User and Network Interplay in Internet Telemicroscopy [*]

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ABSTRACT

Remote access of electron microscopes over the Internet (i.e., Telemicroscopy) is a unique network-dependent immersive multimedia application. It demands high-resolution (2D and 3D) video image transfers with simultaneous real-time mouse and keyboard controls. Consequently, user Quality of Experience (QoE) is highly sensitive to network bottlenecks caused by cross-traffic congestion and network faults. Further, improper user control while reacting to impaired video caused due to network bottlenecks could result in physical damages to the microscope that are prohibitively expensive to fix. Hence, it is vital to understand the interplay between: (a) the user keyboard/mouse actions (i.e., TCP control traffic) towards the microscope and (b) the corresponding network reactions for transport of microscope video images (i.e., RTP media traffic) towards the user. In this paper, we present an analytical model for characterizing *user* and *network* interplay during Telemicroscopy sessions in terms of *demand* and *supply* interplay principles of economics, respectively. To study the trends of the model parameters, we use data obtained from QoE experiments conducted on a Telemicroscopy testbed involving actual users as well as both LAN and WAN network paths. Also, we describe an application called Remote Instrumentation Collaboration Environment (RICE) we are developing that leverages our user and network interplay characterization studies to provide optimum user QoE and also reliably support Internet Telemicroscopy.

1. INTRODUCTION

Increased access to high-speed networks has made sharing of computer-controlled scientific instruments such as microscopes and telescopes widely-feasible over the Internet. There are already several shared instrumentation initiatives being led by OSCnet at the regional-level and Internet2-Abilene at the national-level. The initiatives include:

- The Ohio State University's CAMM-VIM program [1], which uses OSCnet to allow remote industry (e.g. Timken) and defense-lab (e.g. Air Force Research Labs) collaborators to access their collection of the world's most powerful scanning/transmission electron microscopes,
- Gemini Observatory [2], which uses Internet2-Abilene to allow remote users to manipulate their twin telescopes, and
- NanoManipulator [3], which uses Internet2-Abilene to allow remote control and visualization of images from their scanning probe microscopes.

Earlier studies that have developed novel applications for user control in remote instrumentation sessions and that have evaluated performance of remote instrumentation over the Internet can be found in works such as [4], [5], [6] and [7].

Allowing remote access to electron microscopes over the Internet (i.e., Telemicroscopy) has several advantages. Electron microscopes are valuable and expensive equipment that are worth $450,000 - $4 Million. They require significant investment in staffing for operation and maintenance. Telemicroscopy allows remote users to utilize these microscopes during times when the microscopes are not being used by local users. Thus, it provides easy access to users who cannot afford such equipment and also provides a return on investment (ROI) opportunity for the microscopy centers that charge on hourly-usage basis. Telemicroscopy helps in education and hands-on training of latest microscopy technologies for remote users. It also enables multiple remote researchers, each with unique expertise, to jointly collaborate in analyzing samples such as metals and tissues. All of the above advantages, especially the training and collaboration possibilities, drastically shorten the development process involved in innovations related to materials modeling, biological specimens' analysis for cancer research, etc., while improving user convenience and significantly reducing costs.

Assuming a remote user's sample has been shipped to a microscopy center and has been loaded into a microscope, there are two popular use-cases of Telemicroscopy: (i) *Tele-observation*, where a remote user only views real-time (2D and 3D) microscope video images and directs a user (e.g., over a telephone) physically present at the microscope to perform all the control actions, and (ii) *Tele-operation*, where a remote user views the microscope video images and also controls the microscope in real-time. The first use-case is preferred in cases where the remote user is not familiar with the microscope functionalities. It is also preferred if the intermediate network path between the user and the

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microscope has bottlenecks due to cross-traffic congestion and network faults. These network bottlenecks could cause impaired video images at the user that lead to improper user control of the microscope's mechanical moving parts. Such improper user control may ultimately result in physical equipment damages that are prohibitively expensive to fix. The second use-case is preferred for both local and remote users in cases where human presence around the sample could cause undesirable effects. For example, human presence increases ambient temperature, which alters properties of materials being analyzed at sub-angstrom levels on the microscope.

