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Retina

High-Performance, Low-Cost Optical Coherence Tomography System Using a Jetson Orin Nano for Real-Time Control and Image Processing

Wan Wang[1], David A. Miller[1], Hillel B. Price[1], Xiangyue Yang[1], William J. Brown[2], and Adam Wax[1]

[1] Duke Biomedical Engineering, Duke University, Durham, NC, USA
[2] Lumedica Vision, Durham, NC, USA

Correspondence: Adam Wax, Duke Biomedical Engineering, Duke University, Box 90281, Durham, NC 27708, USA.
e-mail: a.wax@duke.edu

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Purpose: Optical coherence tomography (OCT) has become an indispensable tool for the detection and analysis of diseased retinal tissue. Recent advances in reducing the size and cost of OCT systems have aimed at expanding their use for new applications and settings, such as serving as a screening tool at the point of care or in low-resource areas. Here, we report on the development of a compact, low-cost OCT system that offers significantly improved performance while also further reducing cost and system size.

Methods: A high-performance OCT system was realized by leveraging graphics processing unit (GPU)-accelerated parallel processing in a system on module, the NVIDIA Jetson Orin Nano, integrated into a low-cost OCT system. Instrument performance for retinal imaging was benchmarked against current low-cost OCT systems.

Results: A fivefold increase in processing speed was obtained for the Jetson-powered low-cost OCT without loss of image quality. The compact and low-cost nature of the system was preserved while its volume was reduced by 67% and computing cost was reduced by 22%.

Conclusions: The advance in imaging performance can significantly expand the accessibility and clinical utility of low-cost OCT systems.

Translational Relevance: Implementation of the system on module computer improved the computational performance without compromising the cost or size of low-cost OCT systems, which will accelerate the application of low-cost OCT to clinical use.

Introduction

Optical coherence tomography (OCT) is widely used for retinal imaging in ophthalmology clinics around the world. Considering that OCT was introduced a mere 33 years ago,[1] the fact that OCT is now used in millions of procedures each year presents a spectacular example of the translation of biomedical optics technology from the research bench to the clinic.[2] However, there are still several use cases for OCT that have not been fully realized due to the cost, size, and weight of current OCT systems. Clinical OCT systems are feature rich and can cost up to $150,000. The size of an OCT system may be up to 1 m^3, and it may weigh as much as 30 kg. These attributes place constraints on access to this imaging modality outside of large eye clinics and hospitals.[3] Recent research on low-cost and portable systems has begun to tap into the potential of using OCT in new settings.

Our group introduced a low-cost spectral-domain OCT (SD-OCT) system in 2018 which used three-dimensional (3D) printing to reduce the complexity and cost of the spectrometer design.[4] This system cost approximately $7000, weighed 2.7 kg, and relied on multiple developer kits to acquire and process

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spectral data into OCT images. We further refined this system for clinical study by utilizing custom microcontrollers on customized circuit boards. The clinical low-cost OCT system located the light source and interferometer via a handheld scanner.[5] The resulting system was highly compact at 4096 cm^3, lightweight at just 2.3 kg, and low cost with a bill of materials of $5000. The performance of the clinical low-cost OCT system was benchmarked against a commercially available clinical OCT system, the SPECTRALIS (Heidelberg Engineering, Heidelberg, Germany). Although the SPECTRALIS was found to offer superior imaging performance, the dramatic differences in cost, size, and weight suggested a potential role for a clinical low-cost OCT system. Lumedica (Durham, NC) has commercialized low-cost OCT based on these designs. Philophos (Daejeon, South Korea) has also introduced a compact, low-cost OCT device. Recently, a prototype compact, low-cost OCT was introduced for horticultural research.[6] The cost and size of this system are comparable to the above-listed systems at 5647 cm^3 and cost of €6200; however, the relatively low A-scan rate of 7.4 kHz is likely only suitable for imaging static samples.

