LA ROSES

Laser Assisted RObotic Surgery of the anterior Eye Segment

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[1] Dissemination Level:

PU Public
PP Restricted to other programme participants (including the Commission Services)
RE Restricted to a group specified by the consortium (including the Commission Services)
CO Confidential, only for members of the consortium (including the Commission Services)

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Summary

1 Executive Summary

The aim of this report is to describe the LA-ROSES robotic platform final implementation. The concluding implementation appears as final result of an implementation process through the entire project lifetime. Intermediate results, already described elsewhere, have been used to improve initial development solutions for defining the final platform.

2 LA-ROSES Welding system platform

The final version of the laser welding platform has been designed following the indications of the corneal surgeon MD Luca Menabuoni. The main recommendations are: a compact system that enables an effective welding of the corneal tissue during the keratoplasty; a full control of the surgical scene, so that it is possible to make a decision during the surgery (stop the laser, increase the effects, change the laser position, etc.); in other words a result that is "surgeon independent".

Beside this, we promoted a deep study of the surgical scenario, visiting the surgery room during different corneal interventions. The working distance and the characteristics of the final prototype (laser settings and configuration) were thus determined considering different working conditions that can be tailored on the patient and pathology together with the surgeon requests.

As result of this analysis designing specification and requirements arises. The final outcome of the development and realization phases can be summarized and pictured in Fig. 1 and Fig. 2.

