Teleoperated Ophthalmic Examination Robot

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ABSTRACT
Preliminary results of a novel prototype for robotic eye examinations is presented. This work is the first step in implementing a full remote diagnostic and treatment device for ophthalmologists to treat patients quickly and from nearly anywhere in the world.

Keywords
Telemedicine, robotic surgery, remote ophthalmology.

1. INTRODUCTION
The use of robotic technology to perform medical procedures is being increasingly adopted by physicians and hospitals. Though there are some disadvantages such as cost, greater accuracy, smaller incisions and faster recovery times are main advantages that are attractive to patients weighing their options [1]. However, robotic technology is a common option for only a limited number of procedures. Benefits of using robots in current procedures can also be applied to numerous other areas of human health. One such area is ocular care.

Ophthalmology involves the study, diagnoses and treatment of medical conditions of the eye. Major breakthroughs in this field over the last century or so have been the introduction of the slit-lamp with an adjustable light and microscopic eyepiece [2], laser technology for ablation and sealing of eye structures, and refractive procedures to reshape the cornea and improve eyesight [3]. Still, other than some aspects of refractive surgery, ophthalmologic procedures are done by hand. This can be tedious, tiring and time consuming given the small area that is targeted and the accuracy required [4].

2. MOTIVATION
Visual impairment affects 285 million people worldwide [5]. Two major restrictions to care include the high costs and having easy travel distance to specialist care. Though upfront costs can still be high, robotic technology is able to help greatly with the later problem.

Many of those unable to get proper ophthalmic care reside in rural areas or underdeveloped nations. While there are attempts to provide care to some of the individuals via means such as the Flying Eye Hospital [6], the populations reached are still limited. In addition, urgent care is not usually possible given the discrete timing of these roaming clinics. Further, care for rare conditions may be limited due to the limits of on-hand specialists and their areas of expertise. Though any care is usually a great improvement, patients with limited access to ophthalmologists may not be granted second opinions or have any choice in deciding who provides their care.

Ophthalmic surgeries are difficult and risky for several reasons. These include the eye structures being very small, especially with respect to human hand movements and tremors, a high degree of accuracy needed, and limited assistive technology in performing these procedures. This means that many delicate operations are meticulous performed by hand and invite the physician to become easily fatigued. This increases the possibilities for mistakes and irreversible damage to eye structures [7]. Even though semi-automated refractive surgeries such as LASIK are generally very successful, outcomes are not guaranteed and patents may require additional corrective procedures [8].

Robotic technology solves many of these issues. By utilizing standard communication networks, an ophthalmic robot can be controlled and monitored remotely by a physician in nearly any location. This allows care to be extended to rural areas and villages, battlefields and places of exploration. Patents can have options in selecting their providers whether accepting the first-available for an emergency, a trusted physician or an expert for a rare or complicated condition. Care can also be coordinated between more than one physician in one or multiple locations for a rare or complicated condition. Care can also be coordinated between more than one physician in one or multiple locations for a rare or complicated condition. Care can also be coordinated between more than one physician in one or multiple locations for a rare or complicated condition.

Though the overall cost savings may be questionable, there are some aspects of robotic technology that can provide economic benefits. The greatest of these include the travel costs of ophthalmologists. This can be direct savings in transportation, such as fuel or airfare, but also costs associated with travel time. With long-distance mobile clinics in particular, travel time requires that all staff and support stay many nights away from home and paying work. This limits the quantity of volunteers that are available to participate. By removing the travel component, many more physicians can offer their services for free without incurring high financial nor time costs upon themselves.

Another cost-saving aspect is that some physicians could elect to work from home or reduce their use of clinic resources. Other than aspects such as patient billing and nursing care, many
services could be provided with a more limited amount of space. Physicians would not require their own office in clinics and could quickly switch from a patient in one location to a patient in another without any travel delays or scheduling blocks. By seeing patients and multiple practices more efficiently, other physicians can use space for their own practices, reducing rent and utilities, and consolidate support staff to streamline compensation and management.

