Laser **A**ssisted **RO**botic **S**urgery of the anterior **E**ye **S**egment

Project full title:	Laser Assisted Robotic Surgery of the anterior Eye Segment
Project Acronym:	LA-ROSES
Grant Agreement number:	601116
Deliverable no.:	D5.1
Title:	Robotic platform design specification and development and laser system characterization
Contractual Date of Delivery	month 11
Actual Date of Delivery	month 26
Organization Short Name of Milestone Leading Partner	FAST
Organization Short Name of Other Participants	EKY, Fastenica
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Editors	Fabio Leoni, Bernardo Magnani, Francesca Rossi
Version	2.0
Tasks contributing to this deliverable	Task 5
Dissemination Level [1]	RE
Total number of pages (including cover page)	13

[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)

Version Management

Version	Date	Status	Author	Modification
1.0	20.11.2016	Draft	Fabio Leoni	Creation of document
2.0	24.11.2016	Final	Fabio Leoni, Francesca Rossi, Bernardo Magnani	Final revision

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1 Executive Summary

This document reports the activities carried out by the consortium for the design specification phase and provides out the guidelines for the development of a preliminary version of the LA-ROSES SW controller modules, which drives the several subsystem the LA-ROSES platform consists of. This document, in order to provide an overall and detailed comprehension of each SW and HW system here described, makes reference to already released deliverables where possible; as a matter of fact the LA-ROSES system is a complex robotic system and it is has been designed and developed taking into account a modular approach as to simplify the system complexity.

2 Robotic platform design specification

Based on the description and on the general requirements expressed by surgeons about how the laser welding manual procedure of the cornea is currently performed, we designed engineering specifications/functional requirements input the robotic LA-ROSES platform should implement as to mimic the manual procedure. The advantage of the use of a robotic platform, including a specialized handling laser movement unit and vision and thermal camera sensors, consists of guarantee constant velocity control in handling the laser probe, constant laser altitude and angle control, precise and accurate control of powering laser output, accurate check of the temperature dynamics at the laser spot. When the temperature of the corneal irradiated area reaches the desired value, the laser handling system moves the laser spot so as to irradiate (and weld) the adjacent corneal area. The expected results are a standardization of the laser welding procedure in terms of process parameters and, subsequently, a standardization of the welding quality results.

A general diagram consisting of box identifying subsystems and their relations (see also D2.1) is here reported for the sake of clearness.

