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Towards development of a tele-mentoring framework for minimally invasive surgeries

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Abstract

Background: Tele-mentoring facilitates the transfer of surgical knowledge. The objective of this work is to develop a tele-mentoring framework that enables a specialist surgeon to mentor an operating surgeon by transferring information in a form of surgical instruments' motion required during a minimally invasive surgery.

Method: A tele-mentoring framework is developed to transfer video stream of the surgical field, poses of the scope and port placement from the operating room to a remote location. From the remote location, the motion of virtual surgical instruments augmented onto the surgical field is sent to the operating room.

Results: The proposed framework is suitable to be integrated with laparoscopic as well as robotic surgeries. It takes on average 1.56 s to send information from the operating room to the remote location and 0.089 s for vice versa over a local area network.

Conclusions: The work demonstrates a tele-mentoring framework that enables a specialist surgeon to mentor an operating surgeon during a minimally invasive surgery.

KEYWORDS

augmented reality, minimally invasive surgeries, tele-mentoring, telemedicine

1 | INTRODUCTION

As surgery has evolved from open to minimally invasive, the framework of tele-mentoring technologies has largely remained the same.[1-3] It still involves basic exchange of audio and annotated video messages, and lacks augmentation of information pertaining to surgical tool motion and tool-tissue interaction.[4,5] In an operating room setup of minimally invasive surgery (MIS), the surgeon operates on a patient using surgical instruments inserted through small incisions. These surgical instruments can either be manually operated (such as laparoscopic instruments) or robotically actuated. Along with instruments, a scope (camera) is also inserted inside the patient's body to visualise the interaction of surgical instruments' tooltips with the tissue. In the case of manual MIS, the surgeon

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directly controls the movements of the tooltips, whereas in the case of robotic MIS, the surgeon indirectly controls the movement of robotically actuated tooltips via an interface on the console. In both cases of MIS, the surgical field exhibits the complex interaction of highly articulated surgical instrument tooltips with the tissue to be operated. With the current existing tele-mentoring technologies, the expert surgeon can assist the operating surgeon by providing guidance information in the form of either markings or hand gestures. However, this information is limited because of its two-dimensional and static nature. As a result, it is difficult for the operating surgeon to visualise, comprehend and perform the required surgical tooltip movements. The notion of overlaying minimally invasive surgical instruments motion onto the surgical field is advantageous in mentoring scenarios. For example, augmented reality tele-mentoring (ART) platform proposed by Vera et al.[6] showed faster skill acquisition in laparoscopic suturing and knot-tying task. Preliminary studies conducted by Jarc et al. (using the ghost tool platform with da Vinci surgical system) demonstrated effectiveness for both trainees and proctors during robot-assisted dry-lab training exercises,[7] and robot-assisted tissue dissection and suturing tasks on a live porcine model.[8]

In both industry[9-19] and academia,[6-8,20-27] tele-mentoring solutions have been developed. These solutions facilitate transfer of information from a specialist surgeon to the operating surgeon via a communication channel and enables tele-mentoring during different types of surgeries. All these solutions include basic capabilities to share the live video feed of the surgical view over a network, provide verbal guidance and perform screen markings (2D screen annotations).[7-27] Examples of these commercially available technologies includes VISITOR1 from KARL STORZ,[9-12] Connect$^{\text{TM}}$–Intuitive Surgical[26,27] and RP Vantage from InTouch.[13-17] Some of these tele-mentoring technologies (e.g., research prototypes, such as STAR from Purdue University[20-22] and VIPAR from University of Alabama,[23-25] and commercial systems from HELPlightning[18] and Proximie[19]) also display augmented hands gestures of the remote surgeon. It uses computer vision and image segmentation techniques to segment the operator's hand (captured on a video through a web-camera) and overlays it onto the surgical view. This allows the remote surgeon to virtually put his/her hand in the surgical view and provide assistance to point out different anatomical structures, incision positions and surgical instrument placements. Augmented ghost tools have also been proposed for robotic surgery.[7,8] Though dynamic in nature, it renders only the tooltips without complete body of the surgical instrument. Apart from visualisation, this also limits the realism of augmented surgical tools' motion (as the constraints imposed by the incision points and the tools' kinematic are not taken into consideration). Second, the user interfaces are not applicable to laparoscopic instruments used in manual MIS. The ART platform[6] requires a similar surgical setup (with same configuration of incision points and surgical instruments) at both the remote and local site, thus limiting its application to laparoscopic simulated training scenarios only. Although the aforementioned solutions are sufficient for open surgeries, and in some cases for MIS, a more sophisticated mechanism is required for MIS (either manual-laparoscopic or robotic), which involves complex interaction between the highly articulated surgical instrument tooltips and tissues in the surgical field. During MIS, by just analysing the hand gestures or markings provided by remote surgeon, it is difficult for the operating surgeon to visualise, comprehend and perform the required tooltip movements. The proposed tele-mentoring framework aims to overcome these limitations of existing solutions[6-27] by transforming hand gestures of the remote surgeon into virtual surgical instrument movements and superimposing them on the local surgeon's view of the surgical field.

The objective of this work is to develop a framework that would facilitate tele-mentoring between an operating surgeon and a remote surgeon for MISs. An architecture of the tele-mentoring framework is proposed, and the hardware/software modules required for implementation of the framework are described. The framework is assessed for simulated laparoscopic and robotic surgical scenarios. The work also analyzes plurality of parameters to assess the functioning of the tele-mentoring framework over a local area network.

2 | MATERIALS AND METHODS

2.1 | Architecture of the tele-mentoring framework

The architecture (Figure 1) of the tele-mentoring framework is implemented as a distributed system with one setup inside the operating room and another at the remote location. The subsequent two sections describe each setup in detail.

2.1.1 | Operating room setup

The operating room setup of the proposed tele-mentoring framework consists of an operating room workstation, visualisation screens, an optical tracking system, tracking frames to be used with optical tracking system, a scope system, an input device (mouse and keyboard) and a network router (as illustrated in Figure 1). The operating room workstation consists of six software modules (as illustrated in Figure 2) interfacing with the hardware units, processing the data and continuously communicating with each other. The functionality of each module is described as follows:

(i) *Core Processing Module*: The core processing module acts as a central core for processing data at the operating room workstation. The module receives data from the graphical user interface (GUI) module, video module, tracking module and network module and sends data to the graphical rendering module and network module.

(ii) *Video Module*: The video module receives video stream of the surgical field from the scope system, processes it frame-by-frame and sends the video frames to the core processing module. A video frame at time instant '*t*' is denoted by $F_{\text{SurgicalView}}(t)$.