There have been other approaches for increasing access to OCT imaging technology. Handheld OCT devices were developed to image supine patients and found application to imaging neonates.[7,8] These devices focused on a small handheld probe, typically attached to a full-size OCT system. On the other hand, some efforts have sought to miniaturize the components used in OCT. A recent review of miniaturizing OCT detailed current progress on developing photonic integrated circuits (PICs) for this purpose.[9] This approach is compelling, as the potential to integrate an entire OCT system into a monolithic element could result in highly compact and cost-effective systems. A recent approach for OCT is to enable self-examination with home-based devices,[10–12] including a full-field OCT imaging device based on a time-domain approach and a commercial device from Notal Vision (Manassas, VA), which was recently authorized for use by the U.S. Food and Drug Administration.

Here, we report on an advance that will increase access to OCT by enabling higher performance in low-cost systems. Rather than use a full-featured personal computer (PC) for acquiring and processing data, the computing power of the Jetson Orin Nano (NVIDIA, Santa Clara, CA) is used. Operating software has been converted from Windows to Linux and reconfigured to leverage the highly parallel processing capabilities of the Jetson. A fivefold increase in processing is realized while a reduction in cost and size is also achieved, resulting in the highest performance seen in a low-cost system to date. System performance is described here and benchmarked for retinal imaging.

Methods

Optical Coherence Tomography

We modified a low-cost OCT system designed for human retinal imaging (EyeScope; Lumedica Vision, Durham, NC) to use a Jetson Orin Nano microcomputer for system control and graphics processing unit (GPU)-accelerated OCT image processing. Figure 1a shows the overall setup of our OCT system, which consists of two main parts: (1) OCT engine and (2) OCT scanner. The OCT engine houses the Jetson Orin Nano, power distribution custom circuit board, and spectrometer. The OCT scanner includes the OCT interferometer, scanner control board, pupil camera, and superluminescent diode (SLD). The output of the SLD (840 nm, 50-nm bandwidth) is input to the OCT interferometer where a 50:50 fiber coupler splits the light between the sample and reference arms. The sample arm is comprised of a tunable liquid lens for focus adjustment, a micro-electromechanical system (MEMS) scanning mirror, and relay optics designed for retinal imaging. The system delivers 0.7 mW at the cornea. The reference arm consists of a mirror and a tunable liquid lens, which can be controlled by users through the front end of the software for optical power adjustment. Backreflected light from the sample and reference arms recombines at the fiber coupler, and the interference signal is detected by the spectrometer. The e2V OctoPlus camera (Teledyne Vision Solutions, Thousand Oaks, CA) of the spectrometer operates at line rates of either 40 kHz or 80 kHz, depending on the user setting, with 1024 pixels per A-line and 512 A-lines per B-scan. The liquid lenses and MEMS mirror are connected to a scanner control circuit board, which is controlled by the Jetson Orin Nano via a universal serial bus (USB) port. To further reduce the size of the system, we developed a compact housing for the Jetson-powered OCT engine, which is depicted in Figure 1b.

OCT Control Software

We developed custom control software that runs on the Linux (Ubuntu 22.04) operating system of the Jetson Orin Nano. Due to the Arm64 central processing unit (CPU) architecture used by the Jetson Orin Nano, we chose Arm64-supported dependencies to build our software. The graphical user interface (GUI) with OCT display and control software was written in C#, and the real-time OCT processing code was written