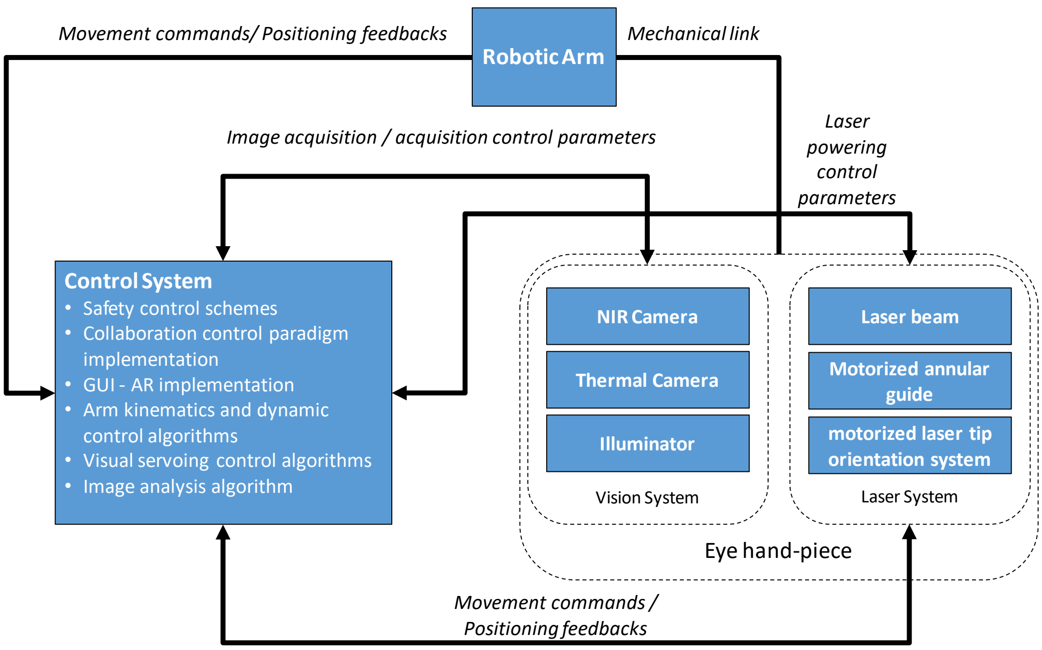


Fig. 1 - Overall system diagram of LA-ROSES functional subsystems

Each component of the subsystem shown in fig.1 has been described in detail elsewhere.

In particular, the LA-ROSES platform has to carry out the following actions and functionalities:

- enabling a circular movement of a laser probe allowing a tracking of the circular path marked by the indocyanine green solution;
- enabling detection and tracking of the laser spot during the welding procedure;
- enabling temperature reading of the corneal area illuminated by the laser spot as to allow automatic laser handling as the reading temperature reached a threshold value (indicating that the correct welding temperature has been reached in that area);
- allowing automatic and assisted handling of the laser (as to control the laser pointing by means of orientation and translation)
- enabling initial gross and accurate positioning of the laser probe above the patient's eye
- accurate laser probe positioning above the patient's eye
- provide out the operator (surgeon) a GUI for:
    - setting of system parameters: laser circular velocity, laser spot tracking error, welding temperature threshold, laser power, laser operational mode (e.g. CW or CCW), communication settings between each control module
    - visual outcomes of process output during the welding process: marking of currently treated area against not yet treated area
    - start & stop welding procedure

3 Development & system integration

From the point of view of system integration, the LA-ROSES platform consists of the following control modules (HW/SW) under development:

- the robot arm controller;
- the laser handling controller;
- the laser powering controller;
- the vision NIR-camera camera controller;
- the thermal camera controller;
- the LA-ROSES master controller.

