Embedding an Eye Tracker Into a Surgical Microscope: Requirements, Design, and Implementation

Shahram Eivazi, Roman Bednarik, Ville Leinonen, Mikael von und zu Fraunberg, and Juha E. Jääskeläinen

***Abstract*— Eye tracking has long been known as a tool for attention tracking, however, the understanding of gaze in the critical domains such as surgery is still in its infancy. In image-guided surgery, studying the role that visual attention plays in eye-hand coordination, situation awareness, and instrumentation control is critical in order to understand the nature of expertise and explore the possibilities for gaze-based interaction. To date, the eye-tracking technology has not been embedded into an operation room microscope and thus limited knowledge is available about the role of attention in real-life image-guided surgery. To advance the state-of-the-art, we adopted an optical solution for eye tracking and embedded a binocular eye tracker into a surgical microscope. We present the design principles and development evaluation cycles, as well as highlight the technical challenges encountered when embedding an eye tracker for a surgical microscope. The developed solution can be applied for other types of microscopes and ocular-based optical devices, for example, ophthalmology, otolaryngology, plastic and reconstructive surgery, and astronomical devices.**

***Index Terms*— Eye tracking, microsurgery, operating room.**

I. Introduction

ADVANCES in eye tracking technologies have impacted widely on various fields of research from uncovering the role of visual attention in human factors training, to gaze-based interaction technologies in human computer interaction (HCI) research. In medicine, eye tracking has been applied as early as the 1980's to study visual search [1] and later to understand the nature of expertise [2]–[5]. The majority of studies used eye tracking in the context of image-guided surgery [6]. Most image-guided surgical techniques, namely, laparoscopy are minimally invasive where direct access to the operative field is not possible and the surgeon sees the field of view via a camera or microscope. Furthermore, image-guided surgery requires special psychomotor and visuomotor skills. As such, eye movement data analysis has also been used to understand the details of these skills in the operating room (OR) [1], [2], [4], [7].

To date, only a hand full of papers have reported the development of OR eye trackers [8], [9] however, arguments for developing eye tracking devices have not been well articulated within the surgical environment. The main reason is that the development of eye tracking systems has focused on implementing sophisticated imaging process techniques rather than adapting the hardware to specific environments. Recording eye movement data in the OR has relatively straightforward requirements: First, eye trackers have to be non-intrusive and allow free movement of the surgeon. Second, it should not violate the sterility of the surgical area. The most commonly used eye tracking setups in medicine are the remote display, and wearable head mounted eye trackers. These setups often use a non-intrusive video-oculography (VOG) eye tracking technique, which is based on recording reflected infrared light (IR) from the eyes with a video camera.

Remote display eye trackers are mounted to a screen and the operator has to keep a distance of 60cm from the display. Thus a remote eye tracker can be used only in surgical domains where the surgeon looks at a screen constantly (e.g. laparoscopic surgery). In practice, these types of eye trackers have mainly been used outside of the operating room because the distance factor places limitations on surgeon's freedom of movements [2], [7], although there is one study which achieved success during actual live surgical procedures [10].

In response to these limitations, researchers developed and used wearable head mounted eye trackers to allow more freedom of movement [11], [12]. With this technique, a surgeon has to wear lightweight eye tracking glasses and eye movement data is transferred to a mobile unit. The main limitation for these systems is that the surgeons cannot use other ocular-based optical devices (e.g. virtual reality glasses, varioscope, or microscope) while wearing the eye tracking glasses because the calibration and mapping of the scene camera and eye movement data is unfeasible. The second problem is that the sampling rates of the wearable trackers are low, often 30 or 60 Hz, and thus they cannot be used for accurate analysis of eye movement data. The duration of eye movement events, namely, saccades, glissade, and microsacade are about 10ms and therefore the smaller the saccades, the higher sampling rate is required [13].

With this in mind, we propose a new type of embedded eye tracker that overcomes the abovementioned challenges and is suitable to be used with ocular-based optical devices, namely, in operations that are performed under a microscope (microsurgery operations).

Microsurgery is one the most common clinical specialties that use a microscope (Figure 1). During microsurgery,

Manuscript received August 22, 2015; revised October 24, 2015; accepted October 30, 2015. Date of publication November 17, 2015; date of current version February 10, 2016. The associate editor coordinating the review of this paper and approving it for publication was Dr. Thilo Sauter.

S. Eivazi and R. Bednarik are with the School of Computing, University of Eastern Finland, Länsikatu 15, 3rd floor, 80110, Joensuu, Finland (e-mail: shahram.eivazi@uef.fi; roman.bednarik@uef.fi).

V. Leinonen, M. von und zu Fraunberg, and J. E. Jääskeläinen are with the Neurosurgery of Kuopio University Hospital Kuopio, University of Eastern Finland, Joensuu 80130, Finland (e-mail: ville.leinonen@kuh.fi; mikael.fraunberg@kuh.fi; juha.e.jaaskelainen@kuh.fi).

Digital Object Identifier 10.1109/JSEN.2015.2501237

Fig. 1. A typical view of micro-neurosurgery operating room (left: a neurosurgeon operating under a microscope, right: a scrub nurse providing instrument for the neurosurgeon).

the surgeon keeps his eyes on the microscope oculars [14], [15] and performs precise and delicate manipulations using micro-instruments. Therefore, microsurgery requires a mastery of indirect eye-hand coordination. To further understand the role of attention in microsurgery we aim to provide the possibility to capture surgeons' eye movements in microsurgery scenarios.

The need for applying eye tracking techniques in microsurgery has implications beyond understanding the visual attention strategies of surgeons. There is a growing body of eye tracking studies examining the use of eye movement information in robotically assisted surgery [16]–[19]. Hence, the integration of eye trackers into surgical microscopes could provide opportunities for gaze contingent or hands-free interaction during microsurgery [14], [15].

Furthermore, in recent years there has been an increased interest for exploring eye movements expertise differences to understand the nature of expertise in domains such as micro-neurosurgery [3] and for potential use of gaze contingent systems for controlling surgical microscopes [14], [15]. Eivazi *et al.* [3] studied gaze behavior of expert and novice neurosurgeons in an off-line situation *outside* the operating room. They asked neurosurgeons to look at four images representing four phases in a tumor removal surgery. The results showed differences in the way that expert and novice surgeons look on the surgery images and in attention control. In a more recent study, [14], [15] show the need for a new hand-free interaction input for operating a microscope in micro-neurosurgery. Their report shows that surgeons spend significant amount of the surgery time for adjusting the microscope manually, a time which could be saved by a gaze contingent control system as suggested by authors.

