Article

Robotic Remote Controlled Stereo Slit Lamp

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Purpose: Our purpose was to develop a robotic remotely operated stereo slit lamp system allowing three-dimensional stereo viewing and recording of the patient's examination via local area network, Internet, and satellite.

Methods: A commercial slit lamp was modified to accept motors and servos to permit control of all optical and mechanical components of the device. The custom graphical user interface with dual high-resolution real-time stereoscopic imaging, control/position indicators, overview video, and audio were transmitted via local area network, Internet, and satellite. Under University of Miami Institutional Review Board authorization, Internet connectivity enabled multiple examiners to simultaneously view and control the slit lamp and to collaboratively discuss diagnosis and treatment options. The remote clinicians used a tablet, laptop, or desktop computer to view and control the slit lamp.

Results: The network, Internet, satellite-connected system was controllable from the United States, Europe, and Canada while acquiring high-resolution, real-time video in all subjects. Control of the slit lamp through Ethernet, WiFi, and 4G exhibited total system latencies of 464 ± 58, 483 ± 64, and 870 ± 66 milliseconds when transmitting within the continent, and Ethernet control exhibited a latency of 606 ± 130 milliseconds when transmitting between continents. High- and low-magnification images of healthy volunteers were acquired by a remote clinician.

Conclusions: The robotic remotely operated stereo slit lamp system allows three-dimensional stereo viewing and recording of the patient's examination via local area network, Internet, and satellite.

Translational Relevance: The robotic remotely controlled stereo slit lamp system enables remote examination of human subjects.

Introduction

In ophthalmology, a slit lamp biomicroscope is generally used as a fundamental diagnostic device. The common approach to teleophthalmology is to capture still or video images of the patient, where the images are acquired by a technician who is familiar with the functions and purpose of the slit lamp.[1] These images are then sent to a different location to obtain a diagnosis from a specialist. Although well-trained technicians are often able to acquire pertinent images with a photo slit lamp, sometimes the images captured do not contain the details that clinicians need, especially when a thin slit is required (i.e., to detect a small patch of endothelium damage or cell flare present in the anterior chamber). In such a circumstance, diagnosis could be aided by remote examination from an ophthalmologist or optometrist. Given the limitation in current teleophthalmic slit lamp examination techniques, there is a significant need for the development of a robotized remotely operated slit lamp biomicroscope.

A remote controllable slit lamp has been discussed,[2] but only a paper-based design (paper model)

has been published formally. It describes remote controls of the slit lamp vertical, horizontal, and height adjustments and telephony, but it does not describe or show that the remote operator can alter the angle between the stereomicroscope and the slit lamp, a crucial function for adequate ophthalmic examination. Neither does the system provide the remote operator control of the slit parameters (height, width, intensity) and control of the biomicroscope magnification changer: four functions that are an absolute necessity for adequate examination of details in the structures of the eyelid, eyelashes, conjunctiva, limbus, cornea, anterior chamber (cell/flare), its angle, the iris, and the crystalline lens or artificial intraocular lens (IOL) if the patient had undergone cataract extraction with IOL implantation. In addition, the system described and presented in a conference by the same group[3] does not permit remote three-dimensional (3-D) stereo viewing of the patient's eye, another crucial function for ophthalmologists and optometrists. Stereo viewing is a necessity to discriminate abnormalities in the ocular tissues, and there are many clinical situations in which 3-D stereo viewing may enable an accurate diagnosis (Table 1).

To address these limitations, we developed the first, to our knowledge, robotic remotely controlled stereo slit lamp system, named the RC Slit-Lamp, or RCSL, that allows 3-D stereo viewing. Using this system, under an approved University of Miami Institutional Review Board protocol, subjects' examinations and recordings were performed via local area network, Internet, and satellite.

Methods

Slit Lamp

Although any commercially available slit lamp can be motorized, we used a Zeiss 100 model (Carl Zeiss Meditec, Dublin, CA) having a 6× to 40× Galilean magnification changer, full slit dimensions controls, a tungsten lamp, and a 50/50 beam splitter.

System Requirements

To facilitate remote operation, the operator required electronic control of the illumination slit intensity, slit width, slit height, slit lamp angle, the biomicroscope position (in 3-D space), and the imaging system magnification. Stereo viewing of the patient, an overhead view of the entire system, audio communications, and power stabilization were also required (Table 2).

Table 1. Some Clinical Situations Where 3-D Stereo Viewing May Be Necessary or Particularly Useful

Stereo viewing may be necessary to:

1. Discriminate particle aggregates, abnormal cells, plasma and or hemorrhages, and other moieties, as well as damaged structures in the depth of the eye's transparent tissues such as the cornea, anterior chamber, and the lens.
2. Assess abnormal growth in cases of nevus, tumor, and any tissue thickness abnormalities.
3. Determine if the tube of a glaucoma drainage implant is touching the iris or cornea.
4. Differentiate between retroprosthetic membranes and fibrous membranes that develop across the anterior chamber (e.g., from the trabecular meshwork, iris, etc.).
5. Assess the extent of capsule opacification (anterior or posterior).
6. Determine the tilt of an IOL implant that may occur in pseudophacos in the postoperative period.

Stereo viewing may enable an accurate diagnosis in patients undergoing:

1. Partial deep anterior lamellar keratoplasty.
2. Partial Descemet's stripping automated endothelial keratoplasty.
3. Full thickness penetrating keratoplasty.
4. Supra or intracorneal implant or a keratoprosthesis.

System Description

Any computer can be used to access the desktop of the remote site computer system. The remote site computer system employed a 2.66-GHz processor (I7-920, Intel Core i7 Processor; Intel Co., Santa Clara, CA) and an ATX motherboard (MB-P6TD-D ASUS P6TD Delux Intel X58/SLI & CrossFire X/A Asustek Computer Inc., Taipei, Taiwan) with 6 GB of DDR3-1800 RAM (WB180UX6G9; Super Talent Technology Co., San Jose, CA). The remote site computer provided control of all slit lamp hardware (Fig. 1) via a Universal Serial Bus (USB) through a seven-port USB hub (DUB-H7; D-Link Co., Taipei, Taiwan).