A pictured diagram of a whole system is given in fig. 2

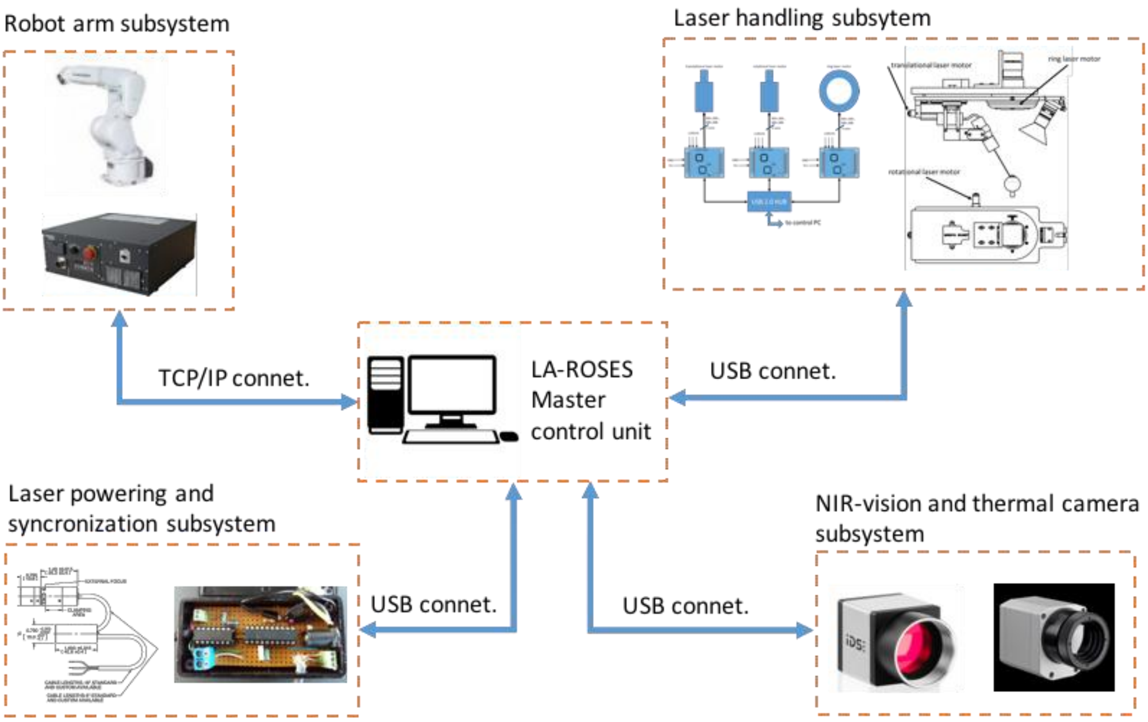


Fig. 2 - Overall system diagram of LA-ROSES subsystems. Arrows show the type of communication channel used to exchange commands and data between the LA-ROSES master control unit and each subsystem

The LA-ROSES Master control unit consists of a set of SW procedures, which coordinates and drives each subsystem in order to accomplish the specified functions associated to each subsystem. In the followings a detailed description of each subsystem is reported.

The robotic arm subsystem

The robotic arm provides positioning capabilities in order to place the laser handling subsystem above the patient eye at a known distance. At the centre of the laser handling system the 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.

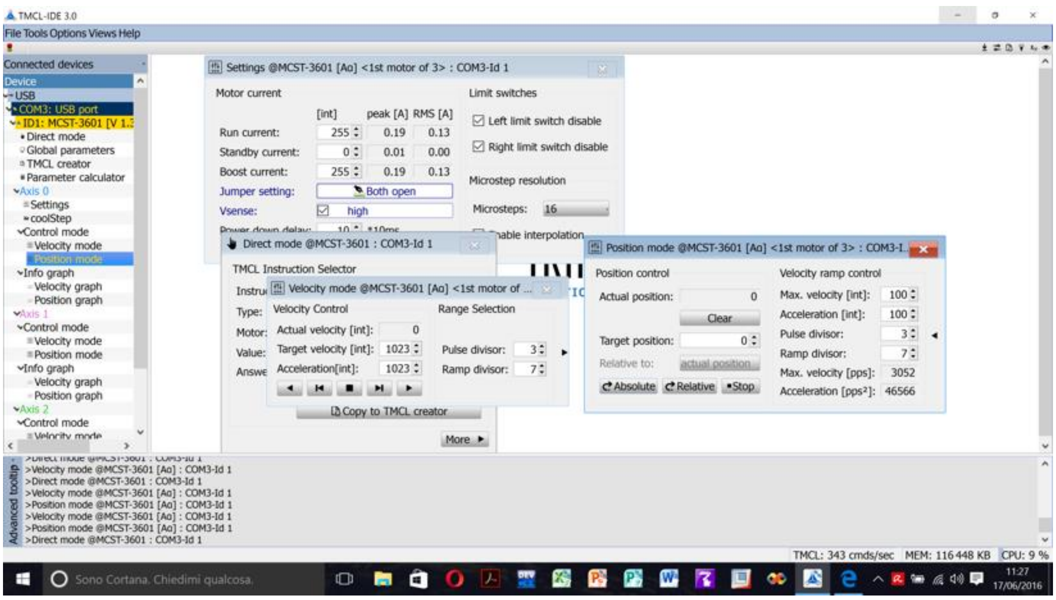
To realize this movement capability we decided to develop 3 SW modules as follows:

- A program running on the robot controller, which aims to accept displacement motor commands and provide out the current tool coordinates. The displacement motor commands consists of in relative distance measures with sign the robot controller should move the tool starting from the current position. 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).

The laser handling controller

The laser handling controller consists of a HW board acting as servo-controllers from Faulhaber as described in D3.2. These servo controller are used by proprietary interface from



Faulhaber named TMC IDE as shown in fig. 3.

Fig. 3 – The Faulhaber Integrated Development Interface (IDE) for motor motion parameter setting

Through this interface it is possible to set the motor parameters of the 3 motors which handles the laser module. These parameters have to be set according to maximum and minimum acceleration and velocity required values, which the laser module has to be moved for circular, translation and inclination, respectively.

When the laser motor parameters have been configured and stored in the internal memory the controller, these can be controlled by using a USB cable and a communication library used by an external program for sending motor control commands.