Until now, only one study has reported the use of eye tracking in the microsurgery [9]. Charlier *et al.* [9] demonstrated an eye-controlled surgical microscope, however the paper lacks a detailed description of the system, its application, and evaluation. In this paper, we further examine eye tracking solutions in microsurgery by showing in detail the implementation steps required to embed an eye tracker into an OR microscope.

Drawing on these insights from literature and in collaboration with expert micro-neurosurgeons, we developed a binocular eye-tracking system that can be embedded into a microscope or similar ocular-based optical devices. In this paper we present a detailed description of the hardware development phases starting from the requirements analysis, to design considerations that shaped the development, and finally validated the eye tracker using custom made software.

II. Requirements and Design Considerations

We used a well known principle, video-oculography (VOG), to develop the microscope eye tracker. VOG is based on recording light reflected from the eyes with a video camera. A few distinguishable features from the eyes such as sclera, iris, and pupil are used to measure the eye movements captured by the camera. For more details on VOG eye tracking see [20]–[26]. Our intent here is to follow the same technique as [22] and [24] and describe the design principles and iterative development-evaluation cycles, as well as highlight the technical challenges of building an eye tracker for a surgical microscope.

In addition to basic requirements (i.e. robustness, and accuracy), an OR eye-tracker should fulfill the requirements related to the human factors and safety in the OR. Thus, in the first step we conducted a series of interviews with neurosurgeons and observations of how the microscope was used in the OR. We observed over 20 micro-neurosurgeries over the course of a year at the Neurosurgery of KUH Neuro-Center, Kuopio University, Finland– and closely collaborated with three surgeons with over 20 years of experience in neurosurgery.

From the observations, we derived six fundamental requirements for integrating an eye tracker into a surgical microscope. These requirements shaped the design and development of the eye-tracker.

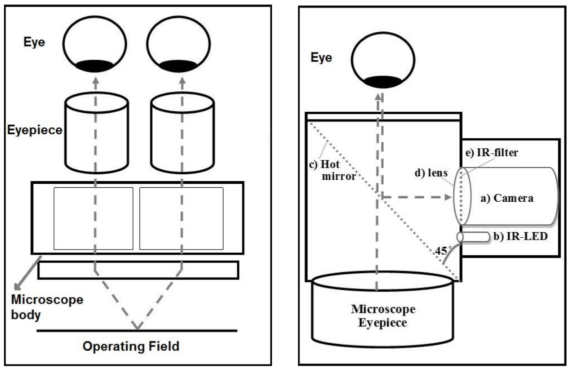
1) The System Should Not Require Any Modification to the Current Microscope: As a propriety product, any physical modifications to the structure of the microscope have to be implemented by the producer. Furthermore, in order to guarantee a high degree of equipment safety in the OR, any appendages to the surgical microscope have to be designed and tested in accordance with various safety standards.

2) The Eye Tracker Should Be Non-Intrusive, Causing No Disruption to Standard Flow for the Surgeon: For example, the position of the eye tracker (e.g. the distance between the eyes and microscope ocular) should not distort the field of the view or distract the surgeon.

3) The Required Time to Setup the System Must Be Short: The surgeon should easily be able to attach or detach the eye tracker to the microscope at any time during surgery.

4) The Sterility of Surgical Area Should Not Be Violated After Adding the Eye Tracker to the Microscope: A surgical microscope is always covered by a sterile drape (Figure 1). Some microscopes have a drape vacuum system which extracts the air from the drape. To keep the sterility of microscope at the same level, the eye tracker should be installable under the current microscope drape.

5) The Surgeon's Face and Eyes Should Be Protected From Harm (When Touching the Eye Tracker Surface): The average duration of a micro-neurosurgery is about two hours, however, in some cases the surgery can last more than five hours. A majority of the surgeon's time is spent looking through the microscope ocular; therefore, direct contact between the tracker and the surgeon's face and eyes should be avoided.



(a) (b)

Fig. 2. Initial hardware design of the eye tracker for the surgical microscope. The components needed to develop a prototype of the eye tracker are: a) Eye camera, b) Infrared Emitters, c) Hot mirror, d) Camera lens, e=IR pass filter. (a) A typical surgical microscope design. (b) Initial eye tracker schema of the proposed system.

6) Eye Safety Should Be Considered Due to the Long Exposure Times of Infrared Light (IR): VOG eye tracking uses IR as a non-distractive light source. However, extended IR exposure may cause retinal damage. Mulvey *et al.* [27] reviewed standards regarding the use of the IR in eye trackers and recommended the use of IR LEDs with very low power densities for long exposure situations.

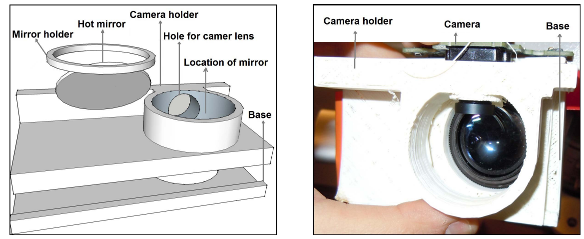
III. Hardware Design

The main challenge of building an eye tracker for a microscope is the design of an adapter that mounts the eye tracker components on the top of the ocular. Figure 2 shows the initial design of our proposed system (right panel) and a typical microscope configuration (left panel). Based on the VOG spectrum imaging technique, our system includes an IR emitter, hot mirror (45 degree), and camera components. The infrared light is emitted to the eye and is reflected back to the camera through a hot mirror, which is tilted at a 45 degrees angle to the ocular's surface. We placed all components on the side of the hot mirror, so they are not visible to the surgeon's eye while looking through the eye tracker. The microscope's built-in camera was used as a scene camera and we used a custom made 3D printer to build the prototype components.

Advances in optical techniques and instrumentation have made eye tracking with high sampling rates cameras possible (e.g. 2kHz EyeLink from SR research LTD). These cameras are large with special optical configurations and therefore are not suited for the microscope eye tracker. Thus we aimed to build the prototype using a consumer level USB camera with Microsoft Windows OS compatibility that has a small sensor and electronics, and performs at a high sampling rate.

Most consumer level cameras however have low sampling rates (30 or 60 Hz) and do not support multi-camera drivers. The microscope binocular eye tracker requires two cameras however it is not common to run more than one identical camera on an OS without a special camera driver.