Table 2. Functional Requirements of the RCSL

Required Function	Description
Illumination	
Slit intensity	Continuous adjustment of light intensity
Slit width	Continuous adjustment of slit width
Slit height	Discrete adjustment of slit height
Slit lamp angle	Continuous adjustment of slit lamp angle ($\pm 45°$)
Biomicroscope motion	
Side to side	Continuous adjustment of microscope side-to-side motion
Front to back	Continuous adjustment of microscope front-to-back motion
Up and down (z)	Continuous adjustment of microscope up-and-down motion
Imaging system	
Magnification	Discrete adjustment of microscope magnification (360°)
Cameras (2) high-res	Right and left eye view for stereo reconstruction
Camera (1) low-res	Overhead view of slit lamp and patient
Control and interface	
Computers (2)	One for the remote site and the other for the specialist
Audio communications	Headset for audio communications between sites
Power stabilization	Backup supply for locations without reliable power
Software	Custom software controller with double joystick interface
Stereo viewer	Prismatic system for fusing right and left view images in stereo

Slit Lamp Intensity, Slit Width, Slit Height, and Slit Angle

The slit lamp intensity is controlled by the addition of a direct current/alternating current (DC/AC) controller (MCPC1225A; Crydom Co., San Diego, CA). This control relay is an MC-series proportional controller with 40-140 VAC, a rated current of 35 A, and a proportional load voltage input of 0-5 voltage direct current.

The MCPC1225A control relay is driven by a Parallax microcontroller consisting of a BASIC Stamp Development Board (28150; Parallax Inc., Rocklin, CA), a BASIC Stamp (BS2SX-IC; Parallax Inc.), and a custom-built digital to analog (D/A) converter, where the D/A converter is used exclusively for the DC/AC controller (Figs. 2A, 2B).

Gear systems were fabricated to adapt to the physical mechanisms used to adjust the slit width, slit height, and slit angle. Each gear system was coupled to a servo motor: slit width (Figs. 2C, 2D) (HS-805BB; Hitec RCD USA Inc., Poway, CA); slit height (Figs. 2E, 2F); and slit angle (Figs. 2G, 2H) (HS-7950TH; Hitec RCD USA Inc.) to provide electronic control of the slit width, slit height, and slit angle. The HS-805BB servo has a three-pole motor and a dual ball bearing, and it can generate a maximum torque of 343 ounce-inch. The HS-7950TH servo has a coreless motor and a dual ball bearing, and it can generate a maximum torque of 486 ounce-inch. Each servo is driven by the same custom-built microcontroller discussed previously.

Fixation Light

A light-emitting diode (LED) based fixation system was added to the biomicroscope objective assembly. An annular ring and set screw is used for fixation, and a semi-annular structural assembly containing a total of five ports is capable of holding one LED each. The central LED is coupled with a Poly(methyl methacrylate) (PMMA) light guide, which is aligned so that the center of the output is coincident with the optical axis of the objective. The central LED is powered through the USB of one of the cameras, and a pulsed or blinking LED was chosen to minimize power consumption and to better maintain patient interest (Fig. 3).

Biomicroscope Motion

A NEMA 17 stepper motor and linear stage was coupled to the body of the slit lamp biomicroscope
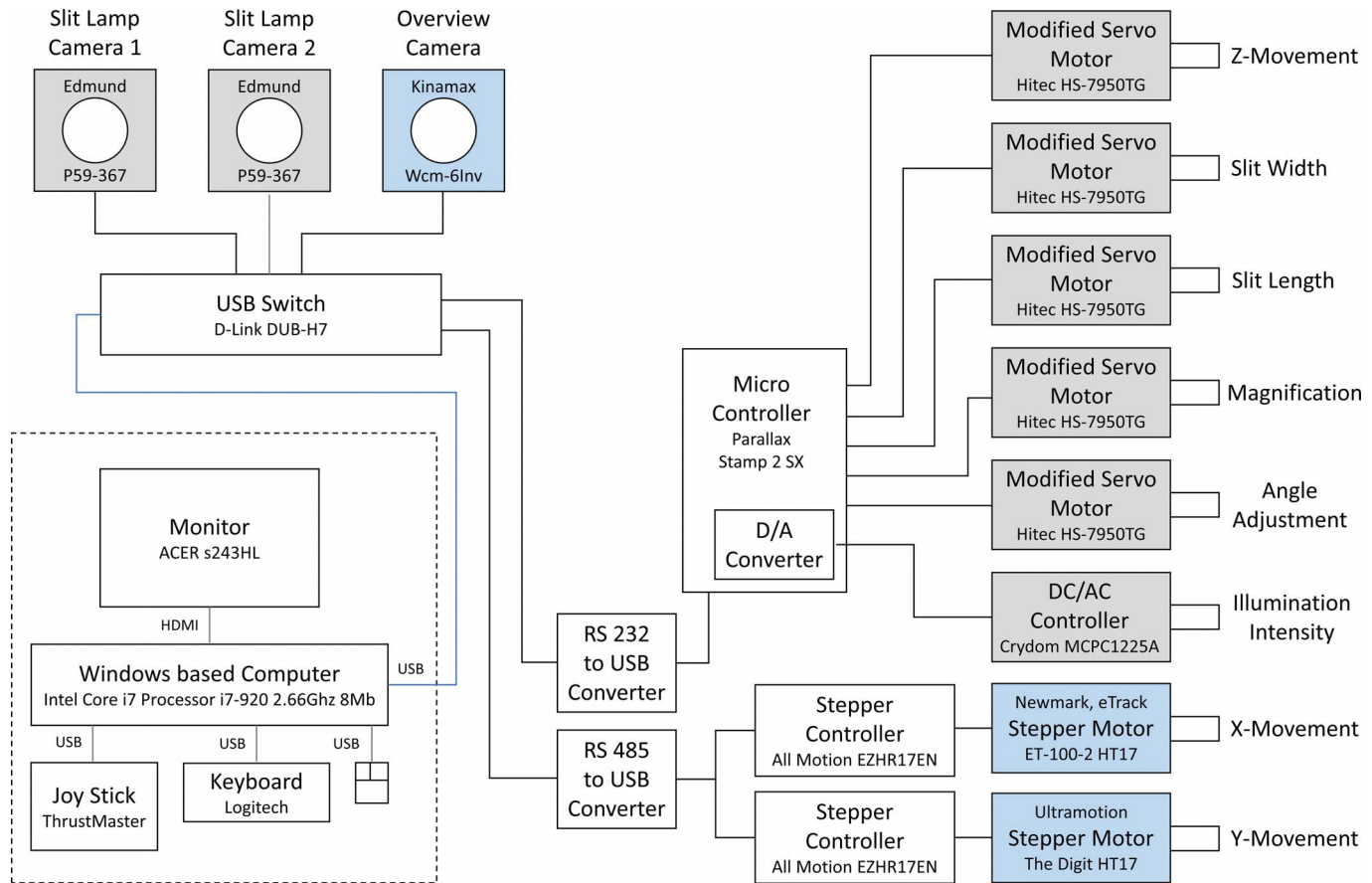
Figure 1. System block schematic diagram of the robotic remote controlled stereo slit lamp.

using a custom-built mechanical interface. A linear actuator (D-A.083-HT17-4-1NO-B/4, The Digit; Ultra Motion Inc., Cutchogue, NY) provided side-to-side motion of the biomicroscope. A rubber spacer was used between the stepper motor and the slit lamp to reduce the amount of torque put on the Acme nut in the linear stage. The Digit is capable of producing up to 75 lb of thrust, has a resolution of 0.00004 in/step, and a range of 4 inches. The Digit is driven by a stepper motor encoder (EZHR17EN; All Motion Inc., Union City, CA). The stepper motor controller is designed to be bolted to the back of the stepper motor. It has dual encoders, operates from 12 to 40 V, and communicates via RS232, RS485, or USB.

