Benchmarking Network Performance of Augmented Reality Based Surgical Telementoring Systems

Dehlela Shabir
Department of Surgery
Hamad General Hospital
Hamad Medical Corporation
Doha, Qatar

Malik Anbatawi
Department of Surgery
Hamad General Hospital
Hamad Medical Corporation
Doha, Qatar

Nihal Abdurahiman
Department of Surgery
Hamad General Hospital
Hamad Medical Corporation
Doha, Qatar

May Trinh
Department of
Computer Science
University of Houston
Houston, TX, USA

Jhasketan Padhan
Department of Surgery
Hamad General Hospital
Hamad Medical Corporation
Doha, Qatar

Abdulla Al-Ansari
Department of Surgery
Hamad General Hospital
Hamad Medical Corporation
Doha, Qatar

Julien Abinahed
Department of Surgery
Hamad General Hospital
Hamad Medical Corporation
Doha, Qatar

Zhigang Deng
Department of
Computer Science
University of Houston
Houston, TX, USA

Elias Yaacoub
Department of Computer
Science and Engineering
Qatar University
Doha, Qatar

Amr Mohammed
Department of Computer
Science and Engineering
Qatar University
Doha, Qatar

Nikhil V. Navkar
Department of Surgery
Hamad Medical Corporation
Doha, Qatar
nnavkar@hamad.qa

***Abstract*—Telementoring in surgery facilitates the transfer of surgical knowledge from the mentor to the mentee. Augmented Reality (AR) further assists this transfer by overlaying visual cues (e.g., in the form of virtual surgical instrument motion) generated by the mentor onto the operative field of the mentee. In this work, we present a benchmark for comparing such AR based surgical telementoring systems. The results compare the network performances of these systems across different types of surgery (open or minimally invasive), based on the locations of the mentor and the mentee (inter- or intra- country), and finally the underlying networking protocols (RTMP versus WebRTC).**

***Keywords*-Minimally Invasive Surgery, Open Surgery, Telementoring, Network Communication, Augmented Reality (AR)**

I. Introduction

Surgical telementoring involves the use of telecommunications and information technology to provide real-time intraoperative guidance during the surgery [1]. It facilitates efficient transfer of surgical expertise from an experienced specialist surgeon (mentor), who could be located remotely, to a less trained or even novice operating surgeon (mentee) [2]. As the procedure is guided by an experienced surgeon, it tends to improve the surgical outcome, thus providing a high quality of surgical care [3]. Also, as the patients can be scheduled even when the specialist surgeon is not present in the operating room, it simplifies logistics and cost for the hospital [4].

Over the past decades, surgical telementoring has evolved from exchange of basic audio and annotated video to the usage of Augmented Reality (AR), where the motion of virtual surgical instruments controlled by the mentor is overlaid onto the operative field of the mentee [5]–[8]. These augmented visual cues (Fig. 1) assist the mentor to virtually demonstrate the required tool-tissue interaction and the mentee to learn and perform precise movements of the surgical instruments during both open and minimally invasive surgery (MIS). The augmentation of the operative field requires the exchange of time-sensitive and accurate data (between the operating room and the remote location) over a network with minimal latency and information loss.

(a) (b) (c)

Figure 1. Virtual surgical instruments rendered onto the operative field in an (a) open surgery setup (b) laparoscopic (manual) surgical setup (b) robotic surgical setup. The movements of virtual surgical instrument are controlled by the mentor and act as a visual cue for the mentee.

While previous studies (shown in Table I) compared real-time data streaming performances with different network protocols, they did not assess the context of surgical telementoring. To ensure visually perceivable surgical guidance [9], this work presents a general benchmark to compare performances of AR based surgical telementoring systems when used with different networking protocols and across different physical locations for open and MIS scenarios.