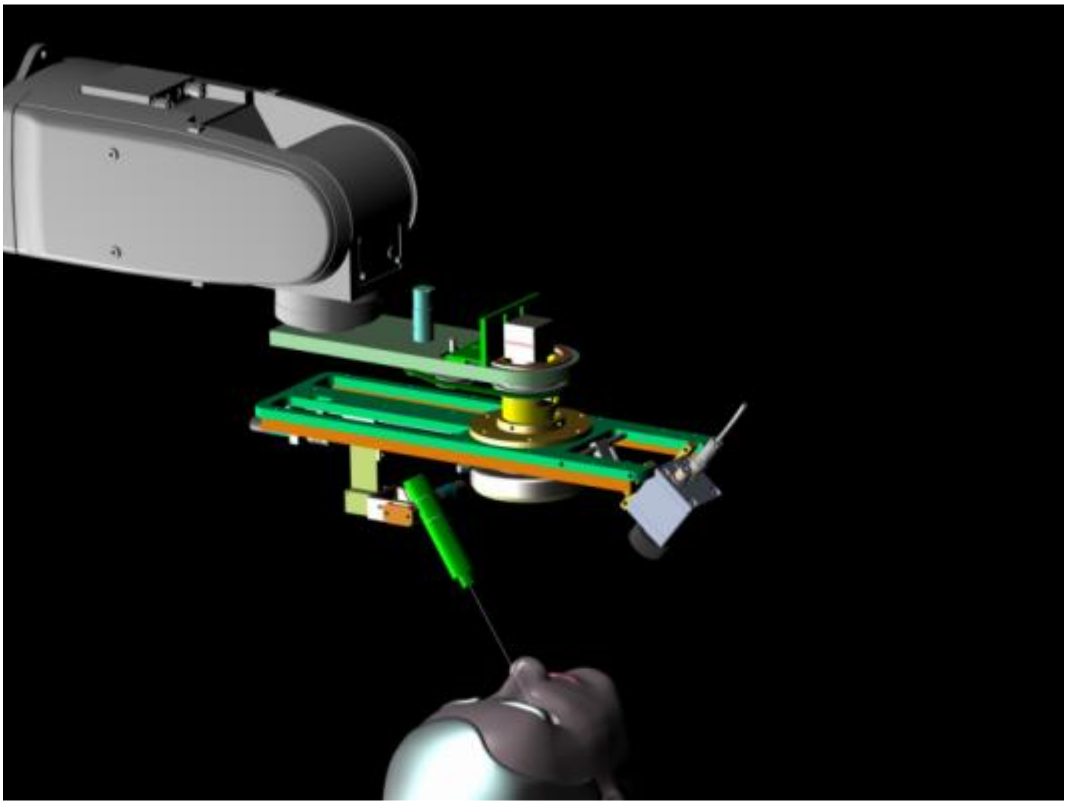


Fig. 1 - LA ROSES system General CAD View

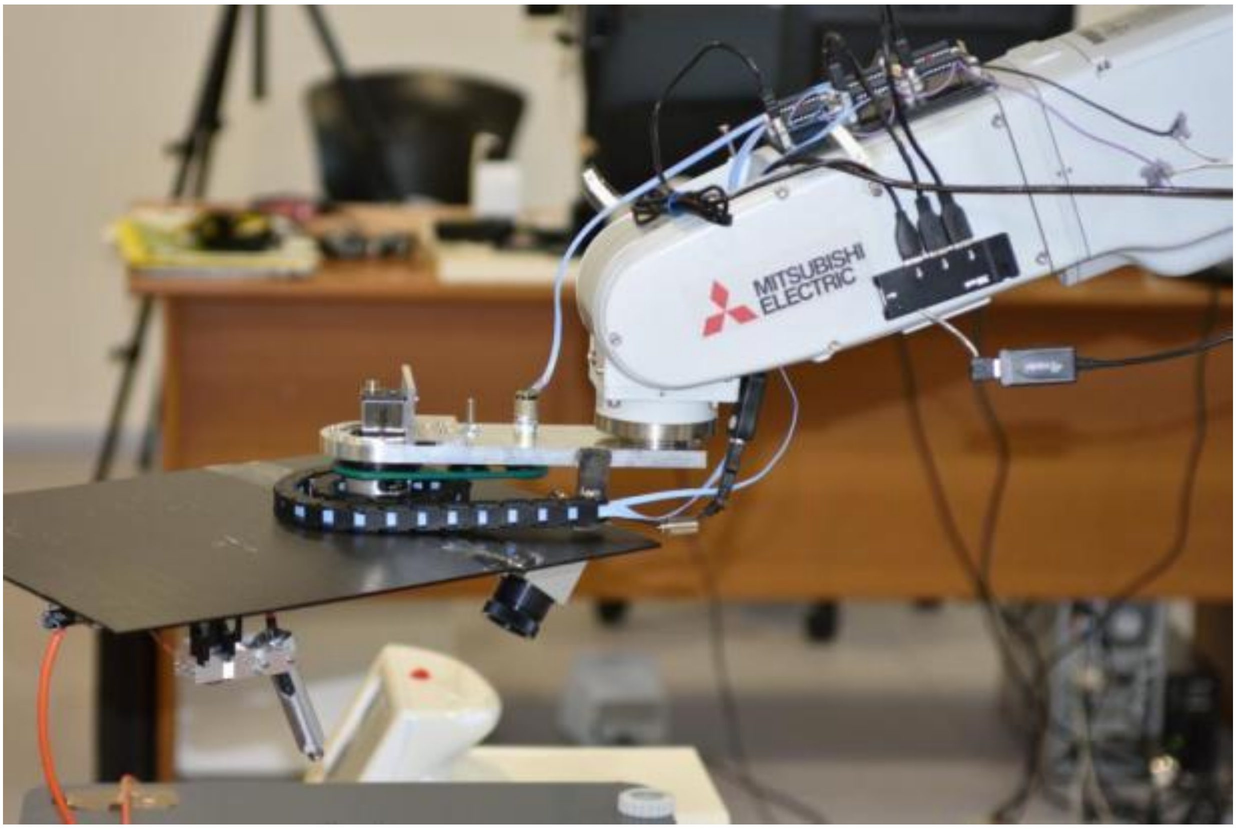


Fig. 2 - LA ROSES final system realization and integration.

Follows a brief description of the implemented final solution of each subsystem.

3 LA-ROSES End Effector

3.1 Mechanical Structure

As reported in the previous reports (D 2.1 in particular) the general scheme of the end effector was based on the following functional scheme (see Fig. 3).

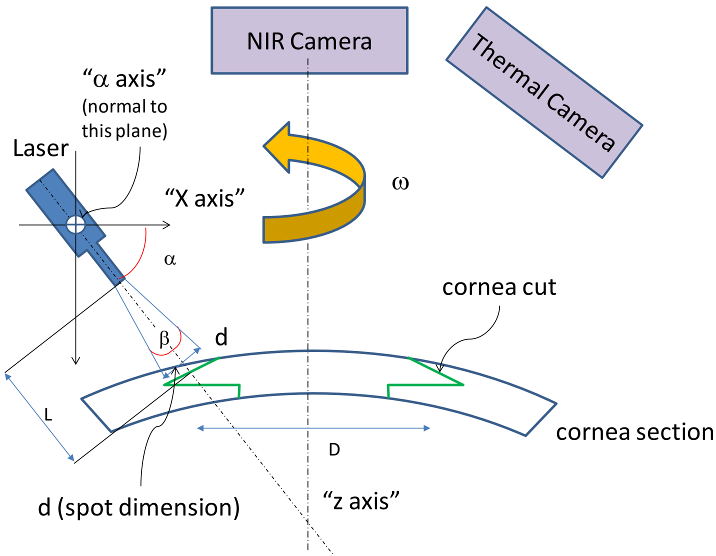


Fig. 3 - General scheme

Precision and repeatability of the sliding and rotating motors are fundamental, but at the beginning of the project, several aspects were not really clear or defined, meaning that the optimisation of working distances in particular were strongly dependant by the tests to be performed at the end of the project. Aspects such the optimised laser, NIR and Thermal cameras positions and working distance were really unknown, but only estimated. Illumination of the field in order to enhance the camera vision, anatomical constraints (Fig. 4) and cabling were also other important points to be evaluated. Those are the reasons why the system was designed in order to have the possibility of rotating the laser axis form 0° (horizontal) to 90° (vertical) and to have an horizontal displacement of 100 mm.

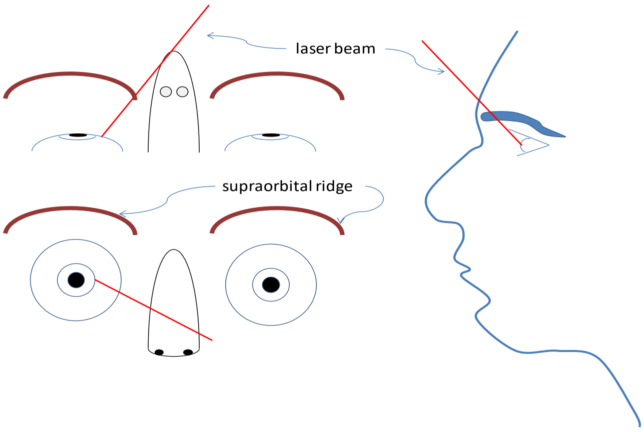


Fig. 4 - Nose and supraorbital ridge interferences

In the next picture a general view of the end-effector is shown, where:

① is the NIR camera

② is the motor for 360° rotation of the end-effector

③ is the thermal camera

④ is the laser

⑤ is the motor for the laser bending 0° - 90°

⑥ is the horizontal motion motor

⑦ is the housing for the lighter (at the end of the project not used)