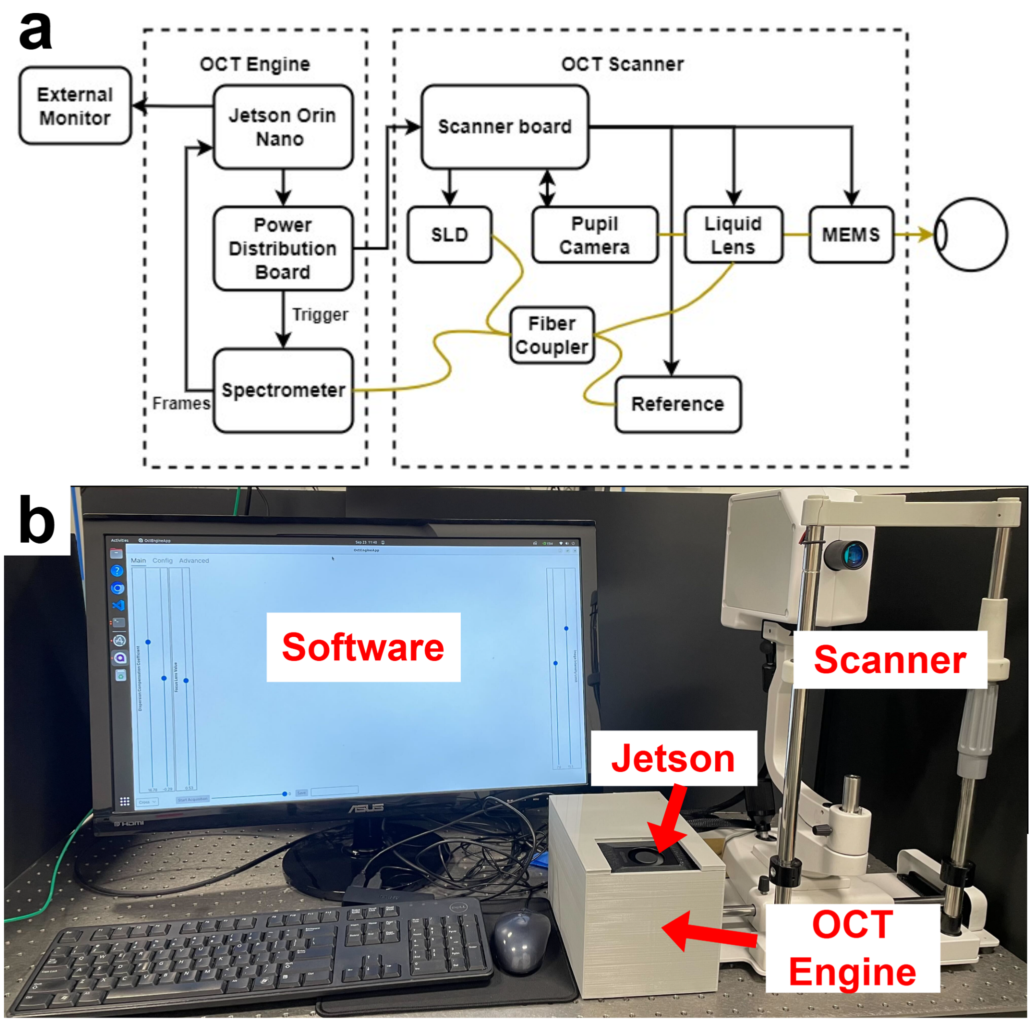

Figure 1. (**a**) Retinal OCT system control schematic diagram. The electronic control signal and optical signal are represented by *black* and *yellow lines*, respectively. (**b**) Photograph of the system.

in C++ and CUDA. A screenshot of the front panel of the GUI is shown in Figure 2; it displays processed B-scan images in real time and allows users to control scan range, focus, and other scan parameters in real time. The OCT control software on the Jetson Orin Nano provides multiple scan modes, including single-line scans (horizontal or vertical) and cross-line scans (horizontal and vertical). Figure 2 shows typical images of a stairstep phantom fabricated using 3D printing (details of the phantom are shown in Figs. 2b–d).

The MEMS scanner is driven by a sawtooth scanning waveform. For a B-scan consisting of 512 A-lines and a line rate of 40 kHz, the line scan rate of the Jetson-powered OCT is 30 Hz and the cross-line scan rate is 12 Hz, with a 38.8% duty cycle. Similarly, at the 80-kHz line rate, the line scan frame rate is 50 Hz and the cross-line scan rate is 20 Hz, leading to a duty cycle of 32.0%. Users can save both raw and processed images to local files on the Jetson Orin Nano. When using a solid-state drive (SSD) for storage, data for 50 B-scans, including raw spectrometer data, can be saved in <1 second. The back-end software acquires the raw data from the spectrometer camera, performs GPU-accelerated OCT processing, and returns the processed results to the front-end software. Figure 3a illustrates the data flow in the back-end software, where a circular buffer queue is maintained. Each buffer in the queue contains a block of memory for raw B-scan data, a block of memory for processed B-scan data, and an integer flag for control flow. When raw data are acquired, the data are enqueued and a processing task is sent to the GPU. The CUDA stream technique allows multiple processing tasks to run simultaneously to reduce the number of idle computing units on the GPU and improve processing efficiency. The detailed steps of OCT processing are shown in the flowchart in Figure 3b. The processing steps followed the general spectral OCT processing

