Iterative Design of Teleoperative Slit Lamp Microscopes for Telemedicine

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***Abstract*—This paper reports a design project of Teleoperative Slit lamp Microscopes for Telemedicine. The project is a case study of development and deployment of a telemedicine system using human-centered design approaches. At the beginning of the design process, we conducted field research and paper prototyping of the doctor's terminal with ophthalmologists. Later, we developed working prototypes for evaluation. We conducted ophthalmologist's fixation data collection to redesign the user interface of the latest prototype.**

Keywords–Human-centered design; ophthalmology; slit lamp microscope; telemedicine; teleophthalmology; usability

I. INTRODUCTION

Telemedicine has been studied to cope with current social issues related to transportation and the uneven geographical distribution of medical service providers [5]. The application of telemedicine to ophthalmology has created *Teleophthalmology* as a research and practice domain [4]. Teleophthalmology is hoped to provide medical services to secluded mountainous and island areas through information and communications technology to screen populations for glaucoma, corneal diseases, and other ocular diseases.

Teleophthalmology has a long history. Ophthalmology is a visually intensive specialty. Therefore, the development of image and video transmission through telephone line makes it possible to conduct ophthalmologic diagnosis over long distances. Li [4] reported a modern teleophthalmology application that appeared in the late 1980s: NASA developed a real time transmission system of retinal images acquired using a portable video funduscope. Shimmra et. al. [6] used a conventional telephone system to transmit slit lamp images of the eye and evaluate the feasibility of real-time video and audio transmission. Yoshida [10] used video conferencing systems to transmit full-motion color biomicroscopic images and biomicroscopic images between a university and hospitals.

Using those early systems, an expert remote presenter who is trained in the use of the ophthalmic peripherals, hardware, and software can capture still and moving images of the eyes and transmit them to ophthalmologists. Therefore, the current status of teleophthalmology applications is limited to specific purposes such as doctor-to-doctor consultation, research and clinical trial collaboration, and distance learning for medical professionals [7, 9]. Furthermore, the indirect operation of a slitlamp microscope, a fundamental diagnostic device for the eye, makes it difficult for ophthalmologists to conduct fine appropriate diagnoses rapidly over long distances. In a synchronous real-time setting, an opportunity to find serious eye problems might be missed.

The purpose of our project is to propose a teleoperative slit lamp microscope as an application of teleophthalmology. To be specific, this paper describes the design process of our *EyeViewRobo* (*EVR*) system: how it is designed, developed, and deployed. It also explains the current state of the project.

II. TELEOPERATIVE SLITLAMP MICROSCOPE FOR TELEMEDICINE

For ophthalmologic examination, a slit lamp microscope is generally used as a fundamental diagnostic device, as shown in Fig. 1. With the slit lamp microscope, the eye specialist's basic tasks include adjustment of the microscope position using the joystick to find a focal position and to switch slit types using the knobs on the slit lamp unit to set an appropriate diagnostic condition. The eye specialist might use a fronting lens and a blue filter together with the microscope to conduct additional examinations. The organization of these special devices requires great skill and experience for microscope control in addition to knowledge of clinical medicine.

Figure 1. Slit lamp microscope in use (Left, patient; Right, ophthalmologist).

Figure 2 portrays differences of approaches between those of previous works and our system (EVR). In previous works, a

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specialist—an expert remote presenter—controls a slit lamp microscope at the patient site. The captured high-quality still or moving images of eyes are sent to a doctor's PC for diagnosis. In this setting, the specialist might be an ophthalmologist engaging in doctor-to-doctor consultancy. In contrast, our approach introduces a teleoperative slit lamp microscope [1, 2]. An ophthalmologist can control it from a geographically distant site, capture high-quality still or moving images through the network, and conduct a diagnosis in a timely manner. This setting might require an assistant at the patient site with limited knowledge related to the ophthalmic peripherals, hardware and software. The assistant might be a general doctor who is not an ophthalmologist, or perhaps a nurse who would support the ophthalmologist's slitlamp operation and assist the patient.

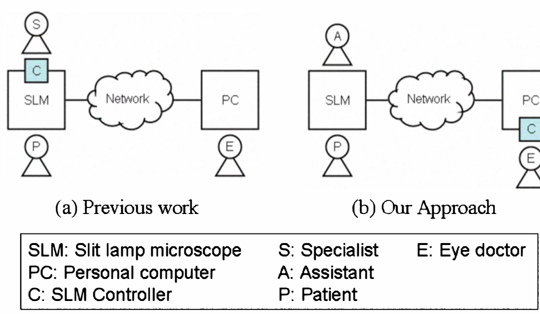

Figure 2. Schematic diagram of network setting on (a) previous work and (b) our EVR approach.

With EVR, the ophthalmologist operates the Input/Output device and inputs the parameters of the microscope position and slit light over a long distance. The I/O device transmits the parameters to the teleoperative slit lamp microscope and enables changes to its appropriate function levels. The microscope's video camera captures still and moving images; then it transmits them to the I/O device at the ophthalmologist's site using DVTS via the internet similar to [8]. The doctor examines the received images using the I/O device and then conducts a diagnosis.