⑧ cabling chain

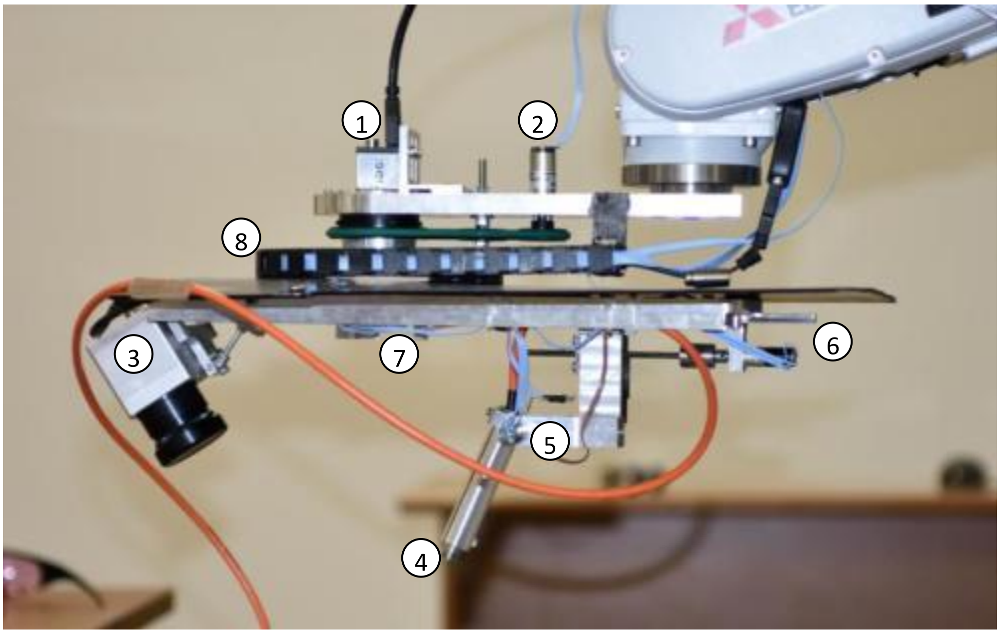


Fig. 5 - End Effector close-up

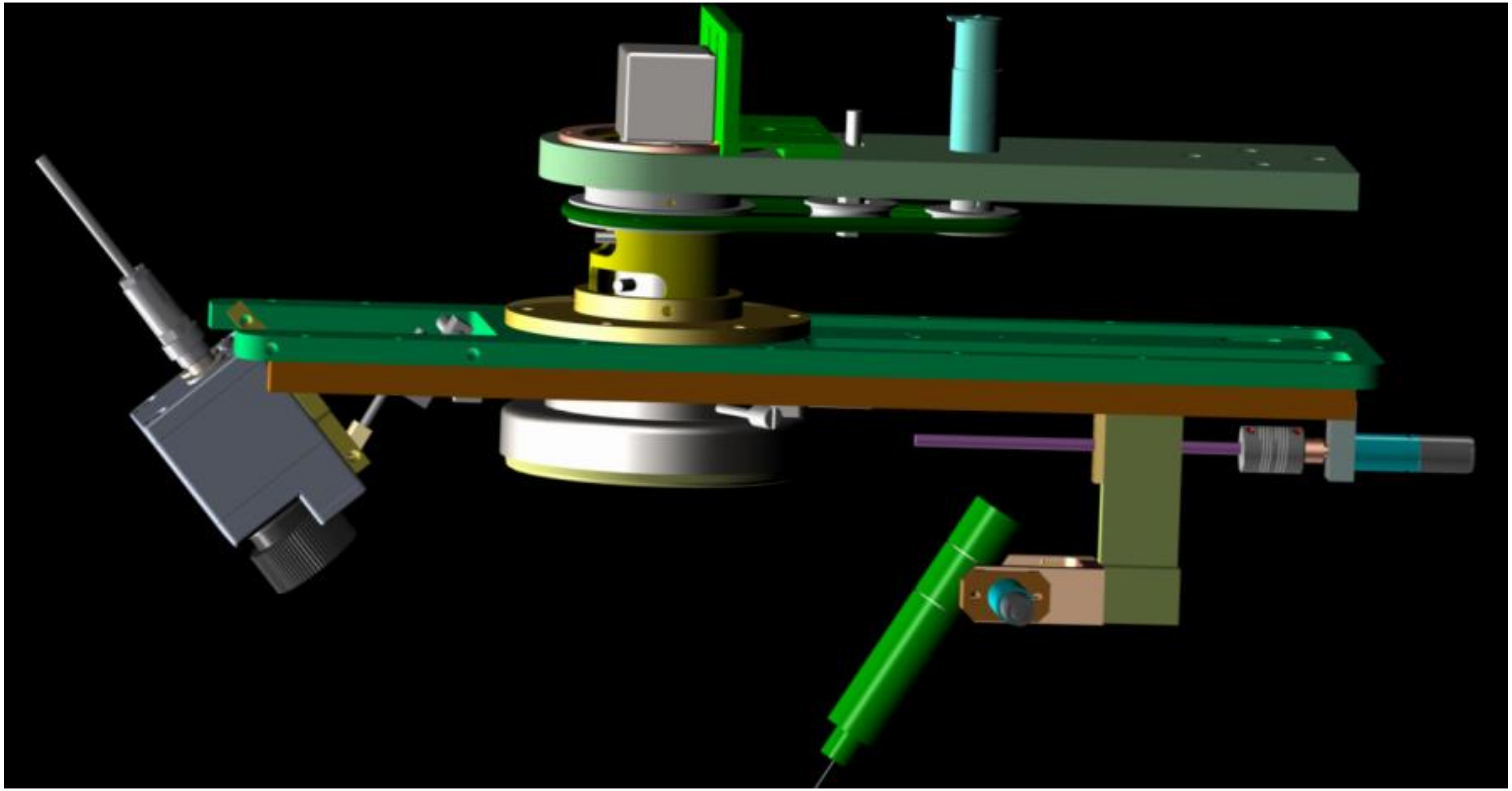


Fig. 6 - End Effector CAD model

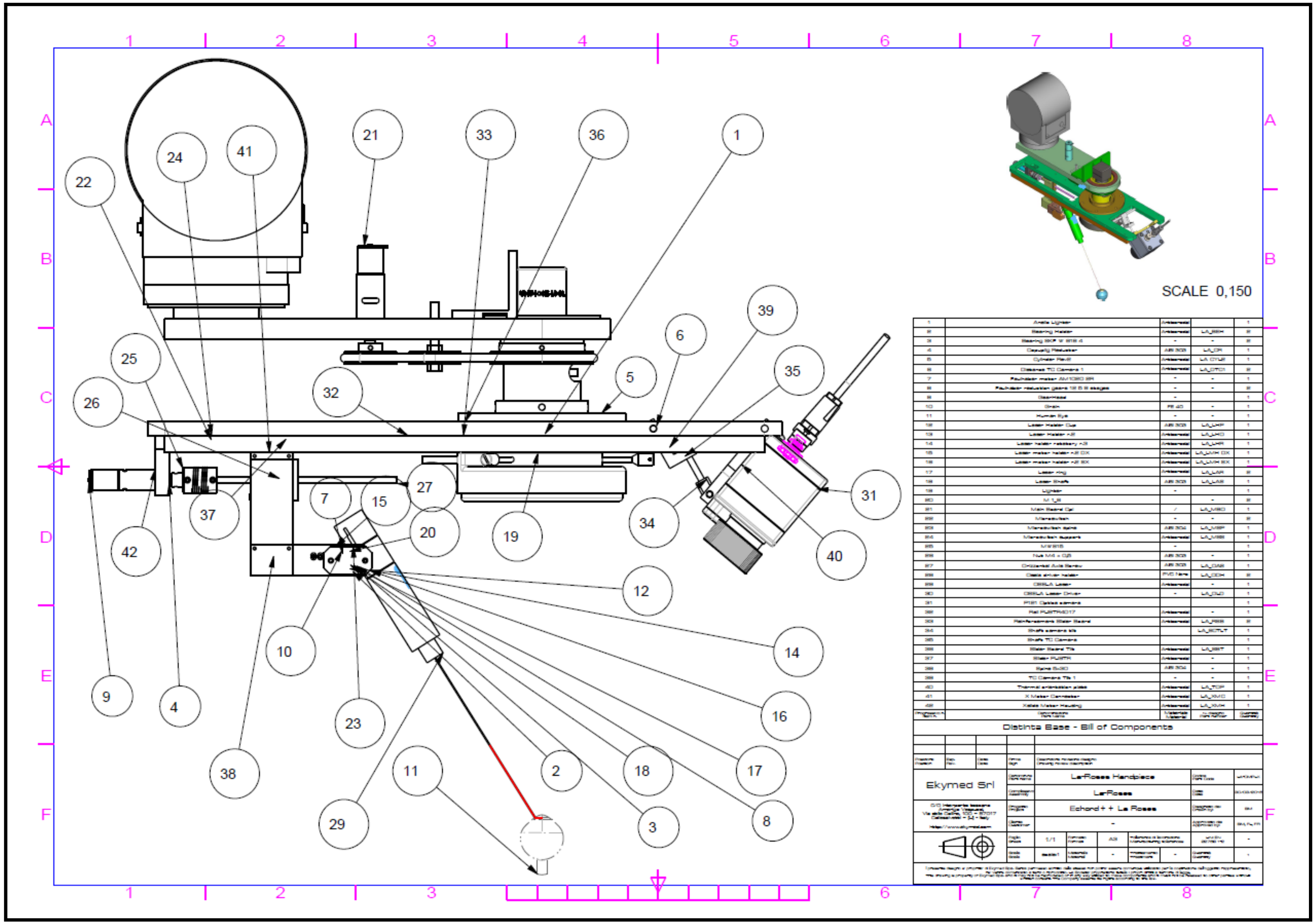


Fig. 7 - End-Effector general drawing BOM

3.2 Laser motor handling control system

The developed laser movement control system is devoted to provide movement control capabilities to the laser tip only: i.e. circular, translational and orientation movements. We used FAULHABER motor as previously described; they are driven by 3 identical servo controller. To simplify the motor control all selected motors are driven by the same type of control unit suggested by FAULHABER. The MCST 3601 is the chosen motor electronic driver. Following instruction of FAULHABER we realized a electrical and communication connection diagram as to be able to control all laser handling motors by using a USB 2.0 HUB. Fig. 8 shows the connection driver diagram.