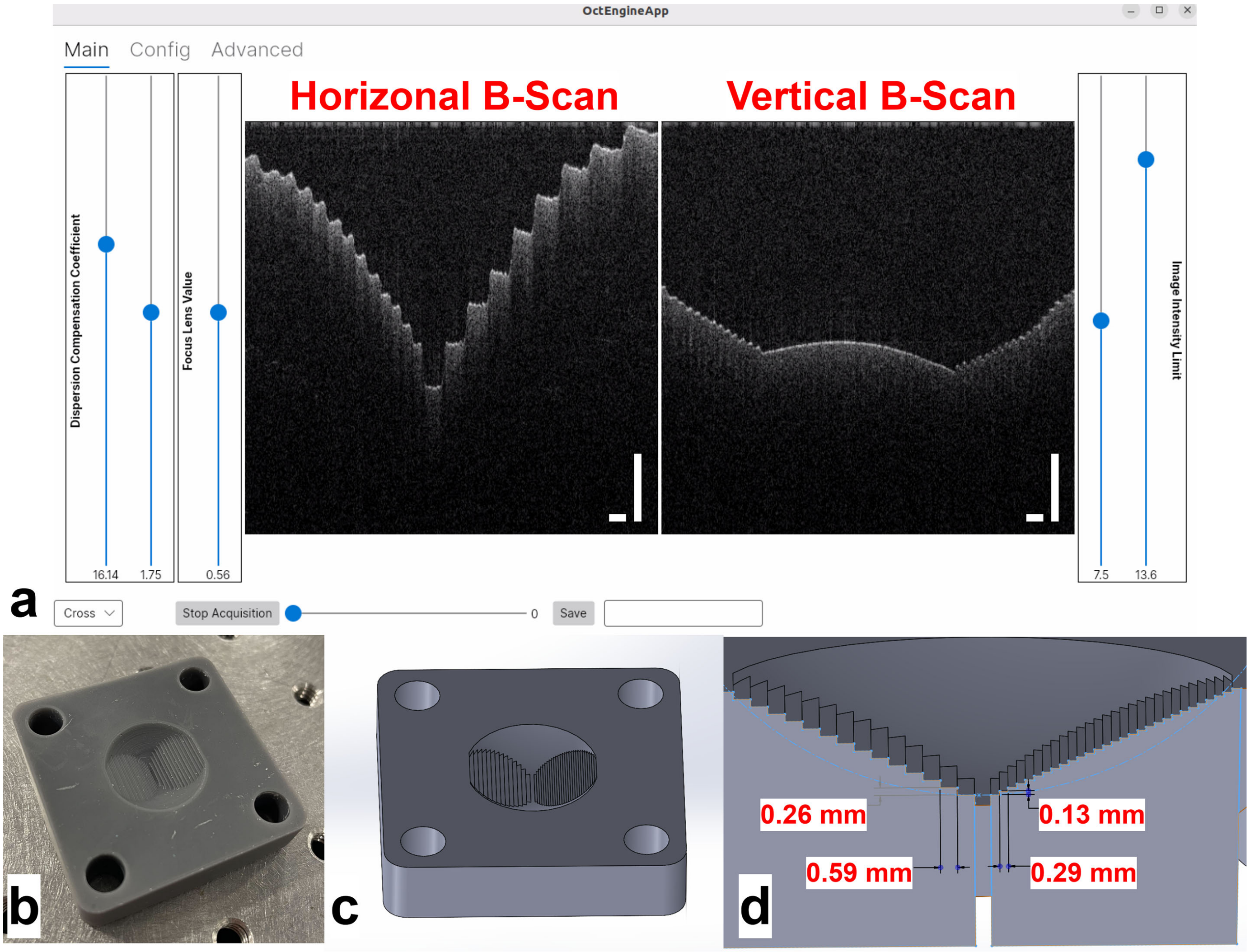

Figure 2. (**a**) Screenshot of the GUI software control front panel showing imaging of the phantom. *Scale bars*: 500 µm. (**b**) Photograph of the stairstep phantom. (**c**) 3D model of the phantom. (**d**) Cross-section of the phantom.

methods, including Hanning window, k-space interpolation, and dispersion compensation. Linear interpolation is used in the k-space remapping step to reduce the computation burden. After processing, the B-scan is written back to the same buffer and read to the front end. Because reads and writes are sequential within the queue, we can ensure that the processed images received by the front end are in the correct order.