A NEMA 17 stepper motor and linear stage (ET-100-2, eTrack; Newmark Inc., Mission Viejo, CA) were coupled to the Digit to provide an orthogonal axis of movement of the slit lamp biomicroscope. The eTrack is capable of carrying a 10-lb load, has a resolution of 0.000009 inch/step, and a range of 2 inches. The eTrack is driven by the same type of

stepper motor encoder used to control the Digit, discussed previously (Figs. 4A, 4B).

A friction-based mechanical system was fabricated to adapt to the mechanism used to adjust the slit height. A small rubber tire was fixed to the spline shaft of a servo (HS-7950TH; Hitec RCD USA Inc.) actuator, and the actuator was fixed to the slit lamp so that the tire remained in contact with the wheel used to adjust slit width. However, when limited by its internal potentiometer, the servo is only capable of 180° of rotation, which is not enough to achieve the full range of motion of the biomicroscope. To overcome this limitation, the internal potentiometer was removed from the servo to provide continuous rotation, where the rotation is then limited by the addition of a different potentiometer (312-9100F-5K; Mouser Electronics, Mansfield, TX) that is mechanically coupled to the body of the biomicroscope (Figs. 4C, 4D). This configuration provides mechanical stops at the limits of the biomicroscope stage. The servo used to drive the up-and-down motion of the biomicroscope is the same type of servo motor system
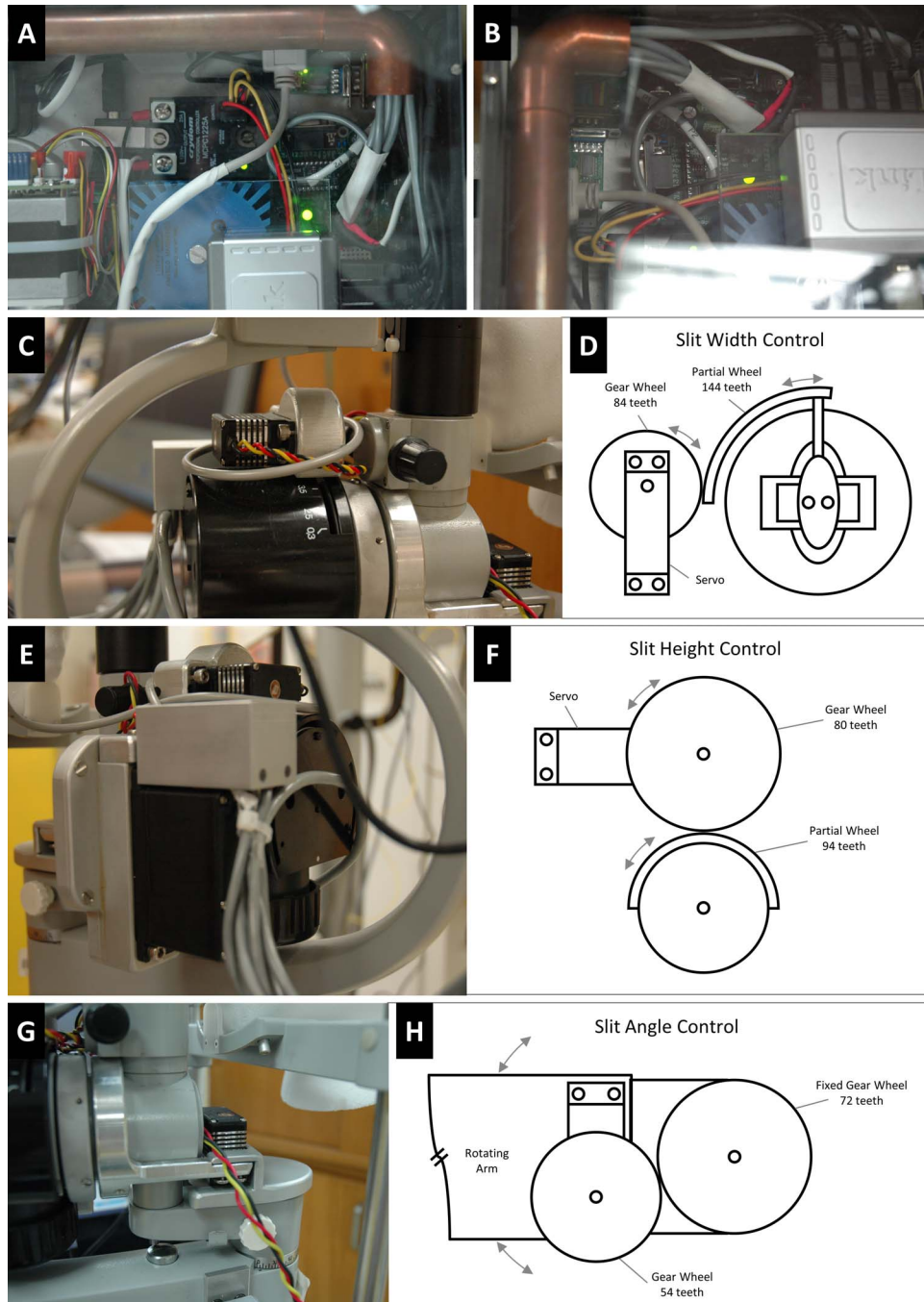
Figure 2. Slit lamp intensity, slit width, slit height, and slit angle actuators and controllers. Control relay for slit lamp intensity adjustment incorporated within the electronics module of the RCSL (A). Microcontroller BASIC stamp shown within the electronics module (B). The servomotor for slit width adjustment was mounted atop the slit lamp assembly (C). Slit width control, gear system (D). Since only 60° of rotation was required, a partial gear wheel was used to actuate the slit width. An 84-tooth gear wheel was used for the servo motor, and the partial gear wheel, if it were whole, would have 114 teeth, providing a gear ratio of 1:1.357. The servo for slit height adjustment was mounted adjacent to the slit lamp assembly (E). Custom brackets were fabricated to achieve a tight form factor. Slit height control, gear system (F). Since only 135° of rotation was required, a partial gear wheel was used to actuate the slit height. An 80-tooth gear wheel was used for the servo motor, and the partial gear wheel, if it were whole, would have 94 teeth, providing a gear ratio of 1:1.175. The servo for slit lamp angle control was mounted atop the axis of rotation of the slit (G). Custom brackets were fabricated to affix the servo inconspicuously, where the gear system is hidden underneath the bracket. Slit angle control, gear system (H). A 54-tooth gear wheel was used for the servo motor, and a 72-tooth gear wheel was fixed to the central column of the slit lamp, providing for ±60° of rotation using a gear ratio of 1:1.333.
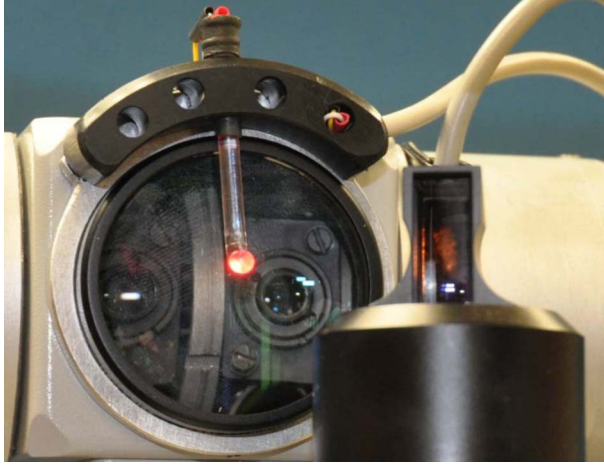
Figure 3. LED-based fixation system is mounted directly to the biomicroscope objective.