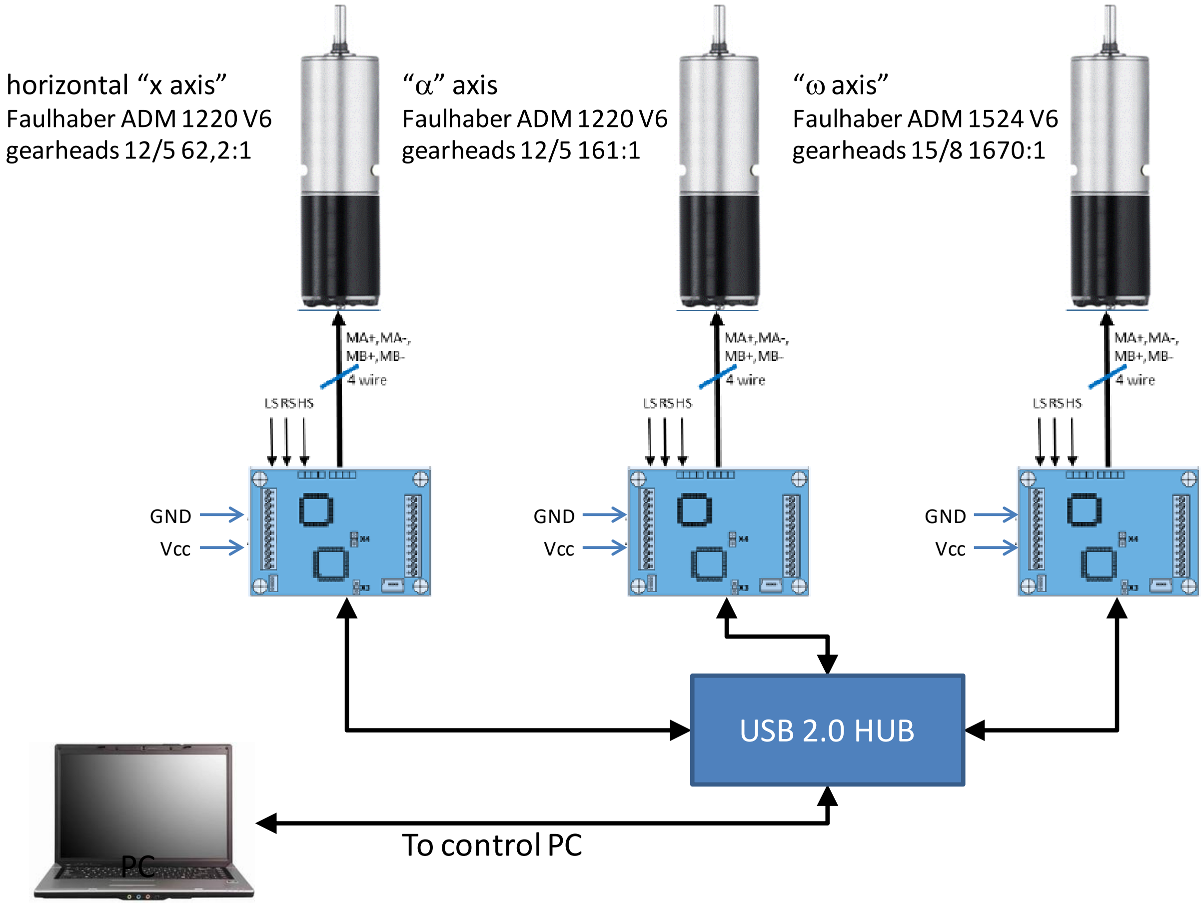


Fig. 8 – connection diagram to control LA-ROSES end-effectors motors

To interact with motor drivers and for setting motion motor parameter Faulhaber provides an Integrated Development Environment (IDE) called TMC. In Fig. 9 the TMC interface is shown.

The interface allows to set acceleration and velocity profiles that the internal PID controller will use to appropriately control the motor actuation. Once the motor parameters were settled the interface allows also to send position and velocity commands in order to evaluate if the motion result is as expected. We found that the chosen motors and drivers were able to achieve the expected resolution movement provided by the mechanical system. In particular the movement forward and reward between the home position of the final position of each axis shows high repeatability in terms of value of position counter reached at each trial.

