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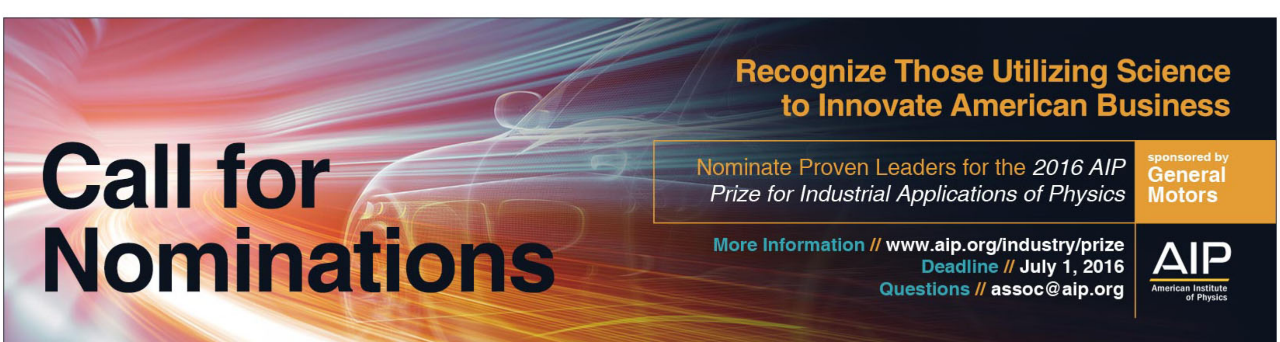

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REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 056108 (2016)

Note: Design and implementation of a home-built imaging system with low jitter for cold atom experiments

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A novel home-built system for imaging cold atom samples is presented using a readily available astronomy camera which has the requisite sensitivity but no timing-control. We integrate the camera with LabVIEW achieving fast, low-jitter imaging with a convenient user-defined interface. We show that our system takes precisely timed millisecond exposures and offers significant improvements in terms of system jitter and readout time over previously reported home-built systems. Our system rivals current commercial "black box" systems in performance and user-friendliness. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4950897]

The dynamics of ultra-cold atoms at μK temperatures have been measured using a multitude of methods, such as pump-probe spectroscopy, Bragg scattering, and parametric driving.[1] The most direct method is imaging via a fast (short exposure time) sensitive charge coupled device (CCD) camera where one typically observes the absorption, dispersion, or fluorescence.[2] In most experiments, the CCD camera is used to observe cold atom expansion as a sequence of short-time exposures ($\leq$1 ms) at precisely defined instants. In experiments with optical lattices and ratchets, the camera tracks changes in the position of the center of mass, and the width, of the cold atom cloud.[3]

It is clearly of interest to many experimental groups to construct a fast, low-jitter CCD camera system to image the atoms. We have chosen to follow previous literature and modify an inexpensive versatile astronomy camera[4] which has the required sensitivity to detect faint light signals. However, the manufacturer-provided software is not configurable for a sequence of precisely timed events as is required for cold atom experiments.[5] The novelty of our approach lies in integrating the camera with LabVIEW, thus enabling a highly convenient home-built user-defined interface for the control of all timing events for the experiment. Importantly, previous attempts at similar home-built imaging systems suffered from large timing jitter (two orders of magnitude higher than this work), necessitating the use of mechanical shutters which cause undesired mechanical and acoustic disturbance to laser systems that need to be frequency-locked with sub-MHz accuracy.[5] In any case, the hardware and controlling software employed in Ref. 5 is now obsolete. Our home-built system's performance rivals expensive new "black box" commercial systems,[3,6] while allowing the experimenter some extra flexibility inherent to a home-built setup, e.g, switching between different cameras.

Table I summarizes features of home-built and commercial imaging systems. The desirable characteristics are as follows:

Low read noise and readout time, large well depth: Read noise arises from reading out electrical signals via amplifiers and analog-to-digital converters. The ratio of read noise (plus noise such as dark current) to well depth determines the dynamic range of the CCD camera. For single-photon resolution applications, cameras with read noise less than 1 e^- are typically employed.[7] Low readout times enable faster experimental cycles.

High spatial resolution: The pixel size determines the resolution of the camera. Decreased readout time can be achieved by binning several pixels (e.g., in our case, bundling an 8×8 array of pixels into 1 pixel).