Processing Speed Benchmark Test

Table 1 shows some of the key specifications of the Intel NUC (NUC11TNBi3; Intel Corporation, Santa Clara, CA) used in the original system and the Jetson Orin Nano (8 GB). Because of their different architectures, it was difficult to compare their actual performance. Therefore, we designed a benchmark test to compare the processing speed of the Jetson Orin Nano using Linux-based software and the Intel NUC using Windows-based software. Given that the actual OCT scanning speed is limited by the line rate of the camera and scanner speed, we used randomly generated noise as raw input data for the test and disabled the real-time display of the processed images. The benchmark included two tests. In the first test, the raw data generation speed was set to 200 frames per second (FPS), and the event logging function was used to record the processing time for each B-scan. In the second test, raw data were generated as quickly as the software allowed, and the maximum processed B-scan frame rate was recorded. Both tests used 512 A-lines per B-scan and 1024 pixels per A-line. Though CUDA is not supported on the Intel NUC, we applied the same GPU processing

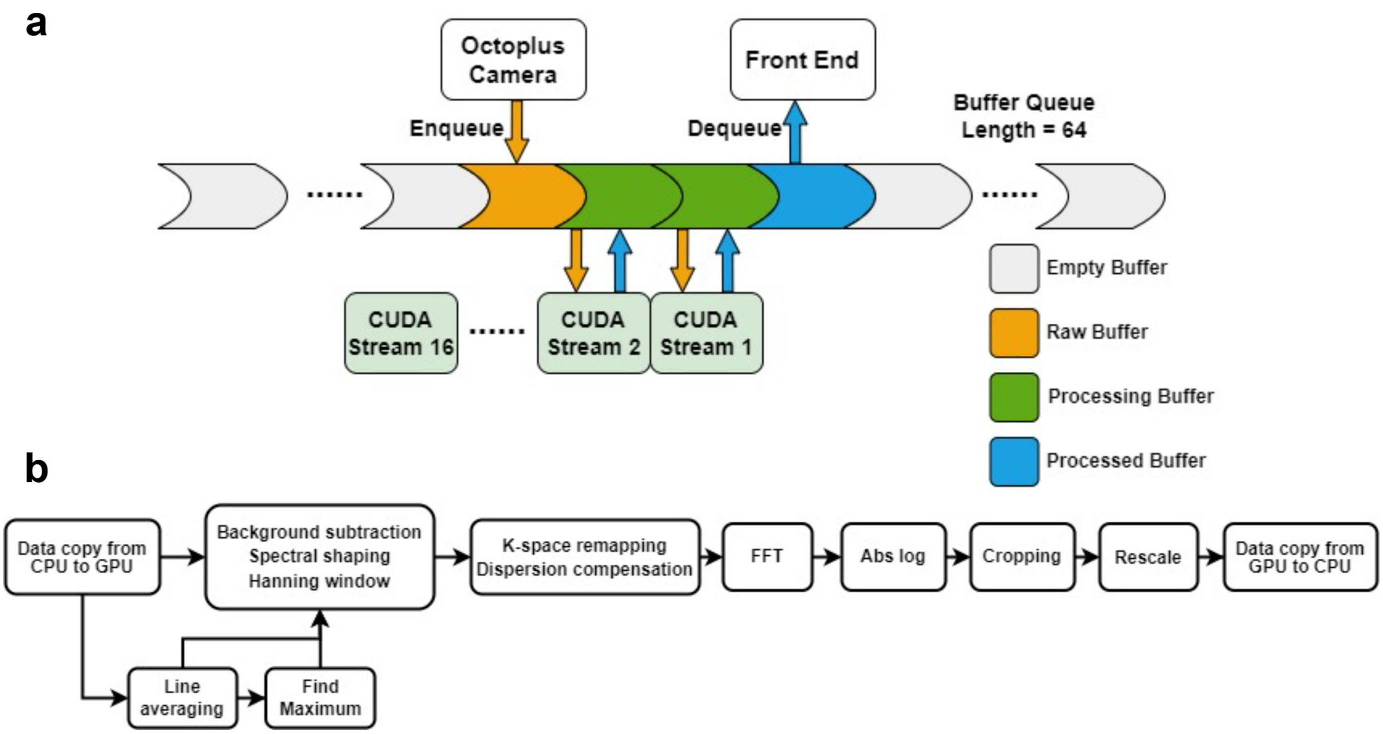

Figure 3. (**a**) Data flow of the OCT software. (**b**) OCT processing steps on the GPU. Each block represents a CUDA kernel.