In response to these limitations, we selected the Sony PlayStation Eye camera, also known as the PS3eye. The PS3eye is a consumer level camera that supports a multi-camera layer API. The maximum sampling rate of the camera is 187 frames per second (fps) for a 320×240 resolution. It is possible to run the camera at a higher resolution, but the fps is reduced; for example, for a resolution of 640×480 the sampling rate is 75fps.



(a) (b)

Fig. 3. First version of the eye tracker installed on the surgical microscope. (a) 3D design of eye tracker including base, camera holder, and mirror holder components. (b) Top view of the eye tracker on the ocular.

Another advantage of using this sensor is that it uses CCTV camera lenses and mounts. This provides easy access to the optical filter of the camera to replace the visible filter. According to the VOG method, in order to remove the noise and unwanted corneal reflection from the eye-images one should use an infrared pass filter [21], [22]. For the prototype we chose an Optolite Infra Red Acrylic visible filter due to performance/cost ratio (Instrument Plastics Ltd Optolite Infra Red Acrylic, n.d.). Although we did not perform accurate measurements, the quality of the eye-images would not be significantly increased by using high-quality filters, since the guiding performance (IR Transmission Characteristics) differs by only about 5-10% between the high-quality and the consumer level versions.

In the following sections we describe the hardware development of the surgical microscope eye tracker through iterative cycles of design, implementation, and evaluation.

A. Version One: Mock Up for Eye Tracker

The first version of the embedded eye tracker prototype is shown in Figure 3. The model consisted of three parts: a base, a camera holder, and a mirror holder. The base part of the model was designed so it could be separated from the other two components and mounted on the microscope ocular (see Figure 3(a)). For that purpose we needed to remove the microscope's eyeguard and attach the base component in its place. The eye-camera was mounted on the camera holder and then connected to the base component (see Figure 3(b)). To complete the eye-tracker the mirror holder was inserted into the camera holder. For this model we chose a circular 45 degree hot mirror. The size of the hot mirror was the same with the ocular diameter (i.e. 25mm).

Typical consumer level video camera lenses and mounts are fixed and are designed to capture objects at a relatively long distance (e.g. 60cm). In our design, however, the distance between the eye and the eye tracker camera is a few centimeters. In order to select a proper camera lens we calculated the focal length of the lens as follow:

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v} \tag{1}$$

where f is focal length, u is distance from camera lens to object, and v is image distance in camera. The image distance (m) can be derived using image magnification formula ($m = \frac{v}{u}$) and therefore

$$f = \frac{u}{(1 + \frac{1}{m})}, \text{ where } m = \frac{\text{sensor size}}{\text{object size}}. \quad (2)$$

In our setup, Ps3eye camera has a 1/4″ CCD sensor (Diagonal=4mm, width=3.2mm height=2.4mm), distance to object (eye) is 30mm, and the size of the object is about 30mm. Thus the camera focal length needs to be in range of 2 to 4mm. Moreover, in order to capture a wide field of view the angle supported by the sensor lens should be chosen carefully. Below is an example of how we estimate angular field of view.

$$\alpha = 2 \times arctan(\frac{\text{Sensor size}}{2 \times \text{focal length}})$$
$$\text{example: } \alpha = 2 \times arctan(\frac{4}{2 \times 2.8}) \text{: } \alpha = 70\text{degree} \quad (3)$$

Based on these calculations we tested various common lenses available on market with different focal lengths (e.g. 2.4mm, 2.8mm, 3.6mm) and as result we selected 3.6 mm focal length lens with a 100 degree diagonal field of view.

After the initial prototype of the eye tracker was built, we conducted an evaluation session with surgeons outside the OR. Three major limitations were discovered: First, the large size (height) of the eye tracker increased the distance between surgeon's eye and microscope ocular (eye relief) and this led to significant decrease in the microscope's field of view [28]. A typical distance between eye and ocular (eye relief) of the surgical microscope is about 20mm and we observed that this distance should not exceed 30mm, otherwise both the magnification and field of view will be reduced significantly (there is an inverse relation between the eye relief distance and the field of view. See [28] for more details on eye relief measurements). High magnification is essential during surgery and facilitates operations under the microscope [29]. Operating under low magnification, with a smaller field of view would increase the risk of error and reduce patient safety.

Second, in this design keeping the mirror at the 45 degree angle was only possible by gluing the mirror to the base part with hot glue (Figure 3(a)). However, this could not be a permanent solution because, any small changes on the model would require re-gluing the hot mirror.

Third, in this version we did not use an IR emitter and we observed that the images from eyes were dark. The amount of darkness was increased when eyes were close to the eye tracker and therefore the camera was unable to recognize the images of eyes properly.

B. Version Two: Hot Mirror Integration

In the second version we focused on reducing the size of the eye tracker and improving the location of the hot mirror (see Figure 4).

We designed the second model as a cube, with two cavities. One of the cavities was dedicated to the eye-camera and other for the microscope ocular (Figure 4(a)). The camera was connected to the model through a tube. We designed a new mirror holder from two separate parts to keep the mirror at a 45 degree incline, thus make it easy to install (Figure 4(b)).

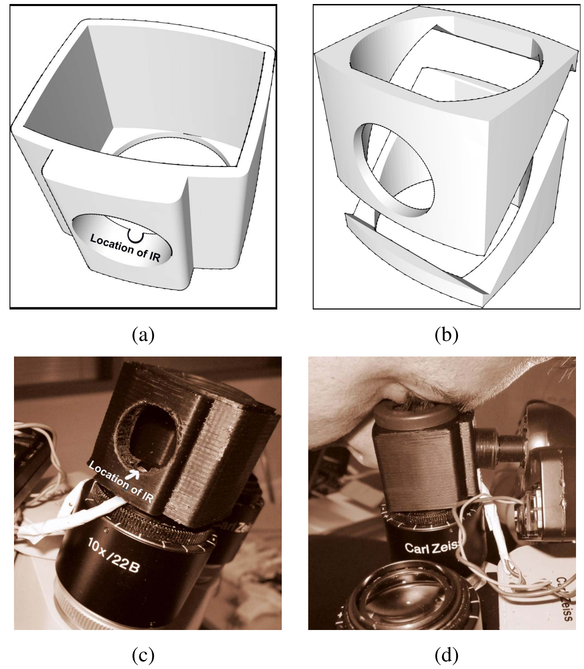


Fig. 4. Second version of the eye tracker with new design approach. (a) 3D design of eye tracker case. Notice new location for IR LED. (b) 3D design of mirror holder. Mirror location is between holders. (c) Eye tracker on ocular. Location of LED is close to edge of the camera holder. (d) Assembled eye tracker in test. Camera is connected to eye tracker via a tube in this version.

