LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
Faculty of Technology
Department of Mechanical Engineering

Mika Ruutiainen

REAL-TIME ADAPTIVE CONTROL OF ULTRA-FAST LASER SCRIBING PROCESS WITH SPECTROMETER ONLINE MONITORING

Examiners: Professor Antti Salminen
Doctor Hamid Roozbahani

ABSTRACT

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Real-time adaptive control of ultra-fast laser scribing process with spectrometer online monitoring

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There exist several researches and applications about laser welding monitoring and parameter control but not a single one have been created for controlling of laser scribing processes. Laser scribing is considered to be very fast and accurate process and thus it would be necessary to develop accurate turning and monitoring system for such a process. This research focuses on finding out whether it would be possible to develop real-time adaptive control for ultra-fast laser scribing processes utilizing spectrometer online monitoring. The thesis accurately presents how control code for laser parameter tuning is developed using National Instrument's LabVIEW and how spectrometer is being utilized in online monitoring. Results are based on behavior of the control code and accuracy of the spectrometer monitoring when scribing different steel materials. Finally control code success is being evaluated and possible development ideas for future are presented.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Tekniikan tiedekunta
Konetekniikan yksikkö

Mika Ruutiainen

Reaaliaikainen mukautuva ohjaus ultranopealle laserkaiverrusprosessille hyödyntäen spektrometrimonitorointia

2016

73 sivua, 40 kuvaa, 3 taulukkoa, 23 liitettä

Tarkastajat: Professori Antti Salminen
Tohtori Hamid Roozbahani

Hakusanat: Laserkaiverrus, mukautuva reaaliaikainen ohjaus, spektrometrimonitorointi

Laserhitsauksesta on olemassa useita tutkimuksia ja sovelluksia mutta laserkaiverruksen ohjaukseen ei ole tehty yhtäkään. Laserkaiverrus yleisesti on erittäin nopea ja tarkka prosessi ja siksi siihen on tärkeää kehittää tarkka säätävä monitorointisysteemi. Tutkimus keskittyy selvittämään, onko reaaliaikaisen mukautuvan ohjelman kehittäminen mahdollista ultranopeaan laserkaiverrusprosessiin hyödyntäen spektrometrimonitorointia. Tutkimus selittää tarkasti, kuinka mukautuva ohjaus kehitetään laserin käyttöön käyttäen National Instrument:n LabVIEW:tä, ja kuinka spektrometriä hyödynnetään reaaliaikamonitoroinnissa. Tulokset ja niiden tarkkuus pohjautuvat metallikaiverrustutkimuksiin laserin kontrollointiin kehitetyllä ohjelmalla ja spektrometrimonitoroinnilla. Lopuksi laserkontrolliohjelman onnistumista arvioidaan ja mahdollisia tulevaisuuden parannuksia esitetään.

ACKNOWLEDGEMENTS

This research has been carried out at the laboratory of Laser Materials Processing in Lappeenranta University of Technology. The research started in April 2015 and completed in February 2016.

Making this thesis has been fairly long but interesting project. The initial idea of Doctor Hamid Roozbahani was to make deeper co-operation between Mechatronic- and Laser Materials Processing laboratory and that goal can be considered to be very successful through this research.

I want to thank my guiding professor Antti Salminen for giving great opportunity to work in high technology laser laboratory and providing me helpful tips whenever needed. Big thanks to my supervisor Hamid Roozbahani for always listening and supporting my opinions and ideas. Special thank goes to Laser laboratory staff Ilkka Poutiainen and Pertti Kokko for always providing all the required equipment and also former APPOLO researcher Matti Manninen for giving great advices regarding research. Last but not least, without my colleague Pekka Marttinen this work would sometimes be dreadful. Was awesome to have you there.

Lastly I want to thank my family, friends and girlfriend for being supportive and listening to my problems.

Mika Ruutiainen

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LIST OF SYMBOLS AND ABBREVIATIONS

ASCII	American Standard code for Information Interchange
BAUD	How fast a device is able to transfer and transmit data
BR	Back reflection
CAD	Computer-aided design
CPU	Central processing unit
DLL	Dynamic-link library
DSP	Digital signal processing
FPGA	Field-programmable gate array
GPIO	General purpose input / output
HG-1	Mercury Argon calibration source
HR	High resolution
IPG	Interpublic group
MIMO	Multiple input multiple output
MRR	Material removal rate
NI	National Instruments
NMR	Nuclear Magnetic Spectroscopy
PCI	Peripheral component interconnect
PLC	Programmable logic controller
PRR	Pulse repetition rate
PXIe	PCI extensions for instrumentation
RS-232	Serial port connection
RTC	Real time clock
SISO	Single input single output
UV/VIS	Ultraviolet / Visible
VI	Virtual instrument
VISA	Virtual instrument software architecture
WP	Work package
YLP	Pulsed Ytterbium fiber laser

1 INTRODUCTION

This research was part of the European Commission funded project APPOLO (FP7-2013-NMP-ICT-FOF) and LUT Laser activities in part of WP 8 section. APPOLO is a collaboration project between several European universities and it focuses on new laser processing applications that need to be customized, tested and validated for commercial use. This means customized service of application labs for trials, experiments at variable conditions, reliability and process quality assessment in the close-to-manufacturing environment through validation. Goal of the project is to exploit new applications and bring them to the wider public in academic application labs, equipment procedures, system integrators and finally to end-users.

During research the most important target in APPOLO project was to monitor laser micro processes with very high quality and the focus of this research was on spectrometer monitoring and process control. Current laser industry, especially in laser engraving, lack of high quality process monitoring. Processes have been monitored and partially offline controlled, for example in laser welding, but since laser engraving is rather new field, there does not exist too many working solutions. Even bigger problem in laser engraving is total absence of process control. Currently it is done offline by turning the laser off and making changes. The biggest focus on this project was to develop functional and accurate process monitoring method and based on that to real time control the laser process itself. Process monitoring was done using Ocean Optics spectrometer with related equipment and the development of monitoring program and real time control was done using National Instruments equipment and software. This research will introduce all the needed equipment for monitoring of laser engraving and closely explain how to develop a real time control code for real time laser control using spectrometer. Research questions are if it is possible to online monitor laser engraving using spectrometer and if it is possible to real time control laser engraving using spectrometer. Rest of the introduction section will deal with previous researches related to laser process monitoring and laser process control.

1.1 Contributions

This research carried out by Mika Ruutiainen (guiding Prof. Antti Salminen, supervisor Dr. Hamid Roozbahani) about "Real time adaptive control of ultra-fast laser scribing process with spectrometer online monitoring" will result into publication of a journal paper which will be published on 9th LANE 2016 - 9th International Photonics Conference, 19-22 September 2016, City hall of Fürth, Rosenstraße 50, 90762 Fürth, Germany. Furthermore, one patent request will be sent of adaptive control for ultra-fast laser scribing process. Special mention to FTMC Vilnius of giving great possibility to test developed system in their laboratory for one week.

1.2 Laser engraving

Laser engraving can be described as a process where a laser beam is focused to a work piece surface which is removing material due to high power intensity. High power intensity makes material to vaporize and liquid is dispelled due to vapor pressure. There are some determining factors to create vaporization and melting: first of those is the interaction time of material being exposed by the laser pulse and the second is the maximum power of the laser pulse. It is generally known that large maximum power and exposure time of a material have strong dependency on the laser engraving. This is why short pulse laser are much more used than long pulse lasers. Nowadays nanosecond lasers are widely used but also shorter pulse lasers such as pico- and femtosecond lasers are more and more available. [1] Generally higher average power means higher productivity rate while making engraving quality less accurate [2]. Then again, ultrashort pulses in pico- and femtosecond lasers produce less heat which means less waste energy and less melting of the process material [3]. Longer pulse laser (nanosecond) has an effect that the thermal effect (heat-affected zone) might greatly affect to the process material while shorter pulse lasers (pico- and femtosecond) have smaller effect. In laser engraving largely heated area is greatly affecting quality of a work piece. Longer pulses generally mean possibility of detrimental effect to the work piece or the components inside the work piece [4].

Efficient engraving with nanosecond pulses appear to be matter of optimizing pulse length according to the application. In general fast processing speed (MRR) requires longer pulses and smaller heat-affected zone and better work quality require shorter pulses. Nowadays MRR is considered equally important with the other criteria. Thus based on application, longer and shorter pulsed lasers should be compared. With shorter pulses the temperature eventually rises and with longer pulses it eventually decreases. As mentioned, also visual look is very different when using nanosecond laser and pico-/femtosecond lasers. For engraving process to be most efficient, the best way would be to use nanosecond laser for processing bulk material and then changing laser to pico-/femtosecond laser for better and cleaner accuracy to finish the product. [5]

1.3 Process monitoring

According to Purtonen et al. [6] "Process monitoring is used to acquire information about the process. Aim of monitoring is to improve reproducibility, assurance of reliability and quality of the process. Process monitoring can also be used for observing, experimenting and systematic gathering of data." Gathered information can then be used to improve understanding of the process and phenomena or to create quality control method, such as closed-loop control of the process. Usually quality control for laser process monitoring is done utilizing optical or acoustic methods of which optical methods are considered to be more common. Emission acquired by optical monitoring can be divided into radiation, acoustic emission and electromagnetic emission. According to Lott et al. [7], "back reflected laser radiation, plasma or metal vapor induced radiation and thermal radiation are the most common types of radiations to be monitored." Laser processing causes laser-material interaction and methods for monitoring laser processes are generally based on understanding and reacting to consequent physical phenomena in according way. Monitoring method can be based on acoustic, optical, electrical or thermal operation [8].

1.4 Closed-loop real time control

It should be noted that there are several different kinds of techniques for process monitoring and control of laser welding but not a single one have been created for laser engraving. That is why this section focuses on reviewing process monitoring and control of laser welding as it has similar principles to laser engraving monitoring and control.

Several authors state, that emitted light from the welding interaction region is normally imaged onto the detector. Usually processing laser is split using suitable beam splitter so that the welding region can be viewed coaxially with the laser light [9-17]. Possible feedback controls strategies have been demonstrated through the laser power control [16-19], the focal point position [13-15,20,21] and the welding speed [17,19].

Maintaining focal point position with vision systems that involve triangulation computation is known to be possible. However, there are some drawbacks with such systems as they require good optical access to the work piece and at the same time they intervene the process. There are also other kinds of on-axis detection techniques that process radiation generated through the focusing optics delivered by optical fiber. Haran et al. [13] and Cobo et al. [15] claim that "the technique that exploits the chromatic aberrations in the optical elements, such that by a spectral analysis of the detected light, the focal error is derived."

Postma et al. [17]demonstrated a power feedback control system that can maintain its full penetration depth in mild steel sheet processing throughout the whole process. They claim that "the feedback control system works in a way that a photodiode monitoring system measures the intensity of the weld pool emitted light which is transmitted through an optical fiber back to the laser source. "Before process, a reference weld has been set to the memory of the monitoring device to which new process values are compared to. However, the control had one flaw as there is a possibility for signal level of partially penetrated weld to be the same as for full penetration. This can lead into incorrect process parameter adjustments. The problem was solved by only switching the controller on after reaching the full penetration regime. Nevertheless, the controller suffered of occasionally instability if a strong distraction suddenly changed the process regime. [17]

Moesen et al. [22] suggests that the problem variations due to local geometry influences in the melt pool can be overcome by two different approaches. First technique is to use prior knowledge of the part that is used combined with the experimental data. Information by these two factors can then be used to adapt the process parameters to match required standard. Authors call this method “feed-forward control”. However, this kind of technique require plenty of experimental data and also a software to detect local features of the melt pool. Another technique is to observe the melt pool and the work process by using optical sensors. Optical sensors are observing the melt pool and work process and the acquired data is fed to the adjusting feedback loop in real-time. Based on acquired information, it is possible to adjust the process correctly to achieve required melt pool properties. For a feedback controller to be stable and robust, it is important to understand the dynamic sensor output and the process input parameters which are determined through experimental procedure. [22]

1.5 Different kinds of optical methods

Based on several articles, it can be said that the most used methods for monitoring laser processing are optical methods. Optical methods are based on light detectors which Kenny [23] divides into quantum detectors and thermal detectors. According to Bollig et al. [24], "sensors can further be divided into three groups: diode-based sensors, camera based sensors, light stripe systems." Furthermore Boillot et al. [25] states that, "optical systems can be divided into active (using external illumination) or passive (without external illumination) of which passive can be further divided into reflective or emissive systems." Generally used division of optical methods by various authors is a classification into three different methods: spatially resolved (cameras), spatially integrated (photodiodes) [7] or spectrally resolved (spectrometers) [26].

Boillot et al. [25] lists several advantages for the optical methods: non-contact operation, versatility and possibility to have plenty of information regarding the spatial and spectral features coming from the optical output. Optical method is also usually considered to be useful based on visual aspect [27]. Nevertheless, optical method may sometimes be inaccurate. This is because of the gas or dust that may alternate the signal of temperature in the optical path [28]. Due to non-contact, optical method also provide very limited information about surface of the processed material [7].

1.6 Spectroscopy and spectrometry

Spectroscopy was developed to study radiation coming out of a matter. Spectroscopy is usually referred to dispersion of light based on dispersed wavelength, for example by a prism. However, spectroscopy can also be used to measure quantity as a function of frequency, referring response to an alternating field or varying frequency. The term spectrum is also related to spectroscopy and is also known as frequency. [29]

Spectrometry is one of the spectroscopic techniques and it is used for examining concentration of a matter. The device to do that is a spectrometer or a spectrograph. The most common use for spectrometry is in physical and analytical chemistry and it is used for identification of a matter. Identification is done by analyzing the emittance or absorbance by the substance. However, spectrometry can also be used for remote sensing which makes it very much used in astronomy. [29]

1.6.1 Classification of methods and measurement process

Spectroscopy can be divided into several different forms and the method depends on the quantity being measured. The most common quantity to be measured is intensity which can be divided into either energy absorbed or produced. According to Free Software Foundation Inc [29] the following describes different classifications of spectroscopy:

- "**Electromagnetic spectroscopy** is used to measure electromagnetic radiation, such as light."
- "**Electron spectroscopy** is used to measure electron beams. Typical variable of this measurement is the kinetic energy of the electron."
- "**Mass spectroscopy** is used to measure the charged species with magnetic and/or electric fields."
- "**Acoustic spectroscopy** is used to measure the frequency of sound."
- "**Dielectric spectroscopy** is used to measure the frequency of an external electrical field."

Mechanical spectroscopy is used to measure the frequency of an external mechanical stress which, for example, deals with torsion applied to a piece of material. "There are also several methods to measure different materials" [29]. The most common way to distinguish spectroscopic methods is to differentiate measurements into either atomic or molecular level based on to what spectroscopy is applied to. According to Free Software Foundation Inc. [29] the following describes different measurement processes of spectroscopy:

- "**Absorption spectroscopy** is used for discovering certain ranges of electromagnetic spectra where a matter is able to absorb. This technique includes atomic absorption and several different molecular techniques dealing with region defined infrared spectroscopy and nuclear magnetic spectroscopy (NMR)."

- **"Emission spectroscopy** is used for discovering certain ranges of electromagnetic spectra where a matter radiates (emits). For radiation to be possible, a substance must first absorb energy. The absorbed energy can be found from various sources and the emission type determines name of the emission. It should be mentioned that emission spectroscopy include spectrofluorimetry."
- **"Scattering spectroscopy** is used for measuring the amount of light scattered by a matter at certain wavelengths, incident angles, and polarization angles. Scattering spectroscopy is several times faster than absorption- or emission spectroscopy processes are. One of the most useful scattering spectroscopy techniques is called Raman spectroscopy. "

1.7 Spectrometers and spectral analysis

There are many different ways of developing of optical sensors but so far the most successful types are considered those that measure spatially integrated optical intensities. A good example of that is UV/VIS emission analysis which can be done using spectrometer [30,31]. According to Al-Azzawi [32] and Wolfe [33], "spectrometers can be considered as analytical instruments that are capable of measuring intensities of wavelengths from spectrum. Generally spectrometers are described based on their sensitivity, geometric, pathing configurations and how well spectral lines are resolved. "According to Khater [34], "a spectrometer is a monochromator of which exit slit is replaced by a multichannel detector interface. "Spectrometers are capable of measuring spectral ranges from gamma rays to micro waves but the most measured range is in the ultraviolet and infrared region [35]. In case of typical laser process, monitoring range covers ultraviolet and visible wavelengths. In these kind of cases usually grating of prism techniques are used in a spectrometer.

General problem in detecting emitted light of the laser processing is due to plasma plume which is occurring due to high intensity power. Spectral analysis is one of the most cost-effective and reliable methods in detecting spectrum from a plasma plume. This method is easy, non-process distracting and very inexpensive. It is also fairly easy to automate. Spectral analysis of laser processing is performed of the data acquired by a spectroscopy sensor. [36,37] In case of welding defects, electron temperature and electron density are the most useful data that can be calculated out of the plasma spectral intensity to predict welding defects [38]. Spectral analysis can also be used for understanding better the laser process itself. One of the oldest applications of the spectroscopy analysis in the physics of plasma is electron temperature measurement which is mostly used for monitoring laser welding [39,40].

2 SPECTROMETER PROCESS MONITORING

Chapter two explains initial equipment used on this research and initial tests carried out in the early stages before code development. End of chapter two focuses on discussing possibilities between different communication protocols leading to choosing the most optimal one.

2.1 Spectrometer HR2000+

The spectrometer used in this research was HR2000+ High-Resolution miniature fiber optic spectrometer from Ocean Optics, which can go to as high resolution as 0.035nm. The spectrometer is capable of wavelengths from 200 - 1100nm but it should be noted that the range and resolution strongly depend on selected grating and entrance slit. This means that the wavelength range is not fully usable all the time. In this research the spectral range is from 200 to 650nm. The spectrometer has capability of transferring 1ms spectra continuously which makes the spectrometer possible to be utilized in online monitoring. [41] Figure 1 illustrates HR2000+ High Resolution Spectrometer and appendix 1 describes its specifications.

Figure 1. HR2000+ High Resolution Spectrometer.

Due to its fairly wide wavelength range and rapid spectra transferring rate, the spectrometer is very suitable for use where fast reaction is needed to be observed, such as online measurements. The spectrometer has its own memory chip which contains calibration coefficients for wavelength, coefficients for linearity and unique serial number. Spectrometer is made to work with a software called SpectraSuite which reads the pre-saved values from the memory chip of the spectrometer. [41]

There are two possible ways of connecting a spectrometer to an operating system. One possibility is through a laptop or a PC via USB port. If this method is used, the spectrometer is powered by the host computer which eliminates external power supply requirements. If the spectrometer is connected to a PC through USB, all the measurements can be done in real time but possible transfer delay due to USB protocol might occur. This eliminates the possibility of online measuring unless a real-time industrial computer is used. There is also another way of connecting spectrometer to the operating system and it is done by using the HR4000 Break-Out Box by Ocean Optics. The spectrometer also has RS-232 connectivity for computers, PLCs and other RS-232 supporting devices. It should be noted that by using RS-232 serial port, an external power supply (unless spectrometer is connected to a PC) should be used which is able to power the spectrometer and the Break-Out Box. By using the Break-Out Box, which is a passive module for separating signals from 30-pin port to different standard connectors, it is possible to connect the spectrometer to other devices as well. [41]

2.1.1 SpectraSuite

According to Ocean Optics [42] "SpectraSuite consists of several different modules that include data acquisition functions, scheduling functions, data functions and the rendering functions, and has compatibility with different operating systems. SpectraSuite is able to control any Ocean Optics USB spectrometer and device and is also capable of controlling all sorts of USB instrumentations as long as they are using appropriate drivers. "Appendix 2 illustrates SpectraSuite having data acquisition on.

There are three basic spectroscopic experiments that can be performed; absorbance, reflectance, emission and absolute irradiance measurements of which reflectance experiment is one utilized the most in laser industry. In addition to these, SpectraSuite also allows signal processing that includes electrical dark-signal correction, stray light correction, box card pixel smoothing and signal averaging [42]. When starting experiments, SpectraSuite is set into Scope-mode which allows spectrometer to acquire raw data through the detector of which signal-conditioning parameters are being established. As previously mentioned, SpectraSuite is capable of viewing acquired data in real-time. User is able to see effects of the chosen setups and make possible corrective parametrical changes if needed. Effect and results can be seen directly. Depending on the connectivity of the spectrometer, data can be either saved to a PC or on-line tuned through industrial computers. [42]

According to Ocean Optics [43], "SpectraSuite is also able to perform time-acquisition experiments for kinetics applications and as part of the time-acquisition function, monitoring and reporting up to six single wavelengths and up to two mathematical combinations of these wavelengths are available." It is also possible to perform reference monitoring in several ways; single wavelength, integrated intensity and wavelength-by-wavelength. It should be noted that with SpectraSuite it is possible to set parameters for different system functions that include the following; data acquiring, designing the graph display and using spectra overlays [42]. A good and easy way is to import data from SpectraSuite to, for example Excel, and modify the data there. SpectraSuite also provides various software-controlled triggering options which can be, for example, laser firing or light source pulsing [42].

2.2 Initial experimental setup

Initial experimental setup consisted of the spectrometer HR2000+ from Ocean Optics, an optical wire and a sensor attached to it, laser and its power source from Uniphase, a laptop and a mouse, a mirror to reflect laser light and a USB cable to connect the spectrometer to the laptop. Figure 2 illustrates the experimental setup and appendix3 describes components of the setup.

Figure 2. Experimental setup.

2.2.1 Test one, hand laser

The experimental setup was used for basic test measurements to ensure functionality of the setup. Test experiments consisted of two different tests; reflection- and relative irradiance tests. Reflection test was done using the spectrometer and sensor attached to the optical fiber, the laser and the power source. The laser was turned on focusing it to a mirror to reflect light. Reflected light was acquired by the spectrometer optical head and spectra was developed to SpectraSuite for analysis. Figure 3 illustrates collected spectra in SpectraSuite.

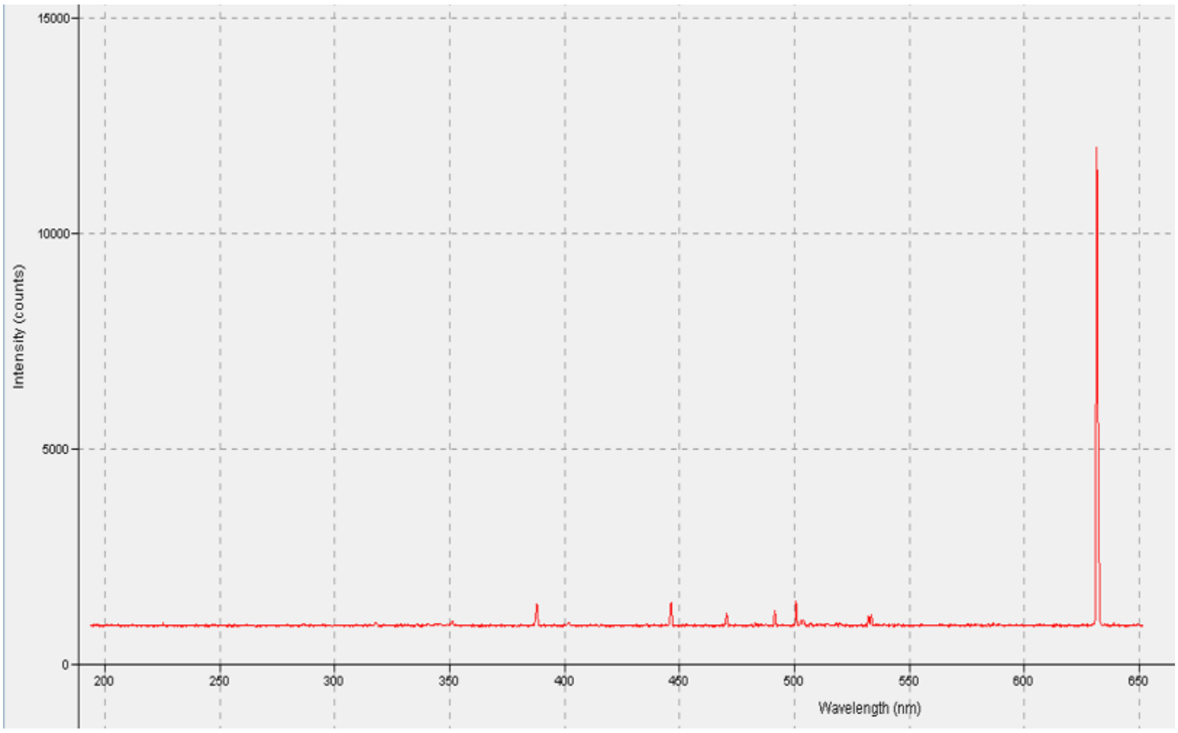


Figure 3. Collected spectra of a laser viewed in SpectraSuite.

Laser light is very intense, coherent and dispersion is very small when no additional lenses are added and when focal lengths are short. Thus it can be seen that the collected spectra is at wavelength of 630nm (red light) with intensity of about 1200 which the laser manufacturer has announced. Smaller spikes along the wavelength axis can be noticed and understood as dispersions of reflection. However, dispersion in this case was very small due to short focal length. Performing the experiment was rather complicated because focusing spectrometer optical head to the freely moving laser was not easy. Thus spectrometer was very prone to external distractions leading to inaccurate results.