used to adjust the slit height. Likewise, the servo is driven by the aforementioned microcontroller.

Imaging System

The detented magnification lens–carrying turret is controlled mechanically with the rotation of a knob, which needs to rotate no more than 360° in one direction. This mechanical system was mechanized by coupling the knob to two servos (HS-5055MG; Hitec RCD USA Inc.) linked end to end. Normally, without special gearing, servos can rotate only 180°, but with two servos combined, 360° of rotation can be achieved (Figs. 5A, 5B). A magnification of 5, 8, 12, 20, and 30 are possible.

Two high-resolution 0.5-inch color CMOS cameras (NT59-367; Edmund Optics, Barrington, NJ) were each coupled mechanically to a single 25-mm diameter, 50-mm focal length, aspherized achromatic
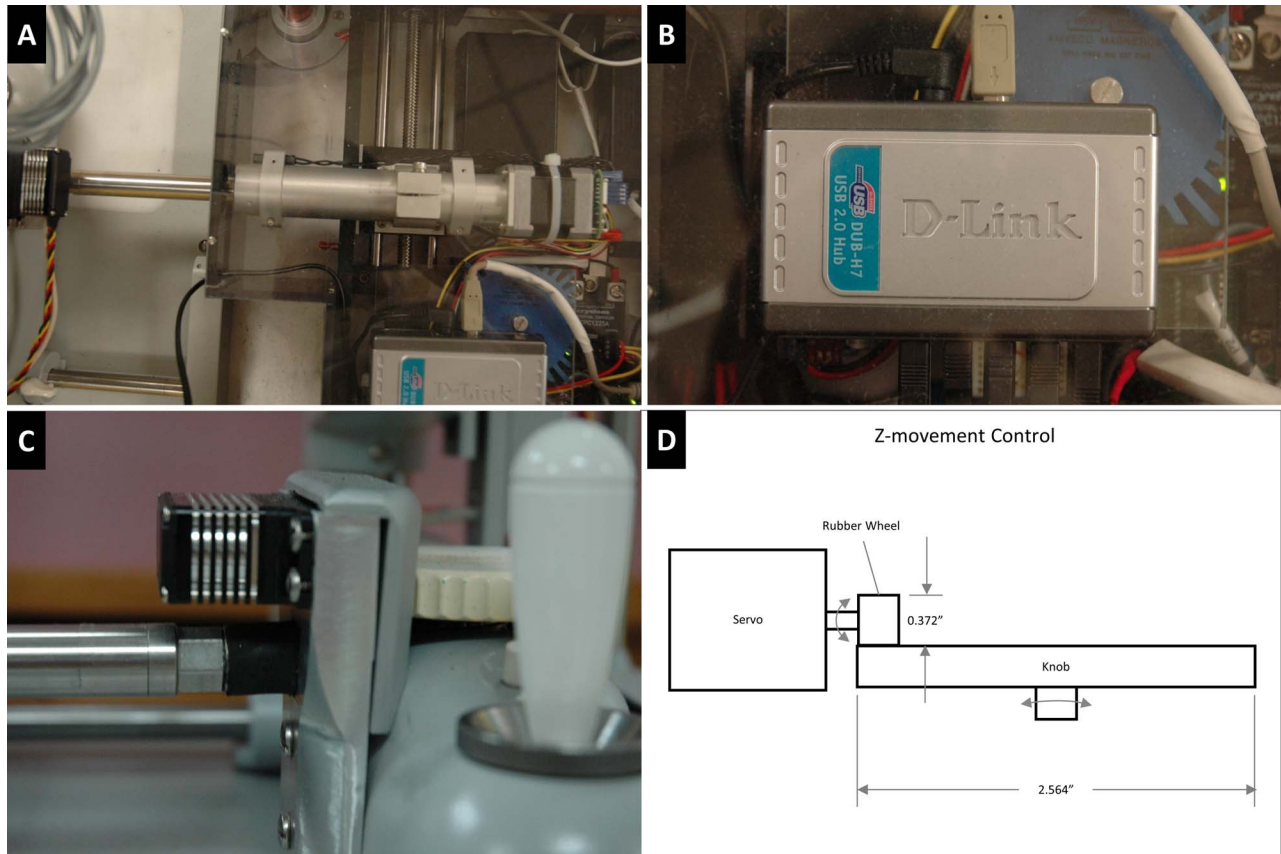