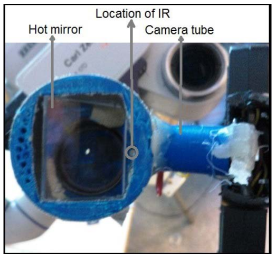
To improve the lighting conditions inside the tracker, we added an IR LED. The IR light was embedded by creating a hole in the bottom of the camera holder, to emit light directly to the eyes (Figure 4(c)). We aimed to use the power source of eye-camera, however the voltage on the PCB was 3.25V while the LED had 1.6V forward voltage; therefore we used an extra resistor in series with the LED in order to solve this problem.

In order to warrant the eye safety we selected a LED that meets the requirement related to the maximum permissible exposure (MPE) standard [27]. We chose a OP166W IR LED which has radiant intensity of 0.0005 w/cm^2 in 950 nm wavelength. The maximum permissible exposure (MPE) for wavelength 950 nm is about $0.004w/sr$ of light power density for long exposure [30]. The power density defines as

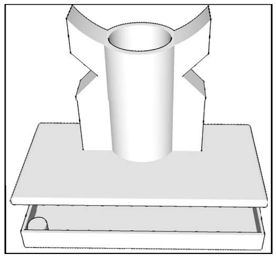
$$RD = \frac{radiant\ intensity}{R^2}$$

The distance between our light source (IR) and eye is 2cm (R=2cm). Thus the power density of the LED in the given distance is equal to 0.000125 w/cm^2. Clearly, this is far less than the MPE safety standard requirement.

We tested the prototype in the similar manner to the first version and we were able to obtain a stable image of the eyes through the eye-cameras. We removed the infrared light filter and installed a visible light filter. At this step, the dark pupil effect was clearly visible due to IR illumination.



(a)



(b)

Fig. 5. Third version of the eye tracker. (a) The top view shows the location of hot mirror inside the new cylindrical design of eye tracker. (b) 3D design of casting for the camera board.

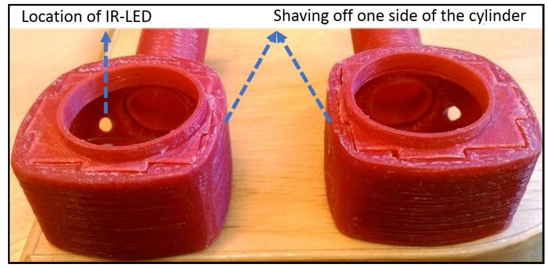


Fig. 6. Fifth version of the eye tracker. Notice the new location for IR LED and design of new rounded-square shape by shaving off the sides of the cylinder.

Testing revealed two main limitations for this version of the eye tracker. Although we reduced the eye tracker's width and height significantly (30%) compared to the first version, the problem with the height of eye tracker still remained. The excessive height still caused changes in the microscope's field of view and as such the microscope eye tracker could not be used in practice. Secondly, the cube casing had sharp edges, which was a potential source of harm for the face of the surgeon, especially when eye-sockets were resting on the eye tracker.

C. Version Three: Ergonomic Aspects

The third version of the prototype is shown in Figure 5. Based on the surgeons' feedback on the second version we made two major changes in which the shape of the camera holder and the position of the hot mirror holder were modified.

The problem with sharp edges was resolved by making the outer casing of the model more cylindrical while inner layout structure remained the same. Moreover, in this version a 45 degree square hot mirror (Figure 5(a)) was used to reflect the IR light. Positioning the square mirror at the front of the camera no longer required a complex design or applying hot glue.

In order to remove the edges of hot mirror from the microscope view, a hot mirror with a surface area a bit larger than ocular size (25mm) was needed. The optimal size for such a mirror was 30-35mm squared. Furthermore, changing the shape of hot mirror reduced the height of the eye tracker by 10%. As there was no longer a need to use a mirror holder, we could fit the square mirror directly inside the model.

Moreover, in this version we designed a custom made casing for the camera board. The camera casing included two parts. The front part was designed to be connected to the camera holder via a tube and the back part was designed to cover the camera board (Figure 5(b)). The unusual shape of the casing tube allowed screws to pass though the tube and secure it to the camera holder.

We tested this version of the eye tracker with surgeons outside the operating room. When both eye trackers (for the left and right eye) were installed on the microscope ocular, some surgeons pointed out that there was not enough space between oculars for the nose (due to the differences in face and nose sizes). In the surgical microscopes the distance between two oculars is adjustable which helps to reserve the needed space for the nose in the center. It was also not easy to install both eye trackers with the new casing, side by side on the oculars, due to the large size (width) of the camera case.

D. Version Four: Reducing the Eye Tracker Size

In the fifth version, we attempted to further reduce the size of the eye tracker, in particular, the width of the tracker. We learnt from the third version that there should be more space between the two trackers to accommodate space for the surgeon's nose. We therefore modified the cylinder design of the tracker to a rounded-square design by shaving off the sides of the cylinder. Figure 6 shows the fifth version of eye tracker.

The location of the IR emitter was also moved from the center to the side of the tube to solve the dark image problem encountered when installing the microscope eyeguard on the top of eye tracker (Figure 6 left side).

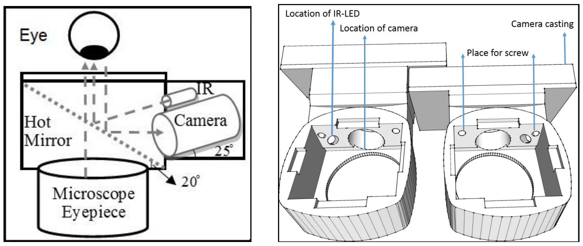
The fifth version solved the issue related to model safety and space for the nose. Based on surgeons' feedback while testing outside the OR we found that, although the brightness of the eye-images was increased, it was not sufficient to run an eye tracking calibration procedure. (we did not measure accuracy of the system in this step but the location of the pupil center was not detected using a common eye tracking software (see experiment section). Installing the eyeguard still caused a dark image effect. This effect was more visible when recording with frame rates higher than 30Hz due to a lower resolution image at the higher sampling rate.

E. Version Five: Complete Microscope Eye Tracker

In the final version, the problems experienced with previous versions were solved by iterating through the whole process step by step. The schema and 3D model of the final version is shown in Figure 7(a).