In order to facilitate the Telemicroscopy use-cases, there are several solutions being used in practice. The most commonly used solution is the PC-based Virtual Network Computing (*VNC*) solution that is incorporated in applications such as Ultra-VNC and Microsoft Remote Desktop. It requires pre-installed software at both the microscope and user ends. VNC uses raw or copy-rectangle or JPEG/MPEG encoding [8] for video image transfers and TCP for keyboard and mouse control traffic. The compression latency of VNC is dependent on factors such as the system CPU speed, other-application task loads, and video card capabilities, at both the microscope and user ends. If these factors adversely influence compression latency levels, they hamper user productivity and thus degrade user QoE. Alternately, a hardware-based Keyboard, Video and Mouse over IP (*KVMoIP*) solution (e.g. ThinkLogical, Avocent) is preferred for overcoming such compression latency bottlenecks. It does not require pre-installed software. However, a pair of encoder and decoder appliances need to be installed at the microscope and user ends, respectively. KVMoIP uses dedicated FPGAs for rapid encoding of video image transfers and a dedicated CPU for handling of keyboard and mouse control traffic.

In this paper, we study the complex inter-play characteristics between the user and the network during Telemicroscopy sessions. We also describe an application we are developing that leverages our study to cope with network bottlenecks and additionally promotes multi-user Telemicroscopy collaboration. More specifically, our unique contributions can be summarized as follows: First (in Section 2), we present an analytical model for characterizing *user* and *network* interplay during Telemicroscopy sessions in terms of *demand* and *supply* interplay principles of economics, respectively. Next (in Section 3), we describe the design of a Telemicroscopy testbed on which several QoE experiments were performed featuring actual users using the VNC and KVMoIP solutions on both LAN and WAN network paths. Next (in Section 4), we discuss the results of the QoE experiments that show the trends of the different session model parameters. Finally (in Section 5), we describe an application called Remote Instrumentation Collaboration Environment (*RICE*) we are developing that leverages our user and network interplay characterization studies to provide optimum user QoE and also reliably support Internet Telemicroscopy. Section 6 concludes the paper and suggests future work.

2. TELEMICROSCOPY SESSION MODEL

In this section, we first describe the parameters involved in a typical Telemicroscopy session. Following this, we model their interactions in different system states borrowing the supply and demand terminology from economics.

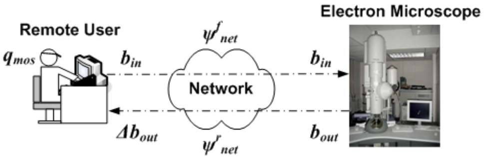


Figure 1: Basic Telemicroscopy system

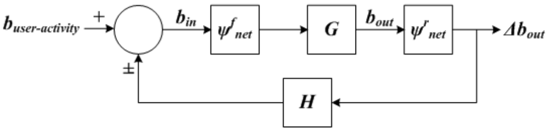


Figure 2: Closed-loop control system representation

2.1 System Description

Figures 1 and 2 show a basic Telemicroscopy system and its closed-loop control system representation with the different session parameters, respectively. The remote user physically controls the functions of the microscope by interacting with a Graphical User Interface (GUI) application (shown in Figure 3) using keystrokes and mouse moves/clicks via VNC or KVMoIP (console). The GUI application actually resides on a computer directly connected to the microscope's video output and control input ports. It allows a user to view real-time video of the microscope's moving parts such as the stage position and also allows for control of the microscope functions such as lens focusing and magnification levels.

Let b_{action} denote the control (i.e., TCP) traffic rate due to keystrokes and mouse moves/clicks to accomplish a particular microscope function. The user-activity during a session involving n microscope functions ($b_{user-activity}$) that results in an average TCP control traffic rate (b_{in}) input to the system can be denoted as shown in Equation (1).

$$b_{user-activity} = \sum_{i=1}^{n} (b_{i^{th}action}) \tag{1}$$

For such an input, the average video image transfer rate i.e., RTP media traffic output at the microscope end (b_{out}) can be denoted as shown in Equation (2).

$$b_{out} = \psi^f_{net} G(b_{in} + b_{seed}) \tag{2}$$

where, ψ^f_{net} corresponds to the network connection quality between the user and the microscope; G corresponds to the input-output scaling factor which is unique for a microscope function; b_{seed} corresponds to the rate at which periodic intra-coded frames (I-frames) are sent from the encoder (at the microscope) to the decoder (at the user) for quick image refresh upon recovery from network partition events during a session.