Figure 4. The Digit linear stage for side-to-side motion was affixed atop the e-Track linear stage for front-to-back motion, giving the microscope full x-y motion capabilities, all of which were mounted within the electronics module. The Digit linear stage was fixed to the body of the microscope (A). All control systems, including the x-y translation systems are linked via one single USB hub, contained within the electronics module of the RCSL (B). The servo for up-and-down motion was attached in close proximity to the height adjustment knob, using a custom bracket. This bracket also serves as the connection for the Digit linear stage (C). Slit z-movement control, gear system (D). A 0.372-inch diameter rubber wheel was used for the servo motor, which activates rotation, via friction, of the knob used to adjust the z-position of the slit. With a diameter of 2.564 inches, this gives a gear ratio of approximately 1:7.
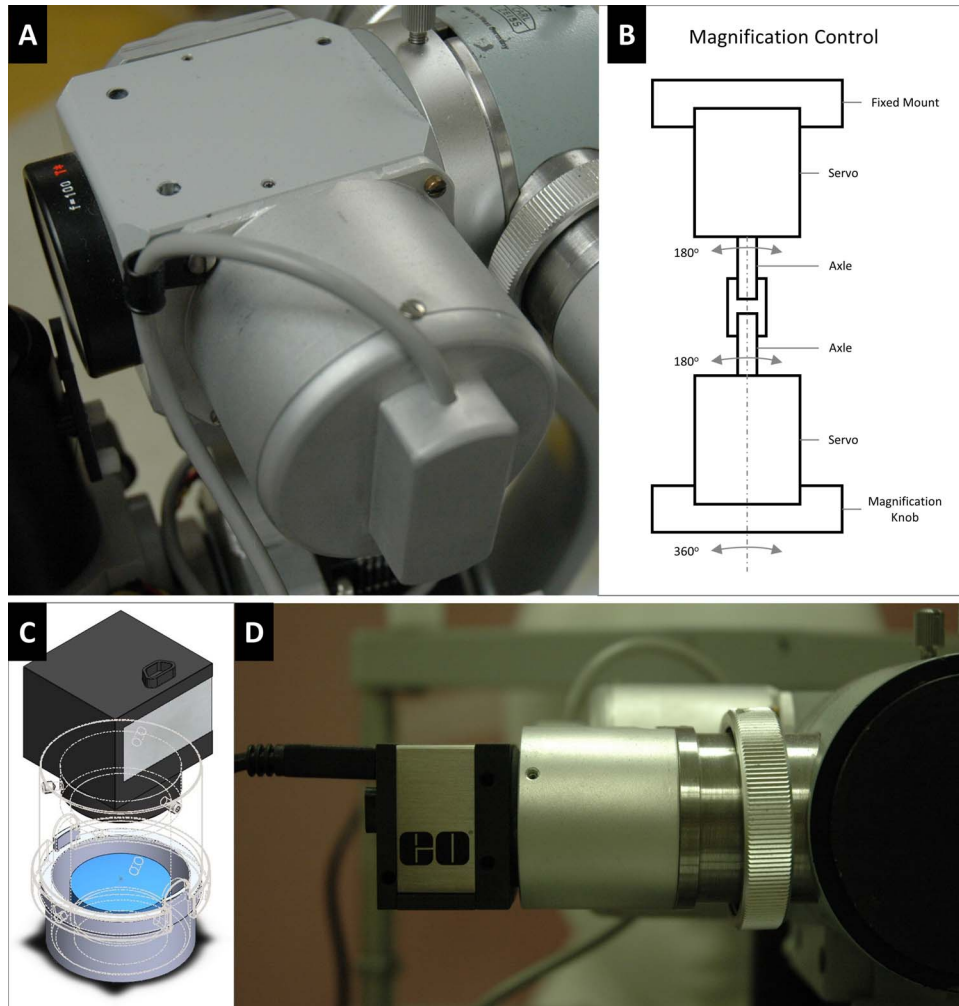
Figure 5. The dual servo system for magnification control was affixed directly to the knob used for magnification adjustment. Custom circular aluminum brackets were fabricated to affix the servo system inconspicuously, where the servos are hidden by the bracket (A). Slit lamp magnification control (B); rotation (360°) was achieved by coupling two servos end to end (B). Custom lens tubes were designed and fabricated to support the relay optics used for each camera (C) of the slit lamp–mounted camera and lens system used for stereo reconstruction (D).

lens to either the right or left eye port of the slit lamp. The selected camera provides a 3.1-MP 6.5×4.9-mm MT9T001 sensor and is C-mounted with USB output. The optomechanical design of the stereo imaging system consists of a single cylindrical interface that mounts to the camera, holds the lens in place, and fits within a Zeiss prismatic beam splitter, which serves to redirect the image away from the ocular and directly into the lens/camera system (Figs. 5C, 5D).

Computer, Software, and User Interface

A small web camera (Blue Microphones Inc., Weatlake Village, CA) was mounted above the slit lamp biomicroscope to provide a view of the patient and the slit lamp. This camera has a 2-MP sensor and a condenser capsule for high-quality sound with a frequency response of 35–20 kHz and a sample/word rate of 44.1 kHz/16 bit.

Any computer- or Internet-capable device can be used to access the desktop of the remote site computer system. The computer system chosen for the remote site used a 3U rack mount server chassis (Take3+650; Antec Inc., Fremont, CA) and a motherboard (MB-P6TD-D, Advanced Technology eXtented; Asustek Computer Inc.) with a 2.66-GHz processor (I7-920, Intel core i7; Intel Co., Santa Clara, CA), 6 GB of random access memory (WB180UX6G9; Super Talent Technology Co., San Jose, CA), and a 512-MB video card (GA-4550D51; Gigabyte Technology Co. Ltd., Taipei, Taiwan).

Audio communications were achieved with a headset, microphone, and speaker system. The ophthalmologist wears a headset (87075; Inland Products Inc., Fullerton, CA), a microphone is mounted above the patient at the remote site, and the patient hears the ophthalmologist through the computer speaker. The headset has a frequency response of 20 Hz to 20 kHz.

In order to maintain constant power, even in remote locations where the power supply may be unstable, a 1500-W pure sine wave inverter (S1500-112B22; DonRowe Co., Monroe, OR) and four 12-V deep cycle batteries (D34M; Optima Batteries Co., Milwaukee, WI) were used. The batteries are charged using an existing AC supply and a heavy duty battery charger (PM-42020; TurtleMarine.com Ltd., New York, NY).

Custom software for the control of the slit lamp was written in LabVIEW (776678-09; National Instruments, Austin, TX). Three different versions of the software were written, one allowing for joystick control of the slit lamp, another allowing for control with a mouse, and still another allowing control with a keyboard. The software displays both images of the patient eye along with the top view of the system and patient. Odometer-like indicators are used to control and display the slit angle, height, width, system magnification, and lamp brightness, and a bar indicator is used to control and display biomicroscope height. In addition, an x-y box with a dot indicator shows the position of the biomicroscope; the nose and eyes of the patient are represented symbolically, and the slit angle is indicated with an arc. Immediately adjacent to this indicator is a similar x-y box with a dot control for continuous adjustment of biomicroscope position. Furthermore, the software provides a staging screen where the doctor or technician can input patient information directly into the Bascom Palmer Eye Institute (BPEI) (Miami, FL) standard patient data form (Fig. 6). With this interface, many specialists can be online at the same time, potentially each at different locations, and can examine and speak to the patient and hear the patient's response.

The operational procedure consists of booting on the system, initializing settings of all actuators, inputting all pertinent patient information, and executing controls for the diagnosis and patient examination, and finally denoting diagnostic information about the patient, closing out of the software, and shutting down the system.