First, the most important problem related to eye tracker size (height) was targeted. Learning from previous versions, it was clear that as long as we used a 35 mm hot mirror, at a 45 degree angle with the camera, the height of the eye tracker would be more than 30 mm. Thus, we reduced the eye tracker height by decreasing the mirror angle to 20 degrees. To do so, the length of eye tracker was increased using the empty space inside the model.

The disadvantage of changing the mirror angle was that it caused the eye-image to become unclear. The mirror was



(a) (b)

Fig. 7. Final version of the eye tracker. (a) Final eye tracker schema. Notice angle of the camera, IR, and Hot mirror. (b) 3D design of eye tracker with camera casting. Notice new location of the screw, and IR.

designed to reflect infrared light at a 45 degree angle with a maximum 90% transmission. Therefore at 20 degrees, the transmission was reduced dramatically. In order to overcome this problem and to capture a clear image, we adjusted the angle of the camera to 25 degrees (Figure 7(a)). With this solution we achieved a considerable reduction on the eye tracker height, from 40mm (in version one) to 20mm.

The second problem was dark images from the eye captured by the cameras. Although pointing the light directly to the eye provided a clear glint, in the fifth version, the brightness of images was insufficient. Additionally, it was not possible to use more powerful IR LEDs due to eye safety issues. In order to increase the brightness of the eye-image, the pointing direction of the IR LED on the eye tracker was changed. The IR light was directed to the center of the hot mirror where the light was reflected to and from the eyes using the mirror (Figure 7(a)). The quality of eye-images was improved to an acceptable level, even at a low resolution set up (320×240), the light would be sufficient for detecting the pupil with common eye tracking algorithms.

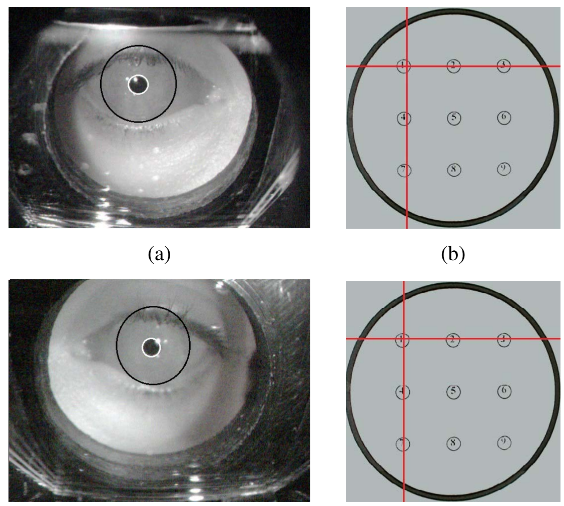
The third problem was the camera casing size. The width of the electronic board could not be accommodated to allow side-by-side setup. To solve the casing size problem, we installed them on top of each other. By reducing the tube size (height) of one the eye trackers by 10mm we could slide the casings underneath each other (Figure 7(b)). Moreover, in order to capture the whole areas of eyes we used two different camera lenses: a wider camera lens (2.8mm) in the tracker with the shorter tube and a 3.6mm focal length lens for the other device.

The final design consideration was how to easily install the eye tracker on the microscope ocular. The eye tracker was designed so that it could be pushed onto the microscope eyeguard and remained stable in place. Figure 8 shows the final version of the eye tracker which was capable of being used in the operating room.

IV. Experiments

We conducted a study to evaluate the accuracy of the microscope eye tracker. Our intention was to use an existing video-oculography (VOG) eye tracking evaluation method that applies standard image processing techniques to detect the pupil center in each video frame. Because, none of the commercial eye tracking software (e.g. Tobii or SMI) supports external hardware for eye movement detection and evaluation, we tested available open source eye tracking software.

Fig. 8. The final eye tracker on a micro-neurosurgical microscope. Notice the overlapping of casting allowing installing both tracker on top of ocular. In this version, the distance between the eyes and the camera is mere 25 mm and the height of the device is 20 mm.



(a) (b) (c) (d)

Fig. 9. A sample frame of eyes being tracked by Haytham software. (a) Left eye image with the pupil and corneal reflection detection (Ps3eye camera). (b) The gaze overlay from left eye on scene image of calibration points (microscope build-in camera). (c) Right eye image with the pupil and corneal reflection detection (Ps3eye camera). (d) The gaze overlay from right eye on scene image of calibration points (microscope build-in camera).

A. Apparatus

We employed the Haytham gaze tracker software. Haytham has been used in several studies [31]–[33] and its interface makes it possible to select different cameras for eye tracking and scene capturing. Figure 9 shows a sample frame of eyes being tracked by the Haytham gaze tracker using the developed microscope eye tracker. We conducted an empirical evaluation of the system outside the operating room with the Carl Ziess micro-neurosurgical microscope (OPMI Pentero).

B. Participants and Procedure

Five participants (three surgeons and two students) with median age of 42(range=29-54) were recruited for the study. All participants had prior experience viewing objects through the microscope and none of the participants wear glasses while using the microscope. The light reflected from participant's glasses might affect performance of any eye tracker, however for our experiment it was possible to adjust the diopter scale

TABLE I
ACCURACY AND PRECISION IN DEGREES OF THE VISUAL ANGLE

Eyes	Accuracy in degree	Precision(RMS) in degree	Precision(SD) in cm
Left eye	1.1	0.6	0.04
Right eye	1.2	0.5	0.03
Average	1.15	0.55	0.035

of microscope eyepieces and therefore our participants did not need to use glasses.

Participants were positioned at the microscope with a viewing distance setting of 70cm between their eyes and stimulus under microscope. All participants first had to pass a standard 9-point eye tracking calibration test before performing the accuracy test. During the calibration an instructor called out numbers and asked participants to focus their gaze on the corresponding number on calibration sheet for period of 2 seconds (see Figure 9(a)). Immediately after calibration we conducted the accuracy test. The accuracy test was a repetition of the 9-point calibration test. In order to calculate the accuracy we later compared the differences between the predicted gaze points and the real gaze values represented by calibration points.

C. Measures

To measure the system performance we extended the Haytham software to include implementations for accuracy and precision validation procedures. System accuracy was defined as the average distance between the real target position and the estimated gaze position [13]. The precision was defined as a Root Mean Square (RMS) of the estimated gaze position samples of the validation data set [13].

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\theta_i)^2}, \quad \text{where } \theta \text{ is iner-sample distance}$$

Moreover, we implemented another commonly used precision metric, namely, the standard deviation of the validation data set.