Figure 3: GUI application for controlling Microscope functions

Although b_{out} is sent from the microscope, there are two network factors that could degrade the average video image transfer rate at the user end (Δb_{out}). The first factor corresponds to the network connection quality of the reverse path, i.e., between the microscope and the user (ψ^r_{net}). The second factor corresponds to the end-to-end available bandwidth in the intermediate network path. If adequate end-to-end available bandwidth is provisioned, Δb_{out} will be equal to b_{out}; otherwise, Δb_{out} is limited to the bandwidth at the bottleneck hop. Hence, Δb_{out} can be expressed as shown in Equation (3).

$$\Delta b_{out} = \psi^r_{net} min(b_{out}, min_{i=1..hops} b_{i^{th}hop}) \tag{3}$$

The degradation of Δb_{out} manifests to users as video signal impairments such as frame freezing, blurriness and tiling [9]. Based on the positive or negative Δb_{out} feedback received at the user end from the microscope, the subsequent user behavior determines the session state. Considering H to be system-state control parameter dependent on the user behavior, we can express b_{in} as shown in Equation (4).

$$b_{in} = b_{user-activity} - H\Delta b_{out} \tag{4}$$

Using substitutions in Equations (1) to (4), we can derive the closed-loop transfer function of a Telemicroscopy system as shown in Equation (5).

$$\frac{\Delta b_{out}}{b_{user-activity}} = \frac{G\psi^f_{net}\psi^r_{net}}{1 \pm G\psi^f_{net}\psi^r_{net}H} \tag{5}$$

Ultimately at the end of a session, the overall user QoE (q_{mos}) will depend on both the effort a user had to expend to perform n actions i.e., $b_{user-activity}$ and the perceivable video image quality i.e., Δb_{out} during those actions. Hence, q_{mos} can be expressed as shown in Equation (6).

$$q_{mos} = f(\underbrace{b_{user-activity}}_{Demand}, \underbrace{\Delta b_{out}}_{Supply}) \tag{6}$$

From Equation (6), we can make an analogous comparison of $b_{user-activity}$ and Δb_{out} to the "demand" and "supply" terminology used in Economics, respectively. In traditional Economics, an increase in demand levels for a commodity causes an increase in supply levels of the commodity. This in turn increases the demand - as increased supply in large-numbers generally drives down the overall commodity price. As long as both the demand and supply increase hand-in-hand by deriving reinforcement from each other, the economy (analogous to q_{mos}) is considered to be in a productive state. However, this is not always the case in the demand and supply reinforcement effect seen in Telemicroscopy with respect to q_{mos}. The overall network health in both the forward and reverse paths (ψ_{net}) adds complexity in the relationship of the demand and supply variables as elaborated in the next sub-section, which severely affects the q_{mos}.

As a note, the above Telemicroscopy session model can be applied for both Tele-observation as well as Tele-operation use-cases. Recall that the Tele-operation use-case employs inband TCP-based control traffic towards the microscope, whereas, Tele-observation use-case employs an out-of-band voice channel (e.g., a telephone) for directing control messages to a local user at the microscope. If we assume a reliable voice channel exists between the two users and that the local user is responsive enough that the remote user does not perceive annoying control delays, the model is identical for both the use-cases.