An electronic clutch mechanism was implemented to actuate motion only when the previous position was found. Normally, when controlling multiple actuators with a single mechanical interface (i.e., the throttle-like interface), where the controlled actuator is activated by the push of a button, a change between actuators will result in a large jump or change in the commanded action of the selected actuator. The electronic clutch mechanism eliminates these jumps and allows for more precise control of all actuators linked to the mechanical interface. It does this by requiring the user to move the throttle back to its resting position (the position it was left in after its last command) before taking in any new commands when the function of the throttle is changed.

Stereo viewing was accomplished with the use of side-by-side images and the assistance of a prismatic, which is similar to Brewster's prismatic stereoscope. Prisms were constructed from PMMA with a wedge angle of 16°. Using these prisms and a 1.6-inch partition, a headgear-type mechanical apparatus was constructed for the ophthalmologist to wear. The system was constructed to allow the ophthalmologist to adjust the distance between the prism and the observer in order to account for differences between operators. In addition, custom-made clip-on prisms were fabricated for easy integration with existing glasses. The prisms were made smaller (only 0.6 inches tall) to allow the user to glance down to see the computer screen, joystick, or keyboard normally (Fig. 7).

Latency Experiments

To characterize the latency during remote operation, the RCSL was used to capture images of an LED bulb turning on and off, and a 400-Hz camera (Nikon 1J1; Nikon, Tokyo, Japan) was used to monitor the LED, desktop monitor, cellular, and tablet and laptop screens. The LED signal duration was 1 second, followed by a pause of 5 seconds. Video frame analysis was used to determine the time between the LED activation and the appearance of the activated LED on the three devices evaluated. Latency was measured with WiFi, Ethernet, and cellular network connections locally, and with WiFi and Ethernet connections from various geolocations using a transcontinental virtual private network. Three trials were performed, and descriptive statistics were used to report the RCSL latency and any additional network- or device-induced latency.

Subject Assessment During Remote Operation of the Slit Lamp

In order to illustrate imaging performance, images of two healthy volunteers were obtained during
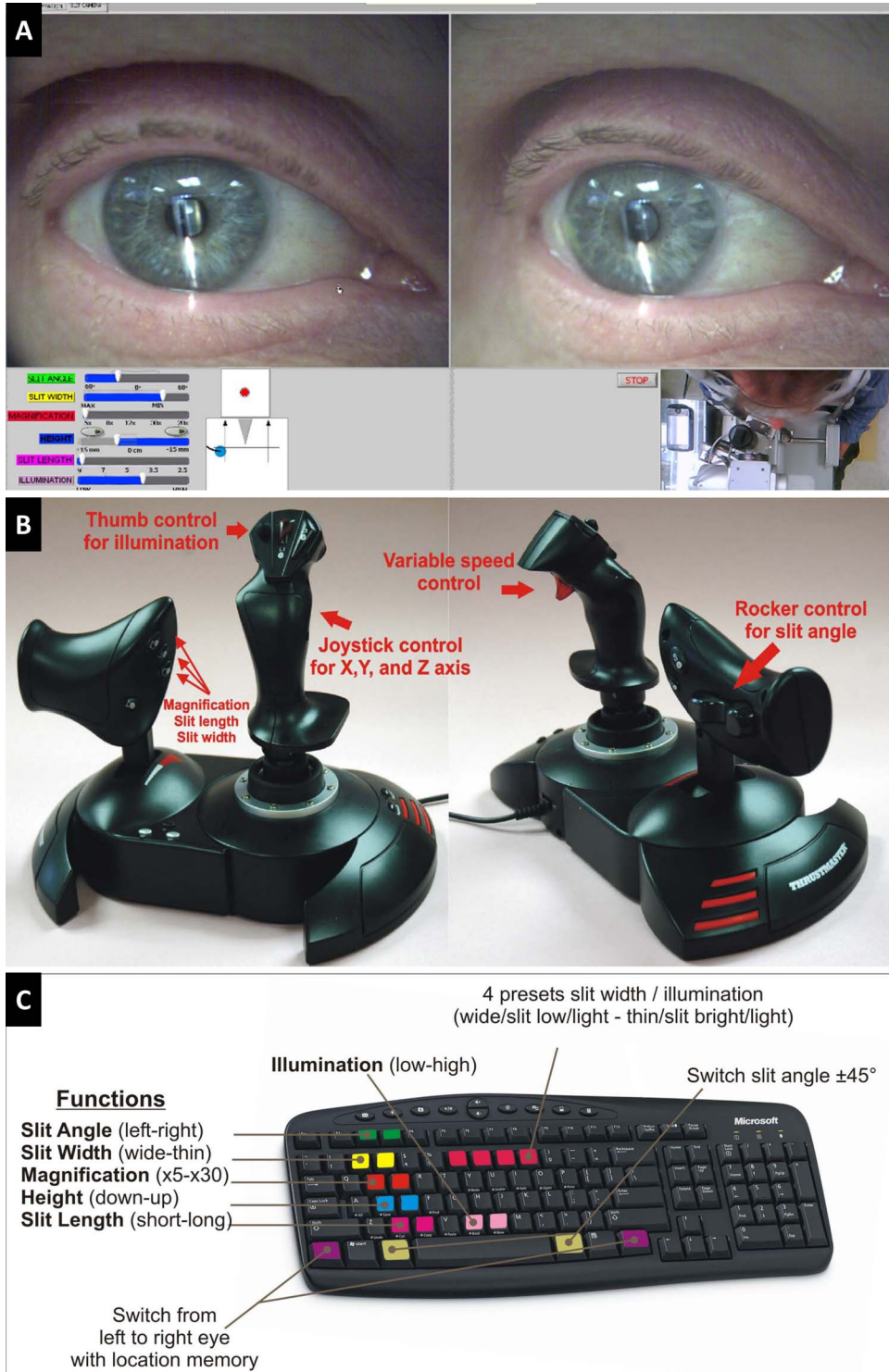
Figure 6. Graphical user interface (A). The two large images in the *top* are of the healthy volunteer eye, and the smaller image in the *bottom right* is the aerial view of the subject. All controls and indicators are along the *left side* of the interface. Joystick controller for the slit lamp (B). Keyboard control for the slit lamp, with presets for right and left eye, slit width, and illumination (C).
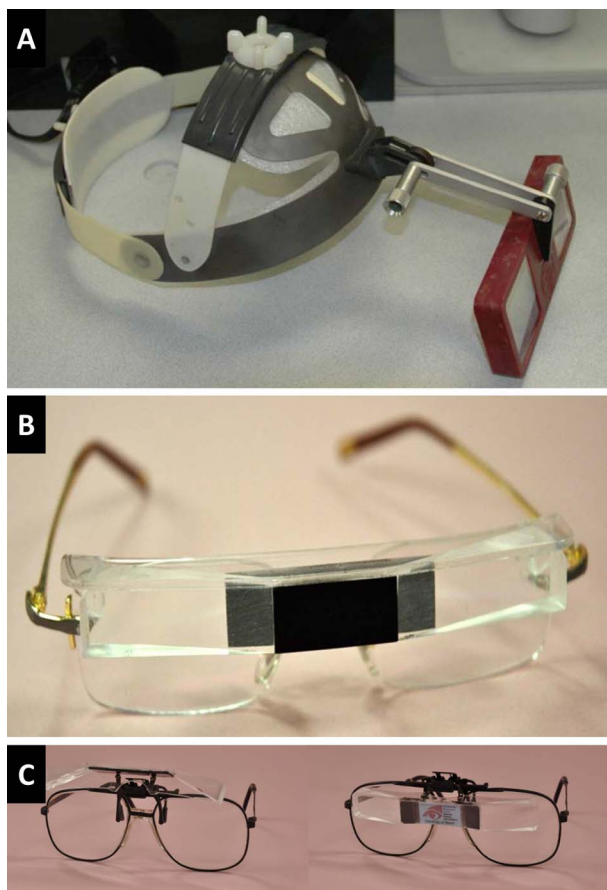
Figure 7. Head-mounted PMMA prism stereoscope (A), clip-on prism stereoscope (B), flip up/down clip-on prism stereoscope in the up (C, *left*) and down positions (C, *right*).