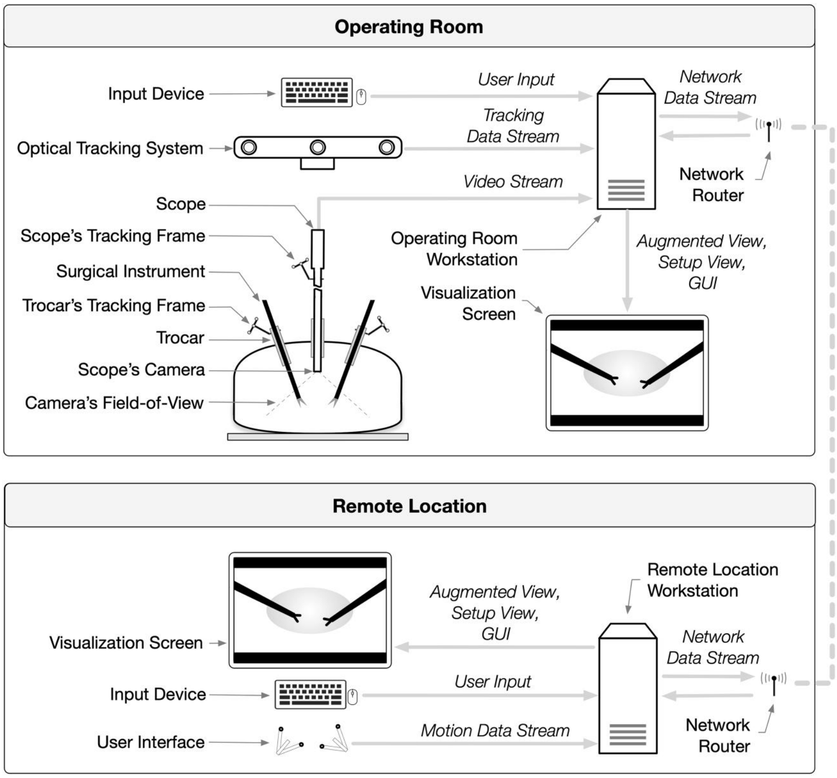

FIGURE 1 Architecture of the proposed tele-mentoring system illustrating the flow of information among the hardware components physically located in the operating room and at a remote location. GUI, graphical user interface

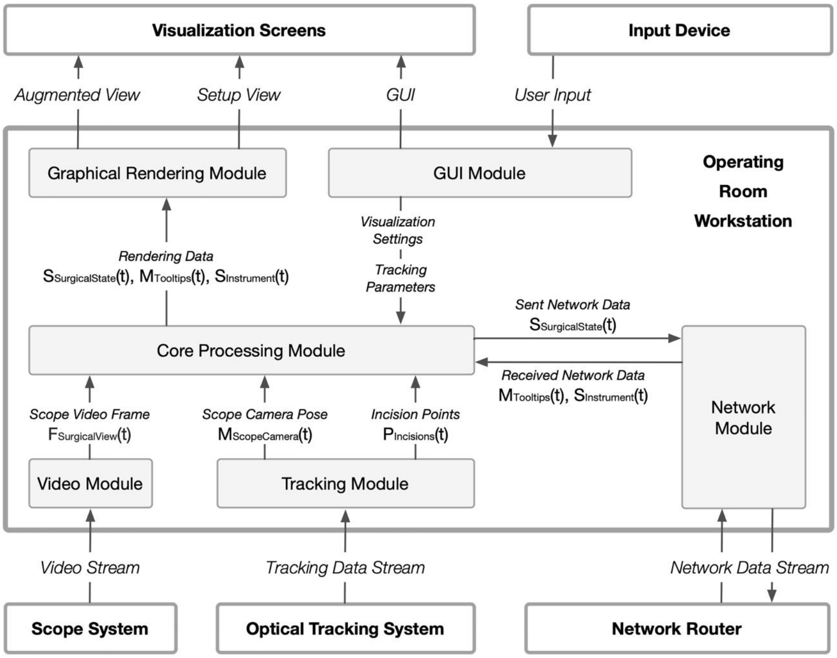

FIGURE 2 Schematic representation of the flow and processing of information on the software modules of the operating room workstation. GUI, graphical user interface

(iii) *Tracking Module*: Tracking frames (with unique arrangement of retroreflective markers) are attached to the scope and trocars. The optical tracking systems continuously sense the poses (position and orientation) of the tracking frames and send the tracking data stream to the tracking module. The tracking module processes the stream and computes the pose of the scope camera and the positions of the incision points (shown in Figure 3A). The scope camera's pose at time instant 't' is represented by a 4 × 4 homogenous transformation $M_{\text{ScopeCamera}}(t)$. Whereas, the positions of the incision points are stored in a tuple $P_{\text{Incisions}}(t)$, where each element represents an incision point $P_{\text{Incisions}}[i](t)$ (where i = number of incisions). $M_{\text{ScopeCamera}}(t)$ and $P_{\text{Incisions}}(t)$ are measured with respect to the coordinate system of the optical tracking system inside the operating room and are fed to the core processing module.

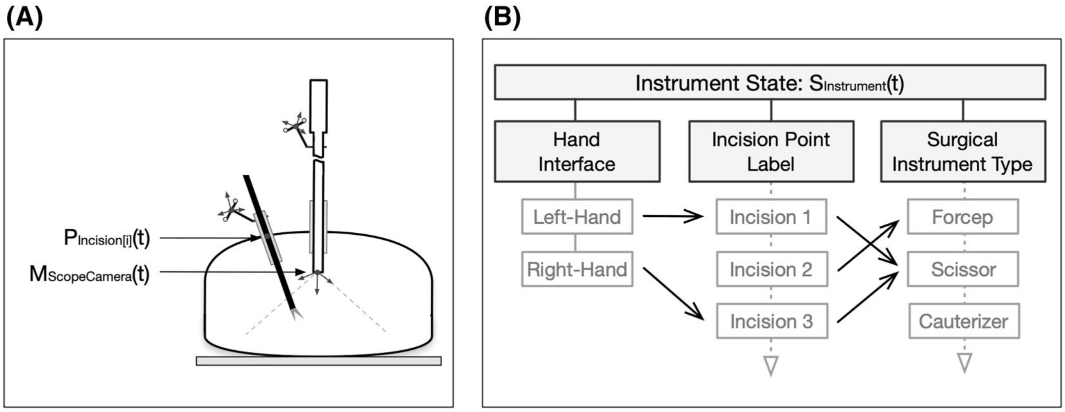

FIGURE 3 Pictorial representation of (A) an incision point and pose of a scope camera frame and (B) instrument state

(iv) *GUI Module*: Graphical User Interface is used to alter the visualisation setting and to set the tracking parameters for the tracking module. It allows the user to add/delete incision points, set deflection angle for angulated scopes, toggle visualisation of augmented instruments and display instruments selected by remote surgeon and status of the operating room workstation.