2.2.2 Test two, candle

Another test was performed by observing relative irradiance of a candle. This experiment consisted of the spectrometer and of the optical head attached to the optical fiber. A candle was observed spectrometer focused to it and the collected spectra was viewed in SpectraSuite for further analysis. Figure 4 illustrates collected spectra in SpectraSuite.

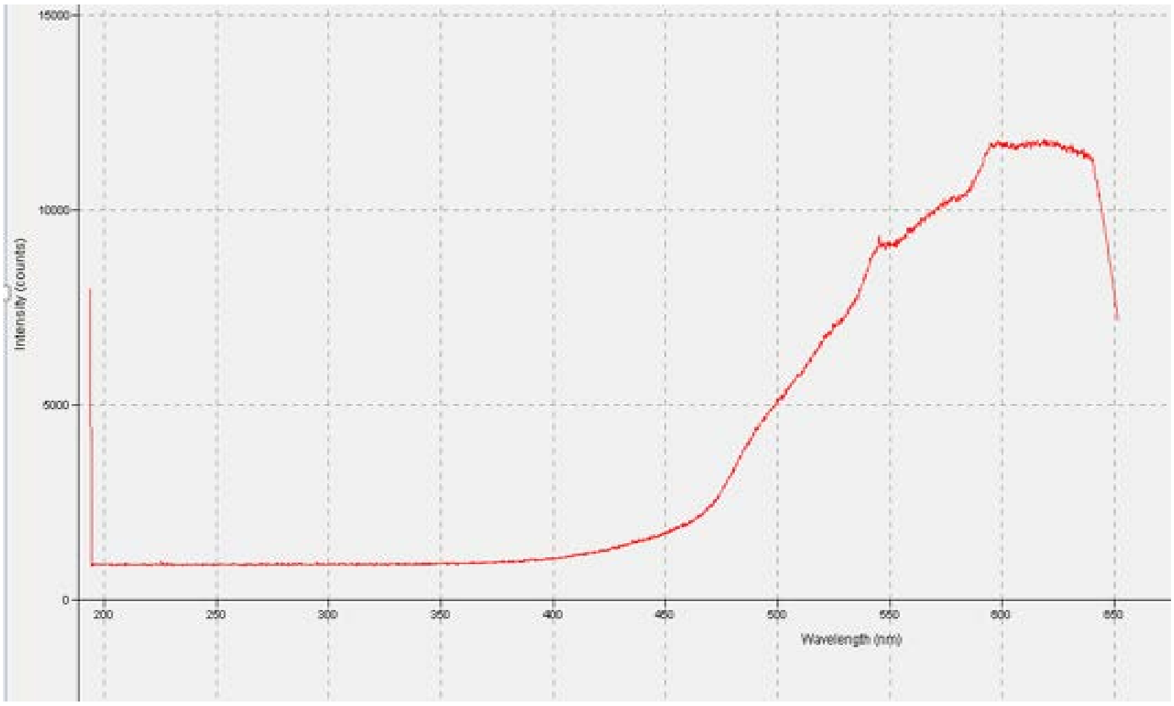


Figure 4. Collected of a candle viewed in SpectraSuite.

It can be noticed that the wavelength range of the candle is larger than incase of the laser light because candle radiation is not that intense, it disperses a lot and is less coherent. Intensity starts to rise at wavelength of about 470nm and peaks at about 640nm. After that intensity suddenly drops. This is due to grating of the spectrometer which cannot process data after 650nm and due to color (intensity) of fire, which is turning more into orange. If larger range was required, the grating should be changed. In reality spectra would go a little longer, however, dropping as fast because the burning candle at its highest intensity point has wavelength of about 650-670nm. Otherwise the spectra curve is rather smooth and as expected.

2.3 The Break-Out Box

Initial idea was to use the Break-Out Box for on-line measurements. One end of the spectrometer would be connected to the laptop using USB for power source and the other end to the Break-Out Box using HR4-BB-CBL cable from Ocean optics. The Break-Out Box would directly be connected to the laptop using serial port. It should be noted that if serial port RS-232 (J4) of the Break-Out Box would be used, a separate external power source of 5V (ADC-USB-SER) should be used unless the setup is powered by USB connection from a pc or a laptop.

Idea was to connect the Break-Out Box to an industrial computer of dSpace utilizing serial port RS-232 (J4) because of good capability for customization. Designing software was supposed to be Matlab + Simulink by MathWorks and the final control would have been done in a software called Control Desk from dSpace. Matlab is a text based environment for code making and Simulink is graphical coding environment which means that all the blocks in Simulink already include necessary codes to be used. Both Matlab and Simulink can work simultaneously and data can be transferred between the two. Figure 5 illustrates the Break-Out Box connected to the spectrometer and figure 6 port connections of the Break-Out Box.

Figure 5. Spectrometer connected to Break-out Box using serial cable HR4-BB-CBL.

Figure 6. Port connections of the Break-out Box.

However, to be able to make a code for spectrometer using Matlab + Simulink, additional toolbox add-in called Instrument Control Toolbox should have been installed. Unfortunately that add-in was missing so LabVIEW of National Instrument was instead decided to be used as all of the required licenses were available. LabVIEW is graphical coding environment which means that all the used blocks and items in the software already include necessary codes. Another reason to change into LabVIEW environment was because other participants of APPOLO project in LUT were using LabVIEW. Thus integration of the equipment and developed codes would be easier.

2.3.1 Initial tests with the Break-Out Box

Simple codes for testing serial functionality of the break-out box were developed using LabVIEW 2013 (32Bit) and later LabVIEW 2014 (32Bit). Figure 7 illustrates a simple serial test in LabVIEW 2013.

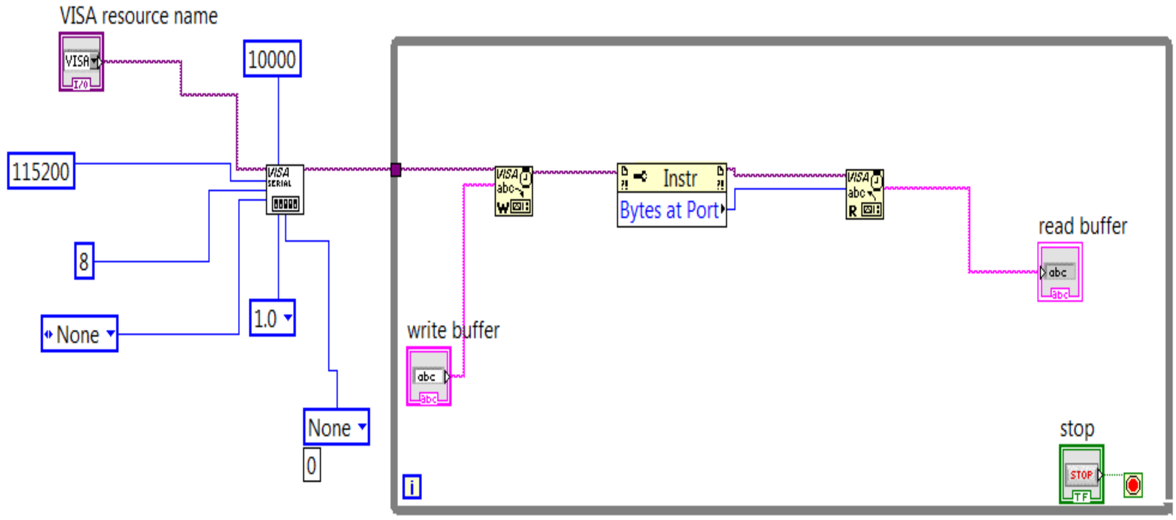


Figure 7. A simple serial test in LabVIEW 2014.

In this serial test the initial serial port data had to be set correctly between the communicating partners (in this case the laptop and the spectrometer + Break-Out Box) and commands to be executed were written to the write buffer. Commands were executed in VISA serial blocks and the read buffer sent back the reply. However, the break-out box connected to the spectrometer never replied to any of the inquiries sent to the serial port. Also simple tunneling tests with different software were tested but nothing was received. This lead to believe that the Break-Out Box could have been broken. Simple signal mapping was done using NI USB-6259 connecting platform to validate the signal functioning of the break-out box. Figure 8 illustrates NI USB-6259 connecting platform.

Figure 8. NI USB-6259 connecting platform.

Signal mapping proved the break-out box to be functional as volt output was received. However, returning signal from the laptop was not received which could indicate that part of the Break-Out Box to be broken. The Break-Out Box was sent back to Ocean Optics for a check but after receiving it back it still remained inoperative.

2.4 USB connectivity of the spectrometer

As serial connection was found to be malfunctioning, USB connection possibility was taken into consideration. USB can transfer data multiple times faster and more than conventional serial connection but USB can suffer from package delay in Windows environment. In real-time system this is not acceptable. Table 1 describes data transfer rates of different communication protocols.

Table 1. Data transfer rates of different connection protocols.

Typical transfer rates	
Gbit-Ethernet	1Gbit/s – 10Gbit/s
HDMI	8.16Gbit/s
USB 3.0 / Super	4Gbit/s
Firewire S3200	3.2Gbit/s
eSata 2.0/1.5	3.0Gbit/s – 1.5Gbit/s
HD-Video	2.4Gbit/s
Firewire S800	800Mbit/s
USB 2.0	480Mbit/s
Firewire S400	400Mbit/s
Ethernet	10Mbit/s – 100Mbit/s
VDSL	52Mbit/s
Profi-Bus	12Mbit/s
USB 1.1	12Mbit/s
RS-485	10Mbit/s
FlexRay	10Mbit/s
CAN-Bus	1Mbit/s
RS-232	500kb/a

Even if possible package delay could occur, USB 2.0 was still taken into consideration. Connection should be tested as the spectrometer will eventually end up being connected to the industrial computer where delay should be as low as possible. Test code for controlling the spectrometer through USB connection was developed using LabVIEW 2014. Test code was based on the code developed by Ocean Optics. Appendix 4 illustrates the test code.

Basic idea of the code is that everything was built using wrappers (data is acquired by spectrometer and connected to the code using wrapper-block) that transfer acquired data from spectrometer to the LabVIEW environment. Transferred input data is in numeric form and it is changed into graphical output which can be viewed in a graph in real-time but with a very small delay due to Windows environment. The code was confirmed to be successfully working. Next step was to purchase a real-time capable industrial computer, in this case it was PXIe-8880 of National Instruments.

3 TEST EQUIPMENT

3.1 Industrial computer NI PXIe-8880

To be able to on-line monitor laser scribing processes, it is necessary to acquire data from the spectrometer in real-time. Industrial computer PXIe-8880 Embedded Controller from National Instruments was purchased for this project. According to National Instruments [43], "PXIe is a PC-based platform for measurement and automation systems. PXIe combines PCI electrical bus features with modular, Eurocard packaging of Compact PCI and then adds specialized synchronization buses and key software features. PXI deployment platform is used in applications such as manufacturing test, military and aerospace, machine monitoring, automotive and industrial test". Figure 9 illustrates PXIe-8880 Embedded Controller.

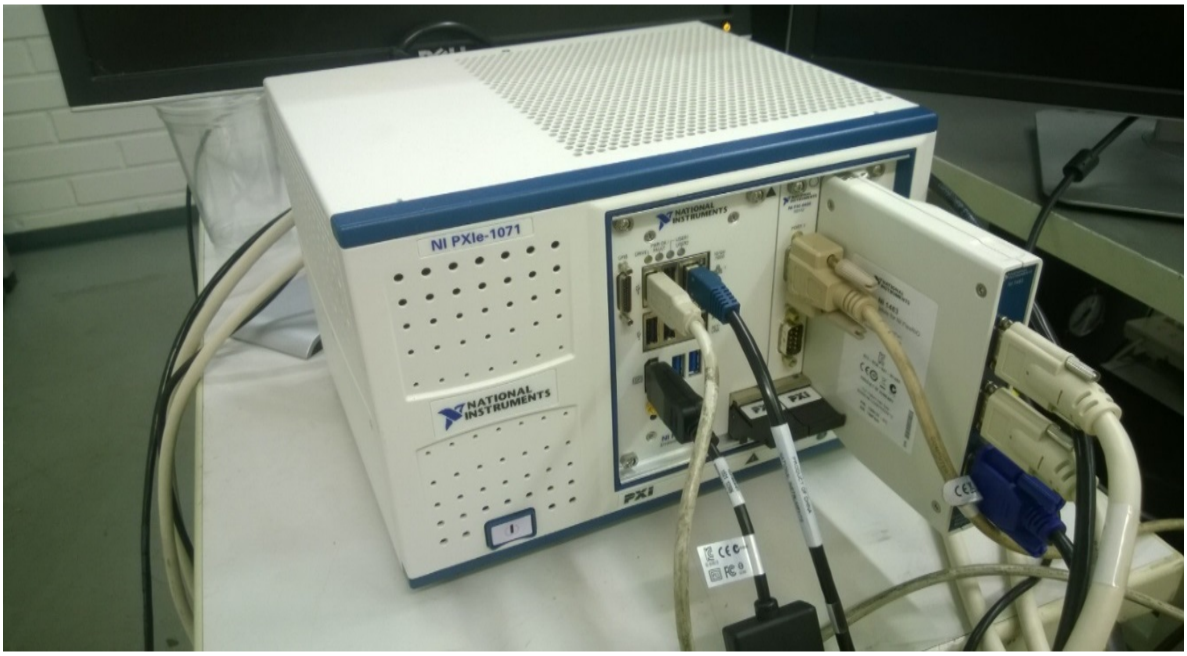


Figure 9. NI PXIe-8880 Embedded Controller

Purpose of this unit is to handle all the necessary calculations related to data acquiring and equipment tuning. PXIe-8880 was purchased with NI 1483 Camera Link Adapter Module, NI PXIe 7966R FPGA Module, NI PXIe-8880 Real-Time Module and NI PXI-8430 Serial Port Module for better equipment integration. By default the PXIe already includes USB ports, Ethernet ports and display ports. [44] It should be noted that NI 1483 Camera Link

Adapter module and NI PXIe 7966R FPGA Module were used by APPOLO colleague Pekka Marttinen and were not used in this project. Appendices 5 and 6 describe more thoroughly the modules that were used in this project.

National Instruments is offering several software that directly work with the PXI unit. However, all the software need to be integrated to work together. That can be done by setting all the necessary information to the PXIe-8880. First software to be used is NI MAX which is a platform to integrate devices of NI. As PXIe-8880 is connected to the laptop using Ethernet cable, the software should automatically recognize PXIe. As PXIe is recognized, drivers of the add-in modules and software should be deployed to the PXIe. Figures 10 and 11 illustrate how to deploy drivers to the PXIe.

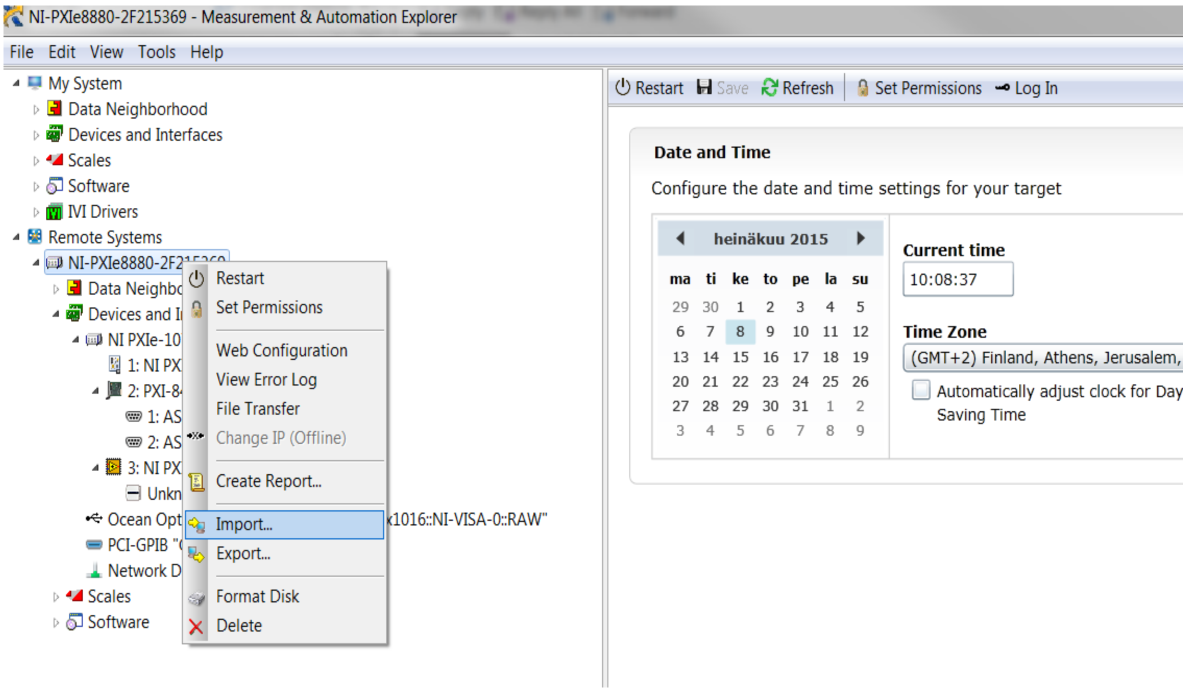


Figure 10. Data import to the PXIe-8880.

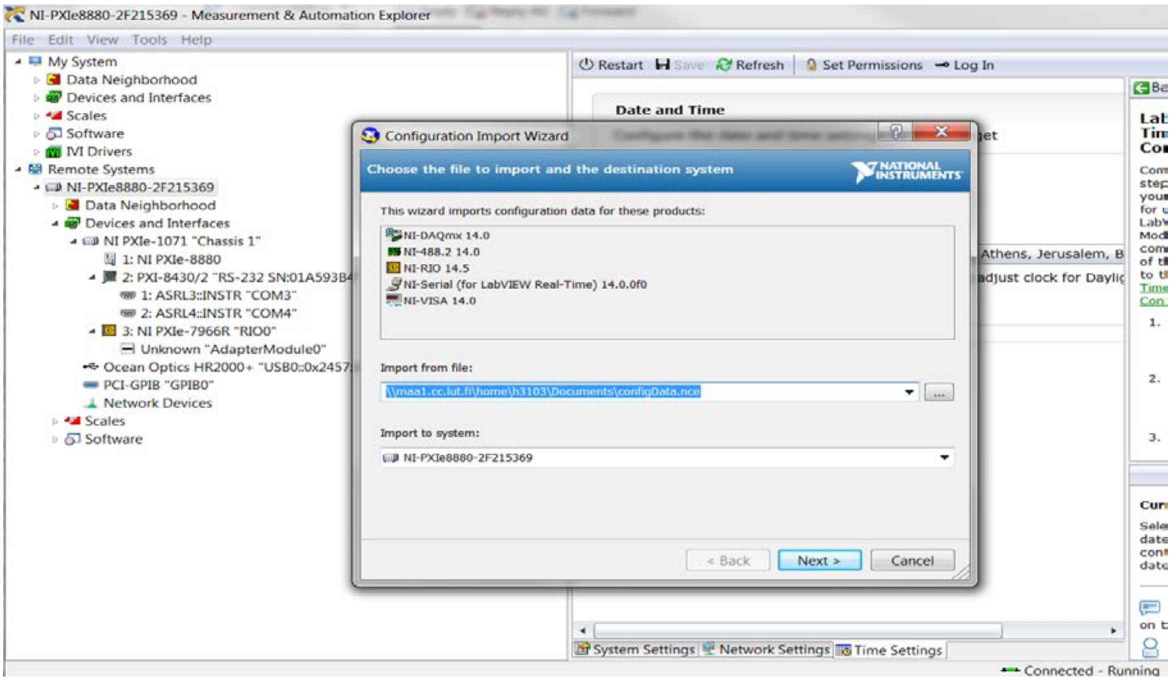


Figure 11. Deployment of the module drivers to the PXIe.

Every NI equipment also require software so that they can be utilized. Software can be deployed to the PXIe in the similar way as drivers. Figures 12, 13 and 14 illustrate how to deploy software to the PXIe.

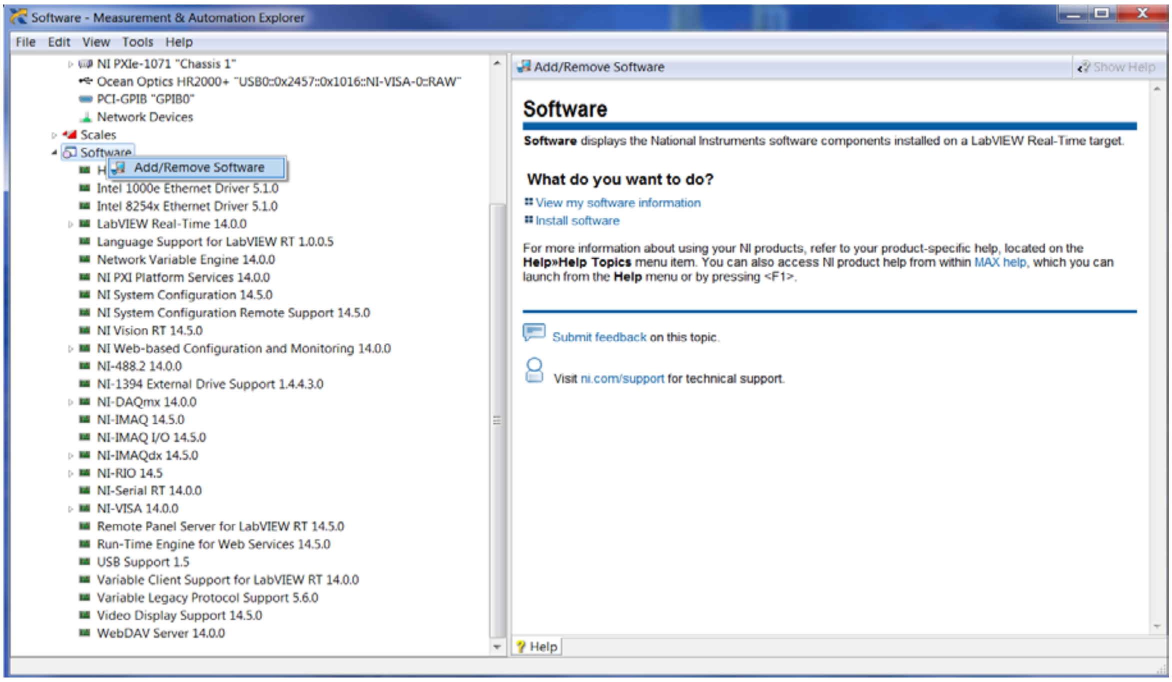


Figure 12. Add/Remove of the software.

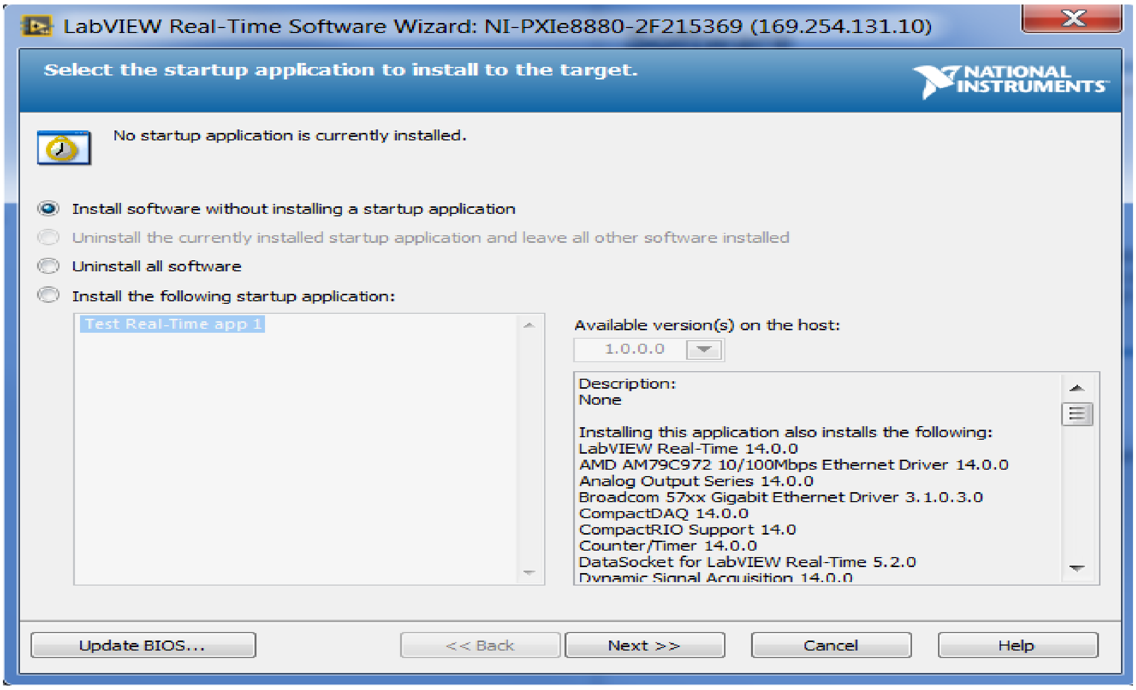


Figure 13. Selection of whether to install or uninstall the software.