Table I
STUDIES ON NETWORK PERFORMANCE FOR DATA TRANSFER

Study	Streaming	Network Protocols
Aloman et. al. [10]	RGB video data	MPEG-DASH, RTSP, and RTMP
González et. al. [11]	RGB video data	WebRTC and RTSP
Khan et. al. [12]	RGB video data	HTTP, RTSP and IMS
Cao et al. [13]	Mobile AR data	HLS, MPEG-DASH, RTP, RTMP, RTMFP, and RTSP
Liu et al. [14]	Point cloud data	MPEG-DASH

II. METHODS

A. Telementoring for Minimally Invasive Surgeries

The system proposed by Shabir et al. [5], [6] was used for MIS setup. It comprised of workstations at an operating room and at a remote location connected via networks. The operating room workstation is connected to a laparosocpy tower and an optical tracking system. The optical tracking system is used as the reference frame and tracks: (i) the position and orientation (pose) of the laparoscope, and (ii) the position of incision points. The video feed from the laparoscope is bifurcated to the operating room workstation, which is combined with the optically tracked data and sent over the network to the remote location. At the remote location, a virtual surgical instrument is rendered in front of the operative field (as shown in Fig. 2a). The mentor controls the motion of the virtual surgical instrument by maneuvering its tooltip using an input device [15]. The pose of virtual surgical instrument's tooltip is sent back to the operating room. The motion of the virtual surgical instrument is reconstructed and augmented onto the operative field (Panel A of Fig. 2a). This acts as a visual cue to provide guidance to the mentee. The setup was tested with two networking protocols RTMP [6] and WebRTC [5]. In the former implementation, the data comprised of laparoscope poses, incision point positions, and tooltip poses, is sent using sockets, whereas video feed is transmitted through the RTMP server. In the latter implementation, the data comprised of laparoscope poses, incision point positions, and tooltip poses, is sent using a WebRTC data thread, whereas video feed is transmitted through a WebRTC video thread.

B. Telementoring for Open Surgeries

For the open surgery setup, the aforementioned system proposed by Shabir et al. [6] using WebRTC was modified. An RGB-D camera (Azure Kinect device by Microsoft) was used to acquire the operative field. The depth data (representing the surgical field point cloud) was compressed (using a delta compression algorithm), merged onto the operative field video feed metadata, and sent over the network from the operating room to the remote workstation using a WebRTC video thread. At the remote location, the data was

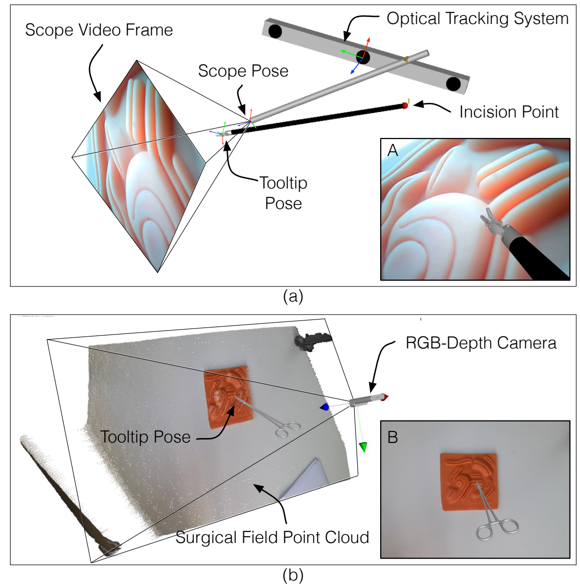

Figure 2. Virtual environment of the operating field generated for surgical tele-mentoring in (a) minimally invasive surgery and (b) open surgery.

uncompressed and the virtual environment was rendered to the mentor (as shown in Fig. 2b). Similar to the MIS setup, the mentor places a virtual surgical instrument (Panel B of Fig. 2b) whose pose is transferred back to the operating room to guide the mentee. In the operating room, holographic rendering using Microsoft HoloLens2 device was used to augment the view of the mentee [16]–[18].

C. Experimental Setup

The setup was tested both intra-country (where both the operating room and the remote location were located in Doha, Qatar) and inter-country (where the operating room was at Doha, Qatar and the remote location was at Houston, TX, USA). Before the experiments, the clocks on the two workstations were calibrated and a common Network Time Protocol (NTP) server 216.239.35.4 (time2.google.com) was used to synchronize the time. The data exchanged over the network (n = 9 trials per scenario) was logged and processed to assess performance of the surgical telementoring system (presented in Table II).

III. RESULTS AND DISCUSSION

The performances of AR based telementoring systems using WebRTC and RTMP network protocols are presented in Table II. The video frame size of the operating field for MIS was set to 640×480 pixels, whereas for the open surgery it was 1280×720 pixels of RGB data stream and 512×512 pixels of depth data field.

