SOPHOCLE:
A Retinal Laser Photocoagulation Simulator
Overview *

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Abstract. Retinal laser photocoagulation has been used for a decade,
but no real improvement in results has been observed.The simulator de-
scribed in this paper, by separating actual practice from apprenticeship,
allows one both to learn how to manipulate the equipment and to train
oneself for making a diagnosis and operating. It has been designed as
close as possible to the actual operation conditions and gives the oppor-
tunity to deal with a large library of current or rare cases. An actual
slit-lamp is supplied with sensors measuring all the degrees of freedom
of the system. The images are calculated by a PC computer and are dis-
played on a miniature screen placed inside the binocular. A user interface
is provided through a Computer Assisted Training software, which allows
users to manage the pigmentations and pathologies data base, to follow
the students skill level and to prepare critical operations.

Introduction

Retinal laser photocoagulation is a widely spread surgical technique. It has be-
come one of the most important part of the ophthalmic area (about 3000 op-
erations are performed in a year at the Regional Hospital Center of Lille). The
therapeutic effects of photocoagulation are no more to be demonstrated in retinal
detachment prevention, diabetic retinopathy, A.R.M.D. (Age Related Macular
Degeneration), etc... However, despite the number of installed equipments, no
real improvement of complications which should have been solved has been ob-
served. These can, in worst cases, lead to a complete blindness. One of the reasons
is undoubtedly the population aging, but one has the right to wonder whether
the teaching of this technique is not to be improved. Today teaching is indeed
based on two points: on one hand, theoretical knowledge is taught authorita-
tively or from books, on the other hand, gestures apprenticeship is learned by
watching the teacher and practicing on actual patients.

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Medicine always gains from the incoming of advanced new technologies: therapeutic laser, phakoemulsificators, diagnosis tools (video-photokeratoscope, visual field, electrophysiology...). Their consequence is a constant change of therapeutic methods. Why not take advantage of these new technologies to improve apprenticeship?

A retinal laser photocoagulation simulator provides a good answer to the apprenticeship problem. It is defined by two steps. First, a diagnosis step means the recognition of pathologies requiring a treatment or not. The second step consists in the treatment of the disease, taking account of the different settings like dosage or impacts locations. The interest of such a simulator lies inside the opportunity that it gives to the student to train as often as he wants and to deal with very rare pathologies which he would have had little chance to meet during his relatively short training course (5 semesters with one half day in a week for photocoagulation). Moreover, it allows ophthalmologists to improve their technique during their continuous education or to prepare critical operations. Finally, it gives the ability to separate actual practice from apprenticeship, and therefore to lower the risks for the patients.

The simulator has been designed as close as possible to the actual operation conditions. The slit-lamp is kept, all the other tools and the patient are simulated. Sensors measure the position of the different degrees of freedom and send the results to a PC computer, which calculates the images. These images are displayed in the binocular by means of a miniature screen. The simulator comes with a user interface (a computer assisted training software), which makes the simulator easy to use and allows the students level to be followed.

After a quick state of the art in medical simulators, we will see a description of the laser photocoagulation. Then, all the sensors, mathematical models and visualization algorithms will be presented, followed by a complete description of the simulator and its user interface.

1 Previous Works

Medical simulators have been a recent research area. Compared to driving simulators, medical simulators utilization increases quite slowly. One of the reasons may be the reserve of the surgeons. Another reason is undoubtedly the complexity of algorithms required within the medical area. Indeed, the surgeon not only visualizes the environment, but also interacts with it. That is why most simulators demand powerful workstations. [6] study laparoscopic gall-bladder surgery simulator, and try to generalize their model to other organs. [16] have designed a complete immersive simulator (including sensors, modeling, real-time deformations, visualization and force feedback) allowing anterior segment of the eye operation to be simulated. Their goal is to find new operation techniques. Other teams (Chapel-Hill, Georgia) are working on complete virtual environments. New domains are visited like childbirth [3][4], cardiology [17]... Cinquin's team in Grenoble is working on subjects like data acquisition, simulation, critical operation preparation and computer assisted intervention in areas like stereostatic

neurosurgery, knee surgery, plastic and maxillo-facial surgery, rigid endoscopy
[1]... Some other teams are working on 2D-data acquisition and 3D reconstitu-
tion which can be used for teleoperation, for instance [8] on stereostatic MRI.