Table 1. Specifications for the Intel NUC and NVIDIA Jetson Orin Nano

	NUC 11TNBi3	Jetson Orin Nano (8GB)
CPU	11th gen Intel Core i3-1115G4	Arm Cortex-A78AE v8.2
CPU maximum frequency	3 GHz	1.5 GHz
CPU cores, *n*	2	6
GPU maximum frequency	1.25 GHz	625 MHz
GPU	48 EUs	1024 cores with 32 tensor cores
Memory size	Up to 64 GB	8 GB
Power consumption	28 W	15 W
Cost	$569	$499

steps using OpenCL to perform the processing benchmark test.

Clinical Experiment

To demonstrate retinal imaging with the Jetson-powered OCT system, we recruited a healthy volunteer between the ages of 20 and 30 years old. This study was approved by the Duke University Institutional Review Board. We obtained 100 macular B-scan images using the original OCT system controlled by the Intel NUC and the system controlled by the Jetson Orin Nano. For both image processing tests, we acquired two datasets with different scan speeds: 40 kHz and 80 kHz. To evaluate the quality of the acquired images, we calculated the contrast-to-noise ratio (CNR) of each scan. Our calculations used the processed B-scans saved from the software directly without additional postprocessing. As described previously,[5] the CNR was calculated using B-scans averaged 10 times. The CNR value for each scan was calculated using the following formula:

$$CNR = \frac{\mu_s - \mu_b}{\sqrt{\sigma_s^2 + \sigma_b^2}}$$

where μ_S and σ_S are the mean and standard deviation of the signal, calculated across all pixels within the segmented retina, and μ_b and σ_b are the mean and standard deviation of the background noise. The background region was selected to be a region 10 pixels in height (10 × 512 pixels) above the segmented retina.

Results

OCT Processing Benchmark Result

The results of OCT processing benchmark testing are shown in Table 2. The OCT processing benchmark test was performed using random noise as input with a targeted frame rate of 200 FPS. Reported processing times were generated by averaging the processing speeds for 10,000 frames. The average processing time for a single frame on the Jetson Orin Nano was 0.944 ms, and the processing time for the Intel NUC was 4.26 ms. After removing the restrictions of raw data generation, we obtained a B-scan rate of 1019 FPS on the Jetson Orin Nano and 205 FPS on the Intel NUC. These benchmark comparison results show that the Jetson-powered system with optimized OCT processing software can process OCT images 4.51 times faster than the Intel NUC–powered system, and the maximum frame rate is 4.97 times that of the old system.

Clinical Scan Analysis

Figure 4 illustrates the clinical retinal images collected by our OCT system. We captured horizon-

Table 2. OCT Processing Benchmark Results

Submodules	Included Steps	Jetson Orin Nano	Intel NUC
Interference fringe extraction	Line average Find background maximum Background subtraction Spectral shaping Hanning window	0.237 ms	1.600 ms
Spectrum preprocessing	k-Space remapping Dispersion compensation	0.172 ms	0.366 ms
FFT	FFT	0.147 ms	1.722 ms
Image postprocessing	Absolute log Cropping Rescale	0.300 ms	0.302 ms
Data transfer	Data from CPU to GPU Data from GPU to CPU	0.129 ms	0.267 ms
Single B-scan processing time		0.944 ms	4.260 ms
Maximum B-scan rate		1019 Hz	205 Hz