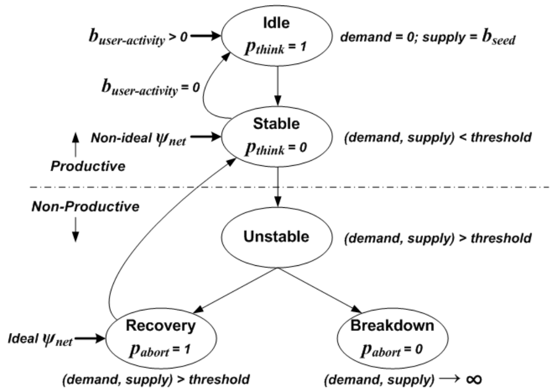


Figure 4: Telemicroscopy system state transitions

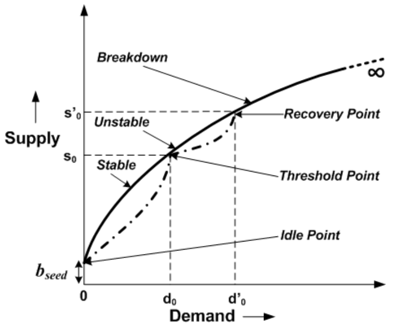


Figure 5: Telemicroscopy system performance at different supply and demand conditions

2.2 System States

We now explain the interactions of the Telemicroscopy session parameters due to user behavior that affect the H parameter. The changes in the H parameter influence the ± sign (positive or negative feedback) of the Equation (5) denominator which in turn causes the different system state transitions shown in Figure 4. Initially, the system is in the "Idle" state when the user is inactive with a probability p_{idle} and the microscope GUI application is operational. In the Idle state, the demand is zero and the supply equals b_{seed} as shown in Figure 5. The Telemicroscopy session begins upon user-activity, and the demand and supply steadily increase. Assuming ideal ψ_{net} conditions at a given time t, the system attains a "Stable" state where the demand and supply are below the system's optimum performance threshold point (s$_0$, d$_0$). In this state, the user is successfully controlling the microscope functions and is being productive. We can now say that H is causing negative feedback in the system. At random times in this state, it is possible that a user will still be in session but idle in terms of control - presumably due to a thought process driven by a visual inspection of a sample's area of interest. Such an inactive user behavior brings the system back to its Idle state where the system is still productive. During such user inactivity times under ideal ψ_{net} conditions, we refer to p_{idle} as p_{think} as shown in Equation (7).

$$p_{idle}(t) = \begin{cases} p_{think}, & \text{if ideal } \psi_{net}(t); \\ p_{abort}, & \text{if non-ideal } \psi_{net}(t) \end{cases} \tag{7}$$

If suppose the ψ_{net} were to change to non-ideal conditions due to network bottlenecks caused by cross-traffic congestion and network faults, the system enters an "Unstable" state. Here, the demand and supply rapidly increase beyond the system's optimum performance threshold point. This is because, the user in this system state experiences QoE degradation affects (e.g. frame freeze) that force him to misjudge his control actions that result in *unwanted* supply. This is subsequently followed by a retry of the previous actions before the unwanted supply transfer completes, which further increases the demand and the QoE degradation affects and so on. Soon, the system becomes non-responsive to the increasing demand, and is pressured into handling large volume of unwanted supply that is introduced from the microscope end. It is important to note that - although, the demand and supply rapidly increase hand-in-hand beyond the threshold point, the system is non-productive. We can now say that H is causing positive feedback in the system. If the user persists in his retry demand behavior, the system soon advances to a "Breakdown" state where the demand and supply tend to ∞. However, if the user aborts his actions and becomes idle at a recovery point (s'_0, d'_0), the system transitions into a "Recovery" state. During such user inactivity times under non-ideal ψ_{net} conditions, we refer to p_{idle} as p_{abort} as shown in Equation (7). During the Recovery state, the demand and supply gradually tend towards the system's optimum performance threshold point. Once the ψ_{net} returns to ideal conditions (e.g. due to reduced cross-traffic congestion or stabilization of the impulsive demand and unwanted supply), the system regains its Stable state and becomes productive again.