Since the equipment required for complete environments is costly, some teams
are working on cheaper simulators. For instance, [2] use images recorded on CD-
ROM. [10] have designed a cranofacial surgery simulator, with intend to predict
the result of an operation.

Some areas like observation, laser or endoscopy do not require very costly
hardware [13], for the surgeon watches the organ through a binocular or a screen,
and there is not or few mechanical interactions between the surgeon and the
organ. Our simulator is lying in this frame, since it has been implemented on a
general purpose PC, the vision of the surgeon is limited by the binocular and
only a laser is used for the therapy.

2   Retinal Laser Photocoagulation

The goal of laser photocoagulation is to heal retinal diseases. The ophthalmolo-
gist beams a high power laser in order to create a barring around the lesion. The
equipment includes a binocular, a slit-lamp, which provides the surgeon with
light for the fundus observation, and the laser outfit.

A 3-mirror lens is placed on the patient's eye. It is made of three mirrors,
spaced at 120 degree intervals, around a central lens. These mirrors have different
inclinations so that the surgeon can observe different retina zones.

The operation and simulator description is showed on Fig. 1. The surgeon
looks through the binocular, at the eye, which is lit by means of a slit, located
at the back of the apparatus. A control lever enables the user to move the slit-
lamp horizontally, and vertically by rotating it. A micro-manipulator can make a
mirror rotate around two axes, in order to choose the orientation of the laser. A
control panel allows the settings of the laser to be changed (power, fire duration).

The surgeon makes the 3-mirror lens slip around the eye, and looks at the
fundus through the central lens or through one of the mirrors. In the same way,
the laser beam can reflect onto a mirror before passing through the central lens.
A low power laser sets the target site for the surgeon to fire the high power laser
by pressing a pedal.

In an actual operation, about one hundred impacts are fired.

3   Mechanical Features

In our simulator, only the slit-lamp is kept. The patient and the lens are com-
pletely simulated. So, what the surgeon sees in the binocular has to be syn-
thetized. The image depends upon the degrees of freedom of the system, which
are measured by sensors. Here is the list of the degrees of freedom:

1. 3 translations (2 horizontal, 1 vertical) of the slit-lamp, which are measured
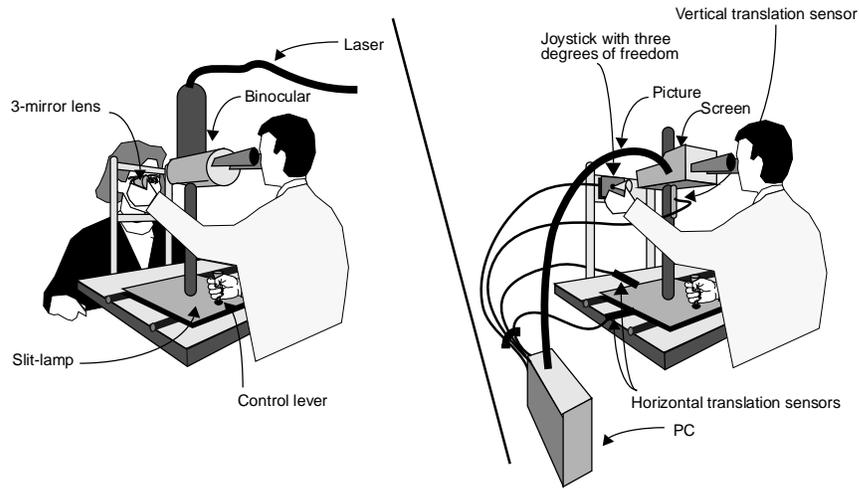   by linear potentiometers, fixed on the observation statif.