During the study, there were several limitations while using RTMP. First, inter-country connection was not established for RTMP due to restrictions imposed by service providers, thus limiting its usage for intra-country only. Even with intra-country usage, RTMP was restricted within

Table II
PERFORMANCE OF AUGMENTED REALITY BASED SURGICAL TELEMENTORING SYSTEM

Settings for simulated surgical telementoring scenario	Type of Surgery	**Minimally Invasive Surgery**			**Open Surgery**	
	Network Protocol	**RTMP**	**WebRTC**		**WebRTC**	
	Mentor–Mentee Location	**Intra–country**	**Intra–country**	**Inter–country**	**Intra–country**	**Inter–country**
Average latency in transferring data from operating room to remote location		1560 ± 426 ms	78 ± 7 ms	163 ± 12 ms	93 ± 7 ms	227 ± 19 ms
Average latency in receiving two consecutive data packets from operating room to remote location		40 ± 49 ms	33 ± 27 ms	33 ± 6 ms	40 ± 3 ms	41 ± 2 ms
Percentage of dropped frames while transferring data from operating room to remote location		0%	0.59%	0.03%	0.03%	0.09%
Average latency in transferring data from remote location to operating room		89 ± 17 ms	21 ± 2 ms	132 ± 23 ms	17 ± 2 ms	140 ± 1 ms
Average latency in receiving two consecutive data packets from remote location to operating room		58 ± 650 ms	26 ± 15 ms	33 ± 8 ms	116 ± 8 ms	94 ± 1 ms
Video quality metric comparing frames sent before encoding and received after decoding [19], [20]	Mean Square Error (MSE)	31.28	242.67	245.02	214.3	175.8
	Peak Signal-to-Noise Ratio (PSNR)	33.18	24.28	24.25	23.78	24
	Structural Similarity Index Measure (SSIM)	0.98	0.93	0.93	0.79	0.81

the same local network where port-forwarding was not required. This issue was resolved while using WebRTC as a STUN server (stun.l.google.com) was used to discover the public IPs for establishing an initial connection and then a direct peer-to-peer connection was made using a signaling server (DigitalOcean.com) for exchange of data [21]. Second, with RTMP, the depth data (required to be sent in the case of open surgery) could not be encoded, limiting its usage in MIS. Third, it was also observed, though it provided superior video quality of the operating field (MSE of 31.28, PSNR 33.18, and 0.98 SSIM) with zero frame drop, the latency was high for RTMP intra-country. Due to these limitations, RTMP based surgical telementoring is more suitable for minimally invasive intraoperative surgical guidance scenarios, where (i) both the operating surgeon and an expert surgeon (guiding the procedure) are present in the same operating room on a local network, and (ii) the operative field is stable (as it reduces the effect of latency in viewing the live operative field).

The low latency of WebRTC enabled surgical telementoring for both inter-country and intra-country, whereas the open-source nature facilitated modifying the protocols to transfer data streams required for remote open surgery as well as MIS. The latency (varying from 21 ± 2 ms to 140 ± 1 ms) for demonstrating the tool motions from the remote location to the operating room were below the recommended limit of 200 ms [22]. Similarly, the delays (varying from 78 ± 7 ms to 227 ± 19 ms) in transferring the information (comprising of operating field video, scope poses, and incision points for MIS, and operating field video and depth map for open surgery) from the operating room to the remote location was within the recommended range of 450 ms [9]. The video quality metric for WebRTC was within the acceptable quality for depicting structural content in the operating field [5], [6].

Our work focuses on the exchange of information between the operating room and the remote location over networks. In addition to this, it is also vital to understand whether the information provided by the mentor to the mentee is useful in the surgical procedure. This would require conducting scenario-specific end-user studies to assess the efficacy of the mentee in understanding the information provided by the mentor via user interfaces [23]–[26]. It would also require designing a structured method for effective communication (e.g. a standardized lexicon) between the mentor and the mentee [27]. Learning theories [28] and conceptual frameworks [29] suited for surgical telementoring system would need to be developed to facilitate efficient communications.

IV. CONCLUSION

In summary, WebRTC is preferred as a real-time communication protocol for exchange of surgical data over network required for AR based surgical telementoring systems. The implementation and the performance of WebRTC varies depending upon the surgery (open or minimally invasive) and locations of mentor-mentee. The benchmark would aid in development and assessment of new network protocols tailored for surgical telementoring.

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