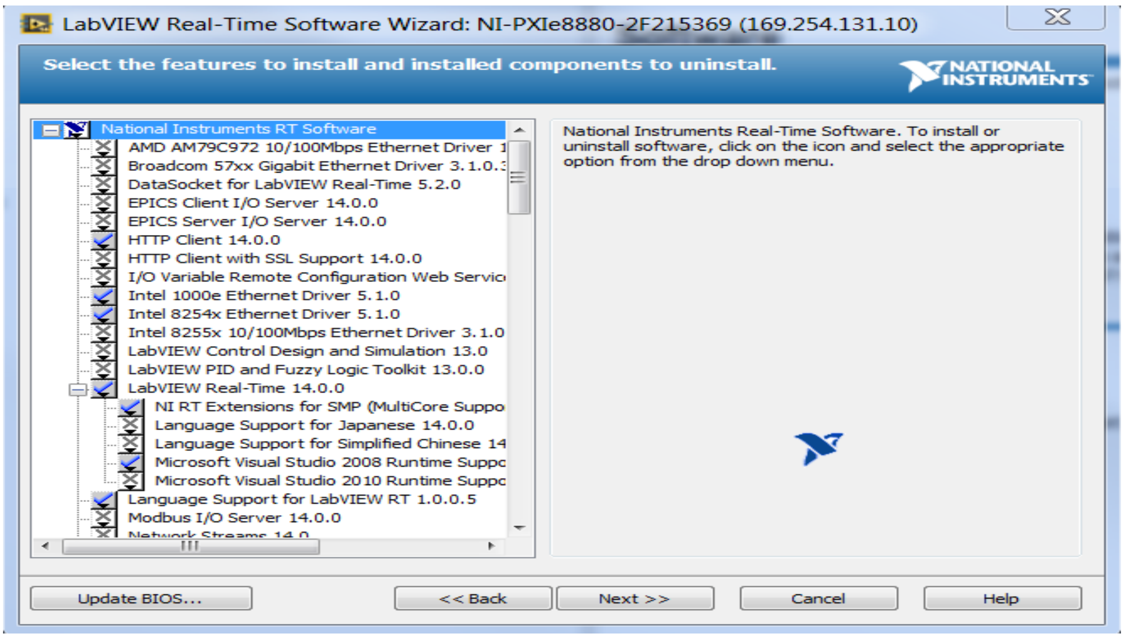


Figure 14. List of possible software to be installed or already installed.

As all the required drivers and software were installed to the PXIe, it was ready for use. It should be noted that it is possible to update PXIe whenever needed or required.

3.1.1 Spectrometer deployment to the PXIe-8880

As all of the drivers and modules were deployed to the PXIe, it was possible to start deploying LabVIEW projects. LabVIEW projects consist of single VIs (Virtual Instruments, representing real measuring instruments) that basically are code clusters created in LabVIEW. In this case the first VI to be tested was the spectrometer USB data acquiring code. However, since the PXIe does not have Windows-based operating system, it cannot directly read USB devices unless their drivers are deployed. Ocean Optics does not provide driver for the PXIe. However, drivers are provided for Windows environment and it was possible to utilize them for the PXIe. Drivers from Ocean Optics come with the product OmniDrive which is meant for customizing their own products. National instruments provide simple data type checker software called DLL checker, which states whether data type is suitable for real-time environment or not. Figure 15 illustrates DLL checker data check view.

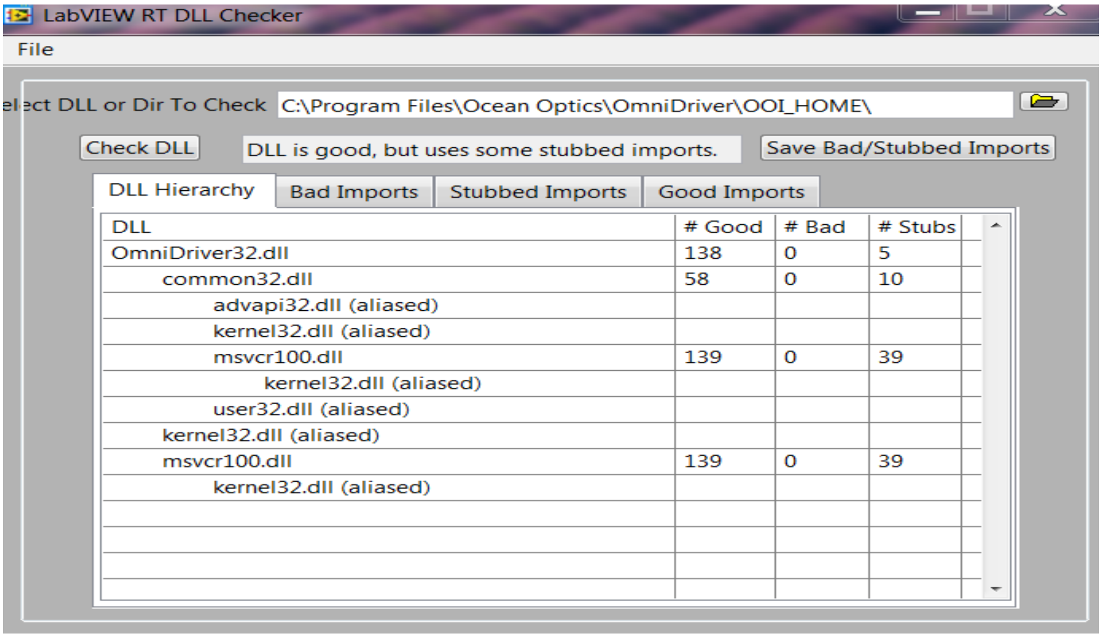


Figure 15. NI DLL checker.

DLL checker is used for .dll files that are required to be “good” in type so that they can even possibly be deployed to the PXIe. Ocean Optics driver was “good” in data type so it was possible to try deploying driver as it was. All of the driver were directly deployed under the PXIe in LabVIEW project and after tweaking, it started to work. Figure 16 illustrates deployed files to the project tree of LabVIEW.

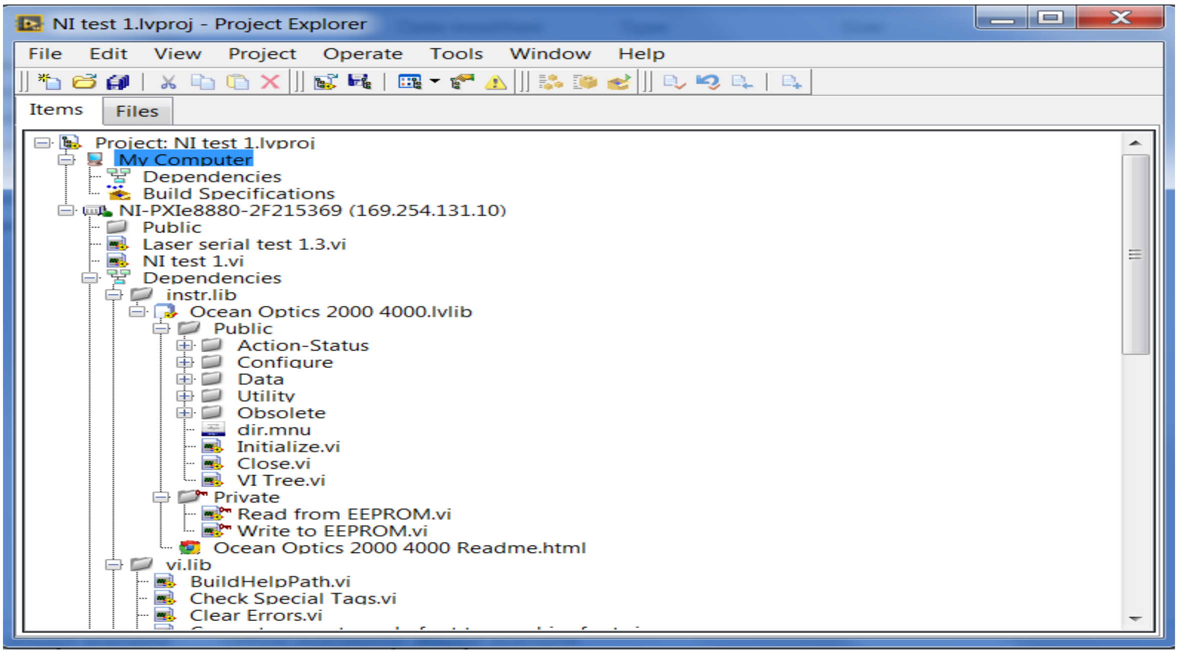


Figure 16. Spectrometer USB driver deployed to the PXIe-8880.

As all of the driver files were successfully deployed to the PXIe, also the code for USB control of the spectrometer could be deployed. It is good to note that everything deployed to the PXIe have very low latency meaning that everything works in real-time. Figure 17 illustrates USB code for the spectrometer.

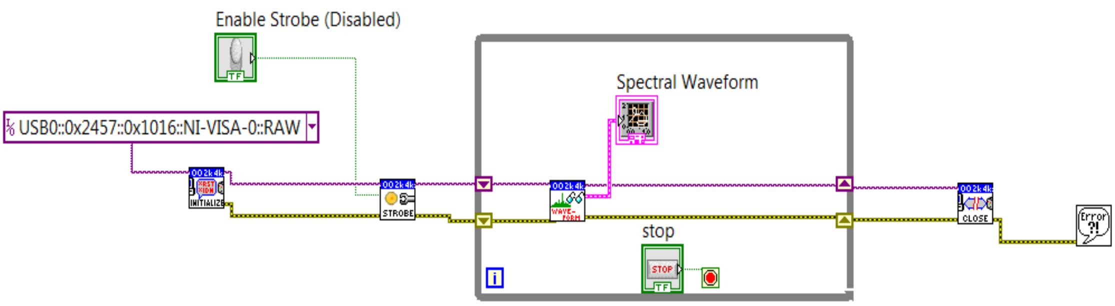


Figure 17. USB code for the spectrometer.

USB code was built based on USB VISA control which is certain instrumentation system controller in LabVIEW. Output in this case was chosen to be USB and data was acquired and displayed in graphical form. It should be noted that the acquired data can also be displayed in numeric form which later on should be used because laser control parameter tuning should be based on numerical output.

3.1.2 Spectrometer calibration

When real-time monitoring is performed for laser scribing, a user has to be sure that all of the equipment are well calibrated. Spectrometer tend to lose its accuracy due to yearly decay and thus it should be re-calibrated every now and then. A good way to check and re-calibrate a spectrometer is to use Ocean Optics HG-1 Mercury Argon calibration source to ensure consistency of the light source as it is standardized. Figure 18 illustrates the calibration source.

Figure 18. Ocean Optics HG-1 Mercury Argon Calibration Source.

Ocean Optics provides a simple guide for the spectrometer calibration check and re-calibration if values are not too much off of the required. Table 2 shows values that spectrometer should meet to be exact.

Table 2.Ocean Optics calibration values for HR2000+ spectrometer [45].

Independent Variable → True Wavelength (nm)
Dependent Variables → Pixel #, Pixel # ², Pixel # ³
Values Computed from the Regression Output → Predicted Wavelength, Difference

True Wavelength (nm)	Pixel #	Pixel # ²	Pixel # ³	Predicted Wavelength	Difference
253.65	175	30625	5359375	253.56	0.09
296.73	296	87616	25934336	296.72	0.01
302.15	312	97344	30371328	302.40	-0.25
313.16	342	116964	40001688	313.02	0.13
334.15	402	161604	64964808	334.19	-0.05
365.02	490	240100	117649000	365.05	-0.04
404.66	604	364816	220348864	404.67	-0.01
407.78	613	375769	230346397	407.78	0.00
435.84	694	481636	334255384	435.65	0.19
546.07	1022	1044484	1067462648	546.13	-0.06
576.96	1116	1245456	1389928896	577.05	-0.09
579.07	1122	1258884	1412467848	579.01	0.06
696.54	1491	2223081	3314613771	696.70	-0.15
706.72	1523	2319529	3532642667	706.62	0.10
727.29	1590	2528100	4019679000	727.24	0.06
738.40	1627	2647129	4306878883	738.53	-0.13
751.47	1669	2785561	4649101309	751.27	0.19

Spectrometer calibration check is done in a way that the true wavelength value should be close to the given value at the corresponding pixel spot. According to Ocean Optics [45], calibration can be checked based on following equation:

$$\lambda_p = I + C_{1p} + C_{2p^2} + C_{3p^3} \quad (1)$$

Where:

λ = the wavelength of pixel p

I = the wavelength of pixel 0

C_1 = the first coefficient (nm/pixel)

C_2 = the second coefficient (nm/pixel^2)

C_3 = the third coefficient (nm/pixel^3)

R_λ= the third reference intensity at wavelength λ

Based on equation 1 multiplications of pixels can be estimated and finally the wavelength and the difference can be predicted. The difference should be under ±0.3 for calibration to be exact enough. Spectrometer calibration check can be done using SpectraSuite from Ocean Optics. Appendices 7, 8 and 9 illustrate measured wavelengths at certain pixel spots.

In appendix 7 the minimum peak width and the baseline were set so that enough peaks could be found to make accurate calibration check. At pixel spot 251 the wavelength was 253.19nm. Compared to the value of the guide, wavelength 253.19nm should be at the pixel spot of 175. In the appendix 8 wavelength was checked at the pixel spot of 174. Corresponding wavelength is 235.09nm as it should have been around 253nm. Based on previous checks, it was noticed that the wavelength difference at certain pixel spots seemed to differ a lot compared to the guide values. Appendix 9 shows wavelength check at the pixel spot of 1021 to understand if the difference increased even more when observing higher wavelengths. At the pixel spot 1021 the wavelength was 430.37nm as by the guide it should be 546.07nm. It was understood that the difference increased even more at higher wavelengths. Based on the results of calibration check the spectrometer was decided to be sent for re-calibration to Ocean Optics. Re-calibration data sheets can be found of appendices 10 and 11.

3.2 Research equipment

The laser equipment consist of an IPG ytterbium pulsed fiber laser of 20W maximum average power + its power sources, Scanlab RTC 4 interface card, Scanlab Hurryscan 14 II scanner head and Scanlab camera adapter. Before this research, the laser was controlled by a PC in LUT Laser laboratory. The laser was connected to the PC through serial connection. The PC also has RTC 4 Interface board to control the scanner head. The scanner head is used to control movement and speed of the mirrors inside the scanner head. Mirrors are focusing laser through focusing lens to the required spots and pathing. The laser was controlled using YLP C-series control utility software from IPG, the scanner head and the laser parameters were controlled using SAMLight version 3.0.5 build-0582 by SCAPS. Following section is describing the research equipment used in the research, starting of the laser. Appendix 12 describes specifications of Ytterbium pulsed fiber laser YLPM-1-4x200-20-20and figure 19 illustrates the laser and its power source.

Figure 19. IPG 20 W ytterbium pulsed fiber laser and its power sources.

Scanlab RTC4 interface card

According to Scanlab [47], "the RTC4 PC interface card from Scanlab is designed for real-time control of scan heads and lasers via PC with PCI bus interface. The card is based on a fast digital signal processor (DSP) system providing full real time control for a wide range of applications. "Driver of RTC4 provides a set of control commands which can be utilized through SAMLIGHT by Scanlab. Due to design of RTC4, it is able to store and process commands independently of the host PC, which allows real-time scan head and laser control even if a PC has to run other tasks. RTC4 can be used with commonly used lasers and offers various laser control signals. The RTC 4 offers four different laser control modes and also possibility to user customize output signals. [47] Appendix 13 describes specifications of RTC4 and figure 20 illustrates RTC 4 card.

Figure 20. RTC 4 card.

ScanlabHurryscan 14 II scanner head

Hurryscan 14 II scanner head is very optimal for nearly all challenges found in industrial laser materials processing. The scan head is mechanically and electrically inter-compatible and have range for various levels of dynamics. Integrated temperature stabilization ensure high long-term stability and low drift values. The advantage of this scanner is that it optimally combine top speed and very high precision. Marking speed can exceed over 1000 characters per second. [48] Appendices 14 and 15 describes specifications of Scanlab Hurryscan 14 II scanner head and appendix 16 dimensions and parts of the scan head.

Scanlab camera adapter

By using camera adapter, it is possible to do process observation through galvanometer scan head. The original purpose of this adapter is to observe process through a camera. However, in this research it is done by a spectrometer. The adapter is placed between the scan head and the laser flange so that it is possible to observe laser light pathing perpendicularly during laser processing. This allows process control or detection of work piece positions and orientations. Installment of the adapter is possible to be done in four different locations which enables easy integration to the system. To observe the working plane, light arriving from there is decoupled in the adapter via a beam splitter for imaging by sensors. This also means that the laser radiation does not suffer of any distractions on its way to the scan system. [49] Appendix 17 illustrates dimensions and parts of the camera adapter and table 3 describe typical optical configuration with the scan head.

Table 3.Typical optical configurations with scan head [49].

Typical Optical Configurations with Scan Head

Laser wavelength	1064 nm	532 nm	355 nm	266 nm
Observation wavelength	880 nm	635 nm	635 nm	635 nm
Scan head aperture	14 mm	10 mm	10 mm	10 mm
Scan head mirror coating (1)	1064 nm + 880 nm	532 nm + 635 nm	355 nm + 635 nm	266 nm + 635 nm
Flat field objective	163 mm	160 mm	100 mm	103 mm
Processing field size	110 x 110 mm^2	110 x 110 mm^2	50 x 50 mm^2	50 x 50 mm^2
Beam splitter				
Laser wavelength	1030 nm - 1110 nm	488 nm - 532 nm	350 nm - 360 nm	257 nm - 266 nm
Range for observation wavelength(1)	450 nm - 900 nm	615 nm - 900 nm	510 nm - 680 nm	630 nm - 670 nm

Camera adapter is a necessary installment as laser pathing needs to be observed through laser focusing mirrors inside the scanner head. By observing the mirrors, it is possible to acquire data using spectrometer by only observing laser pathing through mirrors. However, since the camera adapter has standard C-mounting for equipment attachment, it was necessary to design and manufacture suitable adapter for the spectrometer optical head attachment. Figure 21 illustrates CAD drawing of the adapter and the actual manufactured adapter.

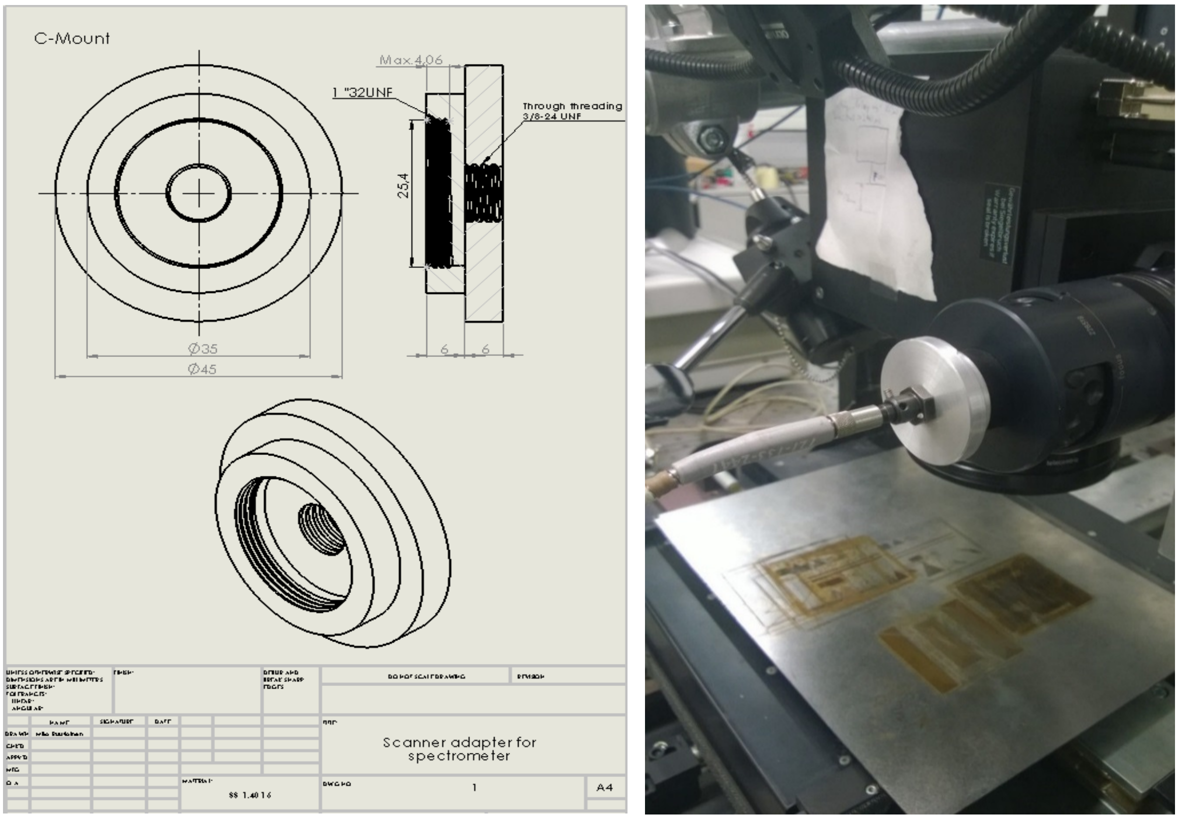


Figure 21. CAD drawing of the adapter and the manufactured adapter.

3.3 Confirming serial functionality of the IPG laser

Purpose of this study was to make a control code for the laser and the spectrometer, independent of the manufacturer software. In the research a laptop was utilized and RTC 4 interface card could not directly be inserted to the laptop. That meant the RTC 4 card to remain in the PC which meant that the scanner head was still being controlled by the PC. Basically this meant controlling movement of the mirrors. However, since the laser was controlled through serial protocol, which the project laptop also includes, code for laser control could be developed.

IPG laser manual explains how to control laser based on serial communication. Communication is done in American Standard code for Information Interchange - form (ASCII). Serial communication works in a way that commands are sent to the working device which return values back to the controlling device. This allows direct query of the data which enables setting the commands. After the laser was connected to the laptop through serial, communication was tested using Hercules software which is a program to test connections of different devices. In this case it was used to test serial connection.

When serial connection is used, it is most important to know the correct port to which the device is attached, the correct BAUD rate (how fast a device is able to transfer and transmit data), data size, parity, handshake and mode. All of the information were stated in the manual of IPG. When setting up serial parity, both the laptop in Windows environment and the laser have to have the same serial values for connection to be successful. As serial connection was proven to be successful, it was possible to move into LabVIEW environment to start developing own control code for the laser control. Following explains how to setup serial parity and how the laser can be read and commanded. Appendix 18 describes query and command codes for the laser.

According to IPG Laser [50] the RS-232C command structure description is as follows:

1. "Initialization of RS-232:
    - BAUD rate: 56700 bits per second
    - Parity / flow control: none
    - Start / stop bits: 8 data bits, 1 start bit and 1 stop bit"
2. "Firmware command structure (ASCII codes for symbols):
    - [$] [Command code] [;] [Optional parameters separated by semicolon] [CR symbol (Hexadecimal 0D)]"
3. "Laser reply structure:
    - [Command code] [;] [Return values separated by semicolon] [CR symbol (Hexadecimal 0D)]"
4. "The command code is a decimal ASCII representation of a number individual for each command. The list of command numbers is shown in the table."
5. "Command parameter is a text string. If the parameter is a numerical value, it should be converted into a decimal ACII string."
6. "The returned value is a text string. If the requested value is numerical, the opposite conversion from text string to the numerical value is required.
7. "All commands should be terminated by “Carriage Return” symbol, hexadecimal value “0D”. The RS-232C buffer of the laser receives bytes until the CR symbol occurs. All bytes before this symbol are interpreted as a command. Bytes after CR until next CR will be interpreted as a next command."
8. "For all “set” commands device returns as the parameter “Y” if the command was successfully executed and “N” if the command was not executed."

9. "For all strings sent to the laser, which were not recognized as valid commands, the laser sends “E” as parameter."
10. "After switching on electrical power device state is the following:
    - Pulse repetition rate: nominal PRR
    - EE and EM are in OFF state
    - Set power is 0"

Simple serial tests in LabVIEW were performed to confirm functionality of the laser. For example, command $5 was sent to the laser to query temperature of the laser module. The command was sent in ASCII form, as requested, and the laser replied in numeric form. It is good to note that this is only a simple query command as it is also possible to set laser parameters through set commands. Figure 7 was illustrated on page 24 and the serial test in LabVIEW was done using the same code. As serial code was proven to be functional in LabVIEW Windows environment, it was easy to deploy serial code to the PXIe as it directly understands serial protocol if correct serial module is installed. This is due to VISA communication protocol which LabVIEW uses in both Windows and real-time environments.

4 REAL TIME LASER PROCESS CONTROL

4.1 On-line monitoring and real time control of a system

On-line monitoring can be described in different ways but in system engineering a system monitor is a process which is part of a distributed system for collecting and storing state data. According to Control Theory [51], "for a system to be considered online, it has to fulfill one of the following requirements:

- Under the direct control of another device
- Under the direct control of the system with which it is associated
- Available for immediate use on demand by the system without human intervention"

Real-time control system can be described as an architecture and methodology to develop an intelligent system out of several online sub systems. Control theory is usually applied to the real-time control systems as control theory is a branch of engineering and mathematics that deals with the behavior of dynamic systems with inputs. [51] Figure 22 illustrates a Single Input Single Output (SISO) system.

Figure 22. Single Input Single Output (SISO) system.

This means applying input to cause system variables to change into different desired values. Input amount is not limited to only one as a system could have several inputs and outputs. It should be noted that also disturbances might affect the system as a type of non-expected input, a distraction. [51] Figure 23 illustrates a Multiple Input Multiple Output (MIMO) system.