Fig. 1. Real and virtual operation description

2. 3 rotations (2 around the patient's eye and 1 around the lens axis), which are measured by an analogical 3-axis joystick. An exact copy of the lens is placed onto the stick part of the joystick. Two joysticks are used to simulate both right and left eyes and are inserted into the eyes slits of a mask.
3. 2 rotations of the laser mirror, which are measured by an analogical joystick.
4. The slit width and spot size are controlled by potentiometers.
5. The power of the laser and the firing duration are modified with the help of +/- interrupters located on the control panel. Their values and the number of laser impacts during the operation are displayed with three 7 segments LED.
6. The slit height, the magnifying level and the power of the lamp are controlled by means of multi-position interrupters.
7. Firing is controlled by an interrupter.

Data from the analogical and digital sensors are sent to the computer by means of a conversion interface. This card encodes values in 12-bit format.

4 Modeling

4.1 Lens Modeling

A 3-mirror lens is simulated since it is a good generalization of all ophthalmic lenses. It allows the eye to be observed directly or indirectly. The proposed model can therefore be adapted to other types of lenses. The three mirrors enable the surgeon to observe different zones of the eye. The lens is represented on Fig. 2.

1. The mirror 2, with a low inclination, allows the zones located around the central fundus to be observed.
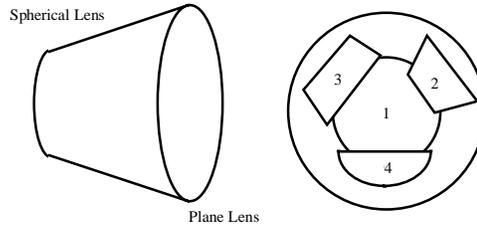
Fig. 2. The 3-mirror lens

2. The mirror 3, with an average inclination, allows the peripheral retina to be observed.
3. The mirror 4, with a high inclination, allows the regions, located just behind the iris to be observed.

The 3-mirror lens is modeled by a cone, and the (spherical) central lens is approximated by a planar circle. Each mirror is modeled by a plane (an equation) and four points belonging to the plane, which delimit the mirror edges. A local coordinates system which is centered on the cornea sphere, is used.

The model must be parameterized by the joystick data, in order to define the orientation of the virtual lens. These data are converted into angles: the 2 rotations around the eye are defined just as the spherical system coordinates (a latitude and a longitude). A space transformation matrix (from the local to the global coordinates) is calculated from the angles and is used to calculate the position of the lens elements. This matrix also allows the new equations of the mirrors planes to be determinated and therefore, the image of space, seen through the mirrors, to be calculated by an orthogonal symmetry.

4.2 Eye Modeling

The eye is modeled by a sphere, the cornea by a half-sphere. The center of the eye and of the cornea are not the same: the cornea center is translated, along the visual axis, toward the pupil. The iris is modeled by a flat ring, orthogonal to the visual axis. As the lens, a local coordinates system is used, and a transformation matrix is calculated, to simulate any movement of the eye. But, this time, the angles are chosen by the computer, depending upon how "nervous" the virtual patient is: random numbers with Gauss distribution give realistic effects.

In order to get a realistic image of the eye, a photomapping is used. Thus, a complete map of an eye is created. At least 20 photographs of an actual fundus are taken and placed side by side with a specific software. Blood vessels continuity is used for the assembly. A complete 2D map is obtained thanks to spherical coordinates.

In order to visualize a textured eye, we decided to use a tessellated sphere representing the eye and associate a texture map to each face. The tessellation triangles do not need to be small: the smaller the triangles, the more faces will

have to be processed, so processing time will increase, but the display time will not change (the same number of pixels will be colored). The tessellation must embody the sphere. Indeed, the surgeon looks at the interior of the eye, and some parts of the eye will not be displayed if the surgeon looks along a skimming direction.

The tessellation we choose is a regular icosahedra, which is a polyhedron with 20 equilateral triangles. The texture map of each triangle is put into an array, the color of each point is obtained by projecting the icosahedra onto the sphere, with a projection whose center is the central point of the sphere.

Only one resolution of the texture is used for the map, for it is optimized for the usually used magnifying level. If the surgeon increases the magnifying level, several pixels on the screen will be displayed with the color of the same texel[1], if he decreases the magnifying level, several texels will not be used.