Hence, a SW controller module to control translation, inclination and circular movements has to be implemented using the provided communication capability. In particular, these motor functions will be used for driving the laser module, so as the laser spot can track the boundary of the corneal cut to be welded.

The laser powering and synchronization controller

The laser powering output module has to be driven accordingly to surgeon settings in terms of maximum power output value, ON-OFF timing (e.g continuous or pulsed operation mode).

The HW needed to drive the laser as just described has been developed using a PIC microcontroller and other electronical components able to drive the laser as required. The laser powering output values are arranged by sending specific commands from a SW laser powering controller interface trough a USB serial connection linking the LA-ROSES Master Control Unit to the laser controller board. Moreover, the laser controller board must provide out a synchronization signal in order to synchronize the NIR-camera image acquisition with the laser pulsed mode. Indeed the NIR-camera provide out a synchronization pin to be used when an image frame has to be acquired by an event rising; in this way the laser pulsed mode triggers the synchronization NIR-camera pin as to acquire a frame image starting from the rising edge provide out by the laser controller unit. In fig. 4 the laser HW controller unit with its connections with the laser module, the synchronization NIR-camera pin and the LA-ROSES Master control station is shown.

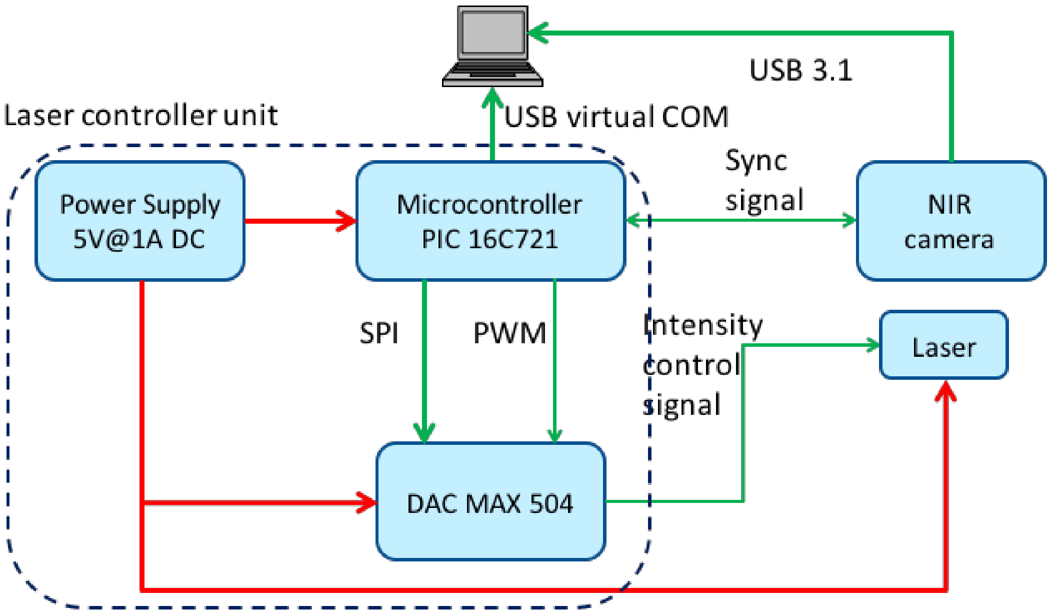


Fig. 4 – The laser controller unit (dotted blue line) and its connection

In fig. 5 the laser control unit schematic diagram is given.