remote operation of the slit lamp. An ophthalmologist controlled the slit lamp over a local Ethernet connection and captured images of the iris, limbus and conjunctiva, crystalline lens, and cornea. The imaging session lasted approximately 2 minutes per eye examined. The ophthalmologists who operated the RCSL reported that approximately 2 to 3 minutes of practice were needed to become accustomed to the system latency. In addition, images from one volunteer were acquired with both the robotic remote controlled stereo slit lamp and with a commercial slit lamp (BM900; Haag-Streit, Koniz, Switzerland)—which was equipped with a Xenon flash—to provide the reader with a qualitative comparison between the two devices. The study was approved by the University of Miami Institutional Review Board and carried out in accordance with the tenets of the Declaration of Helsinki. Informed consent was obtained from all subjects.

Results

The network, Internet, satellite-connected system was controllable from Miami, Florida; Los Angeles, California; Amsterdam, The Netherlands; and Toronto, Ontario while acquiring high-resolution, real-time video and providing slit lamp control.

Latency Experiments

Control of the slit lamp through Ethernet, WiFi, and 4G exhibited total system latencies of 464 ± 58, 483 ± 64, and 870 ± 66 milliseconds, respectively, when transmitting within the continent, and Ethernet control exhibited a latency of 606 ± 130 milliseconds when transmitting between continents. Within the University of Miami network at the University of Miami Medical Campus, latencies were 464 ± 26, 483 ± 29, and 1134 ± 24 milliseconds using a Windows operating system on a laptop with Ethernet connection, on a laptop with WiFi connection, and on a tablet with WiFi connection, respectively. The latency was 870 ± 30 milliseconds with an Android operating system on a cellphone with 4G connection on a T-Mobile network (Fig. 8A). Furthermore, using a laptop with a Windows operating system and an Ethernet connection, latencies were 606 ± 58, 568 ± 24, and 985 ± 81 milliseconds for control locations of Amsterdam, Toronto, and Los Angeles, respectively (Fig. 8B).

Subject Assessment During Remote Operation of the Slit Lamp

Only healthy subjects were examined with the RCSL, including authors of this article and clinicians affiliated with BPEI. All had yearly exams by BPEI ophthalmologists or optometrists using a standard Zeiss or Haag-Streit slit lamp. Although subject comments were not recorded, none reported discomfort during examination with the RCSL.

Discussion

The proliferation of both synchronous and asynchronous telemedicine has been driven by high-throughput demand for certain clinical services and by unmet needs, typically in rural areas.[4] Teleophthalmology is in the vanguard of the burgeoning field of telemedicine, which is being vigorously developed in the clinical areas of dermatology,[5] ophthalmology,[6] wound care,[7] psychiatry,[8] emergency care,[9] and
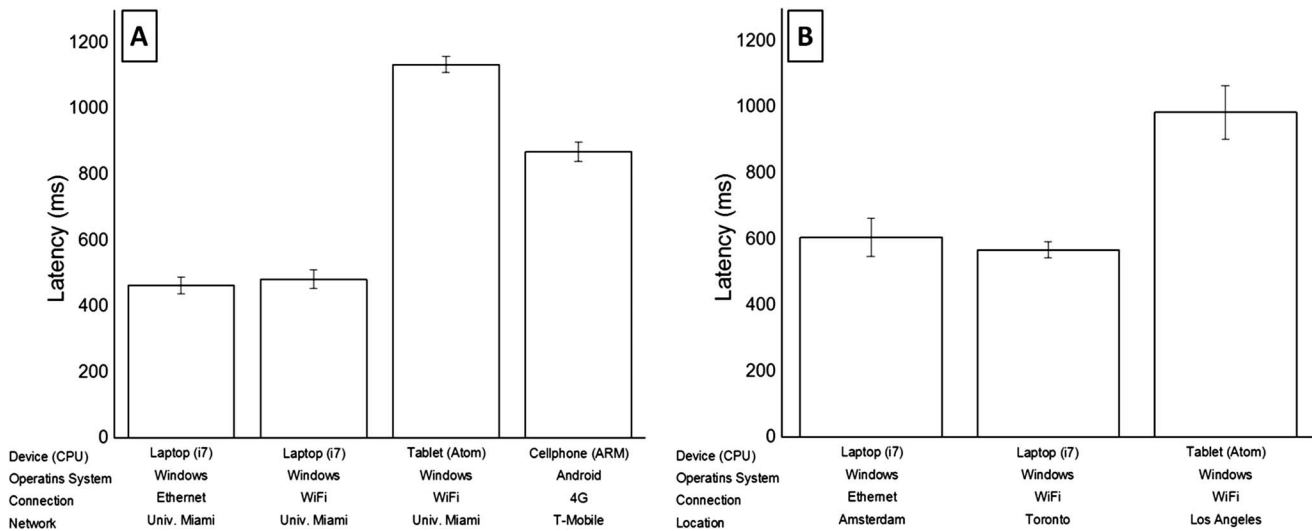
Figure 8. RCSL latency during remote operation within the city (A) and at three different geolocations (B). *Error bars* are the standard deviation.

others. Vascular proliferative diseases such as diabetic retinopathy are the primary applications of teleophthalmology,[10] and there is ample evidence of the efficacy of teleophthalmology in these applications, as measured by clinical outcomes and patient satisfaction.[11]

There is a vast field of technological potential that may be exploited in teleophthalmology. In particular, the intersection of mechatronics and optics (optomechatronics) is promising. The system presented herein, to our knowledge the first robotic remote control stereo slit lamp, is a step in that direction. We imagine the possibility of using feedback controls and the robotic slit lamp to provide an automated examination session. Then, using normative and disease databases, the autonomous slit lamp could classify patients and identify potential pathophysiology. This could result in referrals for subsequent examination or even immediate remote controlled examination by a clinical practitioner. We emphasize that significant further work is needed in the areas of image processing, predictive analytics, and mechatronics, and clinical studies are needed to optimize the sensitivity and specificity of the potential vision for future applications of the remote controlled stereo slit lamp discussed herein.