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2}, \quad \text{where } x \text{ is sample position}$$

Table 1 shows results of the validation procedure. On average we achieved 1.1 degree of accuracy and 0.55 (RMS) degrees of precision which are acceptable levels for custom-made eye tracker solutions [22], [24], [34]–[36].

V. DISCUSSION

Within the medical domain there is a growing interest in the use of eye tracking technologies particularly within intra-operative settings. The primary motivation is to explore the role of visual attention and to explore the possibilities for gaze-based interaction systems in OR environments. Although, the latest versions of eye tracking glasses (e.g. SMI, Tobii) provide the potential for tracking eye movements within intra-operative settings, there are many circumstances where current eye trackers cannot be used, such as during ocular-based medical operations. To overcome ergonomic and safety challenges, we developed an embedded non-invasive eye tracker for a microscope using current eye tracking techniques, namely, video-oculography (VOG).

TABLE II
LIST OF COMPONENTS FOR BUILDING THE MICROSCOPE EYE TRACKER

Components	Quantity	Description
Eye camera	2	PS3eye
Infrared Emitters	2	OP166W
Square hot mirror	2	45 degree, 35mm
IR filter	1	Optolite IR Acrylic
Camera lens CCTV	1	3.6mm, 100 degree
Camera lens CCTV	1	2.8mm, 98 degree
Camera lens mount	2	CCTV
Resistor	2	100Ω
3D-Printer Filament	1	ABS 3mm
Machine screw	4	2mm × 35 and 45mm

TABLE III
TECHNICAL SPECIFICATION OF THE EYE TRACKER

Specification	Technical details
Sampling rate	Up to 187 Hz, depending on sensor settings
Tracking area	Microscope field of view (5-8cm radius of a circle at 50-70 cm distance)
Accuracy	0.5 degree
Data output	Binocular gaze data
Connection	USB 2
Weight	290g
Size	20mm Height × 45mm radius of a circle

Table II shows the final components of the microscope eye tracker. Moreover the technical specification of the system are shown in Table III. The current version of the prototype is fully functional and complies with the design specifications earlier defined in this study. An accuracy test of the eye tracker revealed that the data can be used for further analysis of eye movement patterns.

A. Comparative Advantages

In this contribution, our aim was to provide a prescriptive set of rules and design guidelines for the integration of an eye tracker into a surgical microscope. We highlighted the problems that arose while installing the eye tracker on the microscope ocular, and discussed practical tips for solving these problems.

Until now, only one study has reported the use of eye tracking in the surgical microscope [9]. Both Charlier *et al.* [9] and the eye tracker presented in this paper use similar components to build the microscope eye tracker, namely, hot mirror, infrared light (IR), infrared pass filter, camera, and lenses. The only exception is that our design does not require a beam splitter because we directly point eye cameras to the hot mirror.

We would like to emphasize that the novelty of our approach is the way we design the system. Our particular focus in this paper has been an empirical evaluation and critical assessment of the eye tracker hardware. We argue the eye tracker proposed by Charlier et al. does not fulfill the fundamental requirements identified earlier in this study. In contrast, the proposed system has certain features that warrant integration of the eye tracker in surgical microscope during operations.

First, Charlier et al. eye tracker suffers from the size (height) of the device and thus violating the non-intrusive requirement. As the device height increases the distance between eyes and microscope eyepiece increases which results in a smaller field of view. However, just reducing the size of components does not solve the problem, instead it causes distraction by bringing the internal components within the surgeon's line of vision. Our solution to this problem was to optimize the angle and location of components, as well as the pointing direction of the IR LED. This solution is inapplicable for Charlier et al. system design due to the indirect location of eye camera in relation to hot mirror.

Second, Charlier et al. proposed design violates the ergonomic and aseptic aspects of the microscope. We have shown that the square tracker design would harm surgeon's face. Therefore, in an iterative design manner we made a rounded-square model of the tracker by shaving off the sides of a cylinder design. Furthermore, it is not possible to cover Charlier et al. eye tracker under the microscope drape – to keep the sterility of microscope – due to the size and shape of their device.

After five cycles of the prototype development, now real-time valid eye tracking studies can be conducted in micro-surgical OR. We also envision its deployment within medical domains, namely, pathology, ophthalmology, otolaryngology, plastic and reconstructive surgery, and even in non-medical contexts (e.g. astronomy, forensics and chemistry). We believe the lessons learned in this study are useful for the development of such eye trackers.

B. Implication and Future Work

The eye tracker presented in this paper provides valuable opportunities to record a detailed eye movement data in real-time microsurgery. One area of significant opportunity here is to use this data as part of skills assessment techniques for improving medical training. In modern day of medical interventions the surgical skills assessment of trainees is central [37].

To date, analysis of eye tracking data has been proposed as a suitable objective metrics (e.g. number of gaze fixations or duration of fixations) for assessment of expertise level in many medical domains [37]–[39]. For example in laparoscopic surgery to shorten the training time [40] asked trainees to focus and follow critical fixation point extracted from experts eye movements data.

Other implication here is hand-free surgical microscope. Our eye tracker offers opportunities for gaze contingent microscope control ([16]–[18]). Recent studies by [14] and [15] provided evidence that adjusting the microscope settings manually by hand causes interruption and delay during micro-neurosurgery. Therefore, gaze input offers potential for development of hand-free surgical microscope.

While space does not permit us to go into the technical details, let us name some of the implications of an eye-control microscope.

First, gaze data can be used to improve the performance of current microscope's auto-focus system. Surgeons in [14] and [15] studies reported that the current system often does not focus on desired objects. Providing implicit information about direction of surgeon's gaze on the operating field would increase the accuracy of any auto-focus system [41]. It is also possible to use gaze data for surgical microscope zooming system, for example, a gaze-controlled zooming interface [42] would reduce the number of interruptions caused by adjusting the optical zoom during surgery.

The second area of opportunity for the surgical microscope eye tracker is a gaze-movement command. Gaze control interaction techniques have been extensively studied in various domains where operating a device by hand is not possible [25], [43]–[45], including medical domain [8], [18], [46]. Such a system would remove the need for adjusting surgical microscope manually – by taking hands away from operating field – and therefore, reduce the interruptions and fasten microsurgery operations.