(v) *Network Module*: The video frame of the surgical view, pose of the scope camera and coordinates of the incisions points together define the surgical state $S_{SurgicalState}(t) = [F_{SurgicalView}(t), M_{ScopeCamera}(t), P_{Incisions}(t)]$ at time instant 't'. The surgical state $S_{SurgicalState}(t)$ is sent by the core processing module to the network module, which further passes it as a network data stream to the remote location's workstation. The network module also receives the poses of augmented tooltips $M_{Tooltips}(t)$ and instrument state $S_{Instrument}(t)$ from the remote workstation. $M_{Tooltips}(t)$ is represented by a tuple $[M_{Tooltips[1]}(t), M_{Tooltips[2]}(t)]$ corresponding to left and right tool motion. $M_{Tooltip[i]}(t)$ represents a coordinate frame in form of 4 × 4 homogenous transformation matrix attached to the tooltip of the augmented surgical instrument. The transformation of $M_{Tooltip[i]}(t)$ causes the augmented surgical instrument to move in the virtual space. The instrument state $S_{Instrument}(t)$ stores (a) surgical instrument types used in the surgery, (b) labels of the incision point and (c) mapping between surgical instrument type to an incision point label and left- or right-hand interface to an incision point label (as shown in Figure 3B). The mapping inside $S_{Instrument}(t)$ data is used by the graphical rendering module during rendering.

(vi) *Graphical Rendering Module*: The module renders the information fetched from core processing module onto the visualisation screen. The data comprising of $S_{SurgicalState}(t)$, $M_{Tooltips}(t)$ and $S_{Instument}(t)$ is rendered in two windows displaying view of the surgical setup (Figure 4A) and augmented view of the surgical field (Figure 4B). The setup view renders pose of tracking frames, pose of scope camera, location of the incision points (along with labels), the frustum of the surgical view (along with the updated surgical view frame) and pose of the augmented tools selected. The augmented view displays the surgical view $F_{SurgicalView}(t)$ in the complete window along with augmented tools when selected by the remote surgeon.

2.1.2 | Remote location setup

The remote location setup of the tele-mentoring framework consists of a remote location workstation, visualisation screens, a user interface, an input device (mouse and keyboard) and a network router (as shown in Figure 1). The remote location workstation consists of five software modules (as shown in Figure 5) interfacing with the hardware units, processing the data and continuously communicating with each other. The functionality of each module is described as follows:

(i) *Core processing Module*: The core processing module acts as a central core for processing data at the remote location workstation. The module receives data from the GUI module, user interface module and network module and sends data to graphical rendering module and network module.

(ii) *User Interface Module*: The module fetches the motion data stream from the user interfaces, processes it and converts it into the poses of augmented tooltips $M_{Tooltips}(t)$. The transformation of $M_{Tooltips}(t)$ causes the augmented surgical instrument to move in the rendered view of the surgical setup (Figure 4A) and augmented view of the surgical field (Figure 4B).

(iii) *Graphical Rendering Module*: Similar to the functionality of the module in operating room, the module at remote location fetches the information from core processing module and renders it on visualisation screen.

(iv) *GUI Module*: Graphical User Interface is used to establish a connection with operating room workstation, alter the visualisation setting and set the instrument state. It allows the user to connect to the operating room workstation by entering the IP address, map virtual tools to incision points for left/right-hand tool movements and display the status of the operating room workstation.

(v) *Network Module*: The network module receives the network data stream from the operating room workstation, processes it and

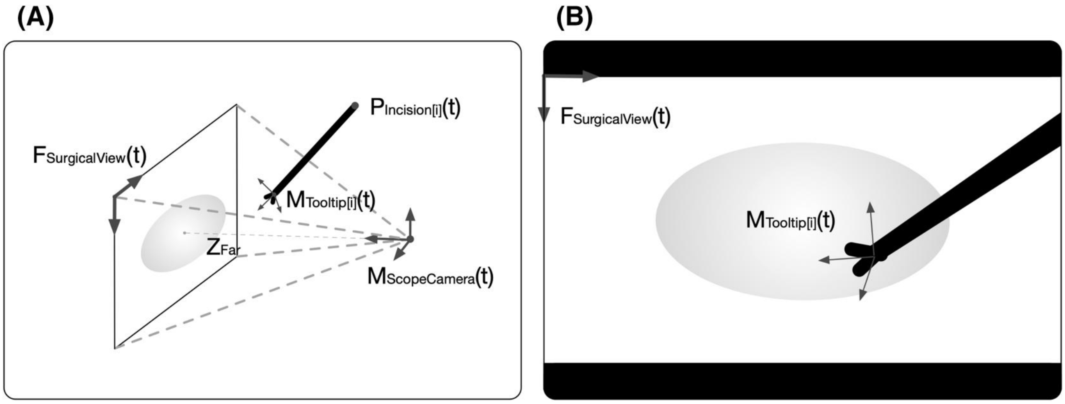

FIGURE 4 Windows rendered by the graphical rendering module displaying (A) view of the surgical setup and (B) augmented view of the surgical field

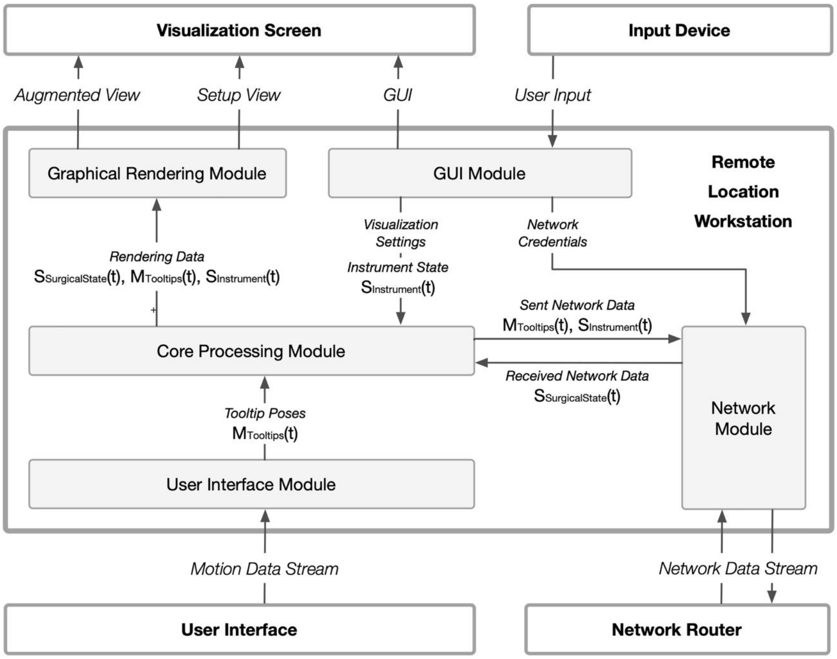

FIGURE 5 Schematic representation of the flow and processing of information by the software modules of the remote location workstation. GUI, graphical user interface

extracts $S_{SurgicalState}(t)$ from it. In parallel, the module also sends poses of augmented tooltips $M_{Tooltips}(t)$ and instrument state $S_{Instrument}(t)$ to the operating room workstation.

2.2 | Workflow of the tele-mentoring framework

Before the start of the surgery, the operating surgeon starts the workstation located inside the operating room. The mentor surgeon starts the remote location workstation. The mentor surgeon sends request to connect to operating room workstation. The request is then approved by the operating surgeon and connection is established between operating room and remote location workstations.