III. Design Evolution of the EVR System

We designed, developed, and deployed EVR through iterative design processes [3]. The first activity for design was a series of interviews of ophthalmologists working at a university hospital. Additionally, we visited their offices to observe their work on ophthalmologic examinations. Using contextual inquiry technique, we remained in the room, observed their activities, and asked questions to understand what they did in context. During the visits, we learned that examination rooms for ophthalmologists at the university hospital are typically small and are already equipped with several medical peripherals and tools. In contrast, an examination area requires an open space for nurses to provide support for the ophthalmologists and the patient. Apparently, no space was available in the examination room to install a set of a new device and terminals to control a remote clinical device. For this reason, we concluded that miniaturization, uniformity, and portability of the teleoperative slit lamp microscope and doctor's terminal should be our engineering goals for the EVR design project. Through those activities, we identified ophthalmologists' requirements for EVR.

To avoid inflation of the rating of a specific design, we created several versions of mock-ups and paper prototypes. We showed them to ophthalmologists and evaluated them. We discussed the characteristics of interaction with the system. The EVR-0 version, in the form of paper-based prototype, was designed to demonstrate how the system is used [1]. The EVR-1 version was designed as a rapid working version of the prototype by modifying current technologies such as a slit lamp microscope to be useful for laboratory tests. The EVR-2 version is a refined version of the prototype, which is intended for a field test [2]. The EVR-3 version is another refined version of the prototype intended for clinical tests. During the process, iterative design by an interdisciplinary team of specialists with continuous user testing is useful for identifying hidden needs and requirements of users and for obtaining a correct design.

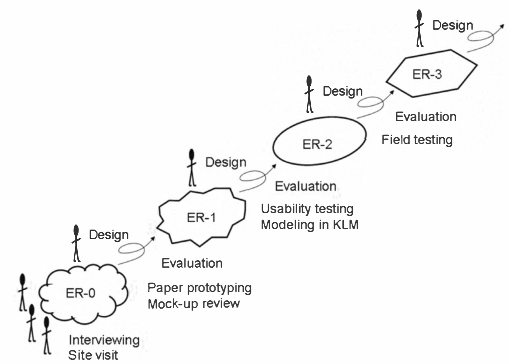

Figure 3. Concept diagram of EVR evolution.

A. *EVR-0: Paper-based design*

Figure 4 shows the basic design of the I/O interface (paper-based version) for EVR-0. We decided to use a dual display for the interface because of the requirements of the maximum eye images on the video display terminal (VDT). For this design, the right screen (main display) displays the video image transmitted from the teleoperative slit lamp microscope at the patient's site. The left screen (sub-display) displays information other than the video image of the eye, such as the camera position and various parameters.

Through the paper-prototyping session with EVR-0 versions and the subsequent debriefing session, we created the idea of a jump button (the two eye-shaped buttons at the bottom of the bottom left panel) and a reset button (at the top left corner). The jump button sends a command to the teleoperative slit lamp microscope so that it toggles the camera position from the pre-assigned right eye center to the pre-assigned left eye center, and vice versa. The reset button changes all slit lamp parameters to the initial settings so that

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the ophthalmologist can always start routine diagnostic examinations in the same manner. We implemented the jump button and the reset button into a working version of the system (EVR-1).

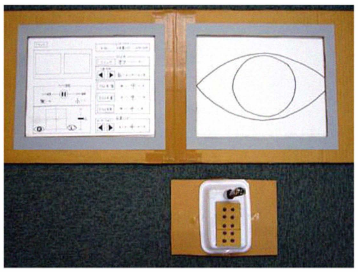

Figure 4. EVR-0: Paper prototype version of EVR [1].

B. *EVR-1: The First Working Prototype for Laboratory Tests*

Figure 5 (Left, Center) shows the telepoerative slit lamp microscope facilitated in an examination room in the emergency department at a university hospital. It is the initial working prototype. Therefore, most parts of the microscope are reused from a conventional slit lamp microscope. We added stepping motors for remote control of its three-dimensional position and switching circuits for remote control of the on/off and intensity of lamps. Figure 5 (Right) depicts the ophthalmologist's terminal for EVR-1. It consists of dual monitors and a joystick. The left monitor is a touch-sensitive LCD; the right monitor is a CRT monitor. We used a CRT monitor for the EVR-1 at an ophthalmologist's request because of his preference for the quality of the video display.

Figure 5. EVR-1: The first working prototype [1].