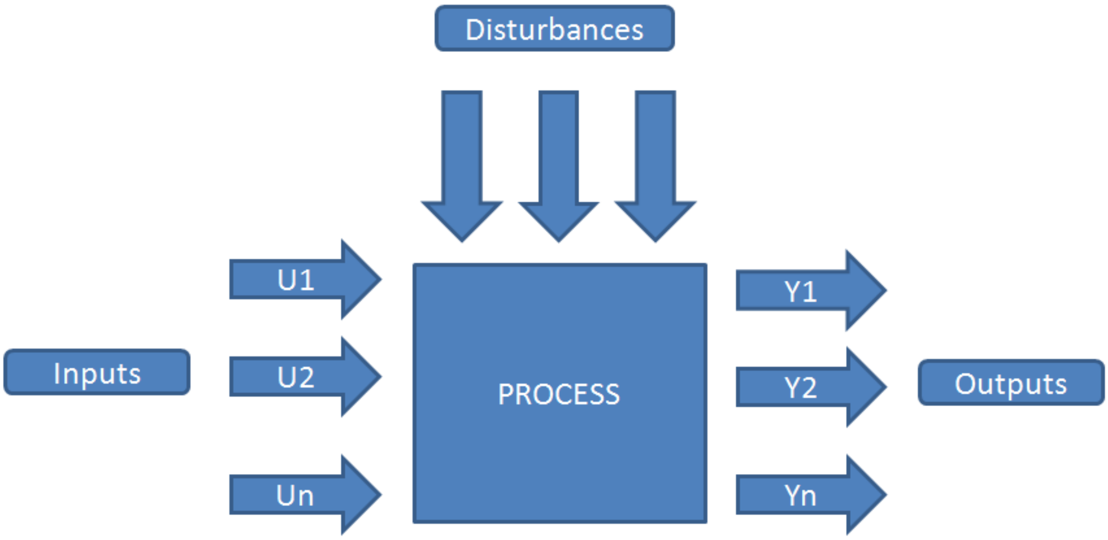


Figure 23. A system with several inputs and outputs (MIMO) under effect of disturbances.

Inputs can be fed to the control loop by different sensors as their outputs and the method is then called intelligent data acquisition. Usual way of processing sensor data is to send it to a central control system, which analysis the data in real time and finds the best command to the processing equipment for optimizing the process. [51] Generally control systems can be divided into two different kinds of control systems that are explained in the following sub section.

Open loop control system

An open loop controller is kind of a controller which computes its current state and model to the system as an input without having feedback of the system state. Currently open loop control systems are the most used control types in laser industry. [51] Figure 24 illustrates an open loop control system.

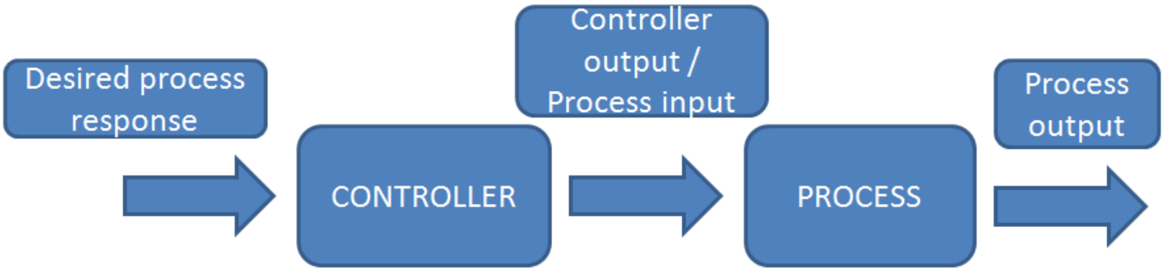


Figure 24. Open loop control system.

Closed loop control system

A closed loop control system basically is an open loop control system with one or more feedback loops. That is why closed loop control systems are also known as feedback control systems. The closed loop utilizes open loop system to forward information and also has feedback loops from its outputs and inputs. The term feedback comes from returned data which, for example, have been acquired by different sensors and the data has been fed back as an input to the control loop for the system adjustment. [51] Figure 25 illustrates a closed loop control system.

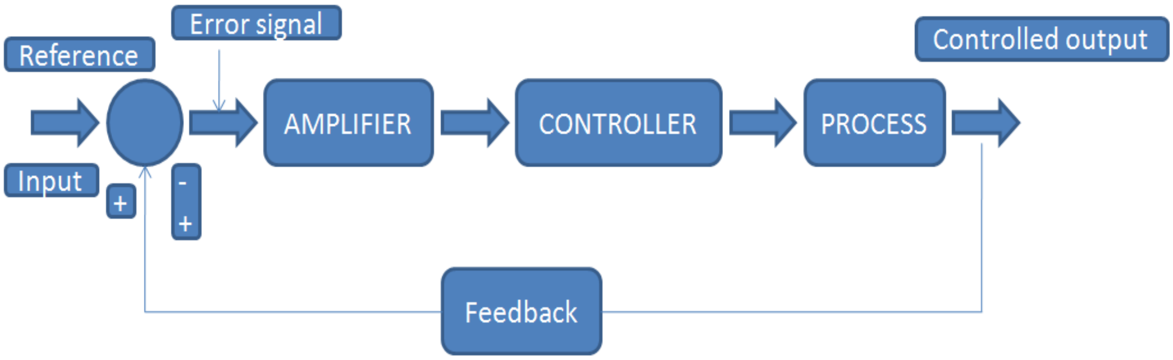


Figure 25. Closed loop control system.

4.1.1 Control design methodology

There is a certain global way of designing a real-time control system. The method starts with describing the mathematical model of a process to be designed and it is used to simulate the behavior of the real process. In this virtual simulation the behavior is observed and if it behaves as a real system based on system inputs, then it is called *model simulator*. When the designed model is behaving as required, a controller can be designed. A controller can be linear, non-linear or just logic controller. As controller has been approved, based on the mathematical method used in the control design, an algorithm can be designed. The algorithm should be designed so that it would be able to control the dynamics of the model with as minimal error as possible. If the system error converges to zero, the controller can be called a *satisfying controller*. This is what the controller design should aim at and the process should be repeated as long as the required state is reached. At the end of controller design, the requirement analysis to ensure performance of the controller should be done. In this analysis the controller should be tested with various parameters to ensure the functionality of the controller in as many cases as possible. [51] Figure 26 illustrates control design methodology.

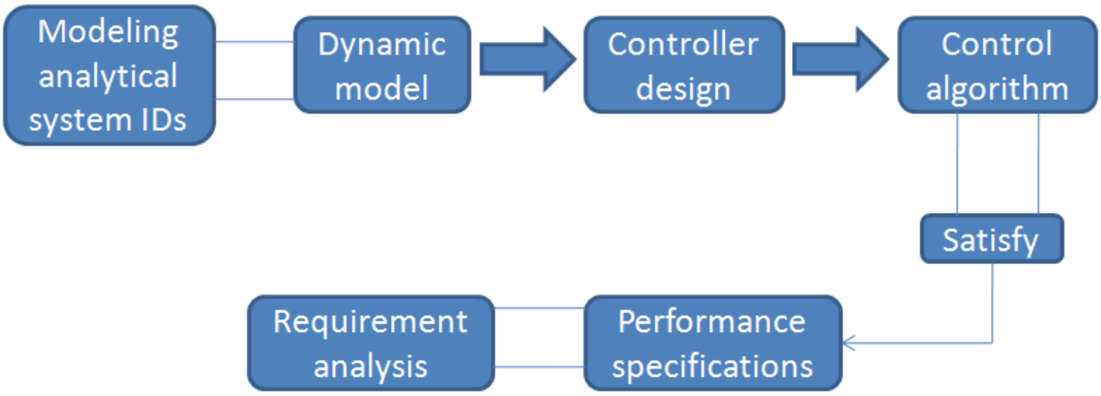


Figure 26. Control design methodology.

4.2 The control code 1.0

To be able to make control code for the laser, both the spectrometer code and the laser querying / commanding codes had to be ready and deployed to the PXIe project. Fundamental idea was that it would be possible to read and set parameters and also to remotely turn on and off the guide laser and the processing laser itself. Building of the code started of setting serial connection between the PXIe and the laser while the laptop was connected to PXIe using Ethernet cable. Idea was that everything would be user-controlled through the laptop while all the calculations would be performed in the PXIe. Serial connection functions in a way that only one command can be sent and received at the time. This meant that every command had to be coded in a way that only one can be executed at the time and wait until it had finished to execute a new one. It is important to note that every command had to be in ASCII form so that the laser was able to understand them. Also, baud rate defines the amount of data being sent and received so it had to be correctly set with all the other serial information. Appendix 19 illustrates serial initialization + commanding part of the laser.

It should be noted that Appendix 19 only partially shows the code as there are 17 different commands coded for the laser. This means that the code is a lot larger than what can be seen. As mentioned, the command codes are done so that only one command can be sent at once and the reply has to be waited before making a new one. The problem was solved using case structures with time delay. This means that in user interface a button has to be pressed to activate related command. After activation the case structure changes into "True" state while all the other commands stay inactive in "False" state. Execution delay can be set if serial port cannot process data fast enough and provide false values. Commands are being executed at the end part of the code which figure 27 illustrates.

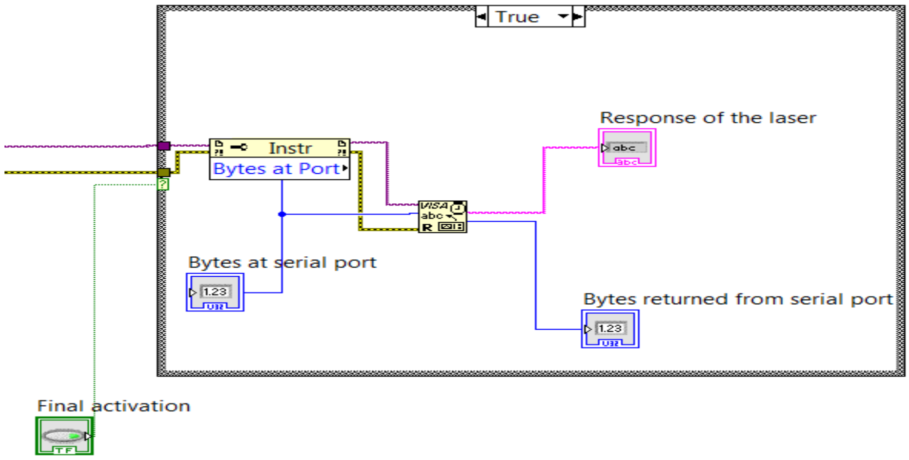


Figure 27. Command execution.

Commands are sent to the "Bytes at Port" block which is counting amount of the data and validating the data type. Then commands are forwarded to the VISA serial block which turn the data into desired output and communicates with NI equipment. In this case the output is response of the laser which can be seen in the command window in user-interface. There is also another output which is "Bytes returned from the serial port" that basically in this case is for validating that the serial communication works. This case structure is active all the time so that the commands can be executed.

There are five different commands that are for the laser parameter adjusting purpose. The first of them is parameter adjusting initialization command which has to be set on before any other parameter can be set. Other three parameters are the actual set commands to adjust the laser parameters. The first of those three is laser beam pulse duration, the second is operating pulse repetition rate and the third one is operating power of the laser. The fifth command is for saving of the parameters to memory of the laser. Set parameters are slightly different than read parameters even if both of the code parts are done under case structure and are initialized as required. First and second set parameters (operating pulse repetition rate and optical pulse length (time) are coded independently and all the accepted parameters were set in the dropdown menu. This is because these parameters should be set before the actual laser processing even if it would be possible to tune operating pulse repetition rate while laser processing is on. Reason to that is that both of the values should be in relation to each other so that processing is as effective and efficient as possible. The third set command about laser power can be adjusted in real-time while laser processing is on. Figure 28 illustrates an example of the parameters set in dropdown menu.

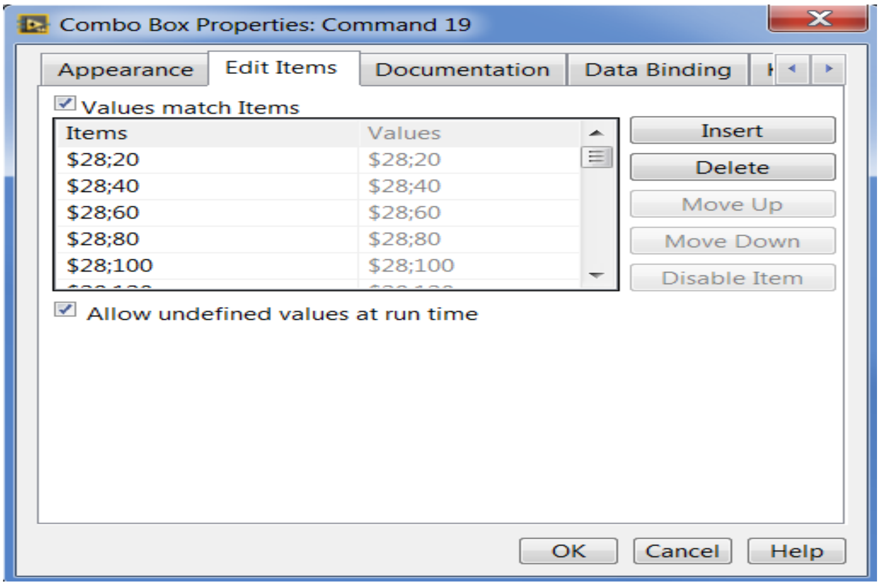


Figure 28. Example of possible parameter set to dropdown menu.

In this example possible pulse repetition rates have been listed and user can choose correct values of the dropdown menu. As mentioned, the control code is able to adjust laser power output in real-time. To be able to do this, spectrometer output has to be connected to the case structure of the laser power control. Idea was that there would be several different intensity ranges that would be connected to the certain power outputs. For example ranges could be as following: if the spectrometer is acquiring intensity of 1500W/m², the corresponding power output would be 60% equaling 12W and then again at intensity of 3000W/m², the corresponding power output would be 30% equaling 6W. Power output range related to the intensity range has to be wide enough for laser tuning to be efficient and accurate. Appendix 20 illustrates spectrometer output connected to the laser power control case structure.

In appendix 20 the spectrometer code is numbered as one and it has been connected to the laser power control case structure numbered as two. Spectrometer code is the same as previously explained. The laser power control code has been built so that there is a LabVIEW block called “Combo Box” which is developed so that it selects corresponding power output related to the acquired input data of the spectrometer. Otherwise the case structure works as every other case structure in this code. Important to note is that the spectrometer is constantly acquiring data and it is fed as input to the laser control code. The laser control commands are only initialized at request. There is also user interface where user can control the laser without understanding the code itself. Appendix 21 illustrates the user interface in LabVIEW.

In appendix 21 the first thing to be pointed out is start and stop of the code. At the control code 1.0 the code had to be turned on and off for serial commands to go through to the laser. This meant shortstop in the spectrometer data acquisition as it was also stopped. This is something which was needed to be developed further in code 2.0 so that the code would perform this automatically. Starting and stopping the code made code 1.0 only semi-real-time. Number two is the set of read commands that are query commands for the laser. In appendix 18 temperature of the laser was queried and pointed 27.1 degree of Celsius. Number three is set commands that are for laser parameter tuning. As mentioned, the spectrometer output is fed as an input to the operating power case structure and the operating power is changing based on the input. Spectrometer data input can be seen as number six. Number four is the laser initiation commands that basically control the guide laser and the processing laser. It should be noted that the guide laser cannot be on while the processing laser is. Number five is response of the laser which shows result of the query and set command. VISA resource name can be seen on blue and it shows the connection method and port where serial cable is connected in the PXIe. It is also possible to view graphical output of the spectrometer which figure 29 illustrates.

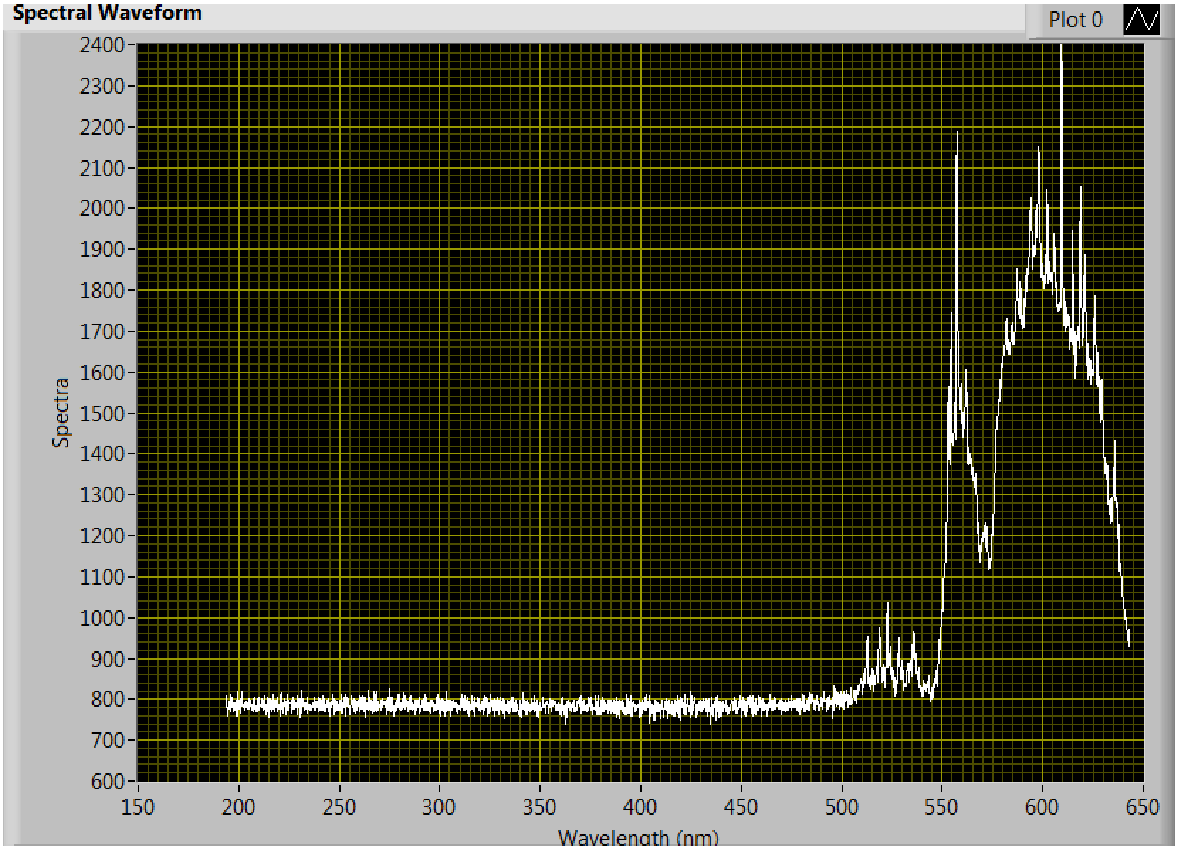


Figure 29. Example of spectrometer data acquiring in waveform graph.

It should be noted that due to grating used in the spectrometer, the current wavelength it shows is from 180 to 650 nm. By changing the grating the wavelength range could be changed from 650 to 1100 nm. However, in this project the current range is enough. Example illustrated in figure 31 was taken of sheet stainless steel scribing process.

4.3 The control code 2.0

As problems of the control code 1.0 had been discovered, it was possible to start developing improved version of the code. Two flaws of the code 1.0 were semi-real-time control of the laser and acquired mean value of the intensity instead of highest intensity peaks. It should be noted that in the code 2.0 the fundamental structure of the code remained the same which means that every command is executed in the same way as in the code 1.0. Figure 30 illustrates modified spectrometer USB control part of the code which affects real-time capability of the whole control code.

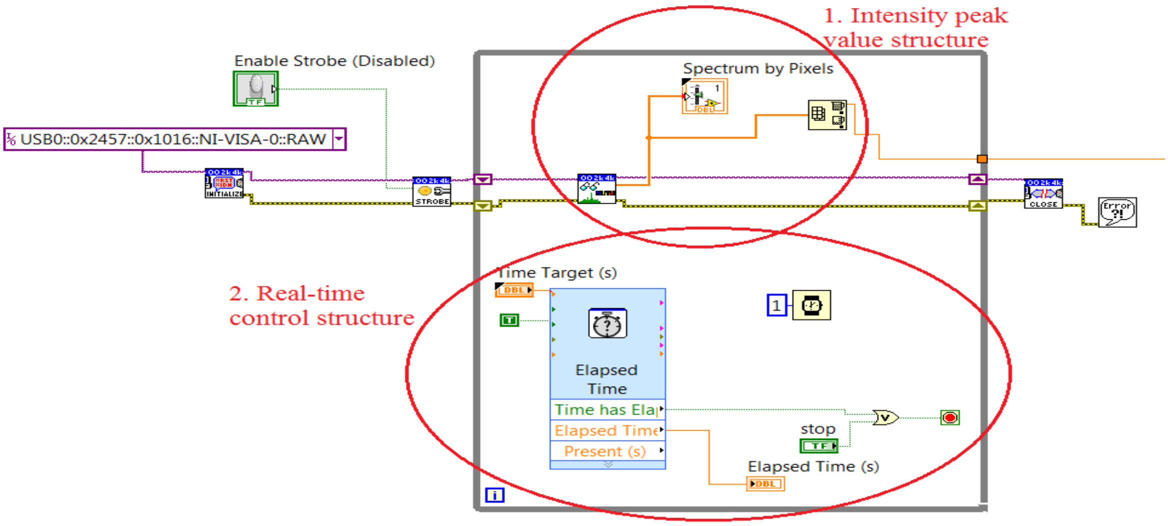


Figure 30. Modified USB control for the spectrometer.

Difference to previous USB code part was that the spectrum was now acquired by pixels instead of mean value. The changed part can be seen as number one in figure 30. However, the USB code part was connected to the case structure controlling corresponding power value which did not accept array values inside the case structure. This posed a problem which was solved by changing the collected spectrum by pixels into single pixel values of which desired value could be chosen. LabVIEW provides a block called Array to do that. Possibilities to be chosen were max intensity value, max index value, min intensity value and min index value. In this case max intensity value was chosen. Spectrum by pixels block divides the acquired spectra into about 2000 (based on Ocean Optics pixel division) pixels with corresponding wavelength values. The array block with the max intensity set searches the highest intensity peak among divided pixels and then feeds the highest value to the laser power control case structure which correspondingly tunes the power amount. These changes made discovering highest intensity peaks possible.

The second problem was about semi-real time control of the laser. It was discovered that the problem was due to serial connection as it required stopping and restarting of the code for commands to be executed. It was also noticed that the code should repeat the command twice before it was executed. This is because the command needed first to be sent to the laser and the laser had to reply the query and after that the command could be executed. Real-time control structure as number 2 in figure 30 was also created inside the spectrometer USB control structure. This was done due to reason that the spectrometer was constantly acquiring data without stopping. Because of this reason it was not even possible to stop the code and thus made serial communication impossible. The problem was solved by making time control for the spectrometer which kind of restarts the data acquisition based on the set time in Time Target block. Reset time was set to be 0.1s (time can be tuned to be anything) which auto-restarts data acquisition very fast. Elapsed time block shows how much time is left until restart although in this case it does not have effect. Stop block can be used to manually restart data acquisition. A clock and number one indicates how fast the spectrometer acquires data. In this case data is acquired every 1millisecond.

These two changes still did not solve the problem with serial command execution. The code did not even function properly as it was not possible to manually stop and restart the control code between automatic restart of the spectrometer USB code. This problem was solved using For Loop which enveloped the whole control code. For Loop can be set such that the codes inside execute certain number of times. As earlier mentioned, it is necessary to execute laser control commands twice for command to come in effect. Thus the For Loop was set to execute twice in relation to spectrometer USB control. This meant that the serial command to be executed was executed once as the spectrometer restarted data acquisition and again after 0,1s. This meant that the serial code was executed in 0,2s after pressing a button in user interface. This change enabled the control code to work in real time. Appendix 22 illustrates For Loop structure enclosing the whole control code with the set execution amount of two. After making changes to the code it was possible to also see changes in the user interface. Appendix 23 illustrates the new user interface.

The difference in this new user interface to the older version is that the code has to be set into constant run so that the For Loop and spectrometer USB control work in relation to each other. Stopping of the code now works by pushing stop button in the software. Constant run and stop button can be seen as number one. Stop button in the interface only restarts data acquisition of the spectrometer. Number two illustrates Spectrum by pixels (it is not actually necessary to see any numbers there as the control is done automatically, values can be viewed if wanted), Time Target is for setting restart cycle of the spectrometer data acquisition and elapsed time shows the amount of time left until restart. Otherwise the control code works as on previous version 1.0; user presses a button which is turning into green and after that the command is executed.

5 FINAL TESTS

Experiments were carried out in two parts. First experiments were performed after the spectrometer was confirmed to be functional and when it was possible to semi-real-time tune the laser parameters with the laser control code 1.0, both in the PXIe. The second experiment part focused on real time laser control with the control code 2.0.

5.1 First experiments with the control code 1.0, initial research setup

Tests were started by modifying the test table to be suitable for the experiments. Figure 31 illustrates the test table.