The operating surgeon then sets the instrument state where the list of surgical instruments to be used in the surgery is added to the operating room workstation. Second, the tracking frames can be attached to the trocars (cannulas), registered with optical tracking system and inserted inside the patient. In this work, we used a tracking tool to select the incision points. For every trocar inserted inside the patient, a label is assigned to the incision point by the operating surgeon and the instrument state $S_{Instrument}(t)$ is updated on the operating room workstation. The instrument state $S_{Instrument}(t)$ is then shared by the operating room workstation with the remote location workstation. Similarly, the operating surgeon also sets the scope parameters, where a tracking frame is attached to the scope, registered with the optical tracking system and inserted inside the patient. The operating surgeon sets the scope parameters comprising of scope's field of view, scope's angulation and rigid transformation between pose of the scope camera and the tracking frame attached to the scope. The scope parameters are also shared by the operating room workstation with the remote location workstation.

Once the instrument state and scope parameters have been set, the operating surgeon observes the operating field on the visualisation screen and starts performing the surgery. The mentor also observes the surgery as it is performed by the operating surgeon on the visualisation screen of the remote location workstation. During the surgery if mentoring is required, the operating surgeon requests for mentoring. When the mentoring request is received by the mentor, the mentor checks if mapping is required (i.e., (i) surgical instrument type to an incision point label and (ii) left or right user interface to an incision point label) and updates the instrument state. The mentor interacts with the user interface which in turn updates the tooltip poses of the rendered augmented tools on both workstations. This motion of the augmented surgical instruments over the surgical field provides mentoring in the form of visual cues to the operating surgeon. When the surgery is completed, both the operating room and remote location workstations are stopped, and connection is released.

2.3 | Implementation details of the tele-mentoring framework

The framework was implemented in C++. The graphical rendering was performed using VTK[28] whereas the GUI was implemented using Qt.[29] The threaded implementation of the modules was performed using Boost.[30] Interfacing with user interfaces (connected to remote location workstation) was achieved using openHaptics[31] and 3DXWare[32] (version 10.7.1) libraries. At the operating room's workstation, an Real-Time Messaging Protocol (RTMP) server was used to transfer surgical view video frames $F_{\mathrm{SurgicalView}}(t)$, whereas Qt sockets were used to transfer poses of the scope camera $M_{\mathrm{ScopeCamera}}(t)$ and positions of incision points $P_{\mathrm{Incisions}}(t)$. At the remote location workstation, Qt sockets were used for sending the poses of augmented tooltips $M_{\mathrm{Tooltips}}(t)$ and instrument state $S_{\mathrm{Instrument}}(t)$. FFMPEG[33] was used for video encoding/decoding. NatNet SDK[34] allowed the streaming of motion capture data from a tracking server Motive.[35]

The workstations at the operating room and the remote location were realised on a standard PC (Intel 2.4 GHz Processor and 64 GB RAM) with an integrated graphics processing unit (Intel UHD Graphics 630 GPU). The optical tracking system used in the operating room was implemented on V120: Trio OptiTrack motion capture system by NaturalPoint, Inc.[36] The tracking data was processed by OptiTrack's software platform called Motive,[35] which ran on the operating room workstation. To fetch surgical instrument tooltip motion data stream from the remote user, two user interfaces were used: (a) Touch$^{\mathrm{TM}}$ device by 3D Systems to simulate motion of robotic tooltips with 6 degrees-of-freedom and (b) SpaceMouse® by 3DConnexion to simulate motion of laparoscopic tooltips with 4 degrees-of-freedom. For communication between the workstations over a local area network, a mobile network router (Nighthawk M1 by NETGAR) was used.

3 | RESULTS

3.1 | Assessment of tele-mentoring framework on a simulated surgical setup

The implemented tele-mentoring framework (architecture depicted in Figure 1) was tested on a surgical phantom for a minimally invasive manual surgery (Figure 6) as well as robotic surgery (Figure 7). The hemispherical surgical phantom with five incision points simulated pneumoperitoneum during surgery and a silica gel structure inside the phantom mimic the surgical field when observed using a scope.

In manual surgical setup (Figure 6A), Karl Storz's camera head (Image 1 HD), light source (Model # 201331 20) and video processor (Model #222010 20) were used. The surgical instruments comprised of angulated laparoscope (30-degree, 8 mm, Karl Storz) and laparoscopic instruments (Richard Wolf Laparoscopic Needle Holder) as shown in Figure 6B. An adaptor (Magewell USB Capture HDMI 4K Plus) converted the serial digital interface video output from the video processor to a USB-C port of the operating room workstation. At the remote location workstation, SpaceMouse® devices (3DConnexion) were used as the user-interface to control virtual models of EndoWrist instrument tooltips (Figure 6C).

The robotic surgical setup of our tele-mentoring framework was tested on Da Vinci Xi surgical robot–Intuitive Surgical Inc. (Figure 7A). The output video stream from the vision cart was connected to the operating room workstation of the tele-mentoring framework using an adaptor (Magewell USB Capture HDMI 4K Plus). The augmented view from the operating room workstation of the tele-mentoring framework was rendered in tile-pro on the surgeon's console mode side-by-side with the view from the scope (Figure 7B). The surgical instruments comprised of 30-degree angulated scope and EndoWrist instruments (470006 large needle drivers) as shown in Figure 7C. At the remote location workstation of the tele-mentoring framework, Touch$^{\mathrm{TM}}$ devices (3D Systems) were used as user-interface to control virtual models of EndoWrist instrument (Figure 7D).

The view of the surgical setup (schematically depicted in Figure 4A) is shown for manual and robotic surgery in Figure 8A,B. Similarly, the augmented view (schematically depicted in Figure 4B) for manual and robotic surgery is shown in Figures 6A and 7B, respectively. The motion of the virtual tools performed by the operator at the remote location workstation was observed by the operator inside the operating room workstation on the augmented view.

3.2 | Evaluation of the tele-mentoring framework over local area network

To evaluate the performance of the implemented tele-mentoring framework, the system was tested for different time periods (varying for 8, 10 and 12 min) multiple times (three trials per time period). The clocks on the remote and operating room workstations were

