A real-time video-rate 4D MHz-OCT microscope with high definition and low latency virtual reality display

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ABSTRACT

We implemented a real-time video-rate 4D-OCT system with virtual reality display. To achieve the required low latencies we optimized the dataflow path and the placement of the necessary synchronization points. Employing temporal reprojection enables to perform volume rendering at 1/3 of the display refresh rate, yet maintaining smooth updates to the HMD; thus we achieve display updates at 90Hz, volume rendering at 30Hz and C-scan acquisition at >15Hz. By mounting of a tracking accessory to the scanning head we can render the OCT volume in virtual space in the position of the actual imaging volume.

1. VIRTUAL REALITY FOR DIGITAL AND OCT MICROSCOPY DISPLAY

An important application of microscopy outside of the laboratory is surgery at small scales, performed on delicate tissues, such as the central and spinal nervous system and the eyes. Recently also in this critical environment a transition replacing the eyepiece with computerized display is underway. Digital surgical microscopes found their way into the operating room, but still show the image as seen through an eyepiece. The data gathered by OCT imaging is in first order depth resolving. The availability of this additional information calls for using novel ways to present the processed images to the user.

Surgeons have pointed out, that in certain circumstances head mounted magnification loupes are preferable over overhead rigidly mounted microscopes, as they offer an intuitive way to change the point of view, albeit at the cost of image quality and stability. Combining a rigidly mounted OCT microscope and a virtual reality OCT image display system presentsa way to bring these concepts together. A real-time OCT virtual reality display system has been demonstrated previously,[1] albeit only at A-scan rates which allow for only less than 10 C-scans to be captured per second.

We previously demonstrated a real-time 4D-OCT pipeline with multi-view volume display at video rate (>20Hz) C-scan scanning and rendering.[2] In this work we present a real-time low latency 4D-OCT virtual reality processing pipeline capable of operating at >25Hz at medium C-scan resolutions (~ 250 A-scans ×250 B-scans).

2. SYSTEM DESCRIPTION

An ultrahigh speed OCT system (Optores OMES) consisting of an FDML swept laser light source, an imaging interferometer and detector and a scanning head microscope is used as a OCT signal source. The imaging system operates at a center wavelength of 1310nm with a freely adjustable sweep bandwidth of 80nm to 110nm. The fundamental FDML sweep frequency is set to 419kHz, after 4× buffering resulting in a 1.68MHz A-scan rate. The optical bandwidth of the used photo detector is ~1.6GHz. Data acquisition happens through an AlazarTech ATS9373 digitizer card, which is externally clocked by a sampling signal generated by the FDML laser source; the light source is capable of generating a sweep locked clock in the frequency range from 100MHz to 4GHz. Thus by configuring it to generate a clock of 2048 cycles per A-scan, a sampling rate of ~3.4GS/s is achieved, which gives a Nyquist frequency that is matched to the optical detector bandwidth and results in a depth resolution of 1024 samples. Scanning beam deflection is done via two linearly driven galvanometer scanners in an enclosed scanning head (fig. 1A) to allow for free choice of the scan protocol. However this comes at the cost of trading in maximum spot deflection velocity along the fast axis, due to the lower mechanical bandwidth of linear galvanometer scanners. The available scanning waveform generator firmware limited the trigger signal generation to the well-known zigzag pattern, though. At lateral scanning of less than $\sim 2\,\mathrm{mm}$ in the fast axis C-scans with a resolution of 250×250 points can be scanned at $>25\,\mathrm{Hz}$.

However increasing the fast axis scanning range requires to redistribute the scanning pattern, so that the fast axis

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OCT processing and visualization is performed on a pair of Nvidia GTX 1080-Ti GPUs. The workload is split, so that one GPU is fully dedicated to the OCT processing pipeline (resampling, FFT, dynamic range compression), while the other GPU is dedicated to volume rendering and virtual reality projection. The OCT processing pipeline has been derived from the Optores OGOP library, to which synchronization hooks for the integration with the VR system were added. The virtual reality system consists of a HTC Vive Pro head mounted display (HMD) and the Lighthouse-2.0 tracking system. An auxiliary tracking accessory was mounted to the microscope scan head, which allows the tracking of the real world position of the scanned volume. Thevirtual reality HMD operates at a fixed $90\,\mathrm{Hz}$ refresh rate.