Low timing jitter: To prevent motional blurring, the cold atoms are flash-illuminated with a resonant light pulse of duration less than the time taken by the atoms to traverse a pixel width, while simultaneously exposing the camera. For example, the width for an 8×8 pixel bundle is 36 μm, so an imaging time-window of $\leq$1 ms suffices for 10 μK atoms with speeds of ~30 μm/ms. The principal obstacle here is the timing jitter in the imaging system. There is jitter in the initiation and duration of the resonant light pulse used to illuminate the atoms for the snapshot, but this jitter is straightforwardly suppressed far below 1 ms by the use of acousto-optic modulators to turn on and off the imaging light pulse. More importantly, there is jitter in the exposure time of the camera, listed in Table I for the different imaging systems. In this work, we show that we can suppress the exposure time jitter to a level that is acceptable for cold atom experiments, comparable to state-of-the-art commercial systems and more than two orders of magnitude less than previously reported home-built systems.[5]

Low dark current, high quantum efficiency: Active cooling via a thermo-electric cooling (TEC) element reduces the accumulation of thermal electrons during the camera exposure time, increasing signal-to-noise ratio.

On-board processing: The advantage to on-board processing and a first-in first-out (FIFO) buffer is that the camera can rapidly capture a set of images. The FIFO buffer serves as an on-board memory, allowing the camera to take one exposure and immediately store the image onto the internal memory, enabling imaging of an expanding cloud of cold atoms at multiple instants.

Fast computer interface: Our camera interfaces with the computer via Universal Serial Bus (USB) 2.0, which, though

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TABLE I. Comparison of commercial and previously reported home-built imaging systems with this work.

Feature of imaging system	Commercial, e.g., Ref. 7	Ref. 5	Our work
Read noise (e^- rms)	2.5–3	10	5
Readout time (s)	~0.1	20	<0.5[a]
Well depth (e^-)	200 000	70 000	40 000
Pixel size (μm^2)	16×16	8.6×8.3	4.5×4.5
Exposure time jitter (ms)	≲1	±250	±2
Dark current (e^-/pixel/s)	0.001 @ −70 °C	<1	0.05 @ −5 °C
Operating temperature	−80 °C	unknown	−5 °C
Quantum efficiency (780 nm)	77%	36%	36%

[a]For 8×8 binned array.

universal, limits data transfer (1 Hz in our case). This could be addressed using a large FIFO buffer or a faster data transfer protocol (e.g., Firewire, Gigabit ethernet, or USB 3.0).

LabVIEW-Camera interface: As indicated earlier, standard astronomy cameras have the requisite sensitivity for imaging faint signals. But these cameras are not amenable to precision timing control because they cannot be triggered by a transistor-transistor-logic (TTL) pulse. They typically operate over a USB connection; therefore, the operating system (OS) must send the exposure command to the camera. However, Windows is not a real-time OS which results in large jitter (typically 500 ms, see Table I), in the time-instant at which Windows sends the trigger command. This is unacceptable for many cold atom experiments, where in addition to controlling the timing for when and how long the camera takes an image, synchronized turning on/off of magnetic fields and intensity/frequency modulation of optical fields are required. The entire experiment may last only few tens of ms; therefore, the timing of the turnon-turnoff/modulating pulses—both trigger and duration—is typically accurate to within several microseconds.

The large exposure time jitter (±250 ms) in the last-reported home-built system with an off-the-shelf astronomy camera meant that the camera had to be exposed for at least 500 ms, forcing the use of a mechanical shutter to reduce stray background count accumulation.[5] In this work, we design and implement a LabVIEW-camera interface that suppresses the jitter in our camera exposure time to ±2 ms, comparable to expensive commercial systems (thus enabling reliable 1 ms snapshots with our imaging system as shown below). Further, in contrast to these "black-box" commercial systems, our method may allow the user some flexibility in switching between different cameras if desired. We emphasize however that our system does not likely permit a simple "hot swap" of the camera. The LabVIEW code may need substantial modification, such as modifying/writing the camera drivers for control of the exposure and temperature and converting the raw data to a usable format.

The most important hardware component of our LabVIEW-camera interface is the National Instruments (NI) PCIe Data Acquisition (DAQ) card.[8] This card allows the transfer of input/output signals in real time to/from a computer. The timing uncertainty in our experimental controls (e.g., initiation and width of laser pulses) is determined by the 1MHz reference clock on this PCIe DAQ card. If we use all 8 hardware-timed channels, the timing uncertainty of any given channel is 8 μs (each channel is updated with a fresh clock pulse every 8 clock pulses). We typically use fewer than 8 channels; thus, our actual uncertainty is lower. The problem occurs when trying to initiate a camera exposure: Because the camera cannot be triggered via a TTL pulse, the LabVIEW program must send a command through Windows mimicking a mouse click, but the uncertainty in when this virtual click actually occurs can be as large as a few hundred ms owing to Windows not being a real-time OS.