Using the EVR-1, we conducted usability tests to evaluate the design of EVR-1 against ophthalmologist's requirements. The purpose of the usability test is to see how effectively ophthalmologists control the teleoperative slit lamp microscope from the doctor's terminal using the joystick. We implemented EVR-1's operation method to be as simple as possible. Each dimension of the xyz position of the slit lamp microscope is controlled independently. For example, when moving from position (0, 0)–(1, 1), one must do it using two steps: move from (0, 0)–(0, 1)–(1, 1), or move from (0, 0)–(1, 0)–(1, 1). We used this straight move approach because ophthalmologists reported that they did not move a slit lamp microscope using a diagonal move approach. In other words, they had understood themselves that they did not control the microscope—for example from the (0, 0)–(1, 1)—directly. We needed to confirm the effectiveness of the joystick operation.

Two senior ophthalmologists and three interns participated in the usability test. They controlled the teleoperative slit lamp microscope from the doctor's terminal using the joystick. The observation and debriefing interview results indicated a new requirement; in fact, the eye specialists require diagonal movement of joystick control even though they expressed that they did not usually control it that way. Therefore, we started to redesign the operation scheme to include diagonal movement.

Furthermore, an ophthalmologist at the university hospital reported that a chief nurse in the emergency department did not like the EVR-1 units because they occupy an important corner of the examination room and can hinder a nurse's activity. The ophthalmologist's report supports our observation during the site visit. Downsizing, uniformity, and portability of the EVR-1 version therefore became specific engineering goals of our EVR project.

C. *EVR-2: A Working Prototype for Field Test*

The EVR-2 version of our EVR system was designed as a revised working prototype for field tests. Figure 6 presents an ophthalmologist's terminal for EVR-2. We created an original chassis for our teleoperative slit lamp microscope for EVR-2 and prepared a smaller PC box for video transmission and slit lamp microscope control. The right monitor of the ophthalmologist's terminal is replaced from the CRT monitor to the LCD. We brought a CRT monitor and an LCD to the ophthalmologists, presented them, and compared the quality of video images of EVR-2. In fact, the ophthalmologists replied that the quality of LCD video images is sufficient to conduct remote diagnostic examinations. However, the operation time of EVR-2 takes much longer than that of original slit lamp microscope. It must be improved to reduce the patient's load.

Figure 6. EVR-2: A working prototype for field tests [1].

D. *EVR-3: A Revised Prototype for Clinical Evaluation*

The EVR-3 version was designed as a revised working prototype for clinical evaluation. We created a much more compact chassis for the teleoperative slit lamp microscope (Fig. 7). Using this version, we conducted clinical test incorporation with hospital patients. Additionally, we attempted to redesign the user interface of the ophthalmologist's terminal. Our hypothesis is that the dual monitor setting of EVR-3 requires redundant time for operating the remote slit lamp microscope. We assumed that if ophthalmologist's focus area is limited in

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space on the main display, then we can show information of the sub-display on the unfocused area on the main display. To test the hypothesis, we used an eye mark recorder to measure and analyze the ophthalmologist's point of fixation.

Figure 7. EVR-3: A revised prototype [2].

The ophthalmologist with the most extensive experience on the EVR-3 participated in the experiment. He regularly uses the EVR-3 to conduct clinical tests. An NAC EMR-Voxer is used as an eye mark recorder. Figure 8 shows his fixation points on the main screen. There are out-of-range data, which represent the ophthalmologist's specific examination of the sub-screen. The result indicates that during remote eye evaluation, the ophthalmologist specifically views the lower center area on the screen, which supports our hypothesis. Therefore, the dual monitors' information might be merged into one screen.

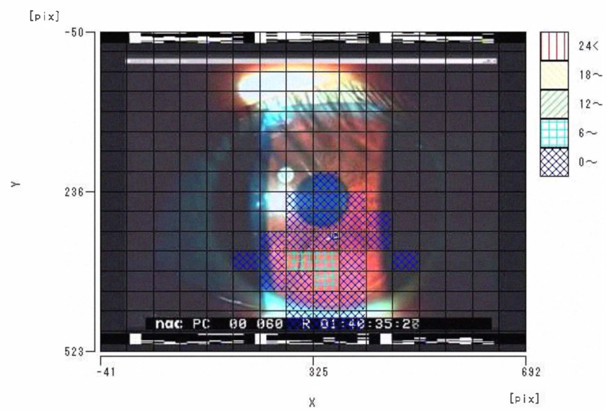

Figure 8. Ophthalmologist's fixation points on the main screen.

IV. CONCLUSION

This paper presented an evolution of our EyeViewRobo system design from EVR-0 through EVR-3. First, EVR-0 demonstrated how the system is used in the form of a paper-based prototype. The EVR-1 was designed as a rapid working version of the prototype by modifying current technologies such as a slit lamp microscope. Intended for field testing, the EVR-2 is a refined version of the prototype; EVR-3 is another prototype for clinical tests. Its evolution was an iterative process of design and evaluation.

We are now designing the EVR-4 version based on analysis of EVR-3 use. We plan to set up the EVR-4 terminal in an examination room at the department and the teleoperative slit lamp microscope in an examination room at a local hospital in a secluded mountain area. We will undertake iterative continuous design through its actual use.

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