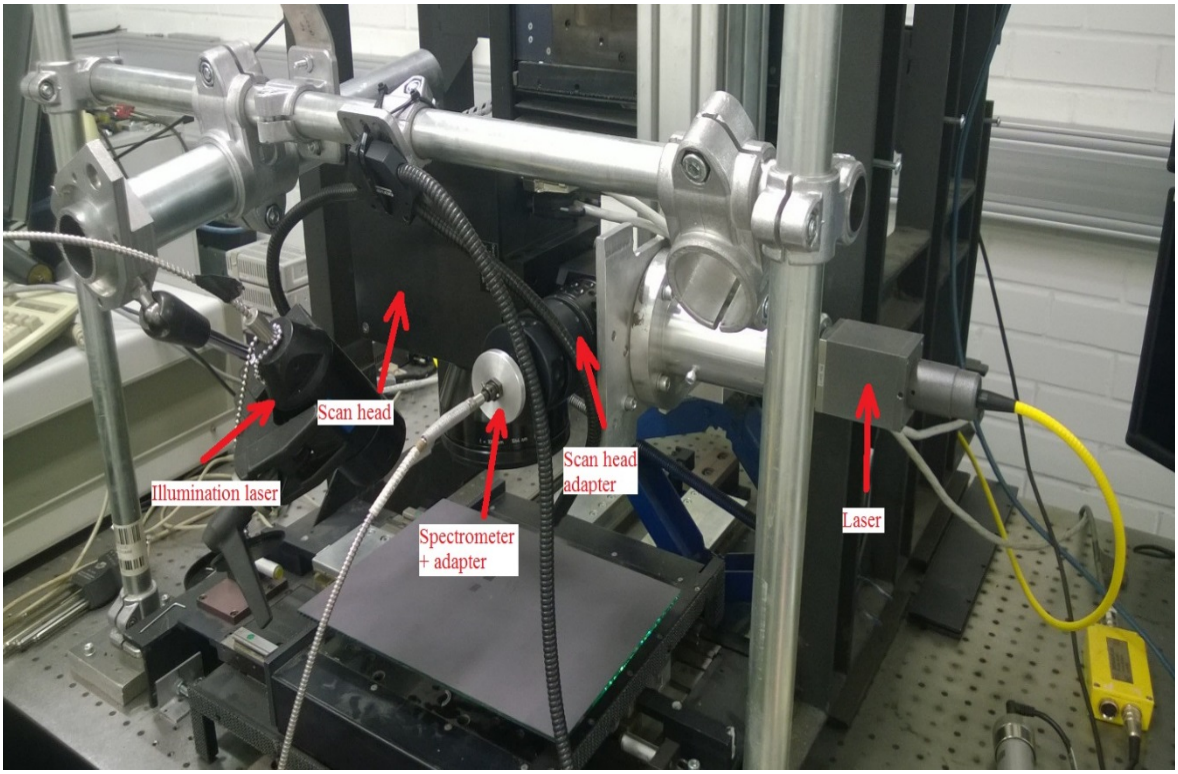


Figure 31. The test table.

Test equipment consisted of the scan head and scan head adapter from Scanlab, the manufactured spectrometer adapter and the spectrometer from Ocean Optics, IPG 20W ytterbium pulsed laser, and illumination laser from CaviLux (was not used in these experiments).The material used in this test was stainless steel SS304L plate, 100x50x6mm^3 in size. The composition of SS304L is C 0.03% max, Mn 2.00% max, P 0.045% max, S

0.03% max, Si 0.75% max, Cr 18.0-20.0% max, Ni 8.0-12.0% max and N 0.1% max. All of the tests were performed while the laser beam was moving within 4x4mm^2 rectangular shape. The hatching space was 0.22mm in one dimension and contour of the shape was not included. Figure 32 illustrates the beam hatch shape.

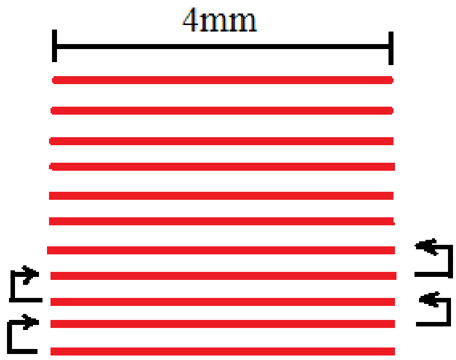


Figure 32. Beam hatch shape.

It should be noted that the same kind of hatch shape was used in every experiment but dimensions of the figure are not in scale. Tests had default laser parameters which were used during experiments, unless otherwise mentioned. The default laser parameters were as following: laser power 20W, pulse length 4ns, laser beam scanning speed 1000mm/s, pulse repetition rate 1000kHz. Most of the tests were carried out so that only one laser parameter was changed at the time while other values were kept constant. One experiment took about one second to perform with the default parameters. These tests were carried out based on parameters and tests by previous APPOLO researcher Matti Manninen from Lappeenranta University of Technology. Test results were compared to see if the spectrometer behaved correctly in semi-real-time environment while the laser control code 1.0was utilized.

5.1.1 Repeatability

Repeatability of the spectrometer readings were tested by using default laser parameters and repeating the same experiment six times. Figure 33 illustrates the repeatability test results.

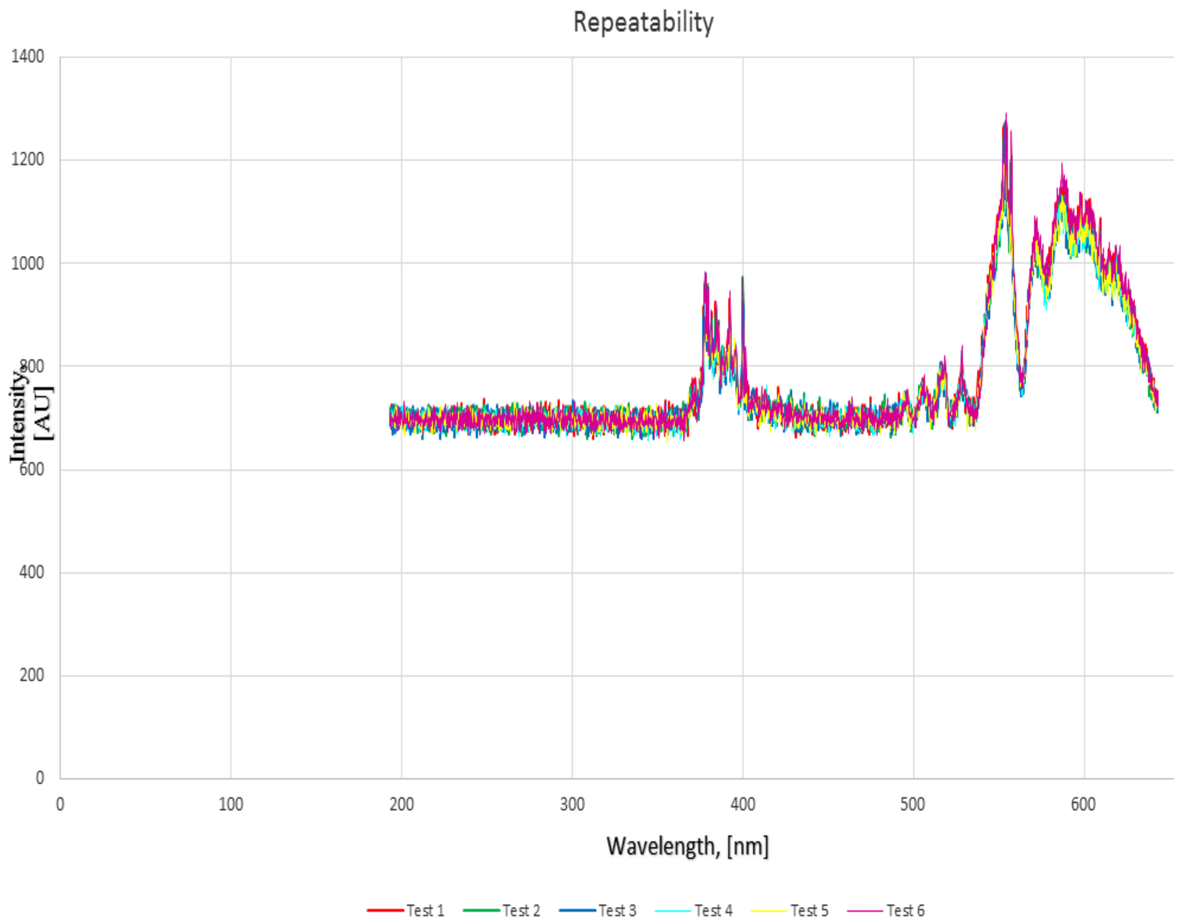


Figure 33. Repeatability test results.

Intensity deviation was measured by the intensity sum of all intensities along the wavelength range (193nm–643nm) for each test. In total that made six intensity sums and the lowest sum and the highest sum were compared. Intensity sum ranged from 1568357 AU to 1585605 AU. Difference between the intensity sums is 17248 AU which is c.a. 0.0109%. Intensities were measured so that the control code was stopped after two seconds and the spectra was saved in numeric form. Of the numeric output it was possible to calculate mean intensity sums. Based on these results it can be concluded that the spectrometer measurement is very reliable and repeatable as well as the process.

5.1.2 Effect of laser power

The second test was laser power test in which the effect of laser power in radiation intensity was tested. This test was carried out by varying the laser power from 2W to 20W in 2W increments. Other parameters remained default. Figure 34 illustrates the effect of laser power test results.

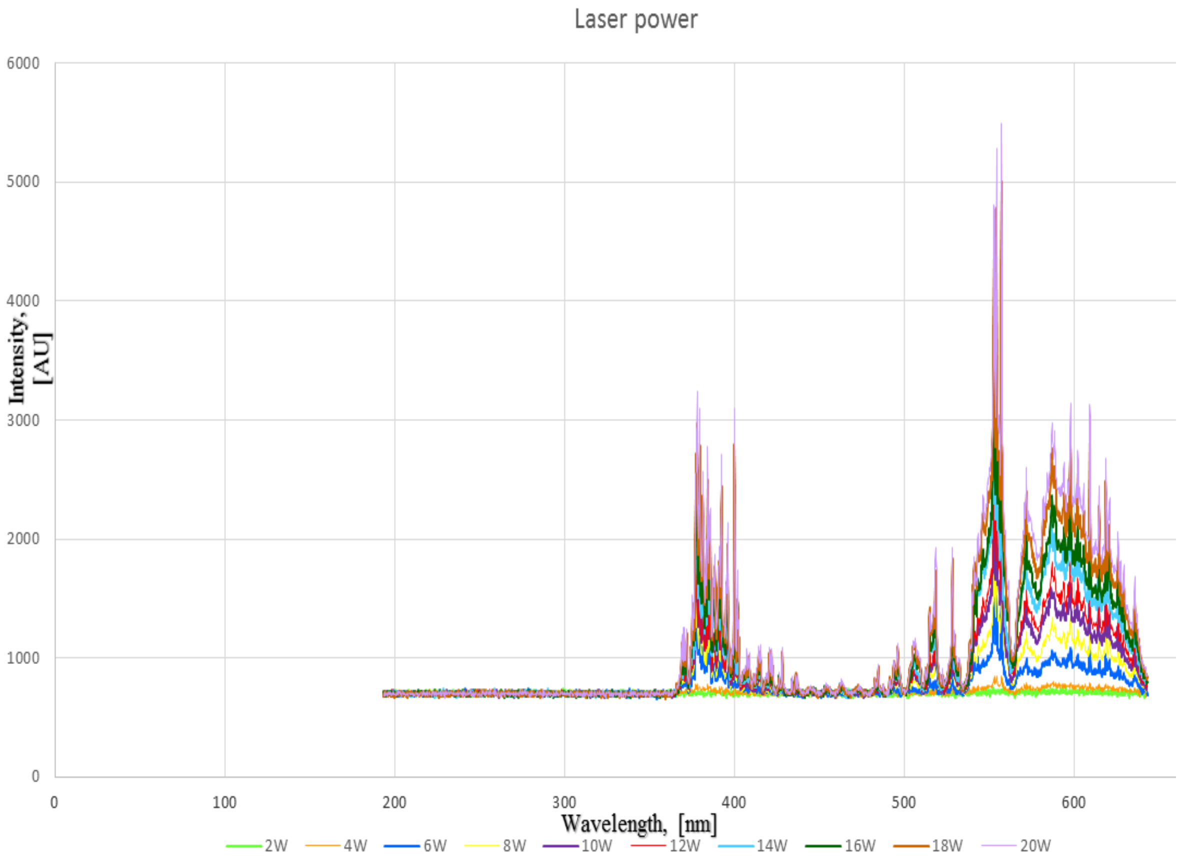


Figure 34. Effect of the laser power.

Of the graph can be understood that the radiation intensity increases with the increase of laser power. It appears that with power of 2W and 4W the difference in radiation intensity is fairly minimal but when moved to higher power, starting from 6W, the radiation intensity increase appears to be c.a. 150 units per watt of the laser power until 20W power. This means almost linear intensity increase with the increase of laser power. It should be noted that the spectrometer is very sensitive, which could be seen by constantly changing spectra. However, based on results the power increase or diminish can be observed with good accuracy.

5.1.3 Effect of the pulse length

The third test was about effect of the pulse length where sensitivity to different pulse lengths was tested. Sensitivity was tested by changing the pulse length with corresponding nominal pulse repetition rate. It is important to adjust corresponding nominal pulse repetition rate to pulse length so that the highest pulse energy for each pulse can be acquired and the average power can be kept constant. Other parameters were kept default. Figure 35 illustrates the effect of pulse length test results.

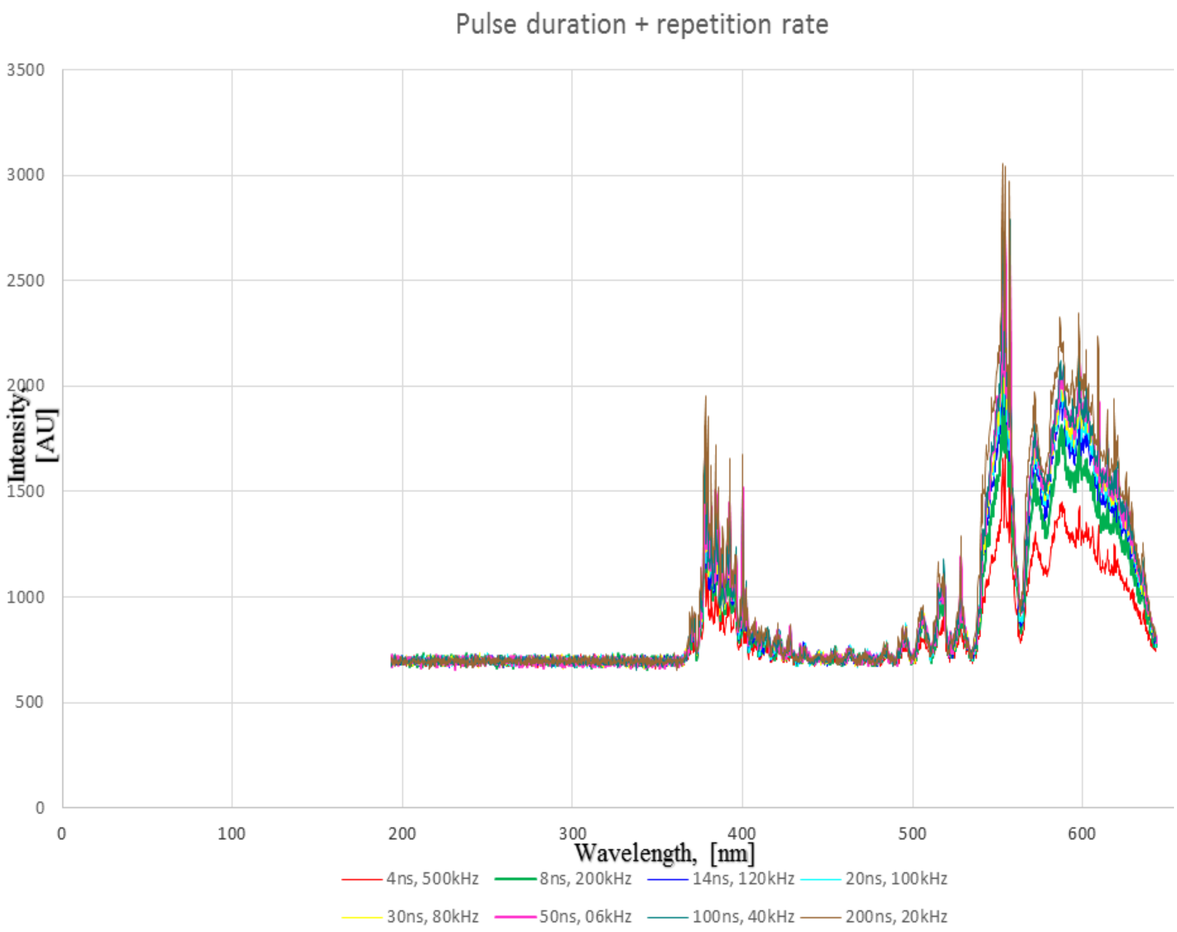


Figure 35. Effect of pulse length test results.

Tests consisted of several different pulse lengths and their nominal pulse repetition rates. Parameters were as following: 4ns with 500kHz, 8ns with 200kHz, 14ns with 125kHz, 20ns with 105kHz, 30ns with 85kHz, 50ns with 60kHz, 100ns with 40kHz, 200ns with 20kHz. Corresponding pulse energies in mill joules were: 0.04, 0.1, 0.16, 0.19, 0.235, 0.33, 0.5 and 1. At wavelength 550nm the intensities of shortest pulse length (4ns) and the longest pulse length (200ns) were c.a. 1650 AU and c.a.3050AU. The difference is c.a. 1400 AU which is fairly significant difference. It can be understood that the laser scribing efficiency is very dependable on correct ratio of pulse length and pulse repetition rate. The maximal scribing efficiency is reached at 200ns pulse length and 20kHz pulse repetition rate, although making scribing quality worse. Then again, when pulse length is 4ns and pulse repetition rate 200kHz, the scribing is very weak although good in quality. Of this can be understood that the spectrometer is very sensitive to the pulse length and pulse repetition rate.

5.1.4 Effect of focal point position

The fourth test was about the effect of focal point position in which the focal plane level compared to work piece surface was changed. The variation was ±2mm in 0.5mm increments while the base level was at 126mm. Sign + indicates that the focal position is above the surface of the work piece and sign – indicates that it is below the surface. Figure 36 illustrates effect of focal position results.

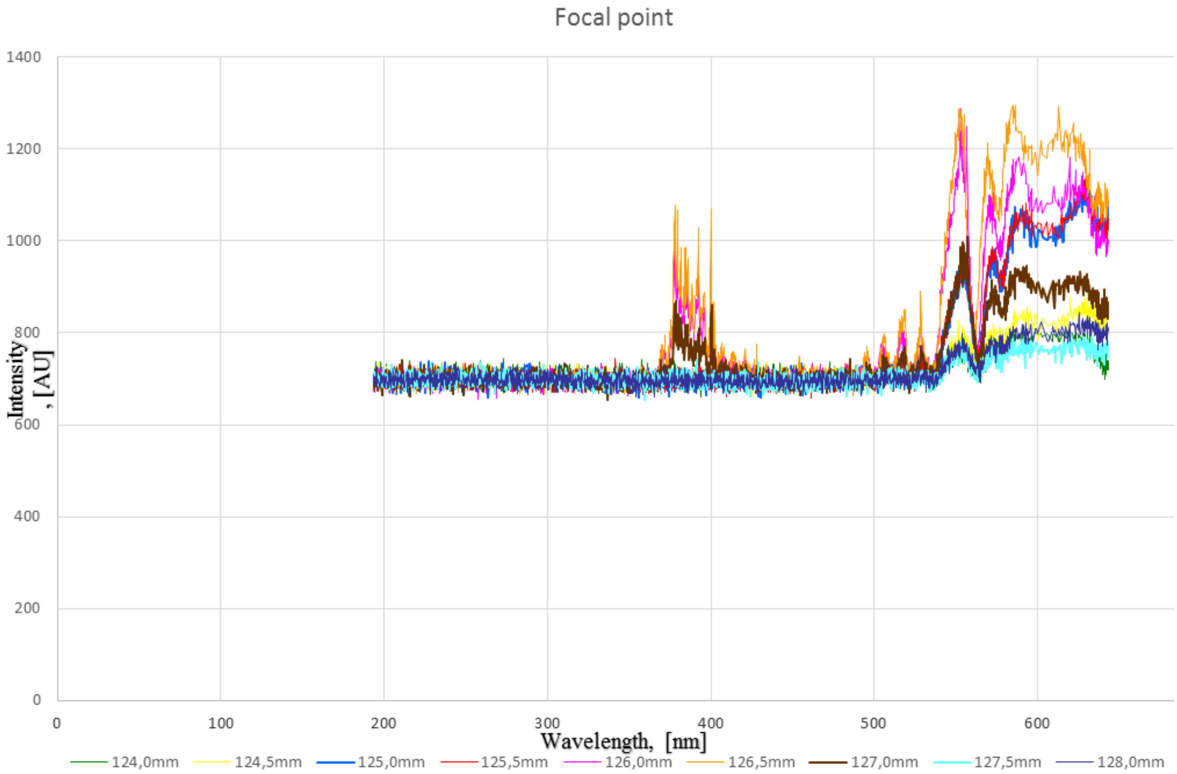


Figure 36. Effect of focal position test results.

It should be noted that the focal position was changed by a screw by which it was possible to lift and lower the scan head. The accuracy of the screw was not the most optimal so the results of this test are not as accurate as other test results. However, it could clearly be noticed that even a slight difference in focal point already changed the scribing process as it could be visually seen very well. When starting the adjusting from 124.0mm, it could be seen that the intensity was very low and the scribing was very un-efficient. However, by adjusting the screw at 0.5mm increments, it could be noticed that the intensity of the process became much higher and the scribing reached the maximum efficiency at 126.5mm. After that the focal point became too long and the intensity started to lower. At 128.0mm the effect was much alike to 124mm focal point. Of these results it can be understood that the spectrometer is very sensitive to the laser beam focus.

5.2 Second experiments with the control code 2.0

Second experiments were performed to test real-time capability of the laser control code 2.0. Experiments were started by choosing two different materials to see how the control code behaved when scribing moved from one material to another. Materials were chosen to be stainless steel SS304L and steel S355. Material properties of SS304L were as following: C 0.03% max, Mn 2.00% max, P 0.045% max, S 0.03% max, Si 0.75% max, Cr 18.0-20.0% max, Ni 8.0-12.0% max and N 0.1% max. Material properties of S355 were as following: C 0.23% max, Mn 1.60% max, P 0.05% max, S 0.05% max and Si 0.05% max. Beam hatch shape was rectangular with dimensions of $40x10mm^2$ with 0.8mm horizontal hatch space. Figure 37 illustrates the beam hatch shape.

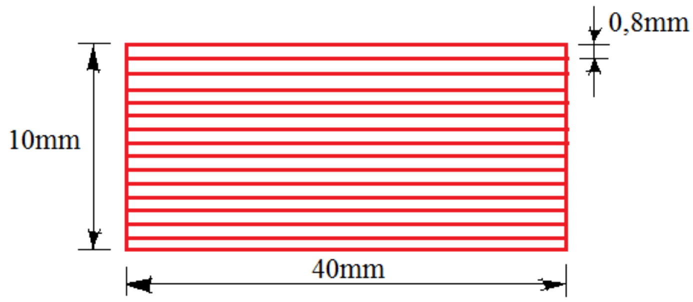


Figure 37. Beam hatch shape.

SS304L and S355 plates were welded together of the upper right and left edges (S355 on the left and SS304L on the right) and the rectangular shape was scribed so that half of the shape was on SS304L and the other half on S355. Figure 38 illustrates plates welded together and the test scribing on the surfaces.

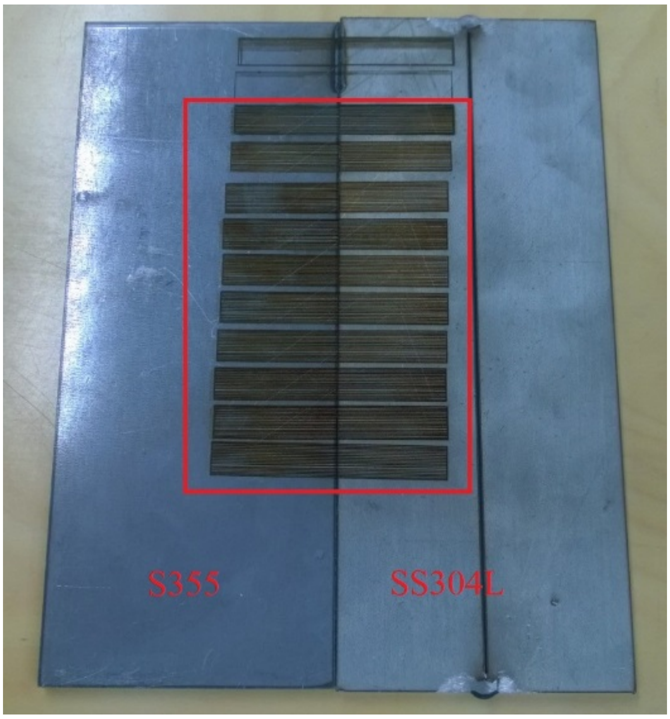


Figure 38. Test scribing on the surface of SS304L and S355.