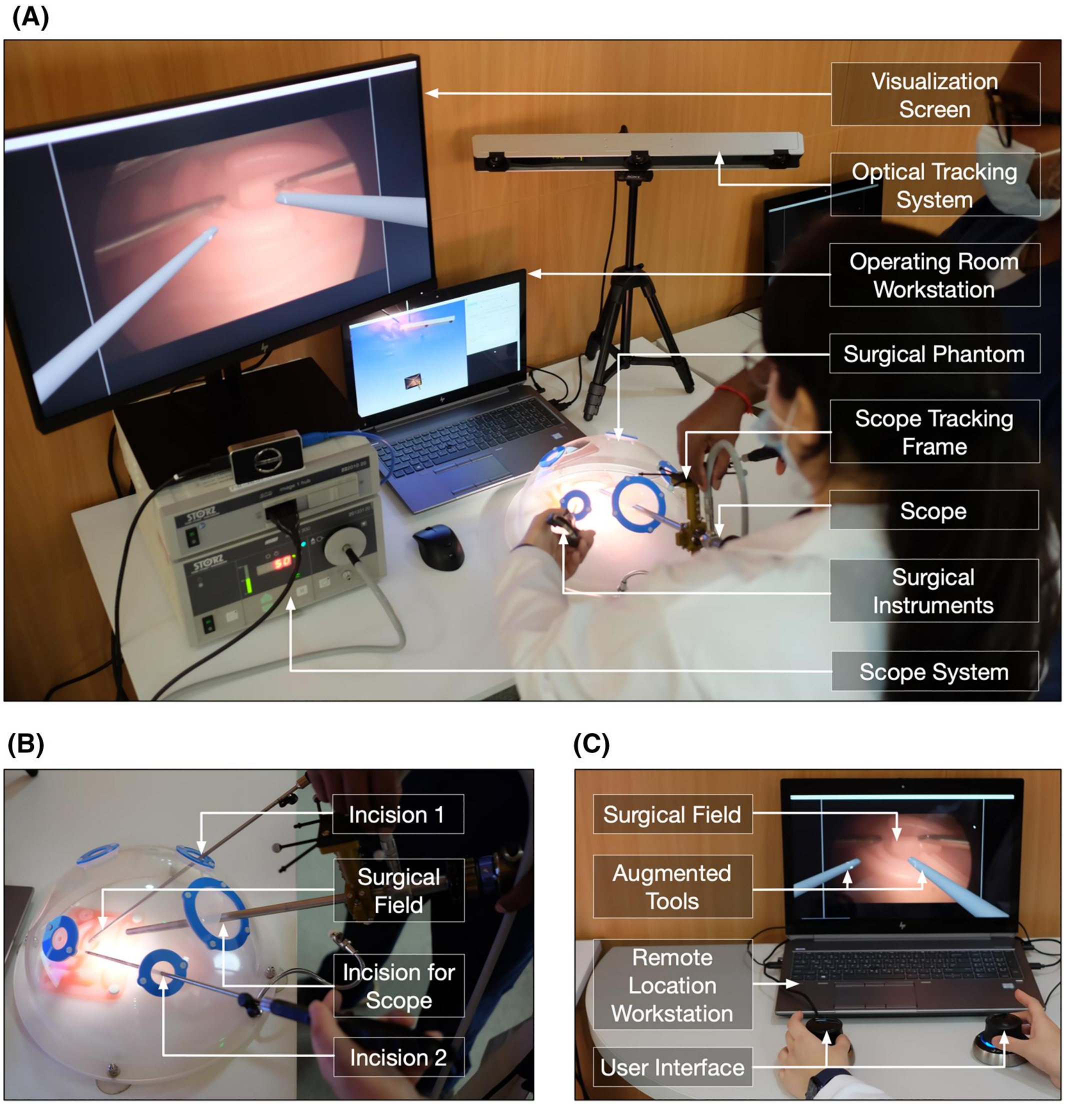

FIGURE 6 Tele-mentoring framework tested for a minimally invasive manual (laparoscopic) surgical setup. (A) Setup of the tele-mentoring framework at the operation room; (B) Surgical phantom used to mimic incisions and surgical field; (C) Setup of the tele-mentoring framework at the remote location

synchronised from a common server (windows time service). The data sent and received over the network at both ends was logged and processed to evaluate the functioning of the tele-mentoring framework over the network.

The surgical state $S_{SurgicalState}(t)$, comprising of incision points $P_{Incisions}(t)$, scope pose $M_{ScopeCamera}(t)$ and surgical view $F_{SurgicalView}(t)$ was sent over the network from the operating room to the remote location workstation. In the current implementation of the tele-mentoring framework, the position of the incision points $P_{Incisions}(t)$ was marked using a tracking tool. The position remained stationary during the study (as the surgical phantom was not moved). The pose of the scope's camera $M_{ScopeCamera}(t)$ was continuously sent over the network from the operating room to the remote location. Figure 9 presents $M_{ScopeCamera}(t)$ decomposed into position (translations along X, Y and Z axis) and orientation (rotations along X, Y and Z axis) measured with respect to optical tracking system.

An average delay of 1.560 ± 0.426 s was observed while transferring $S_{SurgicalState}(t)$ from the operating room to the remote location workstation. The delay was computed by taking difference of the logged timestamps for the received and send $S_{SurgicalState}(t)$ at the remote and operating room workstations, respectively. Figure 10A illustrates the variation in delays between the same surgical state $S_{SurgicalState}(t)$ sent and received for one such trial. To correlate $F_{SurgicalView}(t)$ at sender and receiver ends, a timestamp was written on the image of the surgical view frame $F_{SurgicalView}(t)$ at the sender's end and extracted at receiver's end. No drop of $S_{SurgicalState}(t)$ packets was observed.

Before sending the $F_{SurgicalView}(t)$ over the network, the video stream is encoded by the network module in the operating room workstation and then decoded by the network module of the remote location workstation. The video image quality metrics were used to compare the quality of sent frames before encoding and received

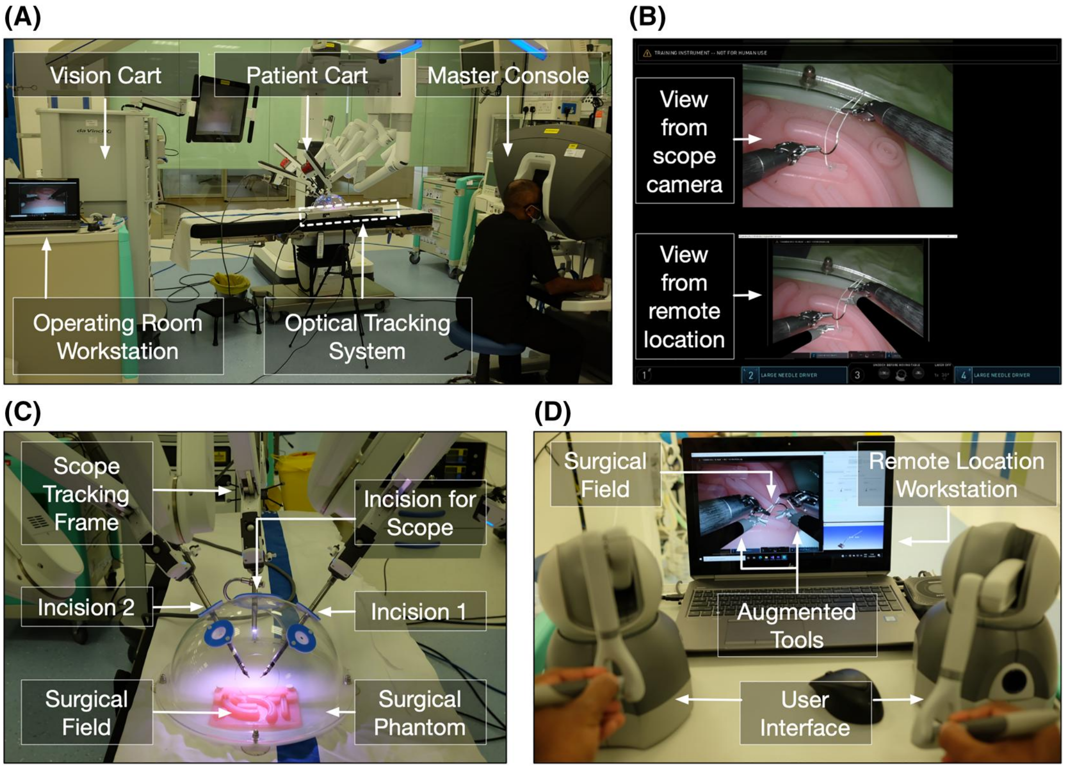

FIGURE 7 Tele-mentoring framework tested for a minimally invasive robotic surgical setup. (A) Setup of the tele-mentoring framework at the operation room; (B) View from the master console; (C) Surgical phantom used to mimic incisions and surgical field; (D) Setup of the tele-mentoring framework at the remote location