4.3   Operation Modeling

An absolute coordinates system is chosen: it is located on the center of the surgeon's eye. So the patient's eye is supposed to move and not the surgeon's eye, although it is actually the contrary. The entire laser path is calculated: it reflects first onto the deflection mirror, then, possibly on one of the mirrors of the lens, and reaches the fundus, if it has not met any obstacle like the lens or the iris. The impact point is then calculated on the icosahedra. Impacts are put in memory for evaluation purpose and in the texture map for display. Impacts color depends upon the type of the fundus, the firing duration, the laser power and focus.

5   Visualization

5.1   Image Drawing

All the objects are projected onto the screen plane with a perspective projection. No usual algorithms for 3D synthesis such as Z-buffer have been used. We preferred instead to use 2D algorithms. Indeed, according to depth order, the objects are always arranged the same way. So, no sort is needed. Objects are displayed sequentially, first the central lens, iris, fundus, then each mirror and image of what is seen through the mirror. In order not to display the hidden parts, we chose to use Sutherland-Hodgman polygons clipping algorithm (see [11]).

An efficient algorithm for texture mapping has been implemented on the PC: a bilinear interpolation has been used [12].

5.2   Rendering

In actual operation, sharpness is controlled by the depth translation which focuses the different lenses. A good focus is required for a good photocoagulation,

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[1] Texture element.

for the focus of the image causes the focus of the laser, which is only effective for a good focus. So it was important to implement a real-time depth of field simulation. Four texture maps of the eye, with increasing blurring level are put in memory. The color of a point is obtained by interpolating between the colors of this point in two blurring levels.

Only the part of the eye which is lit by the slit is visible, the rest is too dark to be seen. The light from the slit looks like a rectangle on the screen. In order to suppress the discontinuous transition between the lit part and the dark one, a gradation on the edge of the rectangle has been implemented (the distance between the point and the edge determines the loss of brightness).

As far as the laser is concerned, the impact point on the icosahedra is known. The spot can be drawn, if it is seen through the central lens and/or through a mirror. In order to draw a translucent spot, it is filled with a grid bitmap: one point out of two are displayed with the color of the laser, the other points are kept unchanged (screen-door transparency).

6   Design

The software has been implemented on a PC with a 80486DX2.66. The video card is a Local Bus one, which makes a 32-bit access at the frequency of the processor possible. The algorithms have been implemented in C and run in protected mode. Images are displayed both on a control screen and on a miniature screen, located in the binocular. In the first prototype, a CGA-resolution LCD screen was used. However, we are now working on a new implementation using a Textronix VGA field sequential color display which give best results. At every step, the PC gets the sensors data, calculates the image with them, and, using a double buffer, displays this image on the two screens. A second PC, called master, runs the user interface under the Windows environment. This interface is described in next section. The Master PC sends orders to the simulation PC (also called slave-PC) by means of a serial link. Any fundus, pathology or fluorography is displayed on the simulation PC screen, on one hand, to take advantage of higher resolutions and number of colors, independently of Windows, and on the other hand, to make the access to the data base easier, since the data base is centralized on the slave PC (the amount of information passing through the serial link is lowered). Figure 3 shows the complete configuration.

7   User Interface - Computer Assisted Training Software

The user interface consists in a succession of explicit menus, which are easy to use, even for people with little knowledge of computers. The first step is the recognition of the user to assume access security. This means that the user types a name and a password. If the authentication succeeds, the software can know what kind of user he is. Three classes has been implemented: *system manager*, *experts* and *students*.
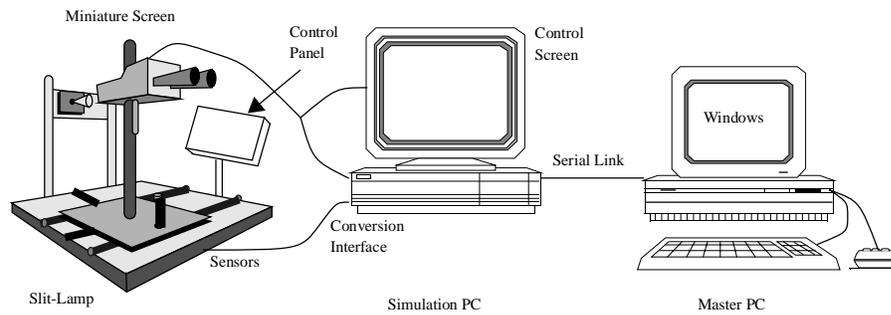
Fig. 3. Configuration

The *system manager* is responsible for the well-running of the simulator and for the data base coherency. Several options are proposed to help making a diagnosis of the simulator, but this is far beyond the scope of this paper. The *experts* are the ophthalmologists who are in charge of students. The software allows them to create photocoagulation exercises for their students, by choosing fundus, pathology, eye side and mobility... The software can help them to prepare a critical operation too.

