bit AC signal data is not used for decoding and visible image recovery. On the contrary, the EC calibration bit used for the P CAOS pixels encoding with P different N-bit sequences produces a summed AC signal EC calibration value for all the P "1" values at PD2. Next the PD2 AC signal for each of the 16 bit sequence AC values is subtracted from the summed EC bit AC value (present in the first encoding time slot, i.e., the EC bit time slot), to produce the correct encoding 16 bit sequence AC levels, i.e., EC bit AC value – Encoding bit AC signal. These computed P AC signal values for the 16 time slots, one for each bit, are the correct AC signal values that next undergo autocorrelation based decoding to correctly recover the PD2-based IR image (see Fig.4 right image). This simple yet powerful novel signal processing method allows the Fig.2 dual point PD CAOS camera to produce independent & simultaneous dual images, one for the IR band and one for the visible band using the same CDMA codes.

III. CONCLUSION

Demonstrated for the first time is near real-time CAOS camera-based imaging and tracking of two simultaneous laser beams, one in the visible spectrum and one in the eye safe IR band. Novel POI CDMA encoding and decoding methods are proposed and deployed for simultaneous bright laser target capture in the visible and eye safe IR band. Laser targeted beam image data is shown for a 12 POI frames/second update rate for 633 nm and 1550 nm moving laser spots.

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