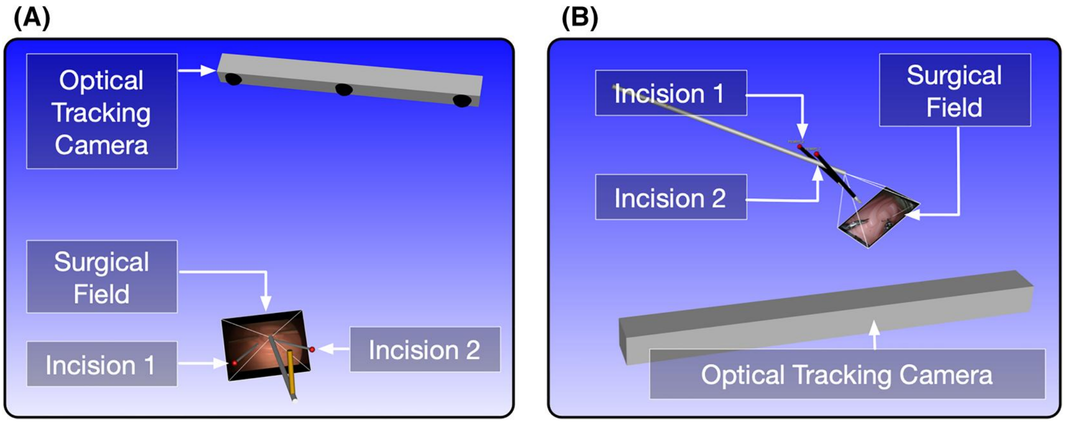

FIGURE 8 View of the surgical setup schematically depicted in Figure 4A for (A) manual surgical setup (Figure 6) and (B) robotic surgical setup (Figure 7)

frames after decoding.[37,38] The computed values of the video image quality metrics were the average mean square error (MSE) of 31.28, the average peak signal-to-noise ratio of 33.18 and the average structural similarity index measure of 98.24% (shown in Figure 10B). The heat map presented in Figure 11 shows the relative values with respect to each other for the MSE of the surgical view frames received and sent.

When the virtual instruments were selected by the operator at the remote location workstation, tooltip poses $M_{\text{Tooltips}}(t)$ were sent over the network from the operating room to the remote location workstation. Figure 12 shows $M_{\text{Tooltips}}(t)$ for the movements of the left and right augmented tools. An average delay of 0.089 ± 0.017 s was observed while transferring $M_{\text{Tooltips}}(t)$ from the remote location to the operating room workstation. The delay was computed by taking difference of the logged timestamps for the received and send $M_{\text{Tooltips}}(t)$ at the operating room and remote workstations, respectively It was observed that the packets sent from the remote location workstation were received in batches at the operating room workstation (shown in Figure 12). Due to this behaviour, a buffer was required to consume the packets at a uniform rate. Whenever there

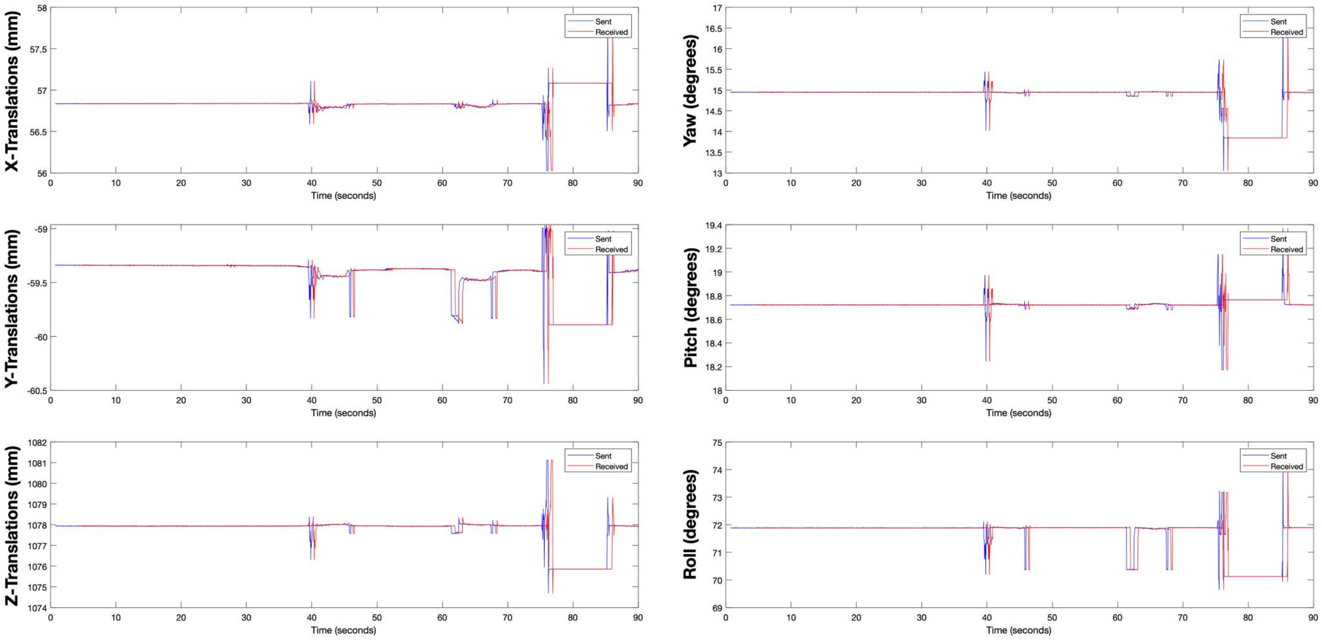

FIGURE 9 Graphical representation of the delay in receiving information at remote location from the operating room. The pose of scope camera $M_{\text{ScopeCamera}}(t)$ is acquired at the operating room and sent to the remote location workstation. The remote location workstation receives the $M_{\text{ScopeCamera}}(t)$ with a delay. The poses are expressed as translation (in X, Y, and Z axis) and rotations (roll, yaw, pitch) with respect to the time and are measured in the optical tracking system coordinate system