3. PROJECT GOALS
The overall goal is to create a robotic prototype that is a proof-of-concept for a remotely operated platform that can be used to perform diagnostic and some surgical procedures. The initial prototype presented here was slated to only perform the diagnostic aspect and thus be a telemedicine platform. The robotic prototype consists of two main parts. A patient-side robotic platform provides the tools needed for diagnosis and care. The physician’s portion provides a means to control the robot. Though these two parts could be used together in one location, connecting them by communication lines for interaction over a distance is the assumed mode of operation. Necessary and desired features for the two ends are described below.

3.1 Patient-End Features
The robotic device is located on the patient side of the interaction. The robot can be kept in a hospital, clinic, mobile clinic, triage or emergency response base, home or any other location that is convenient, allows for adequate privacy and cleanliness for the planned use and local expectations, and meets all legal or medical codes for this device. It is the portion that physically interacts with the patient.

The robotic device is expected to be under the supervision of a medically-trained individual. This person is able to assist the patient at all times, serves an in-the-flesh human aspect to the session, provide some basic services in setting up the telemedicine experience by positioning the patient and generally getting the robot into position, and acts as an on-site back-up to stabilize and advise the patient in the event of a technical malfunction or loss of communication with the physician.

The basis of the robot is built on a slit-lamp, which is ophthalmic equipment that has been in use for over a century. There have been various improvements and designs over the years and ideally the prototype is to be designed so that it could be used on most if not all of these different styles. This allows both for money-saving possibilities as existing equipment could be retrofitted to work robotically, but also allows clinics to select a base unit that has base characteristics such as features and size that works best for their local needs.

The robot is also to operate safely as it will be used with limited supervision in direct contact with human patients. To minimize the risk and severity of any injuries, the motor speed is set to be slow, especially for gross robotic movements. In the absence of control or communication from the physician, the robot is set to stop and wait for instructions rather than continue to move. An on-site emergency stop system disconnects power to all actuators in the event of a malfunction or to halt the system should the patient or environment require such an action. Real-time audio communications between the remote physician and the patient and medical assistant is a requirement so that both sides can stay apprised of the status and expected actions. It is not only important for the physician to be able to relay instructions, procedure status updates and diagnoses, but also to know how well the patient is doing and tolerating the experience. It is just as critical for the physician to know if the patient is tired or about to make a large movement as it is for the patient to know what the doctor is doing and how the robot may be used next.

Other safety features, such as a robust and adaptive control system are desired as well. When possible, components that must be in direct physical contact with the patient are made to be light and compliant so that the risk of cutting or bruising the patient is limited. Work on these aspects is currently ongoing.

Desired, but not necessarily required features of the system include having two-way visual contact between the patient and physician. This not only provides a degree of safety for the ophthalmologist to know what is happening in the patient’s environment, but also gives some degree of reassurance to the patient in being able to see the individual providing their medical care. An electronic Braille display, text-to-speech system or other assistive technologies may be helpful additions for certain populations in order to better facilitate two-way communications between the patient and ophthalmologist.

3.2 Physician-End Features
The Physician-end of the system is to allow for control of the robot to perform the desired procedures. Three main configurations can be used, but the overall set of features remain the same.

The control unit for the prototype can be a website, hardware control box or a slit-lamp. The system selected depends upon the location of use and type of use, though ultimately the physician or medical group will make a selection based on their preference. It is also possible for a physician to use any of the possible systems depending upon the situation.

The first option is to use a personal computer or large tablet to remotely connect to the device via the Internet or other available means of communication. The physician logs into the control system of the robot and an integrated server provides the telecommunications as well as interactive graphical webpages that allow for the control selections to be made. The advantages of this selection are that no special equipment needs to be purchased by the physician or clinic and that there are cost and space savings. In addition, nearly any communication-connected device could be used to operate the robot. This includes even a smartphone, though the small screen and limited visual feedback would limit this to emergency situations. Problems include the possibility of a hacked computer being used to alter the examination or treatment of the patient remotely or for patient information to be illegally obtained. It may also be more difficult for some physicians to treat the session with the same level of professionalism pending their personality, environment and other applications that may be running on the device.