We overcome this obstacle by employing two computers arranged in a "master-slave" configuration, linked via a cross-over cable attached to the ethernet ports of both computers, as shown in Fig. 1(a). The PCIe DAQ card is housed inside the slave computer which functions as a Real-time Target (RTT). The computers are further linked via a USB DAQ.[9] The USB plugs into the master computer[10] and a channel of the shielded BNC connector block[11] is tied to the counter input of the USB DAQ. All controls for the camera are contained within the Windows LabVIEW VI while the timings are located on the RTT VI.[12] The Windows VI allows for a live feed from the camera for alignment but while the experiment is running, the data are retrieved in the form of a matrix of intensity values. These values are saved locally (on a RAMDisk) as a text file before being imported into MATLAB by the user for analysis. The communication between the computers consists of a series of checkups and notifications, shown in Fig. 1(b), that enable the two computers to stay in phase with each other.

Timing jitter measurement and analysis: As indicated above, the timing jitter in the imaging system is determined by two factors. First is the jitter in the duration of the resonant light pulse used to illuminate the atoms for the snapshot. Second is the jitter in the exposure time of the camera which determines, of course, whether or not the 1 ms snapshot is faithfully recorded.

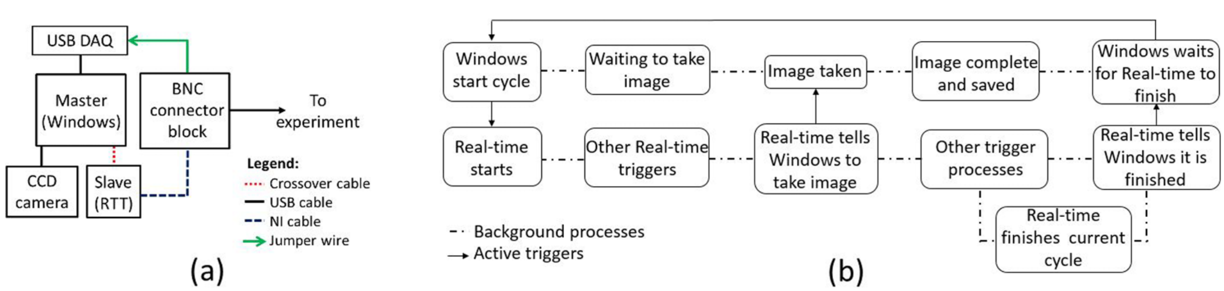

FIG. 1. (a) Master/slave computer configuration. (b) Series of checkups and notifications to keep the master and slave computers in phase. The top and bottom rows contain the processes executed by the master and slave RTT, respectively.

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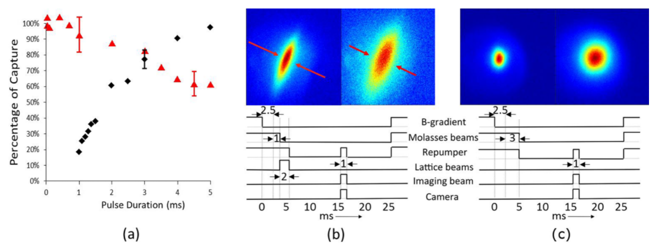

FIG. 2. (a) Measurement of a jitter of ±2 ms in camera exposure time (black diamonds) and a demonstration of precisely timed 1 ms snapshots (red triangles), see text for further explanation. Representative error bars, derived from 30 measurements, are shown for some datapoints. (b) and (c) show snapshots at $t = 2$ ms (left) and 6 ms (right) of the ballistically expanding sample initially confined in (b) a 1D lattice or (c) molasses. The two thin arrows in (b) indicate the counter-propagating 1D lattice beams. Representative timing diagrams are included.