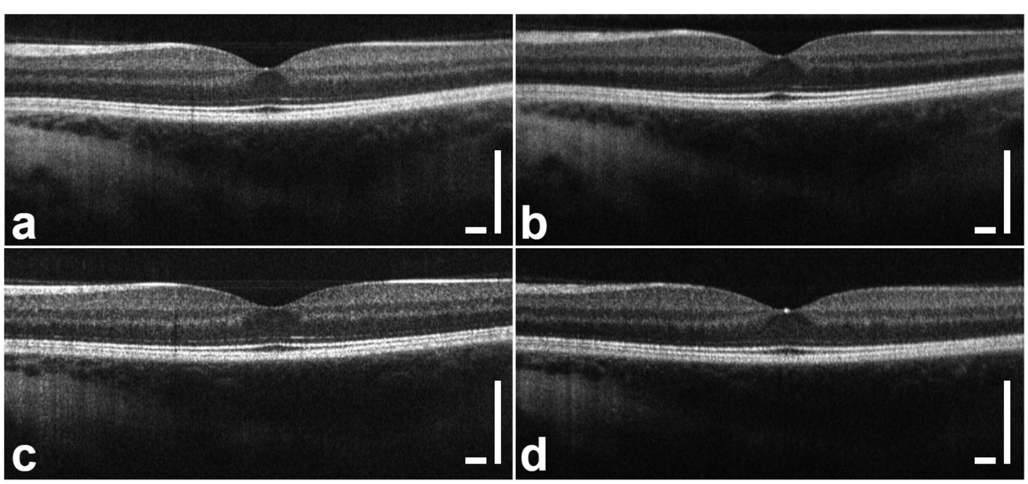

Figure 4. (**a–d**) Example OCT B-scans acquired by the Jetson-powered OCT system (*left panels*) and Intel NUC–powered OCT system (*right panels*) operated at 40 kHz (**a**, **b**) and 80 kHz (**c**, **d**). *Scale bars*: 500 µm.

Table 3. CNR Measurements for the OCT Imaging Data

	Line Rate (kHz)	CNR	
		Left Eye	Right Eye
Jetson Orin Nano system	40	1.51	1.68
	80	1.23	1.53
Intel NUC system	40	1.36	1.49
	80	1.33	1.59

tal line scans centered at the macula at 40 kHz (Figs. 4a, 4b) and 80 kHz (Figs. 4c, 4d) using the Jetson-powered OCT system (Figs. 4a, 4c) and the Intel NUC–powered OCT system (Figs. 4b, 4d). Retinal layers are clearly visible in each B-scan image. Comparing the images acquired from the Jetson Orin Nano–powered system with the Intel NUC–powered system, we found no significant difference in imaging depth, signal strength, or image quality. When comparing the 40-kHz and 80-kHz images, we observed decreased signal strength in the 80-kHz images due to the reduced camera integration time at this line rate. Overall, there were no differences in image quality between the Jetson-powered system and the Intel NUC–powered system. In Figures 4a and 4c, horizontal artifacts were observed above the retina due to the high-level signal kept in the background generated by line average. If a B-scan contains a high-intensity signal at a fixed depth, it will appear in the final image as a line. This can be eliminated by averaging multiple B-scans, such as roll averaging.

We further analyzed the OCT images quality by measuring their CNR values, and the results are shown in Table 3. The results indicate that the Jetson-powered system has a CNR comparable to that of the Intel NUC–powered system.

Discussion

The Jetson Orin Nano–powered OCT engine offers a fivefold increase in processing speed compared to the Windows-based Intel NUC. The Jetson enables a more compact form factor at 21.0 cm × 13.8 cm × 13.5 cm (3912.3 cm^3), which is a 67% reduction in size compared to the Intel NUC–powered OCT engine (Lumedica EyeScope, 23 cm × 28 cm × 18 cm, or 11,592 cm^3). This size reduction is enabled by the smaller form factor of the Jetson Orin Nano compared to the Intel NUC. At the time of writing, the price of the Jetson Orin Nano development kit was $499 using Ubuntu Linux. The cost is comparable to that of the Intel NUC but avoids the need to purchase a Windows license, which costs $150 to $200. This helps further reduce the cost of the microcomputer by 22% without sacrificing processing power. NVIDIA has also announced that the new Jetson Orin Nano Super Developer Kit will cost only $249 and have greater computing capacity, which could help further reduce the cost of our low-cost OCT system, as well as improve the performance.