The *students* can also register, in order to train on their own or to inspect their improvement since their last operation simulations.

Any operation simulation is called a session. Every sessions are recorded and can be reviewed (by means of the simulator), if required by the user, with the help of a video tape-like interface. This film allows an expert to evaluate a session, even if he was not present at that time.

In order to accommodate each *school of therapy*, no standard is imposed. The expert chooses the appropriate treatment, called reference session. The software can then give some pieces of information for the evaluation of the students (number, localization, settings of the impacts). However, only the expert can validate a session.

The data base is put in the hard drive of the simulation PC and consists in the set of fundus and pathologies. Some pathologies (A.R.M.D., diabetic retinopathy) can come with a fluorography, which is also put in the data base. Finally, all the films which have been kept by the users, are recorded into the data base. Each fundus and pathology belongs to an expert, who can therefore have personalized data.

Results - Perspectives

An example of image is given on Fig.4.The current frame rate is about 8 images per second in a 640x400 resolution and 32768 colors and 10 images per second, in a 640x480 resolution and 256 colors. About 35% of time is used for processing, 65% for displaying. The new PC technologies (Pentium, PCI) can improve the frame rate (new processors lower the calculation time, new buses lower the displaying time), and the simulator is soon to be adapted on pentium PCI with

a faster video card. A satisactory frame rate would be between 15 to 20 images per second.

The current work are the improvement of impacts treatment and rendering (iris texture, light interferences...). Some sounds will be added. Long-term project is the inclusion of the entire eye semiology, in order to simulate other diseases (pathologies located in the anterior segment, for instance).

A prototype is being validated by the students at the hospital of Lille. Some other ophthalmologists team will be contacted to criticize and complete the data base. This project has been patented [7] and is aimed to be industrialized.

Acknowledgments

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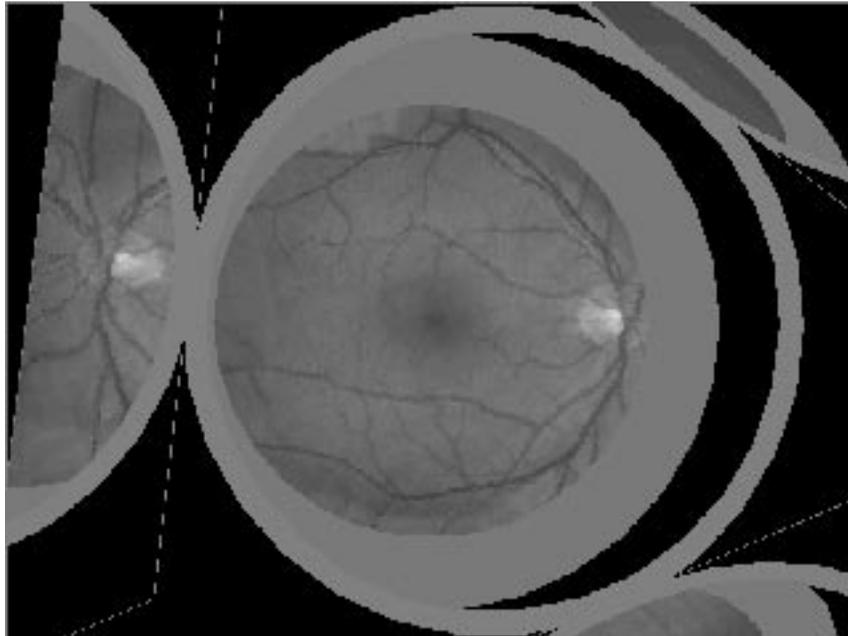
Fig. 4. Synthetized image of the 3-mirror lens and the eye

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