Characterization of the series 1000 camera system

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(Presented on 21 April 2004; published 12 October 2004)

The National Ignition Facility requires a compact network addressable scientific grade charge coupled device (CCD) camera for use in diagnostics ranging from streak cameras to gated x-ray imaging cameras. Due to the limited space inside the diagnostic, an analog and digital input/output option in the camera controller permits control of both the camera and the diagnostic by a single Ethernet link. The system consists of a Spectral Instruments Series 1000 camera, a PC104+ controller, and power supply. The 4*k* by 4*k* CCD camera has a dynamic range of 70 dB with less than 14 electron read noise at a 1 MHz readout rate. The PC104+ controller includes 16 analog inputs, four analog outputs, and 16 digital input/output lines for interfacing to diagnostic instrumentation. A description of the system and performance characterization is reported. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1789261]

I. INTRODUCTION

In the mid 1990s Lawrence Livermore National Laboratory (LLNL) scientists began replacing film cameras with high resolution charge coupled device (CCD) cameras for use in Nova facility at LLNL and at the Laboratory for Laser Energetics.[1–3] The National Ignition Facility (NIF) requires a compact scientific grade camera and a diagnostic controller that can be used with various diagnostics. A primary physical requirement is to fit inside the standard air–box cross section of 13.3×13.0 cm. The series 1000 design was based on experience with the spectral Instruments Series 800.[4]

Additional requirements were that it must be based on a standard bus, form factor, operating system, and be compatible with "Requirements and Recommendations for Target Diagnostic Development."[5] These features provide the flexibility to change boards to meet diagnostic needs and simplify software development and maintenance. The PC104+ architecture was selected.[6] This controller is in the design of the NIF gated x-ray detector and NIF Dante diagnostics.[7,8]

II. DESCRIPTION

The three major subsystems are the CCD camera, the controller, and power supply as shown in Fig. 1. The water cooled camera features are: fully enclosed CCD in the vacuum housing, 1/4 in. cooling lines, supports NIF's electrical and optical triggers, and has both PCI and PC104+ interface boards. The increase from 1/8 to 1/4 in. cooling lines and the elimination of several right angle turns in the camera increased the water flow from 750 ml/min for the Spectral Instruments Series 800 to 1550 ml/min using a PolyScience chiller rated at 5 psi. The CCD is a Kodak 16801E CCD with Incom 33 mm long fiber optic bundle with 6 μm diam fiber attached to the CCD. The CCD is 4096 by 4096 with 9 μm square pixels based on an indium–tin–oxide (ITO) design, which increases light transmission to the active area of the pixel. The chip size of 36.8 by 36.8 mm makes it equivalent in size to the original film based diagnostics. The camera is 9.1 cm high, 9.1 cm wide, and 15.6 cm long. This is 5 cm less in length and 2 cm less in diameter than Series 800.

The controller is based on PC104+ architecture and form factor shown in Fig. 2. The controller consists of the processor board, with both an ISA and PCI bus, an analog board, camera controller, and fiber optic Ethernet board. The processor board is a WinSystems PPM-TX-266-ST board. The board contains: (1) a 266 MHZ Intel Pentium MXCPU with 256 MB of memory, (2) watch dog timer, (3) 10/100 Mbps Ethernet port, (4) two interrupt controllers, (5) seven input/output direct memory acccess channels, (6) three 16-bit counters, and (7) four RS232 ports.

The analog/digital input/output (I/O) board is a diamond MM-16-AT. The board has 16 analog inputs with +10 V range, 16-bit resolution, and 100 kHz sampling rate. There are four analog outputs with 12-bit resolution and a +10 V range. The 16 digital I/O lines can be configured as either input or output. A 50 pin ribbon connector allows access to the I/O.