As a future work, we aim to investigate a number of concerns with the use of gaze-control microscope in microsurgery. We will expand current eye tracking methodology to improve the performance of ocular based eye tracker. Inspiring from study like [34], [47] we will expand the Hyatham eye tracking software to fulfill our requirements. For example, to reduce the set-up time and improve usability of the system we first save the calibration profiles for each surgeon and second investigate, and test possible free calibration techniques [48].

ACKNOWLEDGMENTS

The authors would like thank Alex Gegiuc and Joni Tanskanen for their work on the preliminary version of the eye tracker. Our special thanks also goes for surgeons who provide feedback on the system in each development cycle.

REFERENCES

[1] C. F. Nodine and H. L. Kundel, "Using eye movements to study visual search and to improve tumor detection," *Radiographics*, vol. 7, no. 6, pp. 1241–1250, 1987.

[2] B. Law, M. S. Atkins, A. E. Kirkpatrick, and A. J. Lomax, "Eye gaze patterns differentiate novice and experts in a virtual laparoscopic surgery training environment," in *Proc. Symp. Eye Tracking Res. Appl.*, 2004, pp. 41–48.

[3] S. Eivazi, R. Bednarik, M. Tukiainen, M. von und zu Fraunberg, V. Leinonen, and J. E. Jääskeläinen, "Gaze behaviour of expert and novice microneurosurgeons differs during observations of tumor removal recordings," in *Proc. Symp. Eye Tracking Res. Appl.*, 2012, pp. 377–380.

[4] T. Balslev *et al.*, "Visual expertise in paediatric neurology," *Eur. J. Paediatric Neurol.*, vol. 16, no. 2, pp. 161–166, Mar. 2012.

[5] G. Tien, M. S. Atkins, X. Jiang, B. Zheng, and R. Bednarik, "Verbal gaze instruction matches visual gaze guidance in laparoscopic skills training," in *Proc. Symp. Eye Tracking Res. Appl.*, 2014, pp. 331–334.

[6] F. Hermens, R. Flin, and I. Ahmed, "Eye movements in surgery: A literature review," *J. Eye Movement Res.*, vol. 6, no. 4, pp. 1–11, 2013.

[7] M. Wilson, J. McGrath, S. Vine, J. Brewer, D. Defriend, and R. Masters, "Psychomotor control in a virtual laparoscopic surgery training environment: Gaze control parameters differentiate novices from experts," *Surgical Endoscopy*, vol. 24, no. 10, pp. 2458–2464, Oct. 2010.

[8] G.-Z. Yang, G. P. Mylonas, K.-W. Kwok, and A. Chung, "Perceptual docking for robotic control," in *Medical Imaging and Augmented Reality*. New York, NY, USA: Springer, 2008, pp. 21–30.

[9] J. Charlier, P. Sourdille, M. Behague, and C. Buquet, "Eye-controlled microscope for surgical applications," *Develop. Ophthalmol.*, vol. 22, pp. 154–158, Dec. 1991.

[10] M. S. Atkins, G. Tien, R. S. A. Khan, A. Meneghetti, and B. Zheng, "What do surgeons see capturing and synchronizing eye gaze for surgery applications," *Surgical Innov.*, vol. 20, no. 3, pp. 241–248, Jun. 2013.

[11] L. Richstone, M. J. Schwartz, C. Seideman, J. Cadeddu, S. Marshall, and L. R. Kavoussi, "Eye metrics as an objective assessment of surgical skill," *Ann. Surgery*, vol. 252, no. 1, pp. 177–182, Jul. 2010.

[12] Y. Tomizawa, H. Aoki, S. Suzuki, T. Matayoshi, and R. Yozu, "Eye-tracking analysis of skilled performance in clinical extracorporeal circulation," *J. Artif. Organs*, vol. 15, no. 2, pp. 146–157, Jul. 2012.

[13] K. Holmqvist, M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, and J. Van de Weijer, *Eye Tracking: A Comprehensive Guide to Methods and Measures*. London, U.K.: Oxford Univ. Press, 2011.

[14] H. Afkari, S. Eivazi, R. Bednarik, and S. Mäkelä, "The potentials for hands-free interaction in micro-neurosurgery," in *Proc. 8th Nordic Conf. Human-Comput. Interact., Fun, Fast, Found. (NordiCHI)*, 2014, pp. 401–410.

[15] S. Eivazi, H. Afkari, R. Bednarik, V. Leinonen, M. Tukiainen, and J. E. Jääskeläinen, "Analysis of disruptive events and precarious situations caused by interaction with neurosurgical microscope," *Acta Neurochirurgica*, vol. 157, no. 7, pp. 1147–1154, Jul. 2015.

[16] G. P. Mylonas, A. Darzi, and G. Z. Yang, "Gaze-contingent control for minimally invasive robotic surgery," *Comput. Aided Surgery*, vol. 11, no. 5, pp. 256–266, 2006.

[17] D. P. Noonan, G. P. Mylonas, A. Darzi, and G.-Z. Yang, "Gaze contingent articulated robot control for robot assisted minimally invasive surgery," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sep. 2008, pp. 1186–1191.

[18] D. P. Noonan, G. P. Mylonas, J. Shang, C. J. Payne, A. Darzi, and G.-Z. Yang, "Gaze contingent control for an articulated mechatronic laparoscope," in *Proc. 3rd IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Sep. 2010, pp. 759–764.

[19] G. P. Mylonas *et al.*, "Gaze-contingent motor channelling, haptic constraints and associated cognitive demand for robotic MIS," *Med. Image Anal.*, vol. 16, no. 3, pp. 612–631, Apr. 2012.

[20] A. Duchowski, *Eye Tracking Methodology: Theory and Practice*, vol. 373. New York, NY, USA: Springer, 2007.

[21] C. H. Morimoto, D. Koons, A. Amir, and M. Flickner, "Pupil detection and tracking using multiple light sources," *Image Vis. Comput.*, vol. 18, no. 4, pp. 331–335, Mar. 2000.

[22] D. Li, J. Babcock, and D. J. Parkhurst, "openEyes: A low-cost head-mounted eye-tracking solution," in *Proc. Symp. Eye Tracking Res. Appl.*, 2006, pp. 95–100.

[23] C. Hennessey, B. Noureddin, and P. Lawrence, "A single camera eye-gaze tracking system with free head motion," in *Proc. Symp. Eye Tracking Res. Appl.*, 2006, pp. 87–94.

[24] J. S. Agustin *et al.*, "Evaluation of a low-cost open-source gaze tracker," in *Proc. Symp. Eye Tracking Res. Appl.*, 2010, pp. 77–80.