The drawbacks of the RCSL are its added bulk and weight, which impedes transportation; its tungsten light source, which gives a slit beam of low intensity and a very limited lifetime; the lack of remote selectable blue and green filters for fluorescein and Rose Bengal stains to detect defects in the cornea and conjunctiva epithelium; the required full-size computer; the roughly 0.5-second total system latency; and any additional time associated with the long-term maintenance of its motorized components. Note that we make no claims concerning the equivalence of the remote controlled slit lamp and any standard commercial photo slit lamp, as the two instruments have different purposes and different illumination sources. Additionally, we point out that gain artifacts are present in the images in Figure 9C and 9D due to the relatively low integration time of the camera and illumination intensity of the source, and the color appearance is different between the remote controlled slit lamp and the commercial slit lamp in the images in Figure 10A and 10B. Finally, we note that Internet connectivity is required for remote operation of the RCSL.

Other drawbacks relate directly to the remote nature of the device. Although the RCSL was used to demonstrate feasibility exclusively within the secure network of the University of Miami, a commercial instrument would need to be equipped with the Internet security required by the Health Insurance Portability and Accountability Act. Also, in standard (on-site) examinations, individuals unfamiliar with the primary language of the physician and those with hearing loss will often have an interpreter present to sit and position the patient at the slit lamp and to facilitate communication with the physician. This solution could also be employed with the RCSL, but additional measures could be taken to permit interaction without the interpreter. For example, a
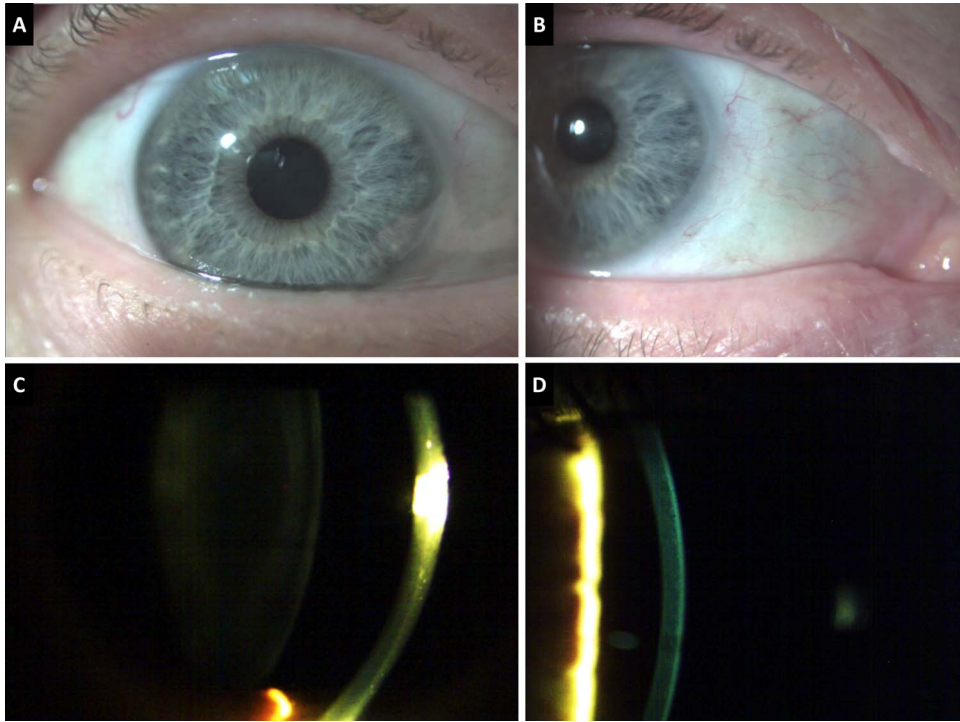
Figure 9. Images of the iris (A), limbus and conjunctiva (B), crystalline lens (C), and cornea (D) of a healthy volunteer. (C, D) Images were acquired with a narrow slit and displayed with the contrast adjusted to reduce gain artifacts associated with the relatively low integration time of the camera and illumination intensity of the source.

language translation software or speech-to-sign language software application could be used in conjunction with the RCSL examination. In addition, during a standard examination, the patient–doctor relationship benefits from face-to-face interaction. With the RCSL, the subject is in direct two-way verbal communication with the physician who can ask and answer questions, but a face-to-face interaction is not supported. As this interaction is missing during RCSL examination, it is possible that the trust needed for patients to make treatment decisions would be hindered.

In summary, we have demonstrated a robotic remotely operated stereo slit lamp system that enables 3-D stereo viewing and recording of the patient's examination via local area network, Internet, and satellite. The robotic slit lamp provides for remote control of the slit lamp intensity, slit width, slit height, slit angle, biomicroscope position (front to back, side to side, up and down), and microscope magnification. To aid in initial alignment, an additional camera provides an overhead view of the patient. A microphone and speaker enable interaction between the examiner(s) and patient. Healthy volunteers were imaged by a remote clinician to illustrate imaging performance.
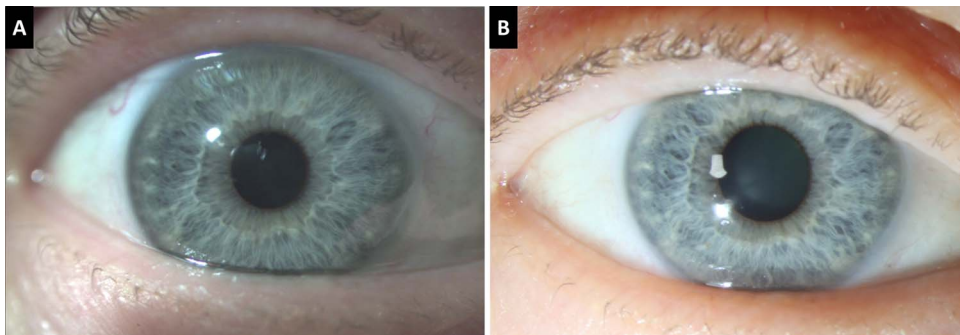

Figure 10. Images of the iris with the remote controlled stereo slit lamp (A) and with a commercial photo slit lamp (B).

Acknowledgments

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