It was important that the plates were welded on the same level as experiment one stated the importance of focal length; even half millimeter difference has a great significance. During tests pulse duration was kept on 200ns and pulse repetition rate at 20kHz, only laser power level was automatically adjusted based on intensity level. When scribing was initiated, it could be clearly seen how intensity changed between materials. Scribing on SS304L sparkled a lot more than scribing on S355. When scribing produced sparkling, the intensity level was a lot higher. Then again S355 scribing was a lot less sparkling and the acquired intensity was lower. However, due to nature of utilized pulsed laser, the intensity on SS304L kept fluctuating from very low intensity to high intensity based on laser pulses. The same also happened with S355 but due to low intensity amount it was not that significant (base intensity level of spectrometer data acquiring was around 800nm with S355). Intensity difference of S355 and SS304L was significant as intensity on S355fluctuatedbetween 750 to 900AU and on SS304L intensity was at the highest around 1400 AU but due to fluctuation it also momentarily was around 800 AU. This made real-time laser power control very difficult. On the other hand the code worked as planned as power was increased on lower intensities and decreased on higher intensities. The problem range was around 800 AU. On SS304L the power was normally tuned correctly for 1400 AU but, as mentioned, due to fluctuation the intensity was also momentarily around 800

AU. After 800 AU. The intensity raised back to normal 1400 AU. The code could not decide whether to adjust power level to higher or to decrease it. Thus the power kept fluctuating from high to low amount. Intensity ranges according to power levels can be tuned as required (for example to lower intensity ramps) but that does not exclude the problem with fluctuation. On S355 this problem did not occur as intensity was around 750 to 900 AU so the power control remained fairly stable. After all the code instantly adjusted power in relation to set intensity values so the code worked as intended even if it was fluctuating. Figures 39 and 40 show the differences in intensities of S355 and SS304L.

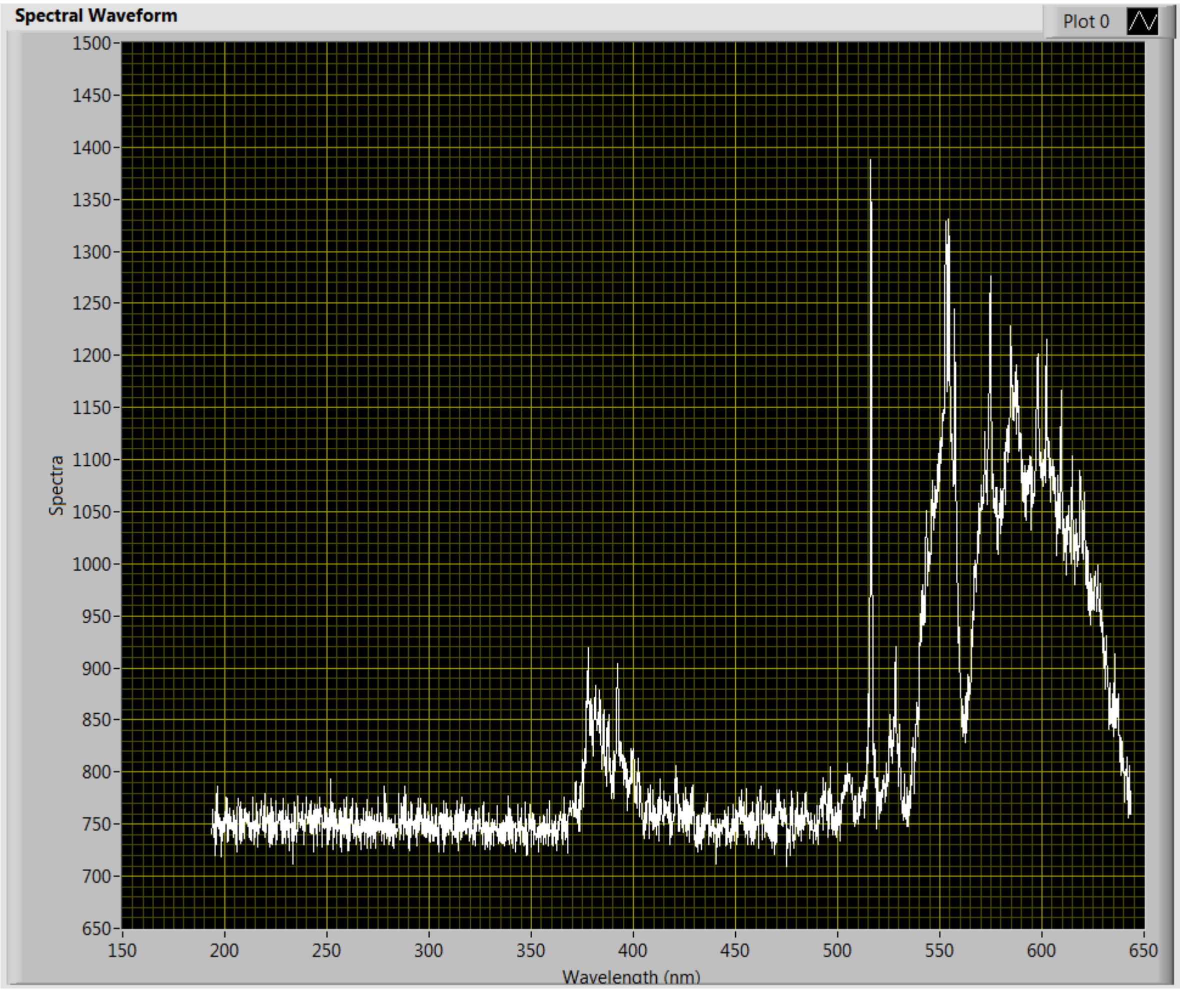


Figure 39. SS304L acquired spectra of scribing process.

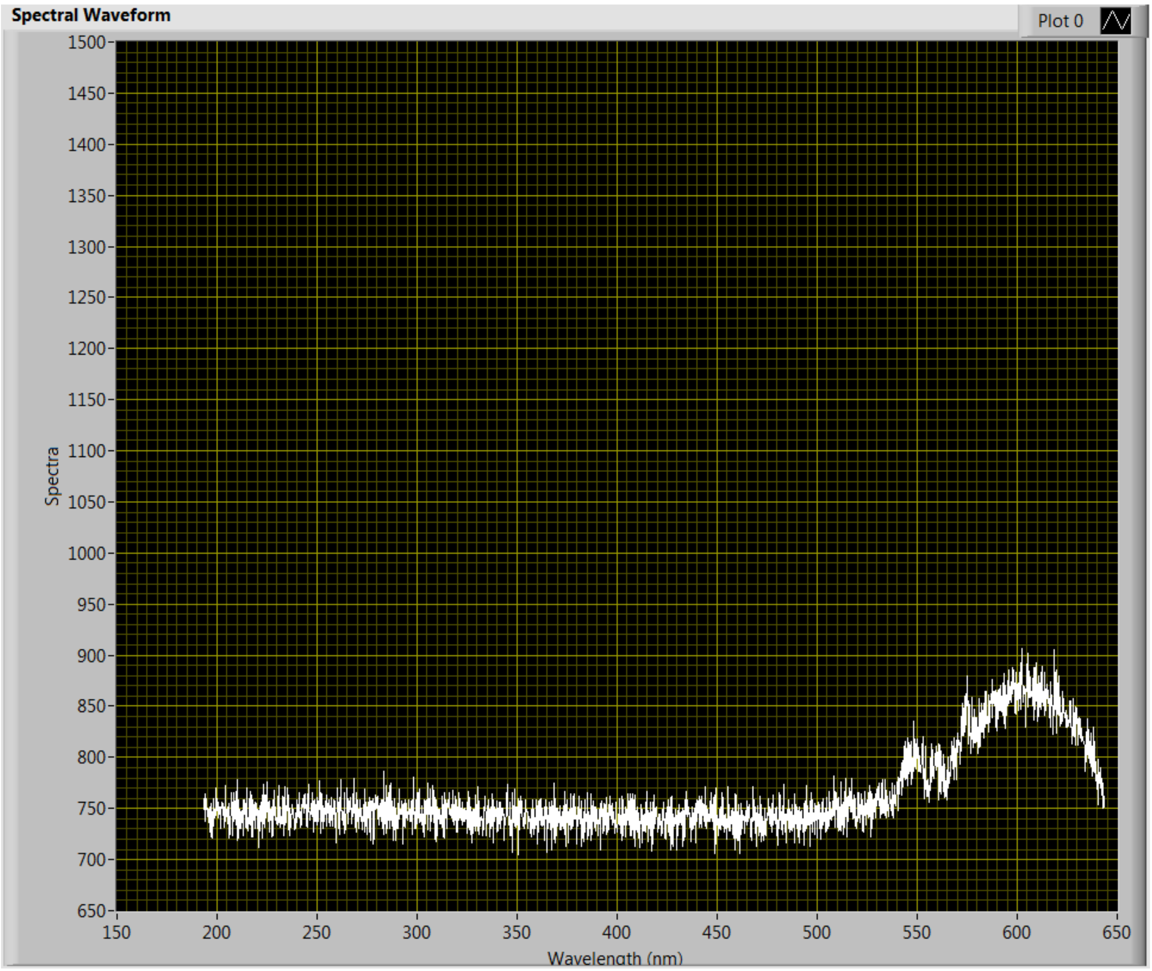


Figure 40. S355 acquired spectra of scribing process.

6 DISCUSSION

6.1 Outcome of the first experiments

Based on first experiments, it could be understood that the spectrometer behaved the same way in semi-real-time environment as in previous APPOLO research carried by researcher Matti Manninen. Laser control code 1.0 could be well utilized to tune laser parameters which included querying and reading the reply of the laser and also commanding the laser. However, as mentioned, laser control code 1.0 was working semi-real-time and the code needed to be developed further. When the code would be able to adjust laser parameters totally in real-time, it would be possible to change power level of the laser based on the spectrometer output without stopping and restarting the code. In control code 1.0 this could only be done manually. A good example of real-time adjustment would be two pieces of metal of different material; the spectrometer would notice intensity difference between metals and would instantly lower or higher amount of laser power based on intensity level. The problem in control code 1.0 was that it was only possible to find average value of intensities along the wavelength range which was way too inaccurate for accurate control. Instead of mean value, highest peak of intensity value at the wavelength range where processing occurred should be used. Another problem in control code 1.0 dealt with running of the code. The control code 1.0 required run and stop of the code for data transmittance even if the spectrometer would acquire data in real-time. This was due to serial communication protocol which required this kind of way to update data.

The spectrometer itself worked as intended as it was able to acquire data in real-time. The acquired spectra could be viewed either in numeric or in graphical form. Numeric form is very useful for laser control and graphical output is useful for observing the process. The research question was whether it would be possible to notice single pulse missing during processing while observing with the spectrometer. If data is being acquired real time, it is very hard to say if pulses are missing or not as intensity fluctuates so much due to pulsating laser light. Results of first experiments show that the spectrometer is much more useful for the laser control and based on intensity peaks. It would be possible to contribute the process by adjusting power of the laser. Another important matter to be mentioned is distance of the spectrometer's optical head of the processed work piece. In previous

APPOLO research the focal length was 180mm at angle of 25º. In this case the distance was around 520mm and the process was observed perpendicular. Longer focal length and perpendicularity can be explained by the adapter of Scanlab to which the spectrometer sensor is attached to. Long focal length has an effect to the acquired spectra as it is fairly faint compared to Manninen's spectra's. However, in this case it would not matter as the code could be adjusted to react smaller changes and the outcome would be as accurate. In this case good focusing lens is required to compensate longer focal length. Based on results of first experiments, the control code 1.0 had to be developed further to solve semi-real-time problem and to find out how to acquire highest peaks of intensity instead of mean values.

6.2 Outcome of the second experiments

Based on second experiments, the control code 2.0 was capable of real-time laser power control. Two different materials, S355 and SS304L, however, were slightly too similar as spectrometer sensed same kind of intensities of both materials. Intensity varied from 750 AU to 1400 AU and the laser power control was adjusted based on those intensities. The biggest problem was due to pulsating nature of the laser which caused intensity to constantly fluctuate. This made laser power control very complicated. The control could keep up with this high phase fluctuation so the code could be declared to be real-time and very successful even if it was very complicated to be adjusted.

More tests with different materials should be performed to further observe control code behavior based on very different intensities. It should also be noted that the intensity ranges on control code might have to be changed because different materials behave differently and have different intensities. Thus correct intensity ranges should be experimentally discovered to be able to adjust laser power correspondingly and accurately. However, the biggest and last problem of the control code lies in the laser pulsating which causes great intensity fluctuation. One possibility to negate this problem is to develop a kind of low pass filter which would ignore some of the fluctuation. This would make fluctuation smaller and the control code would adjust power with a lot lower frequency. After all, laser power should keep relatively stable for process to be accurate and good in quality. Fast phase power fluctuation would lead into poor surface quality and scribing depth. Also another important notion of the scribing process itself was that speed of the mirrors inside the scan head should be around 100mm/s or more so that the intensity coming out of scribing is intense enough for spectrometer to sense it. With lower scan head mirror speed the intensity was so low that it was hard to adjust intensity ranges and thus corresponding power levels. With higher mirror speed the spectrometer could well observe the process.

6.3 Possible improvements

Sometimes spectrometer suffered of difficulties to acquire enough light of the laser process which lead to rather weak spectra. This could be seen as small spectra spikes on LabVIEW waveform graph. It is easier to tune process parameters when spectra spikes are larger as differences between minimum and maximum values are higher. However, there are couple of ways to improve spectra acquiring. Scan head includes reflecting mirrors which also allow some of the process light to pass back to spectrometer optical head. Reflecting mirrors could be coated specifically for the laser process (basically for each process material) to pass desired / required wavelengths. This would amplify the gathered intensity. Also possibility to adjust focusing lens of the scan head would strengthen acquired spectra although that should be done carefully as it also affects the laser process itself. Thus easier way would be to re-design the adapter of the focusing optical head of the spectrometer. Re-design should be done so that the optical head could be moved on vertical, axial and depth directions. This would allow adjusting the optical head for the strongest possible spectra acquiring outcome, apart of the material thickness. Optical heads also have differences as some acquire process light more than others. Thus small research about finding more light acquiring optical heads should be done.

The biggest improvement to be done would be synchronization of the spectrometer data acquisition and the control code laser parameter tuning rate. Currently Spectrometer is acquiring data at unknown rate and tuning rate in the control code is set to 0,1s. It is known that they do not match which causes hardships to tune laser process parameters accordingly. Magnitude of the problem increases due to pulsating nature (can possibly be lowered by using low pass and high pass filters, although it is not removing the problem cause) of the laser which can be seen as control code parameter tuning lacking behind of the spectrometer data acquiring. This means that laser parameters are tuned accordingly but changes come to effect too late. Basically the control code should already adjust new values as it only responds to the previous request. However, there are couple of ways to solve this problem. The first and most likely the most effective way would be to use external triggering. External triggering means that spectrometer data acquisition can be externally controlled. This would mean possibility to control spectrometer using the control code which be optimal solution. Ocean Optics spectrometer has option for this if the Break-Out Box is in use. To be able to use the Break-Out Box, spectrometer should be used in serial connection. However, currently spectrometer is used through USB connection which eliminates this possibility. To change spectrometer into serial mode would require re-designing of the whole control code and thus it would very laborious option.

The second possibility to match data acquisition rate of the spectrometer and laser parameter tuning of the control code would be to do it manually. To be able to do this, it is necessary to know the data acquisition rate of the spectrometer. The data acquisition rate can be found out by using Ocean Optics own software SpectraSuite and by observing when spectral graph is changing or by doing the same using the control code in LabVIEW. It is also possible to ask Ocean Optics what is the data acquisition rate. When the exact data acquisition rate is known, the control code can be set tune laser parameters according to data acquisition rate. A good example would be as following: Acquired spectra is 800 AU, the control code registers it and tunes laser parameters in 0,1s in between the first and upcoming spectra acquisition. New value of 1000 AU would be registered and the control code would again tune laser parameters in 0,1s before the next spectra acquisition would occur. Thus the limiting factor of laser parameter tuning rate would be the spectra acquisition rate itself, it cannot be faster than that. As a summary, possible ways to improve developed monitoring system and the control code would be by enhancing the acquiring process to receive more process light and by matching the spectra acquisition of the spectrometer and control code laser parameter tuning.

7 CONCLUSION

Research questions were whether it would be possible to online monitor laser engraving processes by using spectrometer and if it would be possible to real-time control laser engraving process utilizing spectrometer. Answer is yes to both. Spectrometer has good enough sensing capability for even very faint laser power and repetition rate thus making it very capable for laser parameter tuning. However, if amount of process light is very low, it makes tuning harder as minimum and maximum intensity values differ less. Also one extra goal in this project was to find out if it would be possible to sense missing pulses of laser engraving process. Answer to that is negative as laser pulsates by its nature (at least the nanosecond laser used in this research) which makes sensing missing pulses almost impossible. The magnitude of problem increases as the amount of process light is less. There are better options for that reason, such as high speed cameras. Ocean Optics spectrometer is very capable for real-time laser parameter tuning in laser engraving processes as it has fast enough acquisition rate and it is very easy to adapt into different processes and purposes. It also has capabilities for both USB and serial connections and also possibility to customize even its software for own purposes. Thus spectrometer, especially Ocean Optic's, is very flexible choice. What should also be mentioned is that it is necessary to use industrial grade computers, such as National Instruments PXIe-8880 for real time control. This is to reduce acquisition delay to as small as possible.

In general it is very important to be able to adjust laser processing parameters in engraving process as it is very precise and demanding. Spectrometer real-time control is excellent for this purpose and that is why it could also be used in similar kinds of processes, such as additive manufacturing. Spectrometer could be installed inside additive manufacturing machine and the process light could be acquired in similar way as in laser engraving process. Of course the control code should be customized to correspond demands of the additive process but the basic idea would remain the same thus making it very potential idea.

If this research is to be continued in the future, all the improvement ideas should be implemented to maximize the potential of this real time system. The control code also is very customizable for different purposes so it is easy to adapt for different systems.

LIST OF REFERENCES

[1] Kaldos, A., Pieper, H.J. Wolf, E and Krause, M. Laser machining in die making - A modern rapid tooling process. Mater. Process. Technol., 2004. Vols. 155-156. Pp. 1815-20.

[2] Leitz, K.H., Redlingshöfer, B., Reg, Y., Otto, A. and Schmidt, M. Metal Ablation with Short and Ultra-short Laser Pulses. Phys. Proc., 2011. Vol. 12. Pp. 230-38.

[3] Yao, Y., Chen, H. and Zhang, W. Time scale effects in laser material removal: a review. Int. J. Adv. Manuf. Technol., 2005. Vol. 26. Pp. 598-608.

[4] Chichkov, B.N., Momma, C., Nolte, S., von Alvensleben, F. and Tünnermann, A. Femtosecond, picosecond and nanosecond laser ablation of solids. Appl. Phys. A., 1996.Vol. 63:2. Pp. 109-15.

[5] Manninen, M. Hirvimäki, M., Poutiainen, I. and Salminen, A.Effect of Pulse Length on Engraving Efficiency in Nanosecond Pulsed Laser Engraving of Stainless Steel. Metallurgical and Materials Transactions B. Vol. 46B, October 2015. 2129-2136.

[6] Purtonen, T., Kalliosaari, A. and Salminen, A.Monitoring and adaptive control of laser processes. Phys. Proc., 2014. Vol. 56. Pp. 1218-1231.

[7] Lott, P., Schleifenbaum, H., Meiners, W., Wissenbach, K., Hinke, C. and Bültmann, J. Design of an optical system for the in situ process monitoring of selective laser melting (SLM). Physics Procedia, 2011. Vol. 12. Pp. 683-690.

[8] Vallejo, D. Spectroscopic Investigations of Plasma Emission Induced During Laser Material Processing. Epubli GmbH. Berlin, 2013.

[9] Beersiek, J. New aspects of monitoring with a CMOS camera for laser materials processing. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America, 2002.

[10] Abels, P., Kaierle, S., Kratzsch, C., Poprawe, R. and Schulz, W. Universal coaxial process control system for laser material processing. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America, 1999. Pp. 99-108.

[11] Beersiek, J., Poprawe, R.,Shulz, W., Gu, H., Müller, R.E. and Duley, W.W. On-line monitoring of penetration depth in laser beam welding. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America, 1997. Vol. 83:1. Pp. 30-39.

[12] Dahmen, M., Kaierle, S., Abels, P., Kratzsch, C., Kreutz, E. W. and Poprawe, R. Adaptive quality control for laser beam welding. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America, 1999. Sect. D. Pp. 30-39.

[13] Haran, F.M., Hand, D.P., Peters, C. and Jones, J.D.C. Focus control system for laser welding. Appl. Opt., 1997. Vol. 36. Pp. 5246-5251.

[14] Fox, M.D.T., Hand, D.P., Su, D., Jones, J.D.C., Morgan, S.A., McLean, M.A. and Steen, W.M.. Optical sensor to monitor and control temperature and build height of the laser direct-casting process. Appl. Opt., 1998. Vol. 37. Pp. 8429-8433.

[15] Cobo, A., Bardin, F., Aubry, P., Knapp, W., Collin, O., Jones, J.D.C., Hand, D.P. and López-Higuera, J.M. Optical fiber-based focus control system for laser welding incorporating automatic setup. Proceedings of the Sixteenth International Conference on Optical Fiber Sensors, 2003. Pp. 412-415.

[16] Dietz, C., Jurca, M., Schlichtermann, L., Kogel-Hollache, M., Breitschwerd, S. Schmid, C. and Rowold, L. Closed loop control system for laser welding of

transmission parts. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America, 1998. Vol. 85. Pp. 178-186.

[17] Postma, S. Aarts, R.G.K.M. Meijer, J. and Jonker, J.B. Penetration control in laser welding of sheet metal. Laser Appl., 2002. Vol. 14. Pp. 210-214.

[18] Bagger, C. and Olsen, F.O.. Laser welding closed-loop power control. Laser Appl., 2003. Vol. 15. Pp. 19-24.

[19] Derouet, H. Sabatier, L. Coste, F. and Fabbro, R. Process control applied to laser surface re-melting. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America,1997. Vol. 83. Pp. 85-92.

[20] Gu, H. and Duley, W.W. A novel detector for closed-loop focus control during laser beam welding. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America,1998. Vol. 85. Pp. 69-75.

[21] Tonshoff, H.K., Ostendorf, A. and Specker, W. Quality assurance of laser welding processes by adaptive closed-loop process control. Proceedings of the International Congress on Applications of Lasers and Electro-Optics, Laser Institute of America,2000. Sect. E. Pp. 252-261.

[22] Moesen, M., Craeghs, T., Kruth, J.-P. and Schrooten, J. Robust beam compensation for laser-based additive manufacturing. International Journal of CAD, 2010.

[23] Kenny, T. [Chapter 14] Optical and radiation sensors. In: Wilson, J. (Ed.). Sensor technology handbook. Elsevier Inc., 2005. 691 p.

[24] Bollig, A., Mann, S., Beck, R. and Kaierle, S. Einsatzoptischer Technologien zur Regelung von Laserstrahlschweissprozessen. Automatisierungstechnik, 2005. Vol. 53. Pp. 513-521.

[25] Boillot, J.P., Cielo, P., Bégin, G., Michel, C., Lessard, M., Fafard, P. and Villemure, D. Adaptive welding by fiber optic thermographic sensing: an analysis of thermal and instrumental considerations. Welding Journal, 1985. Vol. 64. Pp. 209-217.

[26] Vallejo, D. Spectroscopic Investigations of Plasma Emission Induced During Laser Material Processing. Epubli GmbH., Berlin, 2013.

[27] Voelkel, D.D. and Mazumder, J. Visualization of a laser melt pool. Applied Optics, 1990. Vol. 29. Pp. 1718-1720.

[28] Köhler, H., Jayaraman, V., Brosch, D., Hutter, F. and Seefeld, T. A novel thermal sensor applied for laser materials processing. Physics Procedia, 2013. Vol. 41. Pp. 502-508.

[29] Free Software Foundation Inc. Spectroscopy: Principles, Theory, Techniques and Applications [web document]. Published 2002. [Referred 20.09.2015]. Available: http://metameso.org/nri/library/free-books/SpectroscopyOvrview.pdf

[30] Tu, J., Miyamoto, I. and Inoue, T. Characterizing keyhole plasma light emission and plume scattering for monitoring 20kW class CO2 laser welding processes. Laser Appl., 2002. Vol. 14. Pp. 146-153.

[31] Zhang, X., Chen, W., Ashida, E. and Matsuda, F. Relationship between weld quality and optical emissions in underwater Nd:YAG laser welding. Opt. Laser Eng, 2004. Vol. 41. Pp. 717-730.

[32] Al-Azzawi, A. Physical optics: principles and practices, CRC Press, 2006.

[33] Wolfe, W. Spectrometers in "Handbook of Optical Engineering". In D. Malarca, B.J. Thompson (Ed.) Marcel Dekker, Inc. New York, 2001.

[34] Khater, M. Characteristics and performance of a VUV spectrometer. Nuclear Instruments and Methods in Physics Research, 2013. Vol. A 714.Pp. 1-4.

[35] Tan, C. Z. Rotary dispersion in optical activity and a rotary Fourier transform spectrometer. Optik 214, 2013. Pp. 2798-2802.

[36] Liu, L. and Hao, X. Study of the effect of low-power pulse laser on arc plasma and magnesium alloy target in hybrid welding by spectral diagnosis technique. J Phys D. Appl. Phys, 2008. Vol. 41. Pp. 1-10.