3. TELEMICROSCOPY TESTBED

3.1 Testbed Setup

For setting up the Telemicroscopy testbed, we collaborated with The Ohio State University's Center for Accelerated Maturation of Materials (OSU CAMM) as part of their Visualization, Instrumentation and Modeling (VIM) program [1]. The testbed featured four different network connections between the remote user console and the GUI application PC: (i) Direct GigE (ii) Isolated LAN (iii) Public LAN, and (iv) WAN. The Direct GigE connection had a Cisco GigE switch connecting the GUI application PC and the remote user console, which were in adjacent rooms. This connection represents the setup for avoiding users to be physically present at the microscope, especially when human presence around a sample is undesirable as explained in Section 1. The Isolated LAN connection was setup by including the CAMM's Cisco Catalyst 2924 switch to the Direct GigE connection. This connection represents Telemicroscopy for users in the same LAN as the microscopes, but in different lab rooms. The Public LAN connection was setup by including three additional Cisco Catalyst 2924 switches located at neighboring buildings, to the Isolated LAN connection. This connection represents Telemicroscopy for users working from different LANs and different lab rooms. Finally, the WAN connection was setup as shown in Figure 6 via OARnet's regional optical fiber network viz., OSCnet (2.5 Gbps backbone) between OSU CAMM and the Ohio Supercomputer Center (OSC). This connection represents Telemicroscopy for users at remote sites on the Internet.

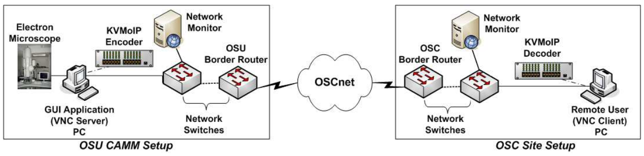


Figure 6: Telemicroscopy testbed setup

3.2 Test Cases and Measurements

The test cases involved performing basic and advanced actions by actual users in Telemicroscopy sessions over the different network connections. The basic Telemicroscopy sessions involved a set of "Novice" users, each performing a set of sequential tasks as follows: *Task-1*: Move view from one location on the surface of sample material to another location, *Task-2*: Focusing for high-resolution imaging, and *Task-3*: Change the quad-screen to a single screen and grab a high resolution image. The advanced Telemicroscopy sessions involved a set of relatively "Expert" users, each performing a set of relatively more intense sequential tasks as follows: *Task-1*: Eucentric Height Adjustment - stage movement in the Z-direction, *Task-2*: Beam Modulation - column alignment for best image, and *Task-3:* Focusing for high-resolution imaging.

During execution of the test cases, both objective and subjective measurements were collected. The objective measurements correspond to passive measurements of the control traffic (b_{in}) and video traffic (Δb_{out}) collected using the popular TCPdump packet sniffing tool. The subjective measurements correspond to the user QoE measurements collected using the popular Mean Opinion Score (MOS) ranking technique [10]. In this technique, at the end of each test case, the user is asked to rate his/her perceived QoE (q_{mos}) on a subjective scale of 1-5; [1, 3) range being *Poor* grade, [3, 4) range being *Acceptable* grade and [4, 5] range being *Good* grade.

4. PERFORMANCE ANALYSIS

In this section, we discuss the results of the QoE experiments and explain the trends of the different session model parameters under different network conditions.

4.1 Network Connection and User QoE

First, we analyze the impact of network connection quality on the user QoE i.e., q_{mos} in a Telemicroscopy session. Figure 7 shows the average q_{mos} comparison between the Novice and Expert users for different network connections. For both types of users, we can observe that the q_{mos} rankings decrease notably with the decrease in network connection quality. The MOS = 5 q_{mos} rankings of the Novice and Expert users' while using the direct GigE connection indicates "at-the-microscope" QoE. Expectedly, for the other network connections, we can see that Novice rankings are relatively more liberal than Expert rankings due to the inherent intensity of the actions involved. The q_{mos} in the case of Isolated LAN and Public LAN are comparable. Interestingly, the MOS rankings for the WAN connection are in the acceptable grade (3 < MOS < 4), suggesting that user QoE in Telemicroscopy is highly sensitive to network health fluctuations caused by cross-traffic congestion.