Tracking is based on *inertial measurement units* (IMUs) integrated into the HMD and tracking accessories, which update with $1\,\mathrm{kHz}$, and optical global frame reference signals, emitted by the lighthouse modules at a rate of $60\,\mathrm{Hz}$.

After sensor fusion, the pose variables for each tracked device are updated with an interval of $\sim 10\,\mathrm{ms}$. An additional feature of the used HMD is the availability of a stereoscopic pair of cameras on the front, which allows to present a video feed through that can be fused with the virtual reality volume rendering (fig. 1C). By tracking the HMD and scanning head in a common frame of reference we thus can create a fused visual in virtual reality of the volume rendering being centered at the location the imaging volume center in the real world as also shown in the video feed through.

Draelos et. al.[1] put emphasis on the implementation of a high performance volume rasterizer, to achieve the high frame rates required for virtual reality displays; this had been achieved by implementing optimized memory access patterns, and a sophisticated voxel data layout scheme. This work also explicitly points out, that it exploits the large factor between C-scan rate and display refresh rate to achieve the required throughput. The volume renderer we developed as part of earlier work[2] is not as advanced, with a render time of $2.6\pm0.3\,\mathrm{ms}$ for a dataset of $1024\times512\times512$ voxels on the GPU model being used. While this is not as performant as the volume renderer presented by Draelos et. al. it does not impose the overhead of repacking the volume data prior to rendering. In order to achieve the high display frame rates required for comfortable virtual reality experience, we instead make use of *temporal reprojection* in which an existing rendering is warped to match the HMD movement as registered by the tracking system. If there are no changes in the displayed content, temporal reprojection allows for smooth display updates at much reduced rendering cost. Unlike Draelos et. al. we cannot rely on an imbalance between C-scan and display refresh rates to distribute the workload, since C-scan rates of well over $50\,\mathrm{Hz}$ have been demonstrated.[2] Thus we had to focus on the latency bottlenecks imposed by the synchronization that is required prior to data transfer between threads of execution. A medium level overview of the dataflow in our system is shown in figure 1B. There are four major execution threads, which execute in parallel: *Data acquisition* (DAQ), *processing*, *rendering* and *VR presentation*. The necessary *GPU resource management* is executed on demand by either the processing or the rendering execution thread.

The main feature of our processing pipeline is, that between data acquisition and processing, the synchronization is focused on buffer releases. While this still requires to wait for the processing of a full C-scan before it can be passed to the volume renderer, on the data acquisition side, each trigger event releases a small buffer consisting of only one or a few B-scans which can be appended to the processing queue in the midst of execution. Thereby the latency between end of C-scan acquisition and processing finish can be as low as one B-scan interval. OCT image volume buffers are managed in a GPU memory pool, using a round-robin handle passing scheme; actual inter GPU data transfers are executed asynchronously.

3. USER EXPERIENCE IN MOCKUP SURGERY

Our system was tested by a trained surgeon, performing a mockup surgery on an ex-vivo porcine eye model. During the procedure, immediate user experience feedback was recorded, giving the following results in short: Since the imaging area had to be as wide as possible, the resulting low C-scan update rate 15Hz was experienced as very limiting.

At narrower imaging range a C-scan rate >20Hz was possible, due to shorter scanner trajectories, however this small imaging area was reported insufficient for practical applications.

A more detailed report of the performance, limitations, benefits and opportunities of the system in a more extensive wet lab study is outside the focus of this publications and will be presented elsewhere.

4. OUTLOOK

We demonstrated, that presenting in virtual reality real-time video-rate OCT volumes of medium C-scan resolution is feasible. The main technical challenge lies in reduction of system latencies, and can be overcome by careful design of scanner can achieve the requested motions, resulting in lower C-scan rates. We successfully operated the system at low lateral range, high C-scan rate parameters, as well as high lateral range, low C-scan rate parameters.

Some preliminary practical experiments showed, that even higher C-scan rates are desirable. Together with the need for denser B-scan sampling this puts up the requirement for significantly increased A-scan rates, as well as faster scanning velocities and/or sophisticated scanning protocols.

A detailed evaluation report will be given in another presentation.

*Figure 1: (A) our scanning head with mounted tracking accessory. (B) medium level overview of our system's dataflow with synchronization points (marked with *). (C) VR view of fusion image of video feed through and volume rendering..*

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