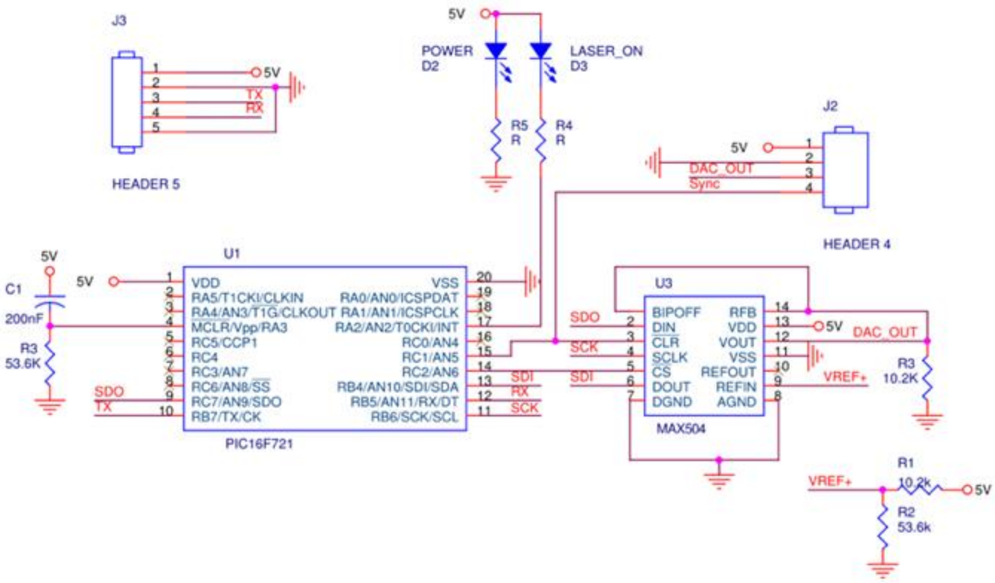


Fig. 5 – The laser controller schematic diagram

The vision NIR-camera controller

The vision system consists of a set of devices and SW modules that are acting together to acquire, to apply image filter, to process and extract useful information data from image features to accomplish some tasks. In the present architecture, the LA-ROSES vision system develops image processing techniques to enable a Visual Servoing (VS) paradigm. A complete description about the implementation of the VS approach carried out for the achievement of the LA-ROSES requirements and specifications is reported in D4.1.

The thermal camera controller

The thermal camera is used as a temperature monitor of the photothermal effect induced in the cornea during the welding process. The selection of the best-suited thermal camera for the LA-ROSES expectations pointed out the optimal characteristics of the Optris PI 450 INFRARED CAMERA. Fig. 6 shows the selected camera.

Fig. 6 – The OPTRIS PI 450 Infrared camera

The main features of the PI 459 camera are the following:

- Dimensions: 46 x 56 x 90 mm
- thermal sensitivity: 40 mK

- thermal image recording in real time at up to 80 Hz
- weight: 320 g incl. lens
- detector with 382 x 288 pixels
- usable at ambient temperatures of up to 70 °C without the need for additional cooling

The selected thermal camera shows acceptable size dimensions and weight. These are important characteristics, because the camera is mounted on the same end-effector which carries the laser system too. The camera also shows a good thermal sensitivity and a fast recording time. These two features are of fundamental importance in this application. The temperature reading system has to be as accurate as possible and as fast as possible: as soon as the temperature in the irradiated area reaches the desired value (i.e. a good welding effect), the laser driving controller has to immediately move the laser spot to another region of the corneal cut boundary. By doing this, an optimal welding is provided to the tissue and thermal damage is avoided. Hence, the thermal camera is a critical component of the LA-ROSES system. In fig. 7 a thermal image of a hand is reported, showing the quality of the acquired thermal images.

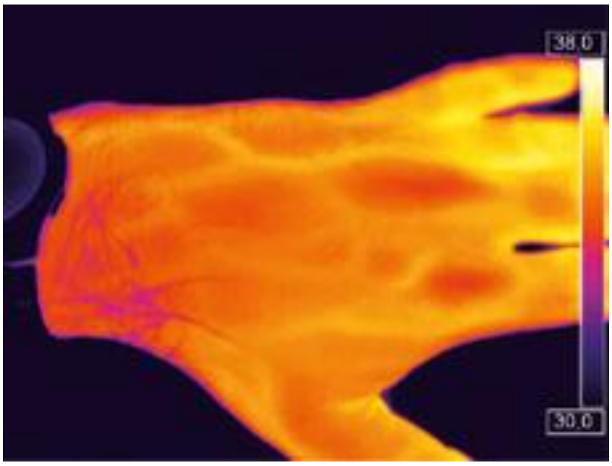


Fig. 7 – An image showing the quality level of the PI 450 thermal camera

The camera provides several SW features, including the activation of the functionality to track a hot spot area in the current image: once the laser power unit is activated, the temperature of the irradiated cornea begins to increase, becoming a hot spot area respect to the rest of the image. If the hot spot tracking area function is activated, a small square is painted around such area and the its maximum temperature value is displayed. The SDK included with the thermal camera provide out a communication channel trough a virtual COM connected to a USB port; using a specified ASCII protocol it is possible to query the camera FW to get out the temperature of the hot spot area.