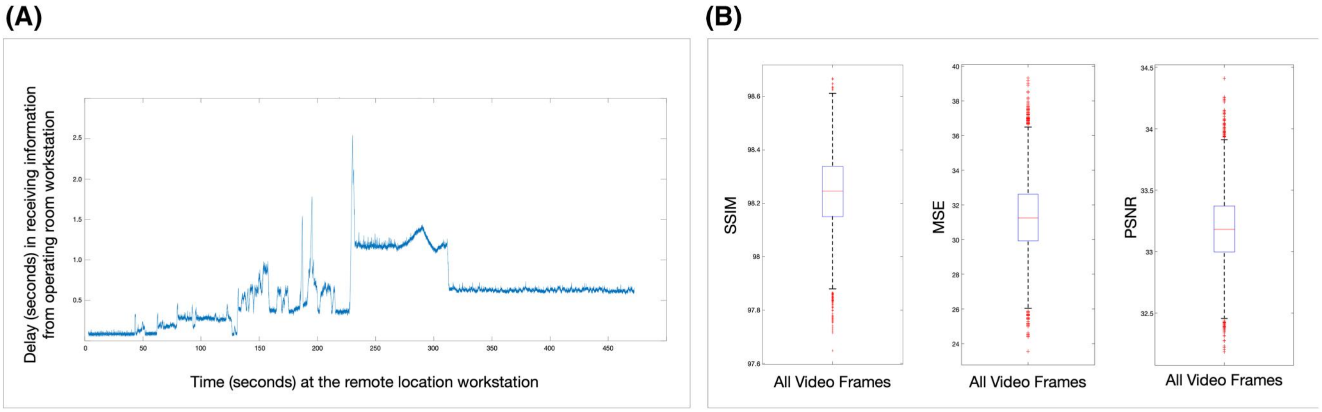

FIGURE 10 (A) Delay in receiving surgical state $S_{\text{SurgicalState}}(t)$ at remote location workstation from operating room workstation over a time period of 8 min and (B) Video quality metric comparing sent frames before encoding and received frames after decoding. MSE, mean square error; PSNR, peak signal-to-noise ratio; SSIM, structural similarity index measure

is an update in the instrument state $S_{\text{Instument}}(t)$, it is sent asynchronously over the network between the operating room and the remote location workstations.

4 | DISCUSSION

The proposed tele-mentoring framework facilitates communication between an operating surgeon and a mentor surgeon via displaying motion of augmented surgical instruments during a minimally invasive manual surgery (Figure 6) and robotic surgery (Figure 7). With dynamic virtual surgical instruments overlaid on the surgical field, the mentor surgeon is able to guide an operating surgeon with surgical tool motion required during the particular surgical step. While the previous studies[6-8] laid the foundation of using augmented tool motion for mentoring during the MIS, this work presents a framework that enables its usage over a network and in an operating room settings.

The information pertaining to the surgical field is transferred over the network from the operating room to the remote location with an average delay of 1.560 ± 0.426 s. At the remote location, the mentor surgeon performs the motion of augmented tools, which is sent to the operating room at an average delay of 0.089 ± 0.017 s (which is within the limit of 0.20 s recommended by Xu et al.[39]). This

FIGURE 11 Heat map of the mean square error (MSE) for a sample of 50 video frames sent from the operating room versus the 50 video frames received at the remote location. The heat map is generated to understand the relative value of MSE for video frames with respect to each other. The value is minimum for the same video frame number sent and received and is seen along the diagonal of the heat map

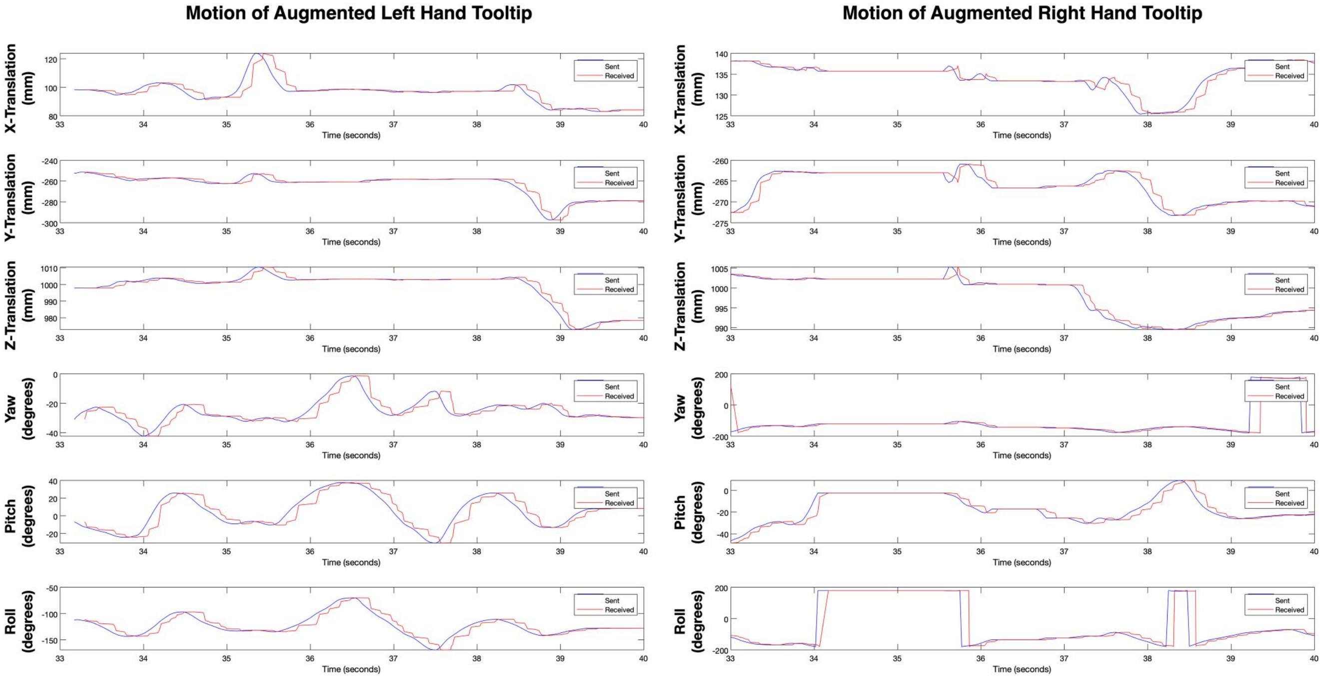

FIGURE 12 Graphical representation of delay in receiving information at operating room workstation from the remote location for a time period of 7 s. The pose of augmented instrument tooltip $M_{\text{Tooltips}}(t)$ for left $M_{\text{Tooltips}[1]}(t)$ and right $M_{\text{Tooltips}[2]}(t)$ hand is acquired at remote location workstation and send to operating room workstation. The operating room workstation receives the $M_{\text{Tooltips}}(t)$ with a delay

delay is acceptable, when the surgical field to be operated is stable. The recommendation provided by SAGES requires a latency of less than 0.45 s for live tele-mentoring.[40] Low latency is crucial especially during live surgery to ensure the remote surgeon is aware of the operating field and can mentor back as complications evolve intra-operatively. Also, the tissue motion induced by breathing or beating heart would require $F_{\text{SurgicalView}}(t)$ received at the remote location to be synchronised with $M_{\text{Tooltips}}(t)$ and sent back to the operating room to be visualised on a separate visualisation screen. As a result, the proposed framework is suitable only for simulated training scenarios and surgeries, where the operating field is stable.