[37] Dadras, S., Torkamany, M. J. and Sabbaghzadeh, J.. Spectroscopic characterization of low-nickel copper welding with pulsed Nd:YAG laser. Opt Lasers Eng, 2008. Vol. 46. Pp. 769-776.

[38] Torres, J., Jonkers, J., Van De Sande, MJ., Van Der Mullen, JJAM., Gamero, A. and Sola A. An easy way to determine simultaneously the electron density and temperature in high-pressure plasmas by using Stark broadening. J Phys D: Appl. Phys., 2003. Vol. 36. Pp. 55-59.

[39] Griem, H. R. Principles of Plasma Spectroscopy. Cambridge, UK: Cambridge University Press, 1997.

[40] Chen, G., Zhang, M., Zhang, Y. and Li, S. Measurements of laser-induced plasma temperature field in deep penetration laser welding. Opt. Laser Technol., 2013. Vol. 45. Pp. 551-557.

[41] Ocean Optics. 2015. HR2000 and HR2000CG-UV-NIR Series High-Resolution Fiber Optic Spectrometers, Installation and Operation Manual, Pp.1 [Online document]. [Referred 10.11.2015]. Available: http://oceanoptics.com/wp-content/uploads/hr2000.pdf

[42] Ocean Optics. 2015.SpectraSuite, Spectrometer Operating Software, Installation and Operation Manual, Pp. 1-3 [Online document]. [Referred 10.11.2015]. Available: http://oceanoptics.com/wp-content/uploads/SpectraSuite.pdf

[43] National Instruments. 2015. PXI Express, NI-PXIe-8880 User Manual, Pp. 1-1 and 1-2 [Online document]. [Referred 20.10. 2015]. Available: http://www.ni.com/pdf/manuals/374684c.pdf

[44] National Instruments. 2015. Overview and Specifications [Web page]. [Referred 20.10.2015]. Available: http://sine.ni.com/nips/cds/view/p/lang/fi/nid/212872

[45] Ocean Optics. 2015. HR2000+ Spectrometer, Installation and Operation Manual [Online document]. [Referred 10.11.2015]. Available: http://oceanoptics.com/wp-content/uploads/hr2000-.pdf

[46] IPG Laser. 2015. Specification Ytterbium Pulsed Fiber Laser YLPM-1-4x200-20-20 [Online document]. [Referred 18.11.2015]. Available: http://www.ipgphotonics.com/Collateral/Documents/English-US/120504-spec%20E27445%20R02%20YLPM-1-4x200-20-20.pdf

[47] Scanlab. 2015. Installation and Operation, The RTC 4 PC Interface Board for Real-Time Control of Scan Heads and Lasers [Online document]. [Referred 07.08.2015]. Available: http://rlab.org.uk/mediawiki/images/3/3e/RTC4.pdf

[48] Scanlab. 2015.HurrySCAN III, HurrySCAN II, HurrySCAN [Online document]. [Referred 07.08.2015]. Available: http://www.scanlab.de/sites/default/files/PDF-Dateien/Data-Sheets/Scan-Systems/hurrySCANIII_EN.pdf

[49] Scanlab. 2015. Camera Adapter [Online document]. [Referred 07.08.2015]. Available: http://www.scanlab.de/sites/default/files/PDF-Dateien/Data-Sheets/Camera%20adapter_EN_0.pdf

[50] IPG Laser. 2015. Interface Specification "Type E" YLP series Pulsed Fiber Laser [Online document]. Referred [18.11.2015]. Available: http://nutfieldtech.com/wp-content/uploads/2014/10/IPG-Interface-Specification-110701-YLP-series-type-E.pdf

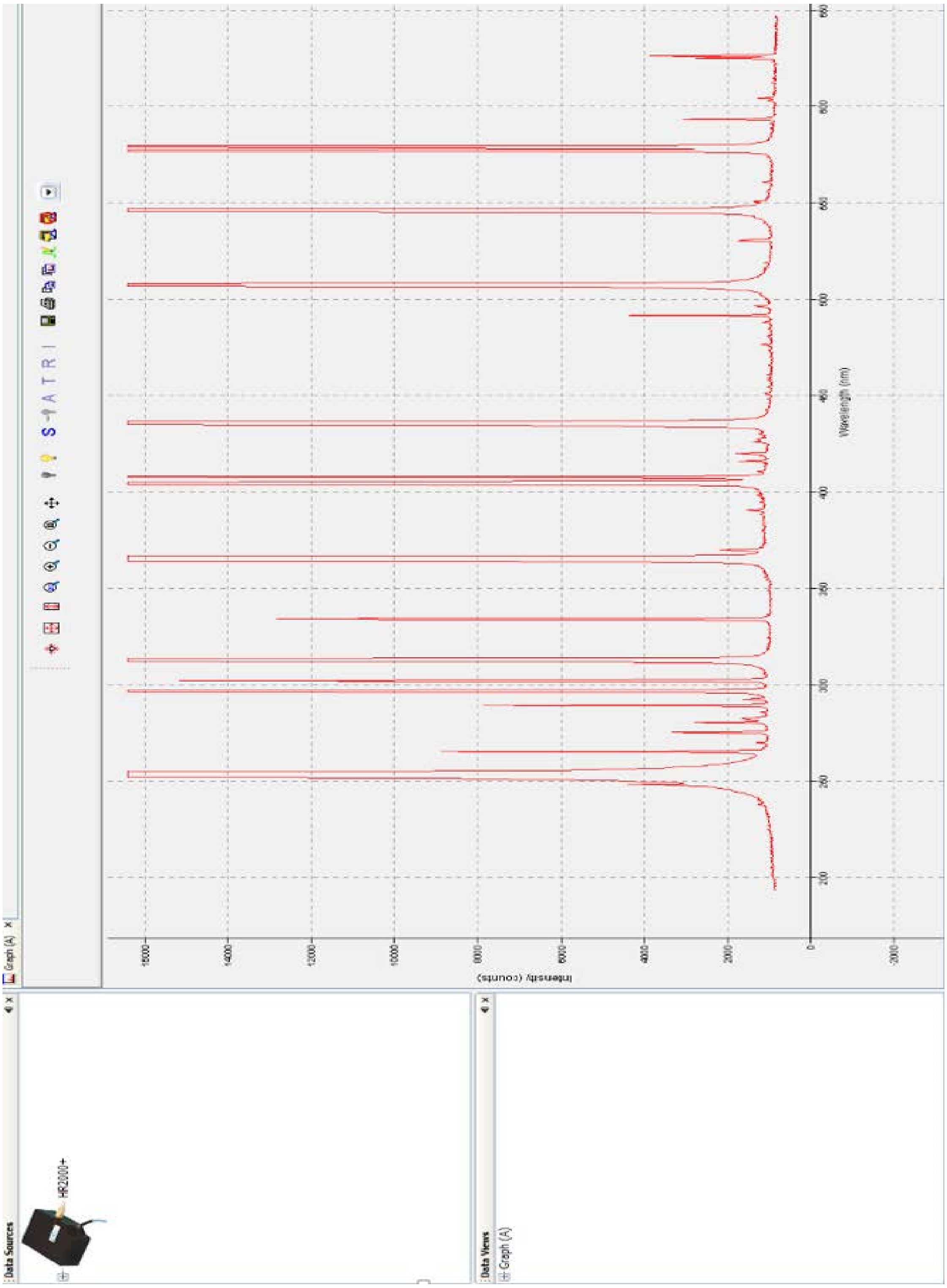
[51] Control Theory. 2015, p. 2-3. [Online document]. [Referred 12.12.2015]. Available: http://www.basicknowledge101.com/pdf/control/Control%20theory.pdf

HR2000+ specifications [41].

HR2000+ Specifications	
Dimensions	148,6mm x 104,8mm x 45,1mm
Weigth	570g
Power consumption	90mA @ 5VDC
Detector	2048-element linear silicon CCD array
Detector range	200-1100nm
Gratings	14 gratings available
Entrance aperture	5,10,25,50,100 or 200µm wide slits
Order-sorting filters	Installed long pass and band pass filters
Focal lengths	f/4, 101mm
Optical resolution	Depends on grating and size of entrance aperture
Stray light	<0,05% at 600nm; <0,10% at 435nm
Dynamic range	2x109 (system); 2000:1 for a single acquisition
Fiber optic connector	SMA 905 to single-strand optical fiber (0,22 NA)
Data transfer rate	USB2.0: full scans into memory every 1 millisecond; Serial: full scans into memory every 600ms
Integration time	1ms to 65ms
Interfaces	USB2.0, 480Mbs, RS-232 (2-wire);SP1 (3-wire);I2C Inter-integrated Circuit 2-wire serial bus
Operating systems	USB port: Windows, Mac and Linux; Serial: any Windows 32 bit operating system
Onboard GPIO	10 user-programmable digital I/Os
Analog channels	One 13-bit analog input and one 9-bit analog output

APPENDIX 2

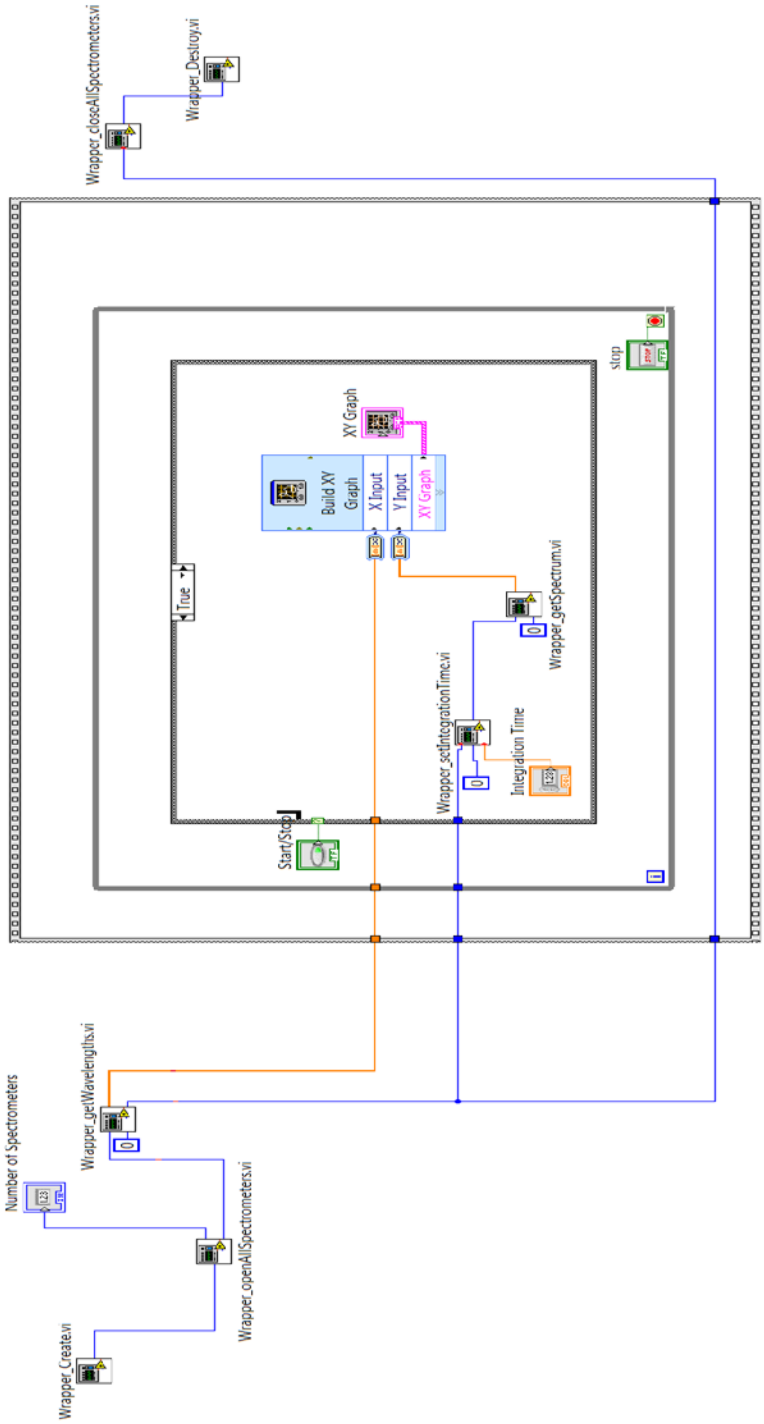
SpectraSuite data acquisition on.



Components of the experimental setup.

Components of the experimental setup
Ocean Optics HR2000+ High Resolution Spectrometer
Ocean Optics QF600-2-SR/BX 600µm Optical Fiber
Ocean Optics HG-1 Mercury Argon Calibration Source (253-922nm wavelength)
Uniphase 220V 0.06A Laser power supply
Uniphase 4mW Class IIIa Helium-Neon Laser
USB 2.0 cable
Laptop Dell Precision M6800
Mouse
Mirror

Test code for USB connection functionality of the spectrometer.



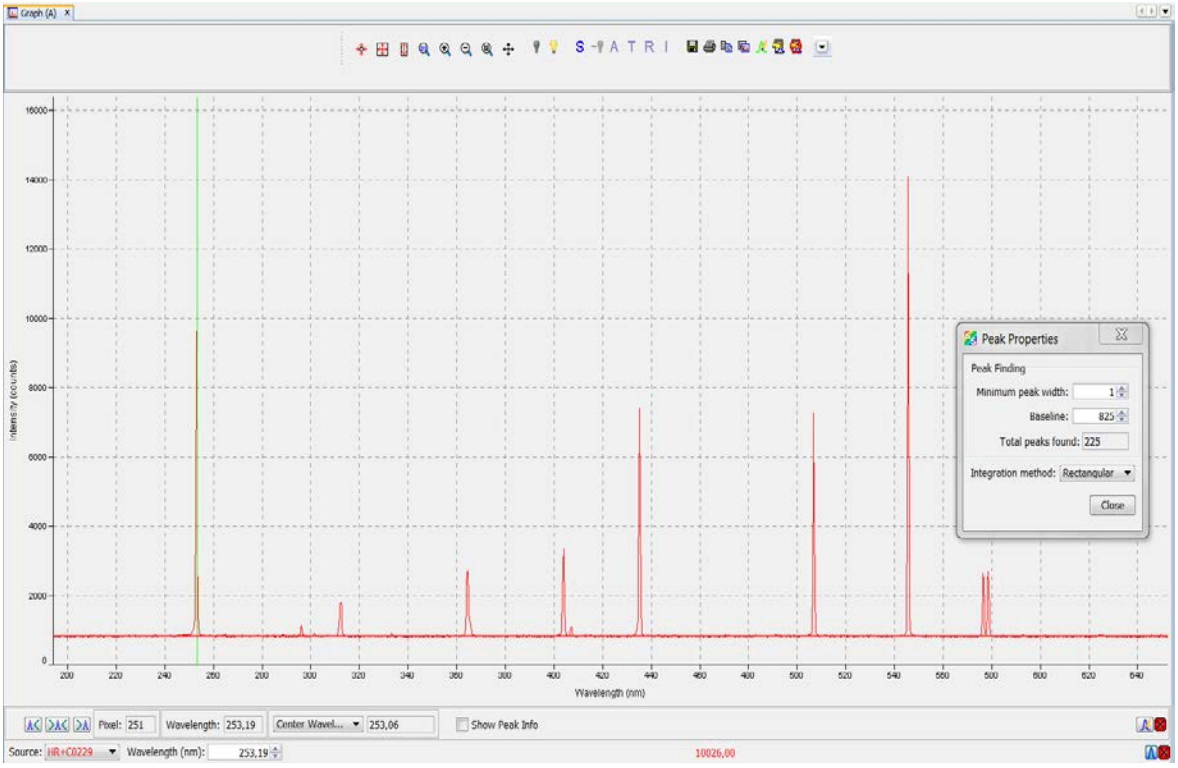
PXIe real-time module [44].

PXIe Real-time Module	
Component	Description
NI PXIe-8880	Intel Xeon E5-2618L v3 processor based embedded controller for use in PXI Express systems
Processor	2.3GHz base (3.4GHz single core turbo boost mode) 8-core processor, 16 hyper threaded virtual cores
Memory	Triple-channel 1866MHz DDR4
Possibilities of the PXIe-8880	
*Ads the power of Intel Xeon workstation CPUs to the test engineering applications	
*The multicore (8-core) processing power of Intel Xeon and PCI Express Gen 3 technology enables possibility for:	
1. 2x bandwidth performance of PCI Express Gen 2 technology	
2. 2x the processing power of a 4-core CPU	
3. Low latency making it very suitable for real-time applications	

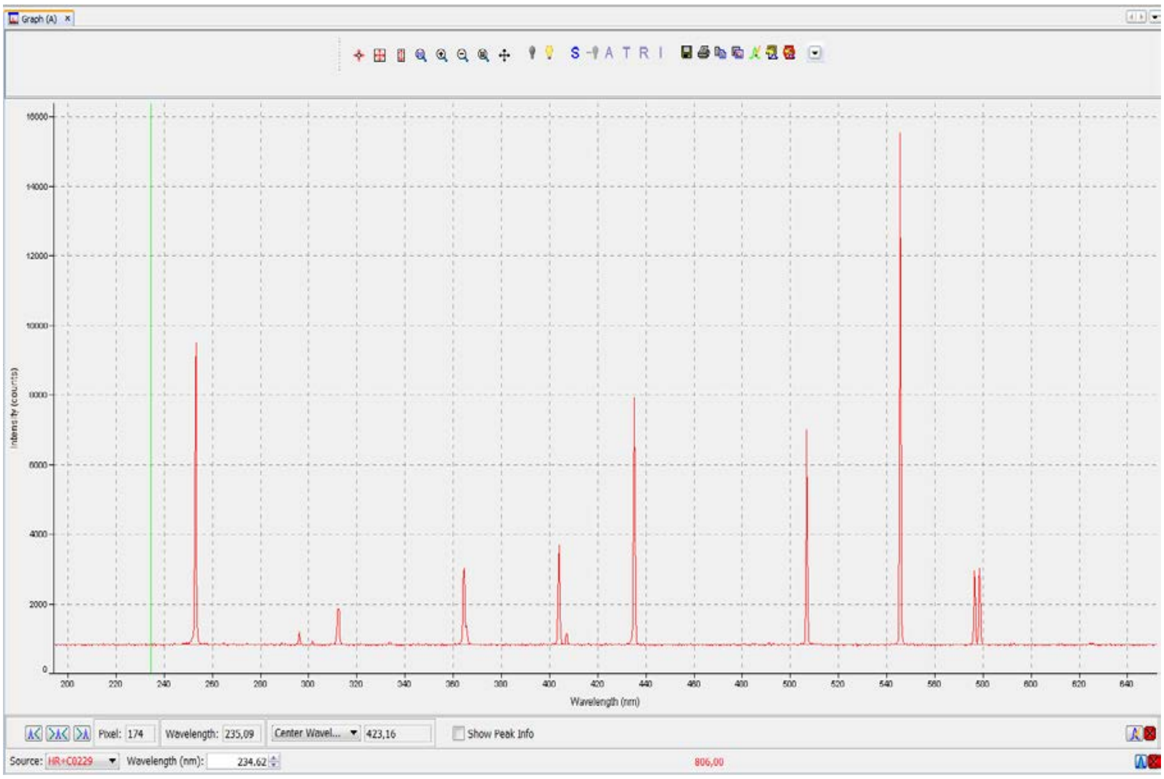
NI PXI-8430 Serial Port Module [44].

NI PXI-8430 Serial Port Module	
Component	Description
NI PXI-8430	Serial port module for enabling connections with PXI-8880 and measuring equipment
Compatibility	Windows, LabVIEW Real Time OS
Technology	High Speed DMA (Direct Memory Access) interface minimizes CPU overheat
BAUD rate	57 to 1,000,000 BAUD which covers standard and nonstandard BAUD rates
Memory	Mapped to prevent I/O resource conflicts; 128B transmit and receive FIFOs
Possibilities	Provides full multiprocessor and hyperthreading compatibility, NI Serial COM port driver and NI-VISA API for easy programming in LabVIEW

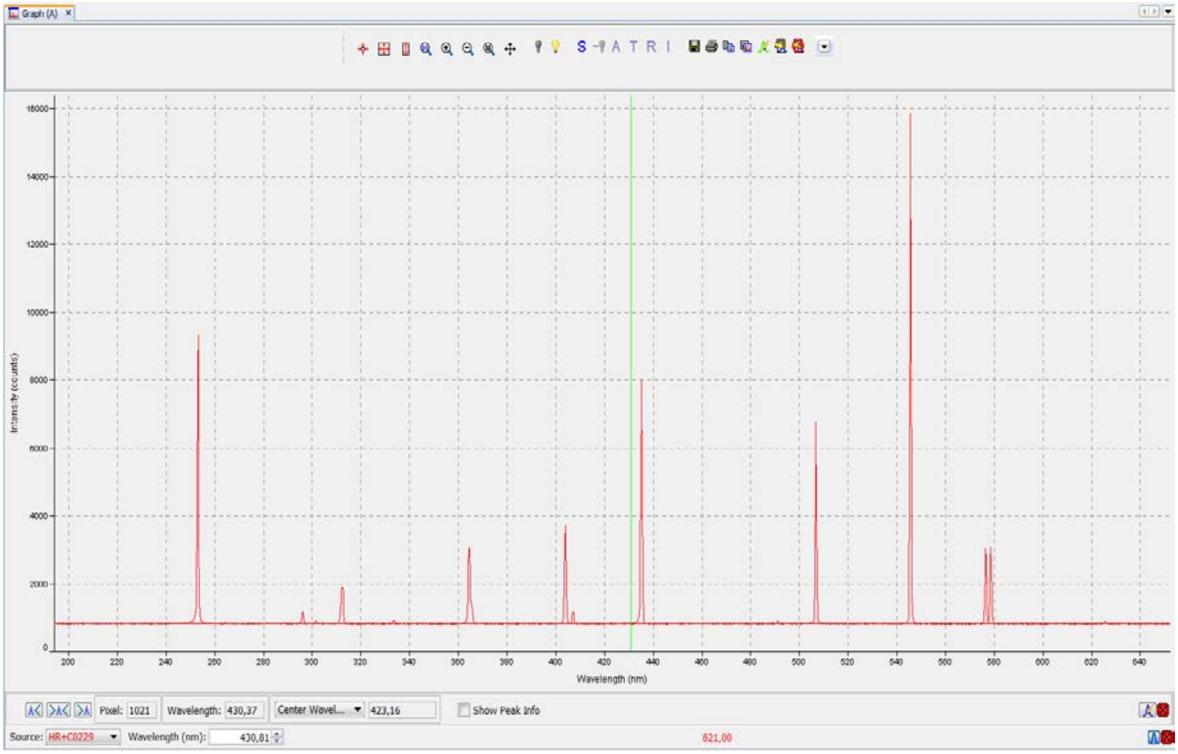
Setting of peak properties, wavelength check at pixel spot 251.



Wavelength check at pixel spot 174.



Wavelength check at pixel spot 1021.



Linearity test.

Linearity Test

Serial Number **HR+C0229**

Tech: Aura.Moreno

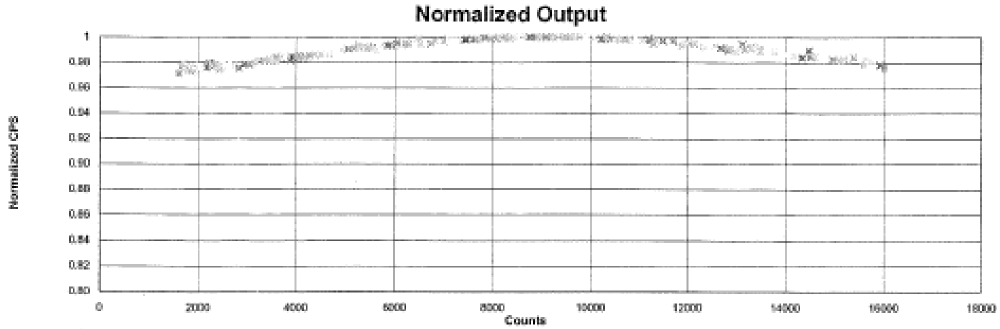
Linearity: **99.86367**

Tested: 8/10/15

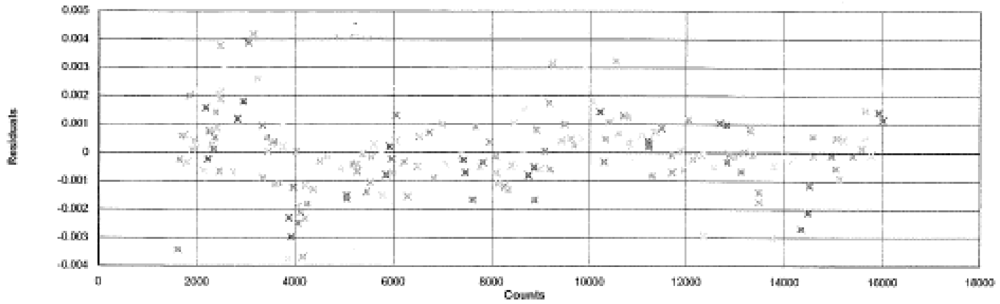
Test # 129,798.00

Intercept	0.972379
Coefficient 1	9.43582e-007
Coefficient 2	9.09286e-011
Coefficient 3	2.7041e-013
Coefficient 4	-5.50917e-017
Coefficient 5	3.91275e-021
Coefficient 6	-1.10647e-025
Coefficient 7	8.29975e-031

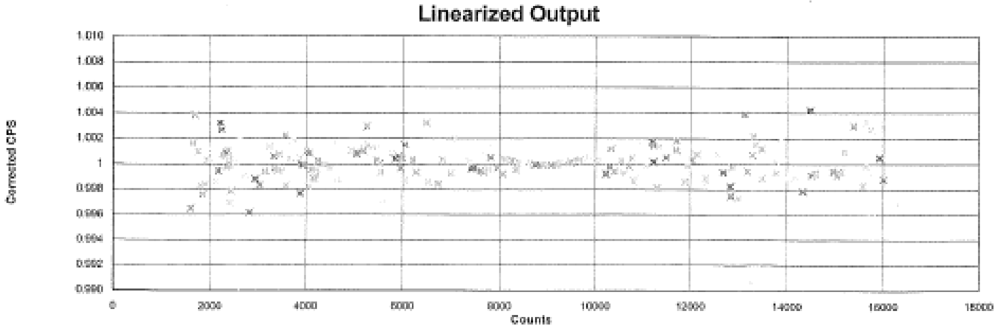
Normalized Output



Residuals

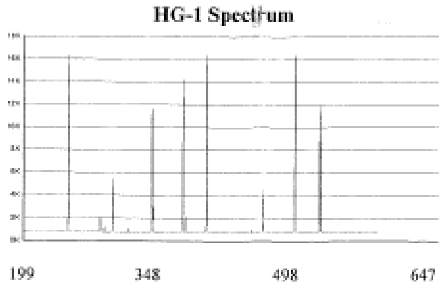


Linearized Output



Max **1.00424647** Min **0.99619585**

Results of linearity test.