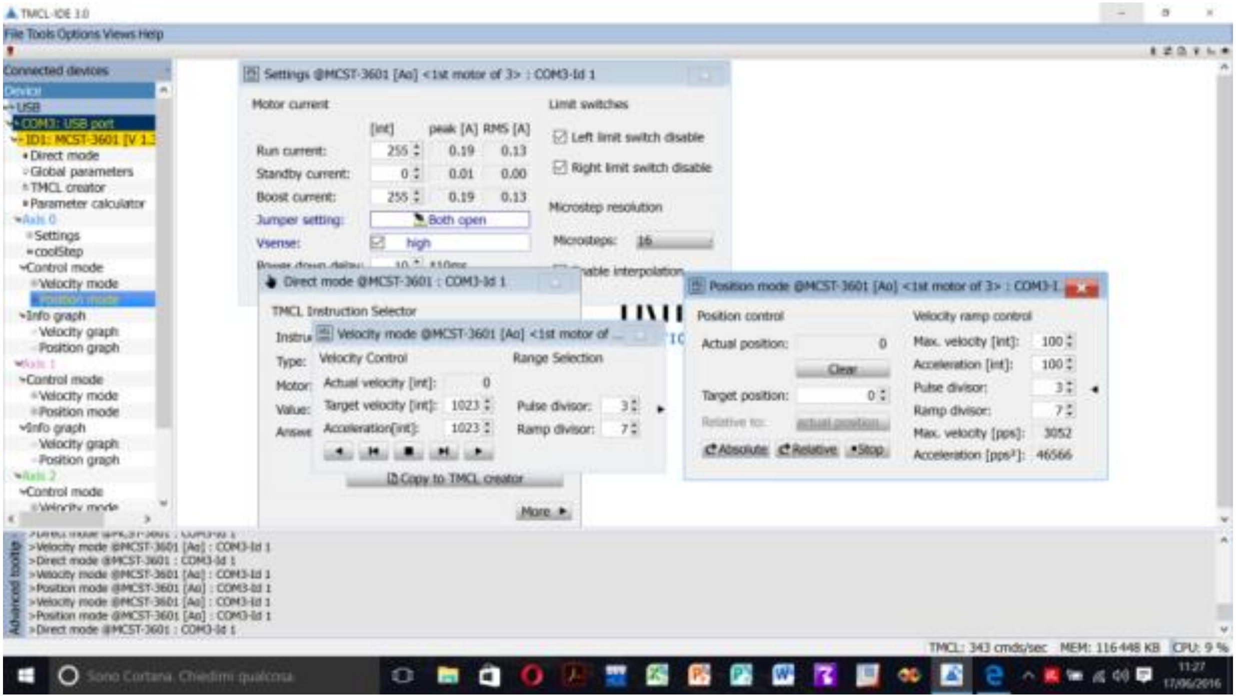


Fig. 9 – Faulhaber IDE for setting motor's motion parameters for laser movement

4 LA-ROSES Robotic arm and controller

A robotic arm has been used to move a mechanical system carrying vision and thermal cameras and laser module handling motors.

The original solution to use the SCHUNK Light Weight Arm (LWA3) has been rejected due to HW problem of such robotic arm. The consortium has had the possibility to use a Mitsubishi RV-13FM robotic arm which has shown positioning capabilities according to LA-ROSES design requirements. The robotic arm has been required to be able to carry the mechanical structure holding the LA-ROSES laser and vision system to be placed above the patient eye at a known distance. At the center of the laser handling system a NIR-vision camera is positioned as it can acquire patient's eye images. The NIR-camera is mounted with its optical axis aligned with the mechanical structure. This allows the laser system to rotate around the same axis. This is a mechanical constrain that must be strictly fulfilled. The robotic arm also provides motor capabilities, so that the laser handling system is moving maintaining the NIR-camera image centre in correspondence with the centre of the patient's cornea. The corneal path to be welded consists of a circular path highlighted by the indocyanine solution which is applied by the surgeon inside the surgical wounds. The robotic arm also provides a system to correct involuntary movements of the eye: when this event occurs, the robotic arm moves quickly in order to center again the NIR-camera optical axis with the new cornea center. Fig. 10 shows the used robotic arm

Fig. 10 – The 6 DOF Mitsubishi RV-13FM.

Main features of the RV-13FM arm are:

- 6-axis
- Repeatability: ±0,05 mm
- Payload: 13 kg
- Linear Workspace: 1094 mm
- Weight: 120 kg
- real-time path control capability

To realize this movement capability, we decided to develop 3 SW modules as follows:

- a program running on the robot controller which aims is to accept displacement motor commands and move accordingly the robot wrist (where the laser handling system is attached). After the movement commands is performed the robot program provides out the current tool coordinates. The robot tool position corresponds to the starting point of the laser circular movement mechanical system which corresponds to the center of the NIR-camera optical axis.
- an image processing program (a SW module running on the LA-ROSES master control station) for NIR-camera image acquisition and detection of the corneal path marked by the indocyanine solution. The SW measures the distance between the image center and the center of the corneal circular cut boundary. These distances have to be measured on the image plane and elaborated, so as to provide out relative distance errors between the image center and the center of the corneal cut boundary.

A SW communication module running on the LA-ROSES master control station. The goal of this software is to link the program running on the robot controller and waiting for the corresponding motor commands to be carried out by the robotic arm; the system then moves the starting point of the laser handling system and aligns it with the NIR-camera image center (i.e. to align the center of the circular corneal cut boundary with the rotation axis of the laser system).

5 LA-ROSES Laser system

At the beginning of the project, we made the decision to find a commercial laser that could be used for welding and that had to show the following characteristics:

1. Emitting @810 nm
2. Very compact and with a low weight
3. Controlled spot dimensions
4. Working distance in the range 10-20 cm
5. Full remote control
6. Continuous wave and single spot emission, with variable duty cycle
7. Variable emission power in the range 0-1W

The motivations at the basis of this choice, that is different from the idea that we had when writing the proposal, are:

1. Substitute the high power laser (10W) with a 1W laser, for security reason in the final device (the effects of an accidental damage are reduced)
2. Reducing the size of the laser system and mount it directly into the final device
3. Avoid the use of a fibre optic in the surgical scene, thus reducing the problem related to the use of a disposable and to the sterilization of the system
4. Avoid the use of a device in contact with the patient's eye, so as to avoid sterilization problems and accidental damage to the patient (excessive pressure)
5. To control the whole surgical scene and used devices, including the laser, in one remote console.