It is necessary to write a SW procedure running on the LA-ROSES master control pc querying the camera in order to get out the temperature of the hot spot area. This temperature value will be compared against the welding temperature threshold value, to move the laser module as the threshold is reached.

The LA-ROSES Master Control Unit

The LA-ROSES Master Control Unit consists of 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. 8 shows a diagram of the SW controller modules implementing the LA-ROSES system

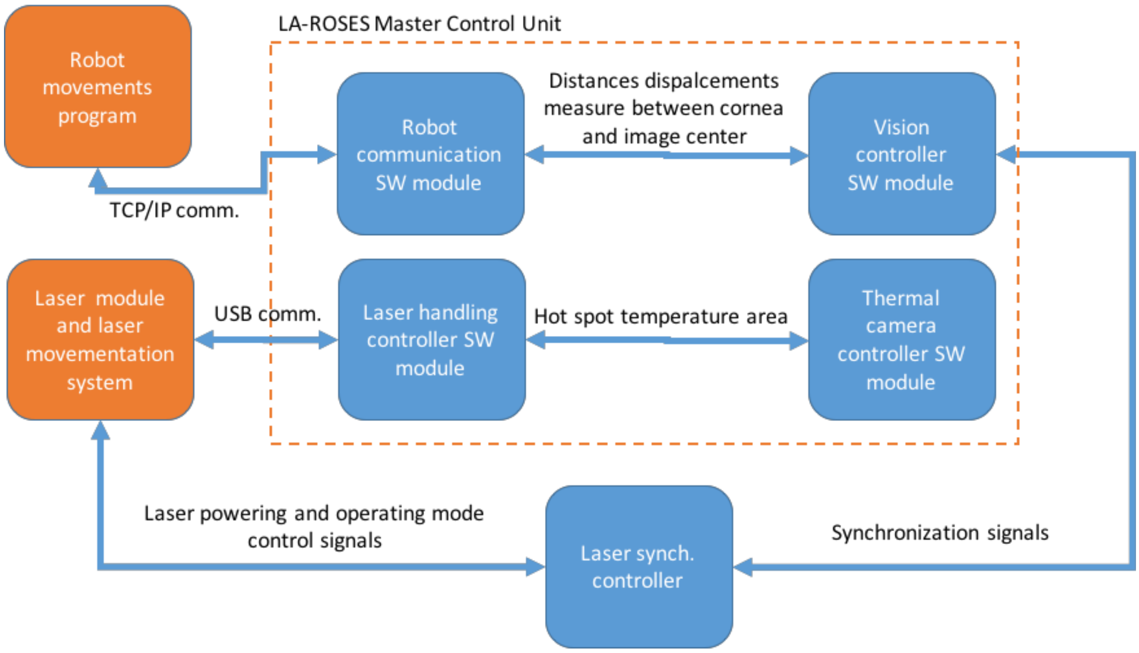


Fig. 8 – LA-ROSES SW controllers diagrams

4 Electrical and Optical characterization of the new laser system

The new laser system, the Thorlabs one, has been characterized with different optical systems.

This laser enabled us to control the laser power emission, the dimensions and weight of the laser source and the dimensions of the laser spot (Fig. 9). The laser used is a 1W laser that we mounted and tested without the cooling accessories. Due to the short exposures that we need in this particular application, we tried to avoid the use of the cooling devices, in order to maintain the smallest dimensions.

The emitted optical power was studied, in order to know the correspondence with the control voltage.

Fig. 9: updated laser welding system, with a very compact laser and collimation optical system.