Comparison with other recent compact, low-cost OCT systems also shows that the Jetson-powered system sets a new bar for compact OCT. The recent design for horticultural research[6] is described as 15.8 cm × 24.6 cm × 14.6 cm (5674.7 cm^3), corresponding to a 31% reduction by the Jetson-powered system. The unit cost is €6200 ($6923). However, this device weighs 6.5 kg, more than twice as much as the 2.7-kg weight of the Jetson-based system. The performance is also sharply reduced at 7400 A-scans/s and 28 B-scans/s but at lower density (256 A-scans per B-scan, but this is not discussed in the presentation). It is still not clear whether this line rate would be useful for in vivo ophthalmic clinical imaging.

A recent commercial low-cost OCT instrument was introduced by Philophos. A handheld OCT scanner for dermatology has been offered by Philophos (KUOS-GW10) with a size of 1656 cm^3 and a weight of 0.75 kg. From the device description, this OCT system requires an external PC so it is difficult to conduct a comparison. Philophos also offers a retinal scanner (KUOS-O100), described as 6458 cm^3 and <5 kg in an academic presentation but listed as 4.5 kg and 8572 cm^3 in the product specifications. For comparison, the scanner used by the Jetson-powered device is 1646 cm^3 and weighs 1.8 kg. At this stage of development, only selected components of OCT systems have been successfully realized as PICs; however, several types of OCT images have been reported in the literature using these systems.

The Jetson-based OCT system uses a system-on-module (SoM) approach, where a board-level computer is used for acquisition and control. A recent effort reported SoM-based OCT using a Raspberry Pi module.[13] Although the size and weight were comparable to those of the Jetson-powered system, the performance was much lower, providing only a 1.5-kHz line rate, likely unsatisfactory for retinal imaging. The high level of processing speed in the Jetson-based system is due to its architecture, intended for use as an embedded artificial intelligence (AI) computer. The Jetson offers a large number of GPU cores (1024) that are easily accessed by the CPU. In general, the Jetson was found to enable transfers to and from the CPU in half the time of the Windows-based NUC. Other key steps in the processing of SD-OCT data are likewise greatly improved. The k-space interpolation is 2.5×

faster than for the NUC, and the fast Fourier transform (FFT) is 11× faster. The Raspberry Pi offers an AI module capable of 13 tera operations per second (TOPS), which is lower than the Jetson Orin Nano (40 TOPS).

Although the Jetson has demonstrated OCT processing speeds beyond 1000 B-scans per second, the actual processing speed is limited by the data transmission speed from the camera. The camera in this study uses USB3 for data transmission, which limits its data transfer rate to 1.25 GB/s. In the future, spectrometer cameras with a higher line rate can be implemented via peripheral component interconnect express (PCIe)-based frame grabbers with a camera link interface (up to 8 GB/s for PCIe ×4).

The Jetson also offers the ability to communicate across several modules using transmission control protocol (TCP). This capability could be exploited to enable even greater throughput by connecting multiple modules to share in the processing load. Another advantage can be gained by using one Jetson module for signal acquisition and processing and implementing a second Jetson module for analysis of the OCT images. Deep learning has been used extensively to analyze OCT images, as described in a recent review.[14] These efforts focus on segmentation,[15,16] improving image quality,[17] and obtaining diagnostic information.[18,19] These algorithms could be implemented on a Jetson module to provide real-time analysis of imaging data provided by an inexpensive high-performance OCT system. A previous study has demonstrated that a field programmable gate array (FPGA) can also accelerate OCT processing through its parallelization capacity.[20] However, a host computer is still required for system control and display. With the improvement in processing speed due to GPU performance, the cost and performance of the Jetson are comparable to those of the FPGA modules. Further, the Jetson offers the potential for future AI analysis as it is optimized for these tasks.

Conclusions

In summary, we have presented a high-performance, compact, low-cost OCT system based on a Jetson Orin Nano. The parallel computing of the Jetson enabled a higher B-scan rate of over 1000 FPS. This improvement does not come at a sacrifice of weight, size, or cost, as the Jetson-powered system offers reduced metrics in all of these areas. Further development is underway to enable real-time volumetric scanning with this low-cost spectral-domain approach.

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