In the final version of the robotic console we are proposing the solution optimized for the spot dimension. We modified the fiber optic of the laser Deka Smarty A-800 (El.En. Group, Italy) that we already use in the clinical settings. The fiber optic (400 micrometer core diameter) was connected to a fixed focus collimation package, so that it is possible to mount only the collimation unit in the end effector and to irradiate the corneal spot without any contact with the cornea.

Fig. 11 -the second release of the welding laser (left), with a fiber optic (middle) and a collimator (right).

With this configuration it was possible to control the laser spot and to test the delivered laser power in a wide range. Moreover, this laser has been approved for the use in laser welding of the cornea.

6 LA-ROSES Vision system

The LA-ROSES vision system comprises a set of HW devices and SW algorithms enabling images acquisition and processing in order to extract useful data from the images which are further used by another (other) system(s) to accomplish the required task(s). The LA-ROSES vision system HW devices consist of:

- Illumination system. The illumination system has to properly illuminate the patient's eye in order to enable the detection of the pupil region and enhance the recognition of the corneal wound edges. A low-power IR illumination system will be used.
- NIR Camera including lenses and optic filters
- Thermal camera including lenses and optic filters

Fig. 12 shows the NIR-camera and the thermal camera used in LA-ROSES project. Detailed description of each camera can be found in D4.1 and D5.1

a) b)

Fig. 12 – a) the NIR-camera IDS camera UI-3240CP-NIR-GL Rev.2 and b) Optris® PI 450 INFRARED CAMERA

All these devices have be mounted onto the mechanical structure holding also the LA-ROSES laser system (the laser module and the motorized laser module handling system). Careful selection of the illumination system was provided, in order to select the best method to help the development of eye tracking, by using images gathered from the NIR camera, both during the initial set-up phase and during the suturing procedure for monitoring and eventually adjust the laser beam movements according to the recorded eye movements. In general, there are two types of eye tracking techniques: bright-pupil and dark-pupil. The difference between this two is based on the location of the illumination source with respect to the optics. If the illumination is coaxial with the optical path, then the eye acts as a retroreflector as the light reflects off the retina creating a bright pupil effect similar to red eye. If the illumination source is offset from the optical path, then the pupil appears dark because the retroreflection from the retina is directed away from the camera. Further investigations have to be done in order to select the best method suitable to be adopted in the LA-ROSES context; a complete analysis and description will be given.

The images acquired by the NIR camera are also processed in order to extract the location of the laser spot projected onto the patient's eye anterior external surface. At the beginning of the suturing procedure the eye hand-piece has to be accurately positioned by using the robotic arm above the patient's eye. In order to accomplish this task the development of autonomously algorithms to perform robotic arm movements using a vision guided robotics approach is required. Using visual feedback to control a robot is commonly termed Visual

Servoing (VS). Thus, machine vision or image processing are part of the vision system. Image processing techniques are required to acquire, filtrate and detect the target position inside images acquired by the NIR camera. This sequence is repeated over the time, enabling a tracking and control closed-loop scheme. Based on this sensory input, a control sequence is generated. In addition, the system may also require an automatic initialization which commonly includes figure–ground segmentation and object recognition. A typical VS task uses image information to measure the error between the current location of the robot and its reference or desired location. Images acquired from the thermal camera will be used to detect the local corneal tissue temperature in correspondence of the laser spot, so that the laser beam is moved along the welding trajectory as the desired correct temperature is reached.

7 LA-ROSES Control System

The LA-ROSES Master Control Unit involves a set of SW modules running in parallel on the LA-ROSES PC. Each SW modules uses specialized SW drivers and SDK to interact with and drive the relative HW devices they are connected to, as previously described. In particular, to control external devices like the robot arm or the laser handling system we used TCP I/P communication channel and USB ports enabling virtual COM features. Through these channel commands and queries ASCII strings have to be sent and received using original high level exchange protocol data we designed ad hoc. Also, the tasks to implement the core of the LA-ROSES Master Control Unit communicate each other using IPC (Internal Process Communication). The Fig. 13 shows a diagram of the SW controller modules implementing the LA-ROSES system

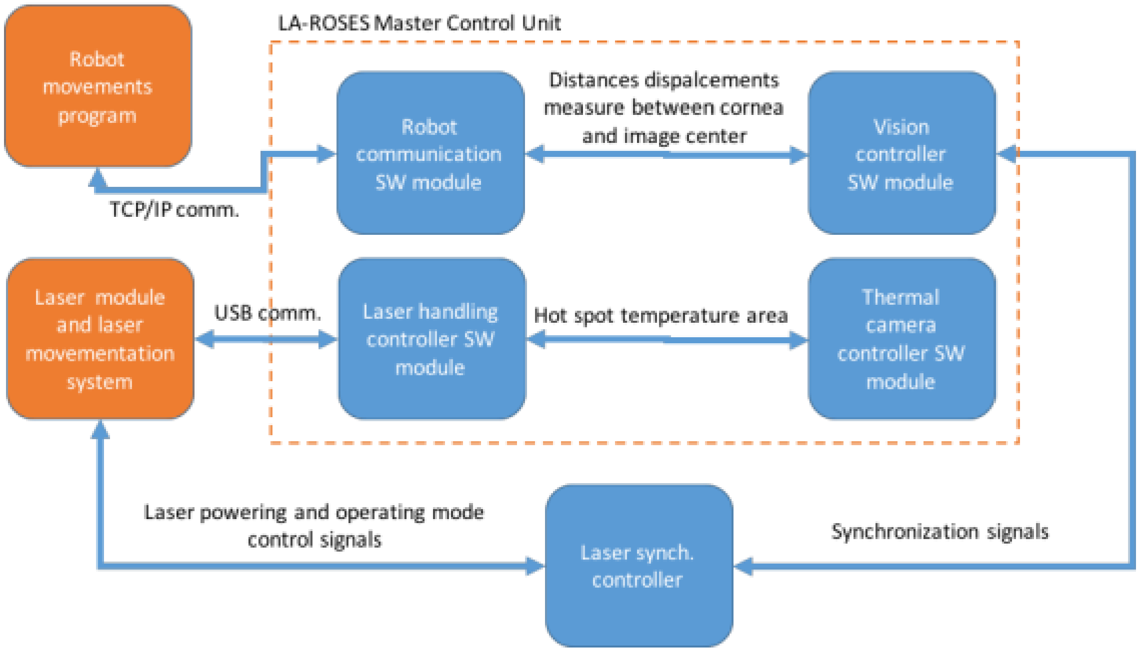


Fig. 13 – LA-ROSES SW controllers diagrams

8 Experimental results

The complexity of the whole system has required to adopt a step-by-step implementation approach for the development of each subsystem; each subsystem implementation and intermediate results have been described elsewhere in already distributed reports.