[25] D. W. Hansen and Q. Ji, "In the eye of the beholder: A survey of models for eyes and gaze," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol. 32, no. 3, pp. 478–500, Mar. 2010.

[26] A. Al-Rahayfeh and M. Faezipour, "Eye tracking and head movement detection: A state-of-art survey," *IEEE J. Translational Eng. Health Med.*, vol. 1, no. 1, Nov. 2013, Art. ID 2100212.

[27] F. Mulvey, A. Villanueva, D. Sliney, and R. Lange, *Exploration of Safety Issues in Eyetracking*. Humanities Lab., Lund University, 2008.

[28] M. Katz, "Angular and linear fields of view of Galilean telescopes and telemicroscopes," *Optometry Vis. Sci.*, vol. 84, no. 6, pp. E522–E531, Jun. 2007.

[29] M. Lehecka, A. Laakso, J. Hernesniemi, and O. Çelik, *Helsinki Microneurosurgery Basics and Tricks*, 1st ed. Balgheim, Germany: Druckerei Hohl GmbH and Co. KG, 2011.

[30] A. Mazzei, "Expanding eye-tracking methods to explain the socio-cognitive effects of shared annotations," Ph.D. dissertation, École Polytechn. Fédérale Lausanne, Lausanne, Switzerland, 2013.

[31] K. Lukander, S. Jagadeesan, H. Chi, and K. Müller, "OMG! A new robust, wearable and affordable open source mobile gaze tracker," in *Proc. 15th Int. Conf. Human-Comput. Interact. Mobile Devices Services*, 2013, pp. 408–411.

[32] A. T. Kurauchi and C. H. Morimoto, "Towards wearable gaze supported augmented cognition," in *Proc. CHI*, 2013, pp. 91–96.

[33] J. Hales, D. Rozado, and D. Mardanbegi, "Interacting with objects in the environment by gaze and hand gestures," in *Proc. 17th Eur. Conf. Eye Movements*, 2013, pp. 1–9.

[34] A. Mazzei, S. Eivazi, Y. Marko, F. Kaplan, and P. Dillenbourg, "3D model-based gaze estimation in natural reading: A systematic error correction procedure based on annotated texts," in *Proc. Symp. Eye Tracking Res. Appl.*, 2014, pp. 87–90.

[35] R. Mantiuk, M. Kowalik, A. Nowosielski, and B. Bazyluk, "Do-it-yourself eye tracker: Low-cost pupil-based eye tracker for computer graphics applications," in *Advances in Multimedia Modeling* (Lecture Notes in Computer Science), K. Schoeffmann, B. Merialdo, A. G. Hauptmann, C.-W. Ngo, Y. Andreopoulos, and C. Breiteneder, Eds. Berlin, Germany: Springer-Verlag, vol. 7131, 2012, pp. 115–125.

[36] H. Lee, N. Iqbal, W. Chang, and S.-Y. Lee, "A calibration method for eye-gaze estimation systems based on 3D geometrical optics," *IEEE Sensors J.*, vol. 13, no. 9, pp. 3219–3225, Sep. 2013.

[37] T. Tien, P. H. Pucher, M. H. Sodergren, K. Sriskandarajah, G.-Z. Yang, and A. Darzi, "Eye tracking for skills assessment and training: A systematic review," *J. Surgical Res.*, vol. 191, no. 1, pp. 169–178, Sep. 2014.

[38] J. Causer, J. N. Vickers, R. Snelgrove, G. Arsenault, and A. Harvey, "Performing under pressure: Quiet eye training improves surgical knot-tying performance," *Surgery*, vol. 156, no. 5, pp. 1089–1096, Nov. 2014.

[39] T. Jaarsma, H. Jarodzka, M. Nap, J. J. van Merrienboer, and H. P. A. Boshuizen, "Expertise under the microscope: Processing histopathological slides," *Med. Edu.*, vol. 48, no. 3, pp. 292–300, Mar. 2014.

[40] S. J. Vine, R. S. W. Masters, J. S. McGrath, E. Bright, and M. R. Wilson, "Cheating experience: Guiding novices to adopt the gaze strategies of experts expedites the learning of technical laparoscopic skills," *Surgery*, vol. 152, no. 1, pp. 32–40, Jul. 2012.

[41] S. Hillaire, A. Lécuyer, R. Cozot, and G. Casiez, "Using an eye-tracking system to improve camera motions and depth-of-field blur effects in virtual environments," in *Proc. IEEE Virtual Reality Conf.*, Mar. 2008, pp. 47–50.

[42] M. Pomplun, N. Ivanovic, E. M. Reingold, and J. Shen, "Empirical evaluation of a novel gaze-controlled zooming interface," in *Proc. HCI Int.*, 2001, pp. 1–5.

[43] V. Raudonis, R. Simutis, and G. Narvydas, "Discrete eye tracking for medical applications," in *Proc. 2nd Int. Symp. Appl. Sci. Biomed. Commun. Technol. (ISABEL)*, Nov. 2009, pp. 1–6.

[44] R. J. Jacob and K. S. Karn, "Eye tracking in human-computer interaction and usability research: Ready to deliver the promises," *Mind*, vol. 2, no. 3, p. 4, 2003.

[45] C. Ware and H. H. Mikaelian, "An evaluation of an eye tracker as a device for computer input2," *ACM SIGCHI Bull.*, vol. 17, no. SI, pp. 183–188, May 1987.

[46] C. Staub, S. Can, B. Jensen, A. Knoll, and S. Kohlbecher, "Human-computer interfaces for interaction with surgical tools in robotic surgery," in *Proc. 4th IEEE RAS EMBS Int. Conf. Biomed. Robot. Biomechatronics (BioRob)*, Jun. 2012, pp. 81–86.

[47] Z. Zhu, Q. Ji, K. Fujimura, and K. Lee, "Combining Kalman filtering and mean shift for real time eye tracking under active IR illumination," in *Proc. 16th Int. Conf. Pattern Recognit.*, vol. 4. 2002, pp. 318–321.

[48] T. Ohno, "One-point calibration gaze tracking method," in *Proc. Symp. Eye Tracking Res. Appl.*, 2006, p. 34.

Shahram Eivazi, photograph and biography not available at the time of publication.

Roman Bednarik, photograph and biography not available at the time of publication.

Ville Leinonen, photograph and biography not available at the time of publication.

Mikael von und zu Fraunberg, photograph and biography not available at the time of publication.

Juha E. Jääskeläinen, photograph and biography not available at the time of publication.