Alternatively, a hardware device connected to a computer system can be used to provide a more tactile interface with the robot. This device has similar options and control buttons as the website, but these are physical. A display screen must be used in addition to a microphone to complete the control console. This option provides a dedicated means to control and doesn’t take up much more room than a personal computer. It can aid in making the interactive sessions more professional by eliminating distractions, but it requires that the hardware be purchased for every location it
will be used or for it to be carried and moved to all locations in which it might be needed. It is also an additional device that must be purchased, but it can be made such that cost is kept to a minimum.

The final option is the use a slit-lamp that has been adapted to be used as a master device to control the patient-side robot as a slave device. Sensors in the master device pick up the motions and options selected by the ophthalmologist and this information is sent via the communication line to the slave robotic device that follows this movement. This interface provides the physician with a very familiar interface in which to perform the procedures and may reduce the learning curve on using the device. It can also provide a measure of safety as the placement of buttons will be much less likely to be confused. This option is the most expensive, however, and it requires modifications to the slit-lamp itself to make it suitable for this task.

4. FIRST PROTOTYPE

The prototype was designed and built to be an up-and-running proof of concept as soon as possible. The project was also to be kept within a limited budget to conserve resources for future iterations and trials required to get the robot to market. To do this, off-the-shelf parts were used for most of the components.

4.1 Components

The prototype focuses mostly on the patient-end robotic platform. The major components used for this include a slit-lamp, single board computer, motor controller, servo motors, and camera.

A vintage Neitz slit-lamp is used as an economical base for the prototype. In addition to the financial aspect, the older model provides more simplicity in the options and features that made actuation simpler. The slit-lamp does not allow for integration of an ophthalmic laser without modifications, but does prove to be a suitable base for a proof-of-concept and to test retrofit designs.

Control is provided through a singleboard computer, namely the BeagleBone Black. This was selected for the low-cost, ease of integration with hardware via the general-purpose input/output (GPIO) pins, and the ability to run a full Linux operating system able to run the robotic program as well as act as a server to allow for remote connection to control the robot via a webpage. Code was written in Python due to the compatibility to run with little or no alterations on a wide variety of platforms and operating systems. This is to ease the porting of code to later iterations of the project as the device proceeds on a path to market. The choice of the BeagleBone was due to the higher processing capabilities at the time, though there are now several other mainstream single-board computers with comparable specifications that could be used.

Large Turnigy hobby servos intended for robotic applications were selected for providing motion for the system. These provide a large amount of torque for their size while being easily controlled through a servo motor controller designed for common hobby servos. A mix of digital standard and analog continuous servos are used pending the range of motion needed for each joint or control of the slit-lamp.

The camera chosen for the prototype is a high-definition webcam. The Logitech c920 also provides built-in audio support and is well supported by multiple operating systems included Linux. It streamlines the teleconferencing aspects while providing a means for the physician to perform an eye exam when affixed to the microscopic binoculars on the slit-lamp.

4.2 Retrofit

Figure 1 shows the prototype. The slit-lamp was retrofitted by attaching servo motors to each rotating joint and to rotating dials with functions necessary for performing ophthalmic exams. Brackets affix the servos at each position and the servo disc arms were made to transfer the torque to the points of motion.

Base movements are made via two servo motors that control Omni wheels on perpendicular shafts. One servo moves the base forward and backwards while the other moves the base side to side. The Omni wheels allow the non-active wheels to slide along the direction of motion with minimal friction introduced. This raises the entire slit-lamp and the guiding tracks are raised to ensure that the slit-lamp cannot be accidently driven off of the table it sits upon.

![Figure 1. Robotic Slit Lamp Prototype](image-url)
logging into this page remotely via the Internet, a physician can use the slit-lamp to perform an ophthalmic exam.

5. FUTURE WORK
The prototype is still undergoing further improvements in testing better control. This is in both the programming and in placement of the servo motors for optimal control of the movements.

There is also continuing work on robotic systems to manipulate tools and accessories used in ocular treatments.

The project will continue on the path to commercialization with the design and implementation of a phase two prototype that will include a surgical laser system. This prototype will allow the physician to plan a laser surgery and will then perform that surgery with limited further input from the ophthalmologist provided the system detects that it remains safe to do so. Though work has begun in this area, further research and improvements will be performed.

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7. REFERENCES