The Spectral Instruments boards are the camera interface and fiber optic Ethernet boards. The interface board communicates to the camera using a giga Hertz MT-RJ fiber optic interface. This board also monitors the current in the two cooling fans and a pair of temperature monitors. The other board converts the 100 base-T Ethernet connection on the processor board to a 100 base-FX fiber optic Ethernet. The controller dimensions are 9.2 cm high, 12.1 cm wide, and 12.0 cm long. Figure 3 shows how the CCD camera and PC104+ controller are used in a diagnostic.

Spectral Instruments power supply has +28 VDC input, which is standard for NIF diagnostics. The power supply provides +5 VDC, +15 VDC, ±13 VDC, +24 VDC to the camera, and +5 VDC, +12 VDC to the controller. The power supply is 7.2 cm high, 10.1 cm wide, and 17 cm long.

The operating system is Windows XP embedded with C and C++ drivers and libraries for the camera and I/O board. JAVA is the desired application development language. The

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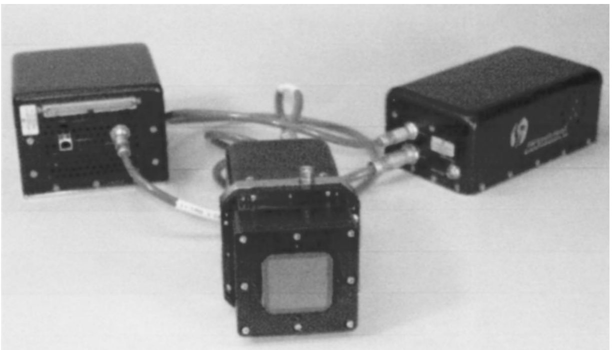

FIG. 1. Spectral Instruments Series 1000 camera system.

operating system is bootable from the network as a diskless system or can operate stand alone from a disk on chip.

III. TEST SETUP

The light source is a Gamma Scientific RS-5 digital light source system with a calibrated dc output. The RS-5 system has 460 nm and 530 nm heads. The RS-5 head was mounted to the flat-field illuminator (FFI) (Gamma Scientific) and a shutter installed in the FFI. A 2.3 ND filter was mounted after the shutter followed by an Edmund Scientific diffuser at the output of the FFI. The camera's fiber optic faceplate made direct contact with the fiber optic faceplate of the illumination system. The camera acquired an image for 2 s, with the shutter open for 1/2 s, starting 200 ms after the start.

IV. TEST PROCEDURE

The camera remained at $-15\,^\circ\mathrm{C}$ for a minimum of 20 min prior to taking data. Tests were done at both 690 and 1000 kHz readout rates. The data acquisition procedure was: (1) with illumination system off—acquire and save two bias images, (2) turn RS-5 illumination system on to $\geqslant 300\ \mu\mathrm{W/cm^2}$ with 530 nm head and acquire and save two flat-field images; (3) repeat step 2 for 200, 100, 70, 50, 20, 10, and 5 $\mu\mathrm{W/cm^2}$; (4) repeat the 50 illumination value to verify data repeatability; (5) repeat bias image with illumination off for verification of system stability; (6) adjust camera software to the second readout rate and repeat steps 1–5;

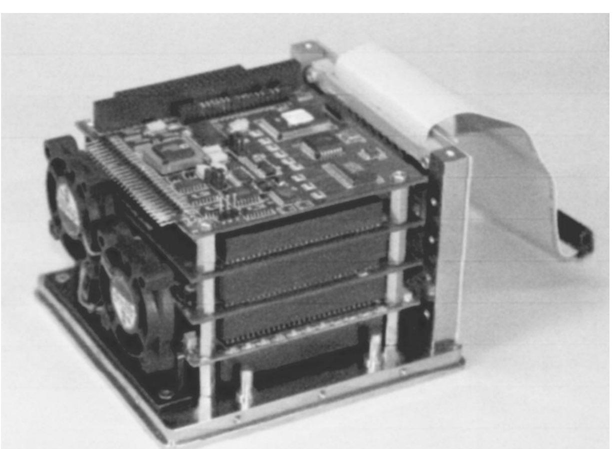

FIG. 2. PC104+ module showing analog to digital converter board.