In detail, in these final report we present the results obtained by the entire system as a whole simulating a complete welding task including final histological results showing the effectiveness of the use of the LA-ROSES system in replacing the up-to-date manual laser welding procedure. In order to achieve this, we developed a GUI integrating all LA-ROSES subsystem SW controllers. This GUI provides out synchronization and exchange data between each SW modules in order to allow the surgeon to set running operative data (laser circular velocity motion parameter, laser inclination value, laser powering output value, temperature threshold the laser illuminated area should reach) start the initial cornea boundary cut detection allowing the robot controller SW system to perform automatic positioning of the laser mechanical handling system above the patient eye. After the system is well-positioned start the welding phase checking that all data provided out by the system are as expected; i.e the system moves the laser spot as soon as the desired temperature at the spot location is reached. The laser handling controller system moves the laser along the welding path combining translational laser movements as to track and keep the laser spot position on the cornea boundary. The procedure ends when the welding trajectory is completed. Fig. 14 shows the LA-ROSES complete GUI.

Fig. 14 – LA-ROSES complete GUI

On the left, command buttons and GUI controls for setting working parameters during the welding phase. In Fig. 15 the system has detected the cornea boundary to be weld and the laser spot has been detected too.

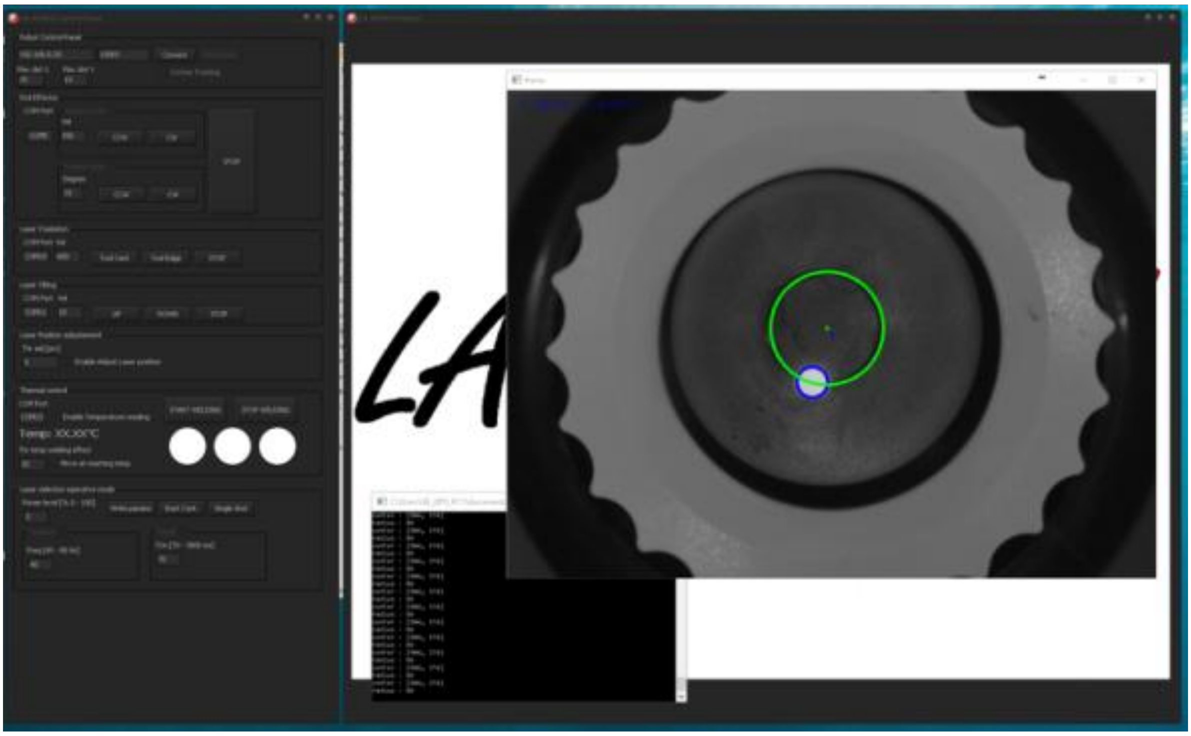


Fig. 15 – the welding phase is ready to start

In Fig. 16 the image provided by the thermal camera is provided.