The setup of the implemented tele-mentoring framework has certain limitations. First, the setup was only tested on a local area network instead of using it on the Internet. To test the setup on the Internet, it would require the RTMP server to be hosted on a cloud hosting service and access to network ports by the service providers. This may affect the delays in transferring the information. An alternative method is to use low latency live streaming protocols (such as WebRTC[41]) to overcome the delays and dependencies on service providers. This could be achieved by changing the networking modules without affecting the remaining modules of the system. Second in the setup, the incision points were tracked and located only once during the start of the experiments. This is acceptable in case of robot-assisted MIS as the remote centre of motion is maintained at the incision point (Figure 7). The incision points marked at the beginning of the robotic surgery using the optical tracking system remain stationary. However, in case of laparoscopic surgery (Figure 6), the incision points need to be tracked continuously by the optical tracking system. This limitation can be overcome by tracking frames that are attached to the trocars. The optical tracking system continuously tracks these frames and triangulates the positions of the incision points during the surgery (as depicted in Figures 1 and 3A).

In a MIS operating room setting (where an experienced surgeon is mentoring a novice surgeon), the experienced surgeon frequently takes control to demonstrate a complex surgical step to the novice surgeon. In this scenario, the novice surgeon either steps down from the console (in the case of robotic surgery) or handover the control of instruments (in the case of manual laparoscopic surgery) and observes the procedure on a secondary screen. This switching between surgeons during the procedure is inevitable as there is no other way to demonstrate the exact movements of the tooltips required to interact with the tissue. This generates a need of a technology that can allow the experienced surgeon to virtually demonstrate the exact tool-tissue interactions required during MIS procedure while the novice surgeon is still in control of surgical instruments.[42]

An MIS usually has a high complication rates unless the procedure is performed by a specialised surgeon experienced in the field.[43,44] To gain experience in the usage of new surgical instruments or new surgical techniques for MIS, the surgeon has to go through a learning curve.[45-47] This requires the local surgeon to travel and get trained or to invite a specialist surgeon to the hospital as a mentor. As a result, it imposes a burden in terms of time (scheduling patients only when the specialist surgeon is available) and logistics (such as travel, stay and cost-per-day). A tele-mentoring technology for MIS could address the associated problems as both the operating and specialist surgeons need not to be present in the same place. It is also worth noting that in developing economies and small countries, a regional shortage of a surgical sub-speciality may arise within a country due to uncontrollable geo-political factors.[48] An imbalance of surgeons' inflow and outflow may affect surgical services.[49,50] In such cases, tele-mentoring technology for MIS could facilitate surgical knowledge transfer across geographical boundaries.[51]

For surgical tele-mentoring, there are several conceptual frameworks and learning theories.[52,53] Integration of the proposed technology in a structured surgical tele-mentoring curriculum would require engagements on four fronts.[51,54-56] First, as a prerequisite, the mentor apart from having surgical and educational expertise, needs to be trained on using the interfaces of the proposed tele-mentoring framework provided at the remote location. On other hand, the mentee should be able to understand the augmented surgical tool motions visualised on the operating field and replicate it. Second, as the proposed tele-mentoring framework is introduced as a new teaching modality, it should be tailored to suit the surgical setting. It would also require simulation based training and orientation of the proposed tele-mentoring framework. Third, as part of a curriculum, the curriculum components should focus on the technology including communication and troubleshooting. The mentor–mentee need to have a structured method of communication. For example, if a tool motion is demonstrated by the mentor along with audio cues, as reciprocal the mentee should move the tools and stop when needed. In addition to a standardised lexicon, protocols would be required to troubleshoot in case of obstacles to ensure smooth communication. Finally, on assessment methods fronts, apart from traditional methods (360-degree feedback and video based review), the proposed telemedicine technology can log and assess the way mentor wanted to move the tool and the way mentee moved it.

The future work for further improving the tele-mentoring framework will be geared towards three main aspects. First, the tele-mentoring framework tracks the scope poses and incision points and uses the information to generate a virtual 3D environment of the surgical field. However, in certain MISs, such as NOTES[57,58] or single incision surgery with actuated scopes and instruments,[59,60] the current tracking setup is not sufficient due to occlusion causes in the line of sight of the optical tracking system. Additional tracking mechanisms,[61] such as electromagnetic tracking systems (e.g., Patriot™ by Polhemus), ultrasonic sensors[62,63] or mechanical arms with inbuilt gimbal mechanism[64] need to be integrated with the tele-mentoring framework. This will assist to track (a) poses of the camera and (b) positions of the incision points or even the poses from where instruments exist flexible endo-luminal cannulas inside the patient's body. Second, the current implementation facilitates transfer of surgical field and augmented data in the form of visual cues. Another aspect, which is as crucial as visual cues, is the exchange of audio between the operating and mentoring surgeons.[54,65] The future iteration of the tele-mentoring framework will need to have audio and visual cues transferred over the network in synchronisation. This could be achieved by using audio codecs such as advanced audio coding with RTMP server. Another option is to replace RTMP with webRTC, which internally uses Secure Real-time Transport Protocol.[66] The protocol adds sequence numbers/time stamps/unique stream IDs, which is used to ensure synchronisation between audio and video streams. We also plan to optimise the network components and test it across multiple networks. Finally, clinical studies will be required to assess the knowledge transferred using the tele-mentoring framework, especially with respect to the motion of augmented surgical tools, and its applicability in different surgical sub-specialities.[51,67]

5 | CONCLUSION

The developed framework for tele-mentoring shares information of a MIS environment inside an operating room with a remote location over the network. At the remote location, the remote surgeon comprehends this information and mentors the operating surgeon by providing visual cues over the network. These visual cues comprise of motion of augmented instruments overlaid on the surgical field. The cues assist an operating surgeon to perform the manipulation of surgical instruments required during the MIS.

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CONFLICT OF INTEREST

The authors of this submission have no affiliations with or involvement in any organisation or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest and expert testimony or patent-licencing arrangements) or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

AUTHORS CONTRIBUTION

The engineering team developed the prototype of the tele-mentoring framework. Jhasketan Padhan designed the architecture of the tele-mentoring framework, integrated the modules together into the prototype and contributed to manuscript editing. Nihal Abdurahiman conceptualised, developed and tested the core processing and GUI modules of the framework. May Trinh and Zhigang Deng conceptualised, developed and tested the user interface module and contributed to manuscript editing. Elias Yaacoub, Aiman Erbad and Amr Mohammed conceptualised, developed and tested the networking modules and contributed to manuscript editing. The clinical team comprising of Shidin Balakrishnan, Mohamed Kurer, Omar Ali and Abdulla Al-Ansari provided input from the surgical point-of-view to the manuscript, perform literature search and provided revisions of the manuscript. Dehlela Shabir and Nikhil V. Navkar led the manuscript writing, data collection, testing of the framework and revisions.

DATA AVAILABILITY STATEMENT

Research data not sharable.

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