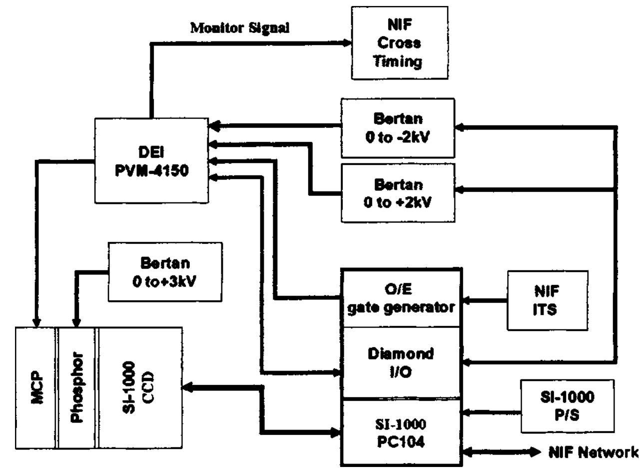

FIG. 3. Block diagram of the NIF Dante diagnostics built around the PC104 and camera.

(7) finally replace the RS-5 530 nm head with the 460 nm head; and (8) repeat steps 1–6 with the 460 nm head.

After the tests, the camera was replaced with an UDT PL8C silicon photodiode and current readings from the photodiode were recorded at the various illumination levels used in the tests.

The final step was to measure the camera resolution. To determine resolution, a 1951 USAF resolution target was projected onto the fiber optic faceplate of the camera by an Optoliner.

V. RESULTS AND DISCUSSION

The first step was to determine the photometric properties of the test setup. Equation (1) shows the calculation photons/s m^2 for a given wavelength in nm. I_d is the photodiode current (A), A_d is the detector area (m^2), R_d is the detector responsivity (A/W), λ is the illumination wavelength (in m), h is Planck's constant: 6.626×10^{-34} J s, and c is the speed of light: 2.998×10^{8} m/s. At 460 nm there are 2.32×10^{18} photons/J and at 530 nm there are 2.67×10^{18} protons/J

$$\text{photons/s m}^2 = \frac{I_d}{(A_d * R_d)^*\left(\dfrac{hc}{\lambda}\right)}. \tag{1}$$

The values from Eq. (1) are multiplied by the 0.5 s exposure time and the 81 $\mu\mathrm{m}^2$ area of the pixel of the camera under test to determine the number of photons that illuminated each pixel. Tables I and II show the photometric parameters.

Next, measure the camera's bias and read noise. The two bias images were averaged together. The average signal from a 50×50 pixel subarray in the camera's overscan region of the image is the camera's bias (or offset). The output circuitry is read out past the active pixel area. This area called the overscan region provides the noise contribution of the readout electronics. The standard deviation of this subarray is the camera's read noise σ_{RDN}.

At each illumination level the average signal and standard deviation were measured, and the gain constant was calculated for a 50×50 pixel subarray region near the center

TABLE I. Photometric values for 460 nm.

RS-5 setting (μW/cm^2)	Photodiode signal (nA)	Irradiance (nW/cm^2)	Photons/pixel
100	25.24	100.97	109 102
70	17.78	71.11	76 836
50	12.75	51.00	55 108
20	5.14	20.55	22 208
10	2.57	10.29	11 117
5	1.29	5.15	5554

TABLE II. Photometric values for 530 nm.