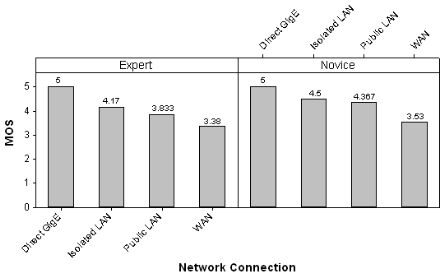


Figure 7: MOS (q_{mos}) rankings comparison

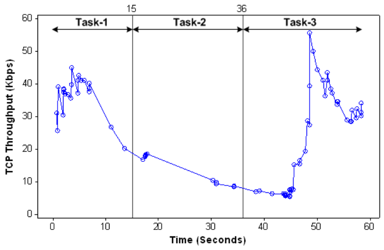


Figure 8: Control traffic (b_{in}) during an Expert session on direct GigE network connection

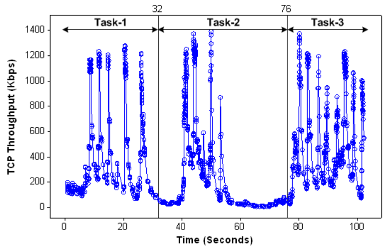


Figure 9: Control traffic (b_{in}) during an Expert session on public LAN network connection

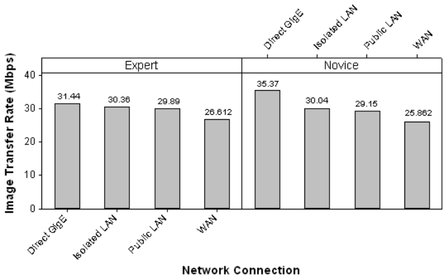


Figure 10: Image transfer rate (Δb_{out}) comparison

4.2 Network Connection and User Control

Next, we characterize how the network connection quality impacts the trends of user control behavior i.e., b_{in}. Figures 8 and 9 show the instantaneous b_{in} throughput levels during an Expert session on direct GigE and public LAN connections, respectively. The throughput levels clearly show the amount of user effort required for accomplishing each of the three tasks of the session. Another notable observation is that user effort is considerably less ($\lceil b_{in} \rceil \approx$ 60 Kbps) in the case of the direct GigE connection as compared to the user effort ($\lceil b_{in} \rceil \approx$ 1400 Kbps) on the Public LAN connection. Also, the throughput trends are significantly less dense in case of the direct GigE connection as compared to the Public LAN connection. Due to space constraints, we do not show the throughputs for the WAN network connection, where the Expert user effort was the most when compared to the other connections ($\lceil b_{in} \rceil \approx$ 2000 Kbps).

We note that such an inverse relationship between the network connection quality and user control effort is a driver for the "congestion begets more congestion" phenomenon, where a user expends more effort (i.e. mouse moves/clicks and keyboard strokes) on poor network connections, which cumulatively adds to the congestion already inherent in the poor network connections. The nature of the "Unstable" and "Breakdown" states and their transitions explained in Section 2.2 can be attributed to the occurrence of this particular phenomenon with different intensity levels. The intensity levels are based on the instantaneous network connection quality and the impulsive user reactions to video signal impairments such as frame freezing.

4.3 User Behavior and Video Image Transfers

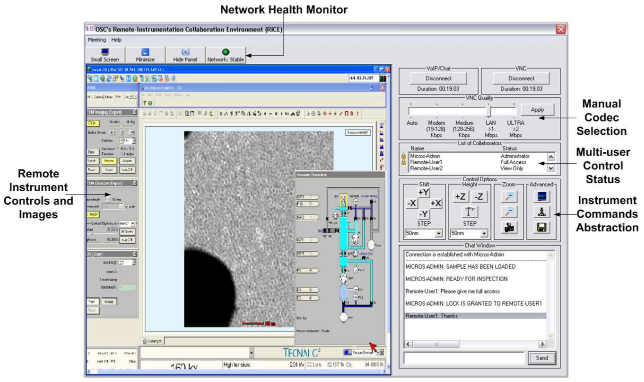
Lastly, we analyze how a user's control behavior and network conditions impact the video image transfers from the microscope at the user end i.e., Δb_{out}. Figure 10 shows the Δb_{out} comparison between the Novice and Expert for the different network connections. Cross-referring to the MOS = 5 results shown in Figure 7 for the direct GigE network connection, we can observe that obtaining an "at-the-microscope" user QoE requires end-to-end available bandwidth in excess of 30 Mbps between the user and the microscope ends.