The characterization was performed with single pulse emission of the laser, and measuring the optical power emitted during the “laser pulse on” time (Ton= 2 ms). The power control has been set with a limitation on the maximum current of 1100 A, allowing an emission of about 990 mW, in order not to damage the diode. The results are shown in Fig. 10

amp [I]	Power mW
1	0.09
2	0.20
3	0.34
4	0.52
5	0.74
10	2.95
11	3.96
12	7.98
13	26.00
14	45.70
15	67.10
16	90.00
17	113.00
18	135.20
19	158.00
20	182.00
22	229.00
25	297.00
27	345.00
30	410.00
32	460.00
35	529.00
37	575.00
40	645.00
42	692.00
45	757.00
47	808.00
50	875.00
52	918.00
53	940.00
54	965.00
55	986.00

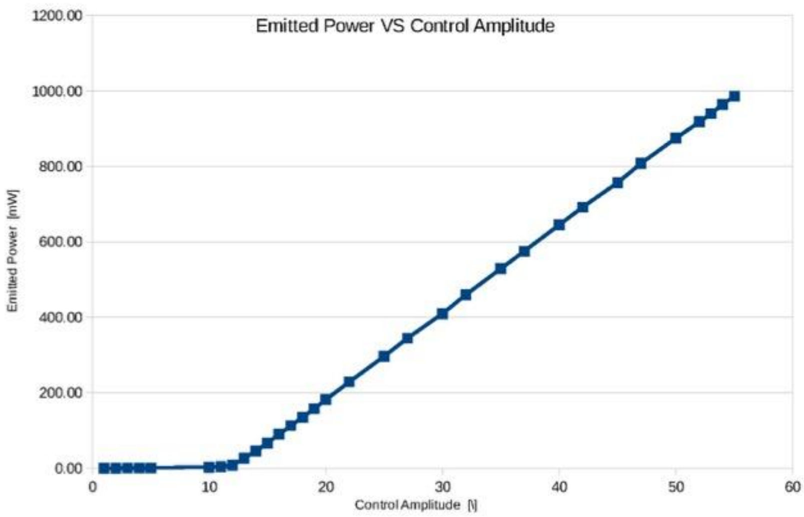


Fig. 10: Optical power vs control voltage.

The same measurement was performed with different optical systems, used to control the laser spot dimensions. Obviously, the emitted power is lower (see Fig. 11) respect to the “free” delivering of the laser light. However, it is sufficient to induce the welding effect.

amp [V]	Power mW
1	0.02
2	0.03
3	0.04
4	0.05
5	0.07
10	0.27
11	0.36
12	0.67
13	3.25
14	6.38
15	9.67
16	13.37
17	16.59
18	19.77
19	23.32
20	26.84
22	35.20
25	47.80
27	56.10
30	67.60
32	75.70
35	87.60
37	95.80
40	107.80
42	114.60
45	123.70
47	130.20
50	140.50
52	148.10
53	152.30
54	155.70
55	158.50

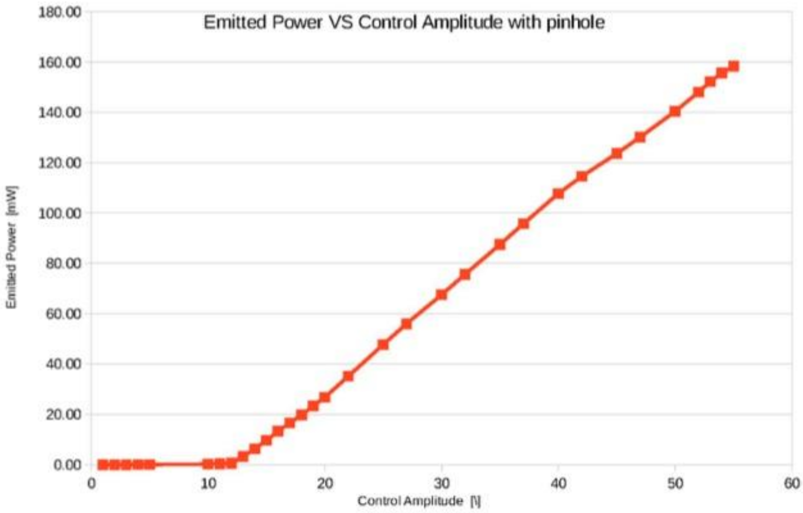


Fig. 11: Optical power vs control voltage and optical system for laser spot control.