RS-5 setting (μW/cm^2)	Photodiode signal (nA)	Irradiance (nW/cm^2)	Photons/pixel
100	15.05	100.34	94 103
70	10.60	70.63	66 243
50	7.60	50.67	47 517
20	3.06	20.42	19 151.
10	1.54	10.26	9622
5	0.77	5.13	4814

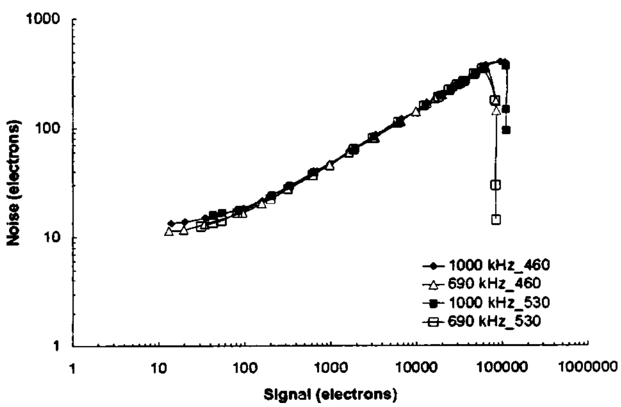

FIG. 4. Photon transfer curve.

TABLE III. Camera dynamic range.

Camera (model_sn)	Readout rate (kHz)	Camera gain (e^-/DN)	Read noise (e^-)	Full well (e^-)	Dynamic range
1000_102[a]	690	1.33	6.9	NA	NA
1000_102	1000	2.64	8.8	103 604	11 773
1000_102[b]	690	1.39	7.3	NA	NA
1000_102	1000	2.72	9.3	106 000	11 398
800_118[c]	333	0.43	7.7	NA	NA
800_118	1000	2.34	10.3	40 000	3883

[a]Full well was not measured at the lower readout rate.
[b]All values below this on the chart are from Spectral Instruments specification sheet.
[c]Camera CCD was not signal ITO design.

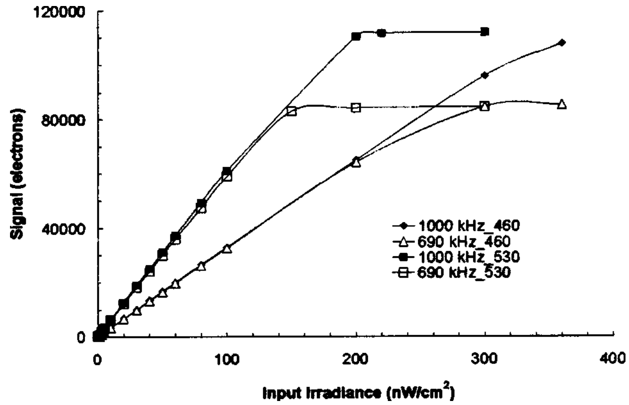

FIG. 5. Responsivity plot for the camera.

for each of the flat-field images. The bias was subtracted to determine the true signal S_{DN} for each illumination level.

A gain constant was calculated for each illumination level using Eq. (2). The standard deviation σ_{SDN} was calculated on the image after subtracting the first image from the second, to eliminate fixed pattern noise. The subtraction increased the noise variance by a power of two; this is why there is a two in the denominator. The camera gain provides the conversion coefficient used to calculate the number of electrons per analog to digital converter number. The conversion factor is e^-/DN (electrons per digital count) used to convert digital number or counts to electrons

$$k = \frac{s_{DN}}{\left(\frac{\sigma^2_{SDN}}{2}\right) - \sigma^2_{RDN}}. \tag{2}$$

The calculated quantum efficiency was 34.4% at 460 nm and 56.9% at 530 nm. A Kodak 16801 CCD without the ITO processing had 14% at 460 nm and 35.1% at 530 nm.

We used a classical photon transfer method to determine full well capacity based on Fig. 4.[9] The 690 kHz data fall off sooner in both the photon transfer curve and responsivity curve shown in Fig. 5 due to the higher sensitivity in camera gain compared to the 1000 kHz readout rate. Table III compares our results and the vendor results for Series 800 and Series 1000 cameras. The resolution showed a contrast transfer function of 50% at 33.5 lp/mm.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U. S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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