However, it is important to note that the average image transfer rates in Telemicroscopy can vary based on the microscope functions and user activity. Thus, they may not always be in the range of 30 Mbps. The reason for the high bandwidth consumption in our experiments can be attributed to the nature of the quad-video panel images in the GUI application shown in Figure 3. Such a nature of video may not be required in every user session. For example, we can envision a session where the user is mainly plotting graphs, editing parameters and occasionally viewing the sample stage video feed while analyzing a sample. For such a session, the end-to-end available bandwidth requirement to achieve "at-the-microscope" user QoE may be considerably less.

5. RICE PROTOTYPE

In this section, we describe the Remote Instrumentation Collaboration Environment (*RICE*) prototype application (shown in Figure 11) we are developing to effectively cater the Tele-observation and Tele-operation use-cases. It is based on the VNC solution but has custom hardware specifications to minimize compression latency bottlenecks. The goal is to make RICE available to instructors and researchers for training students and/or conducting research on advanced computer-controlled scientific instruments (e.g. electron microscopes, NMRs, telescopes) from remote locations on the Internet.

RICE is being designed to leverage our user and network interplay characterization studies presented in this paper to provide optimum user QoE and also reliably support remote



Connection is established with Micros-Admin

MICROS-ADMIN: SAMPLE HAS BEEN LOADED

MICROS-ADMIN: READY FOR INSPECTION

Remote-User1: Please give me full access

MICROS-ADMIN: LOCK IS GRANTED TO REMOTE-USER1

Remote-User1: Thanks

Figure 11: RICE prototype in an active session

instrumentation including Internet Telemicroscopy. Specifically, we are evaluating and integrating control-feedback based adaptation schemes [11] that dynamically optimize the video image quality based on the user QoE tradeoffs - while coping with the network health fluctuations. The optimization includes techniques for adjusting video codec selection and codec bit rate settings, which are triggered by online analysis of the user QoE trends seen in the control traffic flows. As for reliability, current GUI applications provided by instrument vendors do not assume remote users controlling the instruments. Hence, user actions in unstable states are not checked and blocked. Our strategy is to identify times of non-ideal network health conditions that may lead to unstable system states and proactively alert the user and also block user actions on the RICE GUI if needed. Doing so, we can protect the system from imminent breakdown that can be prohibitively expensive to fix.

In addition, RICE is being designed with a "lock-passing" feature for user control management. This feature is useful when multiple users are collaborating simultaneously by passing control amongst each other on an instrument while training or conducting joint research. As shown in Figure 11, RICE provides VoIP, text chat, instrument command abstraction and annotation features for enabling multiple users in a remote instrumentation session to effectively communicate with each other. Further, it is being designed to allow workflows that enable image archiving, offline/online image processing and image retrieval for managing video image datasets collected during remote instrumentation sessions.

6. CONCLUSION

In this paper, we modeled and characterized the complex interplay between the user control behavior and network video image transfer performance in Internet Telemicroscopy sessions. Our Telemicroscopy session model borrowed demand and supply terminology from Economics and identified the various system states (Idle, Stable, Unstable, Breakdown and Recovery) and their transition conditions. The transition conditions were found to be primarily driven by time-varying user behavior and connection quality of the network path between the user and the microscope.

Our major findings from the performance analysis of Telemicroscopy sessions involving actual users as well as both LAN and WAN network paths are: (a) user QoE is highly sensitive to network health fluctuations caused by cross-traffic congestion, (b) both the user's control traffic throughput and microscope's video image transfer rates need to be sustained at optimum levels throughout the session for superior user productivity and for preventing the system to enter into unproductive states (i.e., Unstable and Breakdown states), especially during advanced microscopy actions, and (c) the real-time control and video image transfer traffic is extremely computation and bandwidth intensive, and may require in excess of 30 Mbps end-to-end available bandwidth per session for achieving "at-the-microscope" QoE. Thus, Telemicroscopy is a very demanding network-based multimedia application and is comparable to other applications of its class such as Internet Gaming, High-definition Videoconferencing and IPTV.

Our future work is to develop the RICE prototype into a full-feature open-source application to meet the remote instrumentation needs of the scientific community. Also, given that Telemicroscopy is extremely bandwidth intensive, we plan to study network management issues for handling large-scale Telemicroscopy traffic without impacting commonly co-existing VoIP, videoconferencing and file transfer applications.

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