In order to measure the jitter in our camera exposure time, we place an light emitting diode (LED), connected to an output channel of the LabVIEW system, directly in front of the camera. The LED is normally off but is pulsed on for varying durations between 1 and 5 ms. At each pulse duration, the camera is exposed for 1 ms and the total counts in the image are summed. Because of jitter in the exposure time, we expect the camera to miss part of the LED pulse, especially when the LED pulse is short. To determine the percentage of capture, we repeated the measurement for each LED pulse duration but this time used an exposure time of 10 ms to ensure that all of the LED pulses are definitely captured, and divided the sum of the counts from the 1 ms exposure by the sum from the 10 ms exposure. The results (black diamonds in Fig. 2(a)) show that for 100% image capture (within experimental error) the LED pulse duration cannot be less than 4 ms. Thus the jitter in camera exposure time is measured as ±2 ms.

Next we demonstrate that we can achieve our stated goal of obtaining precisely timed 1 ms snapshots. Based on the LED measurement above, we set the camera exposure time to 4 ms but this time, instead of the LED, we illuminated the camera with a laser beam that is turned on/off by an acousto-optic modulator. The laser beam is mostly off but is pulsed on for varying durations between 0.1 and 5 ms. Because of jitter in the exposure time, we expect the camera to miss part of the laser pulse, especially for longer pulses approaching 4 ms. As in the previous paragraph, we determine the percentage of capture by repeating the measurement for each laser pulse duration but this time using an exposure time of 10 ms and dividing the sum of the counts from the 4 ms exposure by the sum from the 10 ms exposure. The results, displayed by the red triangles in Fig. 2(a), show complete capture (within experimental error) of images with duration 1 ms and less, meaning the experimenter is certain of the timestamp of the image to ±0.5 ms, i.e., half the imaging pulse-width. Thus we have demonstrated that by using a resonant pulse of width 1 ms, we can obtain precisely timed 1 ms snapshots despite our camera having exposure time jitter of 4 ms. This is possible because background count accumulation (due to stray light and dark counts) during 4 ms is a non-issue, unlike previous home-built systems where the exposure time jitter was much longer and mechanical shutters had to be employed. As the laser pulse duration lengthens, the 4 ms exposure time jitter dominates causing us to miss parts of the imaging laser pulse in nearly every exposure.

Application–Detect 1D optical lattice: Finally, we demonstrate that our home-built imaging system can take precisely timed millisecond exposures of faint optical signals radiated by cold dilute atomic samples confined in a one dimensional (1D) optical lattice. The lattice is formed by two counter-propagating orthogonally linearly polarized laser beams (lin⊥lin configuration).

We start by creating a 1-2 mm sized cold (10-20 μK) trapped sample of ^{85}Rb atoms in a standard magneto-optical trap (MOT). Figs. 2(b) and 2(c) display snapshots taken 4 ms apart with our camera system of the cold atom cloud, initially confined in (b) a 1D lattice or (c) molasses, now expanding ballistically in the absence of magnetic gradients or laser fields. Indirect evidence for the presence of the lattice is provided by the spatial confinement along the direction of propagation of the lattice beams in Fig. 2(b). We recall that this spatial confinement is a direct consequence of the presence of potential wells due to a spatial polarization gradient formed by the two lin⊥lin lattice beams.[1]

In conclusion, we have demonstrated a flexible, user-defined home-built imaging system capable of taking precisely timed 1 ms snapshots of cold moving atoms.

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[1]G. Grynberg and C. Robilliard, "Cold atoms in dissipative optical lattices," Phys. Rep. **355**, 335–451 (2001).
[2]See, for instance, H. J. Lewandowski *et al.*, "Simplified system for creating a Bose-Einstein condensate," J. Low Temp. Phys. **132**, 309–367 (2003).
[3]F. Renzoni, "Ratchets from the cold: Brownian motors with cold atoms in optical lattices," Europhys. News **43**, 26–30 (2012).
[4]Atik 460EX.
[5]D. L. Whitaker *et al.*, "Modified control software for imaging ultracold atomic clouds," Rev. Sci. Instrum. **77**, 126101 (2006).
[6]See, for example, S. Mejri *et al.*, "Ultraviolet laser spectroscopy of neutral mercury in a one-dimensional optical lattice," Phys. Rev. A **84**, 032507 (2011).
[7]Princeton ProEm-HS:512BX3 (or, for single-photon resolution applications, Andor iXon Ultra 888).
[8]For example, NI PCIe-6320 and shielded cable NI SHC68-68-EPM.
[9]For example, NI USB 6211.
[10]For example, Windows 7, 120 GB SSD, 8GB RAM (4 GB RAMDisk).
[11]BNC-2110.
[12]M. Gillette, M.S. thesis, Miami University, Oxford, 2014.

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