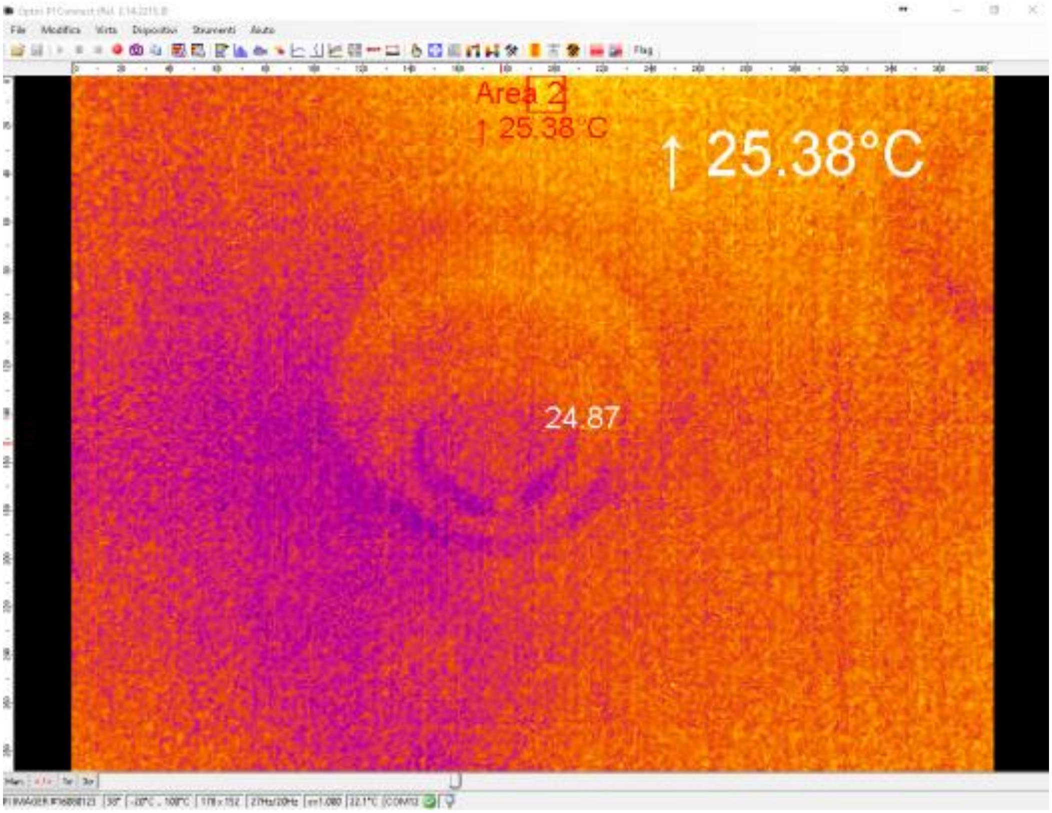
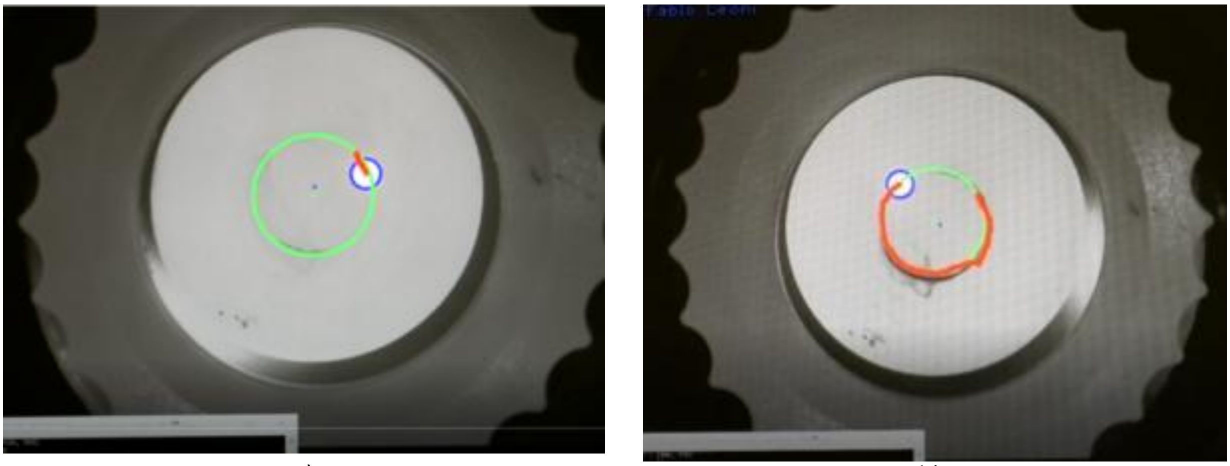


Fig. 16 – The image provided by the thermal camera.

The thermal camera provides out the temperature of the cornea area illuminated by the laser spot because that area is the highest hot area on the entire thermal image.

During the welding process the system continuously update information of the running task; as matter of fact just after the laser irradiation brings the temperature of the illuminated area above the chosen welding temperature threshold the laser is moved along the welding path and the laser spot is traced to provide out evidence of the corneal wound portion just treated. Fig. 17 shows the result of this tracking method.



a) b)

Fig. 17 – a) trace of treated portion of corneal wound just after the start of the welding procedure. b) trace of the laser after about 2min from the beginning of the welding procedure

9 Histological results

The robotic system for laser welding has been tested in freshly enucleated porcine eyes. A penetrating circular cut was performed in each eye using the 8.0 mm diameter Burron trephine. This procedure simulate the surgical incision currently used in penetrating keratoplasty. The surgical cut was than stained in depth with a water solution of Indocyanine Green. The system then induced a photothermal effect at the surgical site.

Standard histology (Hematoxylin & Eosin) of the treated tissue was performed. The analysis evidenced a good welding of the cut walls in the stroma in depth. When irradiating at low power, a homogenous thermal effect on the cut walls was detected. No thermal damage to the surrounding tissue was evidenced.

These demonstrates that it is possible to use the LA ROSES platform to induce a modulated thermal effect in the corneal tissue and to induce laser assisted suturing of the surgical cuts, without inducing any thermal damage to the healthy tissue in the surroundings (see D7.3).

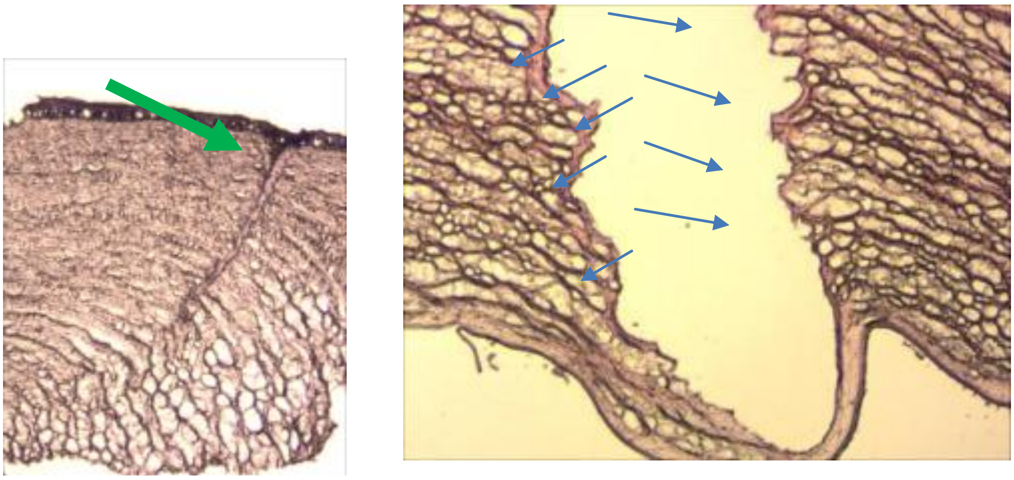


Fig. 18 -A laser welded cornea (left), showing the surgical incision filled with denatured collagen (green arrow). Mild photothermal effects (blue arrow) at wound walls induced by low power emission (right).