Wavelength Calibration Data Sheet

Built for: **Ocean Optics, B.V.**
Order Number: **1417983**
Model: **HR2000+**
Grating: GRATING_#H1 - 600 Lines Blazed at 300 nm
Bandwidth: 199 - 647 nm
Options: DET2-UV Detector, L2Lens, SLIT-5 Slit,

Serial Number: **HR+C0229**

λ	Pixel #	Predicted λ	Δλ
228.802	150	228.822	-0.020
253.652	257	253.679	-0.027
296.728	443	296.718	0.010
302.150	467	302.181	-0.031
307.590	491	307.574	0.016
326.106	571	326.119	-0.013
334.148	607	334.123	0.025
340.365	634	340.358	0.007
346.620	662	346.647	-0.027
361.051	725	361.086	-0.035
365.015	743	365.024	-0.009
404.656	919	404.667	-0.011
407.781	933	407.771	0.010
427.397	1021	427.410	-0.013
431.958	1042	431.955	0.003
435.834	1059	435.846	-0.012
437.612	1067	437.632	-0.020
446.369	1107	446.398	-0.029
467.816	1204	467.835	-0.019
468.014	1205	468.031	-0.017
472.216	1224	472.235	-0.019
479.992	1260	480.006	-0.014
481.053	1265	481.065	-0.012
508.582	1391	508.599	-0.017
546.074	1565	546.085	-0.011
557.029	1617	557.040	-0.011
576.959	1710	576.945	0.014
579.065	1720	579.063	0.002
585.249	1749	585.230	0.019
587.091	1758	587.091	0.000
594.483	1793	594.479	0.004
597.553	1808	597.534	0.019
602.999	1834	602.971	0.028
607.434	1855	607.403	0.031
621.728	1923	621.706	0.022
630.479	1965	630.451	0.028
633.443	1979	633.412	0.031
636.235	1993	636.251	-0.016

This is a sample of calibration peaks used as there were more than can be shown on this page

Calibration Coefficients

First Coefficient:	0.2354911119
Second Coefficient:	-6.01658e-006
Third Coefficient:	-3.49505e-010
Intercept:	193.54081726
Regression Fit:	0.9999999404

Stray Light Measurements (AU)

Holmium Oxide (444nm):	1.43
Yellow Dye:	3.05
Blue Dye:	N/A
Molybdate:	3.58
OG550 Filter:	3.03
RG850 Filter:	N/A
FG3 Filter:	1.29

Naika Y. Delgado

Calibrated By: Aura.Moreno
Calibrated: 10-August-2015

Specifications of Ytterbium pulsed fiber laser YLPM-1-4x200-20-20 [46].

Ytterbium pulsed fiber laser YLPM-1-4x200-20-20

1. Optical characteristics

N	Characteristics	Test condition	Symbol	Min	Typ	Max	Unit
1	Mode of operation				Pulsed		
2	Polarization				Random		
3	Selectable pulse duration		T1-T8		4,8,14,20,30,50,100,200		Ns
4	Central emission wavelength	Pout=Pnom	λ	1055	1064	1075	Nm
5	Emission bandwidth	FWHM	Δλ		5	10	nm
6	Nominal average output power		Pnom	19	20	21	W
7	Output power adjustment range			10		100	&
8	Extended pulse repetition rate		RR	1,6		1000	kHz
9	Maximum pulse energy	Pout=Pnom, T=T8 (200ns)			1		mJ
10	Maximum peak power				15		kW
11	Laser switching ON/OFF time				2	3	µs
12	Long-term average power instability	Pout=Pnom over 5hrs			2	5	&

2. Optical output

N	Characteristics	Test condition	Min	Typ	Max	Unit
13	Protection cable type			Metal shielded / PVC coated		
14	Delivery cable diameter		6		7	mm
15	Output fiber cable length			2		mm
16	Output beam diameter	1/e^2 level	6		9	mm
17	Beam quality M2			1,5	2	

3. Electrical characteristics

N	Characteristics	Test condition	Min	Typ	Max	Unit
18	Supply voltage		23	24	25	VDC
19	Current consumption				6	A

4. General characteristics					
N	Characteristics	Min	Typ	Max	Unit
20	Environment temperature range: 100% emission time (1), 50% emission time (2)	0		40(1), 45(2)	C
21	Warm-up time to start of operation			10	S
22	Humidity (non-condensed environment)	10		95	%
23	Laser module dimensions	233x59x292			mm

5. Control interface
Control interface, digital signal lines (DB-25 plug connector)
RS-232C interface, control and monitoring (DB-9 plug connector)

6. Delivery configuration and options
*Standard laser configuration includes:
Bit stream 1 (BS1) mode including high contrast (HC)
Extended pulse repetition rate
Output isolator
*Options:
Guide laser (red aiming diode)
Output beam diameter alternation
Delivery fiber length alternation
Power supply 100/240 AC auto ranging
USB remote control, laboratory grade (including PC software)

Specifications of RTC 4 PC Interface Board Card [47].

RTC 4 PC Interface Board Card
XY2-100 enhanced protocol
16-bit positioning resolution
10µs output period
Software drivers for (32Bit and 64Bit) Windows 8 / 7 / Vista / XP
Outputs for controlling a scan head and a laser
Various laser modes selectable (e.g. YAG modes, CO2 mode, fiber laser, polarity)
Two 10-bit analog outputs
One 8-bit digital output
One 16-bit digital output and one 16-bit output for controlling external components
Support of iDRIVE technology for scan system diagnostics and tuning selection
Functionality for controlling of 3-axis scan systems
Processing-on-the-fly functionality for processing objects in motion
Functionality for simultaneous control of two scan systems
Opto-decoupled laser control signals

Specification of Scanlab Hurryscan 14 II scan head (1/2) [48].

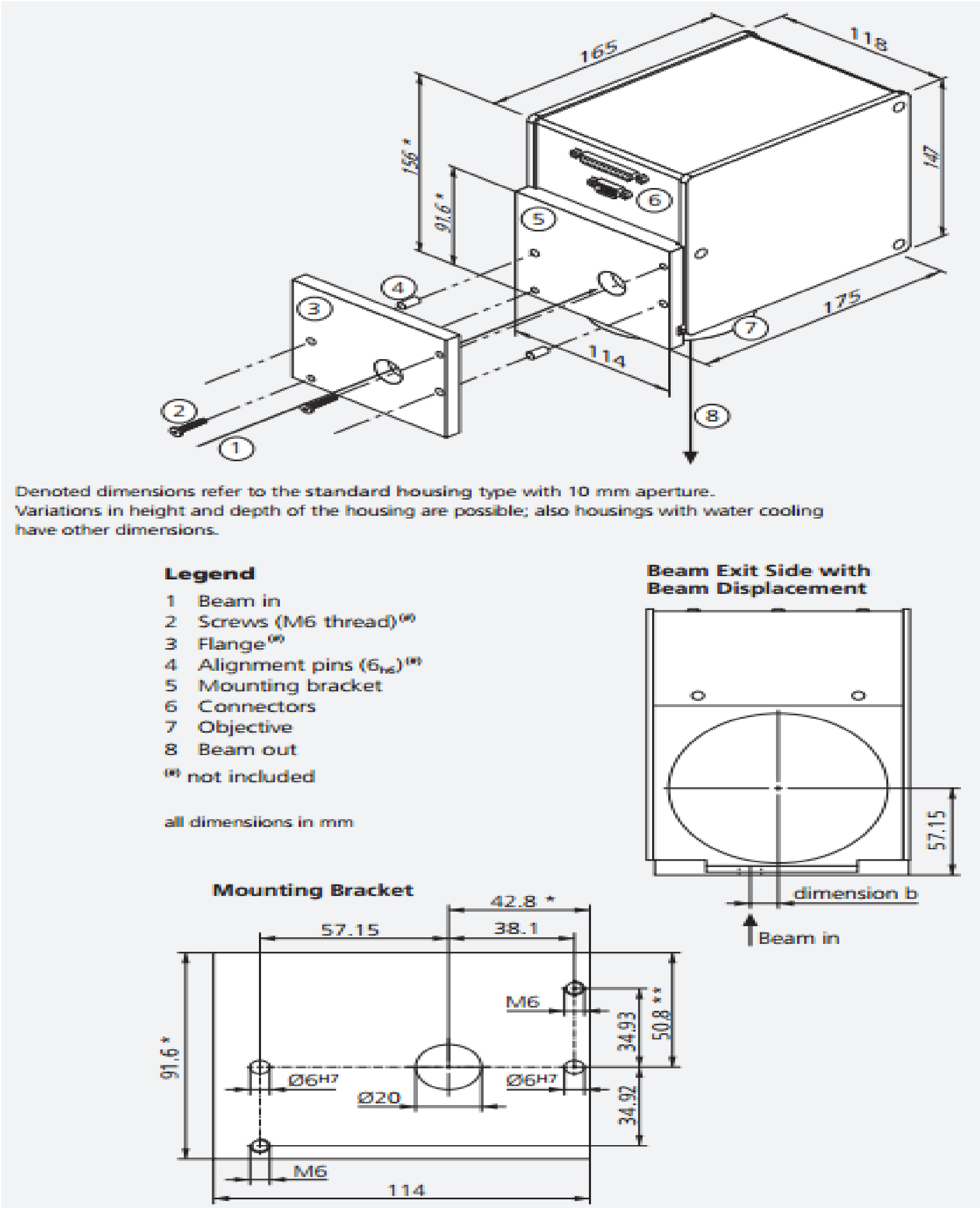
Scanlab Hurryscan 14 II scan head	
Specification	Description
Aperture	14mm
Angle transmitter of galvanometer scanner	Analog position detector
Wavelength range (standard)	1030/515/343nm;1064/532/355/266nm;1070-1085nm;450-2500nm;9300-10600nm
Max laser power (standard systems)	250W@1064nm
Typical scan angle	±0,35 rad
Image field size (1064nm, f=160mm)	95mm x 95mm
Typical spot size (1064nm, f=160mm)	23µm
Fiber adapter	No
Number of installed tunings	1
Tuning	Fast vector tuning
Tracking error	0,24ms
Marking speed	1,5mm/s
Positioning speed	7,0m/s
High writing quality (F-theta objective, f=160mm)	340cps
Good writing quality (F-theta objective, f=160mm)	500cps
Step response time (1% of full scale)	0,40ms
Step response time (10% of full scale)	1,60ms

Specification of Scanlab Hurryscan 14 II scan head (2/2) [48].

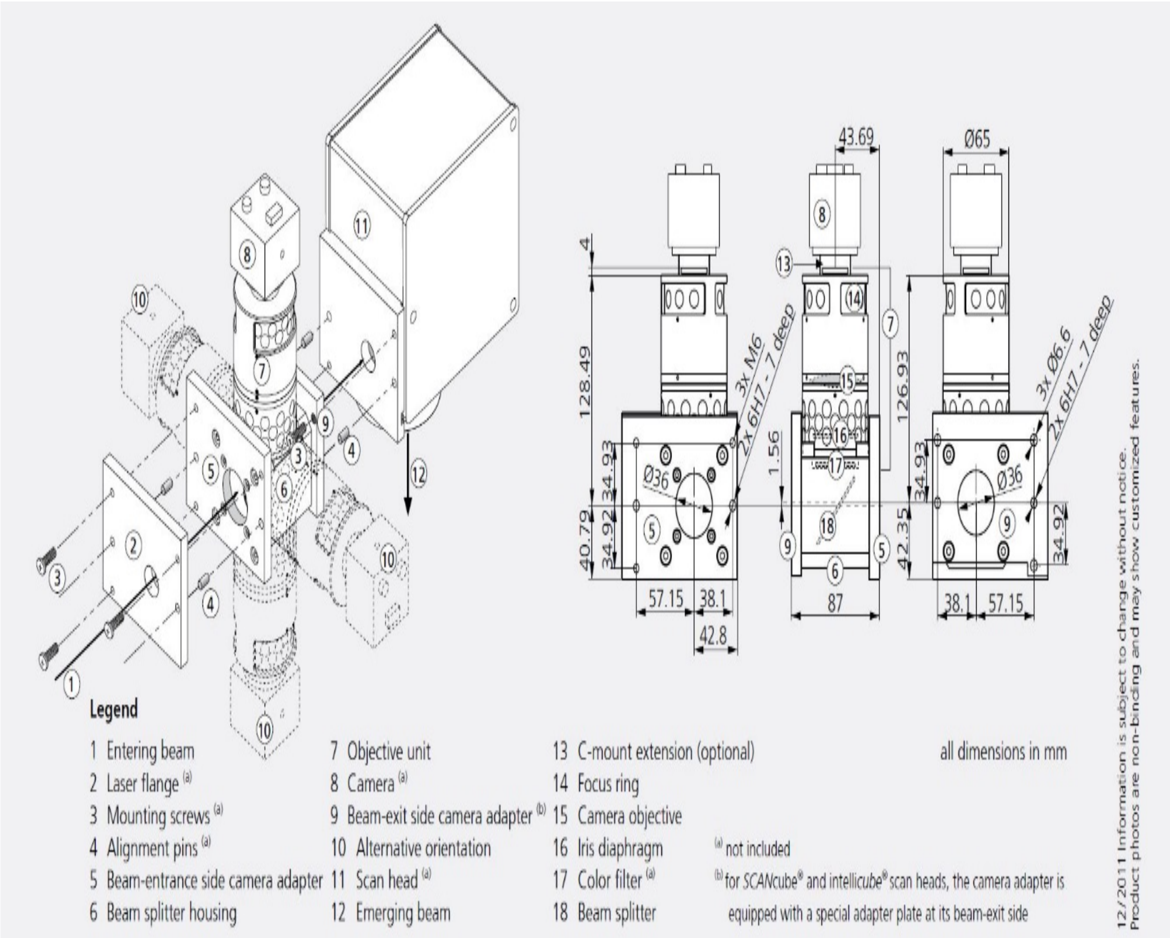
Scanlab Hurryscan 14 II scan head	
Specification	Description
Repeatability	<2µrad
Positioning resolution (max)	18bit
Nonlinearity	<3,5mrad/44*
8-h drift (after 30 min warm-up)	<0,6mrad plus
Servo control galvanometer scanner	Analog servo control board
Control interface (alternatives)	Digital SL2-100, digital XY2-100 standard, optical data transfer, analog ±4,8V, analog ±9,6V
Advanced diagnostics options	No
Scan axes	2-axis system
Housing variants (alternatives)	Standard: scan head; Alternative: module (without housing)
Connector-positions at the housing (alternative)	Opposite to the beam exit side, beam entrance slit
Dimensions (L/W/H) – standard housing	175 x 144 x 147mm
Weight without objective (standard housing)	Approximately 3kg
Water cooling	Optionally
Air cooling	Optionally
Options	Sensors for automatic self calibration (ASC), light weight mirrors, also available as scan module without housing
Power requirements	±(15+1,5)VDC
Beam displacement	16,42mm
Gain error	<5mrad
Zero offset	<5mrad
Skew	<1,5mrad

APPENDIX 16

Dimensions and parts of the scan head [48].



Dimensions and parts of camera adaptor attached to the scan head [49].

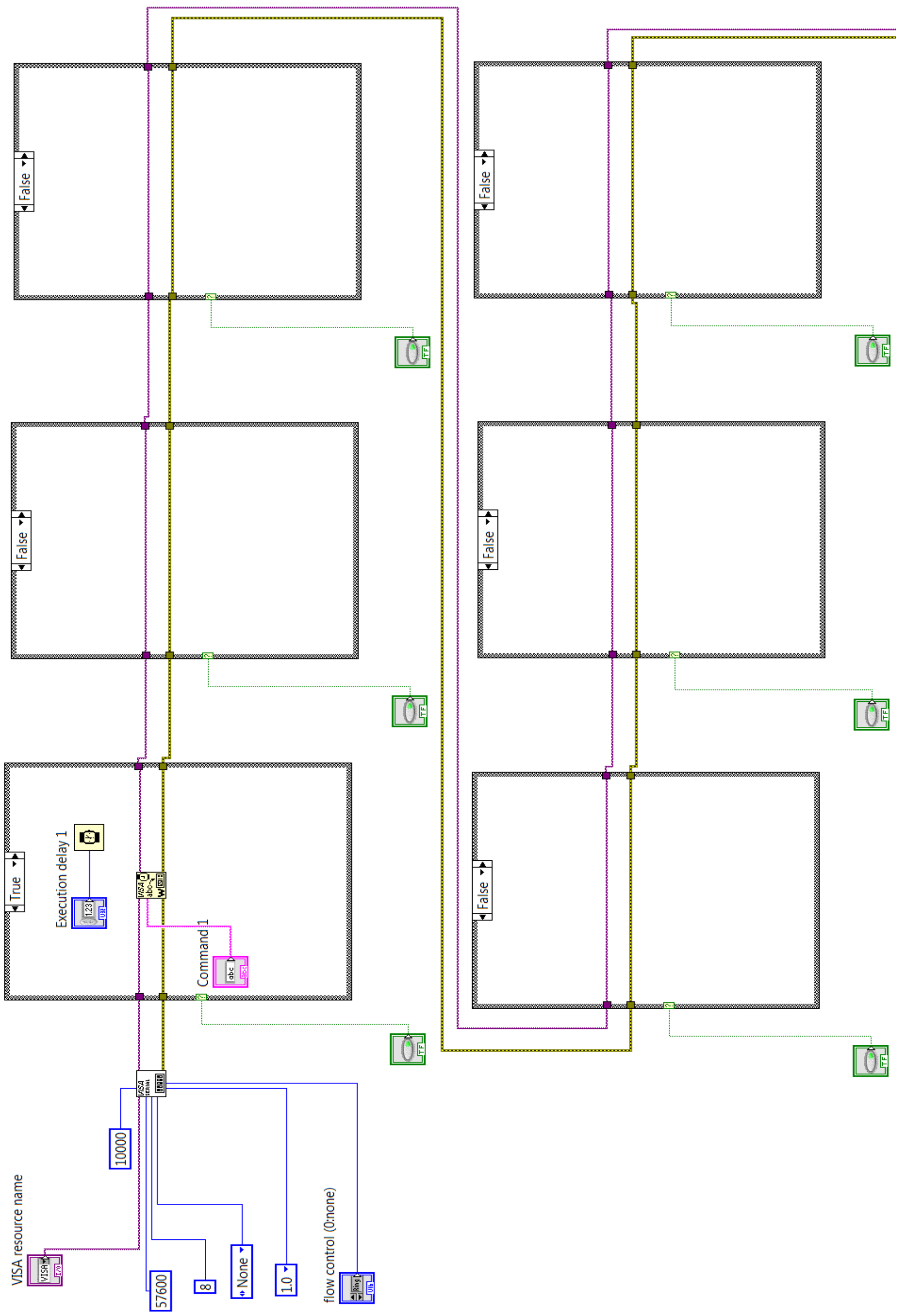


Query and command codes for the laser [50].

RS-232C				
Command codes				
Type	Command	Command code	Parameters or return values	Description/Parameters
Read	Device ID	1	String, up to 24 char	Read device identifier written to the laser in the factory
Read	Device SN	2	String, up to 24 char	Read device serial number
Read	FW revision	3	String, up to 255 char	Read device firmware version
Read	Vendor	99	String, up to 255 char	Read device vendor written to the laser in the factory
Read	Device status	4	Up to 32Bit integer	Read device status, decimal to binary decoding is required
Read	Device temperature	5	Float, 1 digit after point	Read module temperature in degrees Celsius
Read	Digital interface status	10	Up to 32Bit integer	Reads digital interface status, decimal to binary decoding is required
Read	Extended status	11	Up to 32Bit integer	Read device extended status, decimal to binary decoding is required
Read	BR counter	12	Up to 32Bit integer	Read back reflection counter
Read	Session BR counter	13	Up to 32Bit integer	Read back reflection counter for the current session. The session starts with supplying voltage to the laser module.
Read	Nominal average power	14	Float, 1 digit after point	Read nominal average power of the laser in [W]. Return value is float in [W].
Read	Nominal pulse duration	15	Up to 32Bit integer	Read nominal pulse duration of the laser in [ns]
Read	Nominal pulse energy	16	Float, 2 digit after point	Read nominal pulse energy of the laser in [mJ]
Read	Nominal peak power	17	Float, 1 digit after point	Read nominal peak power of the laser in [kW]. Value is calculated from the nominal energy and the nominal pulse duration.
Read	PRR range	18	See description	Read pulse repetition rates ranges. Return values is two floats separated by a semicolon, corresponding to minimum and maximum PRRs in [kHz].
Read	Head temperature	19	Float, 1 digit after point	Read remote head temperature in degree Celsius, if the head is installed
Read	Main supply voltage	21	Float, 1 digit after point	Read main supply voltage in [V]
Read	24V housekeeping voltage	22	Float, 1 digit after point	Read 24V housekeeping supply voltage in [V]
Read	Operating mode	23	16Bit integer	Read active control interface operating mode, decimal to binary encoding is required

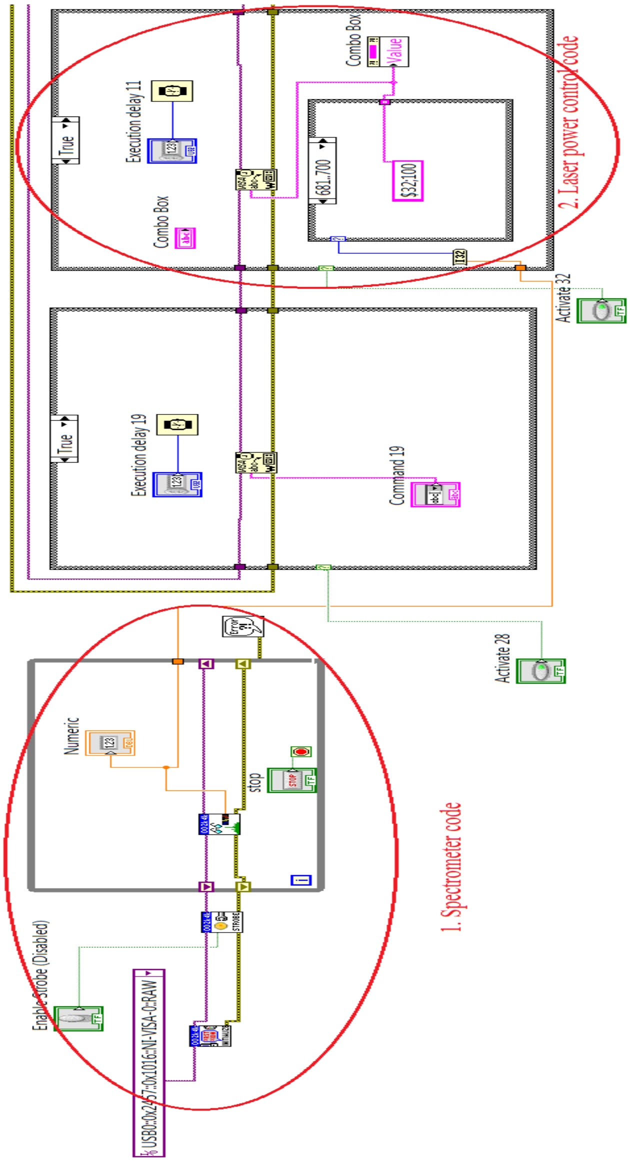
Command codes				
Type	Command	Command code	Parameters or return values	Description/Parameters
Set	Operating mode	24	16Bit integer	Set active control interface operating modes, decimal to binary decoding is required
Read	Installed options	25	16Bit integer	Read list of installed options and operating modes, decimal to binary decoding is required
Set	Start operating mode	26	16Bit integer	Set initial control interface operating mode, binary to decimal decoding is required. This mode becomes active after supplying the laser with electrical power.
Read	Start operating mode	27	16Bit integer	Read control interface operating mode, which activates after connecting the laser to the supply voltage. Decimal to binary decoding is required.
Read	Operating power [W]	33	Float, 1 digit after point	Read back operating power in [W] set by command 32 (in RS-232 mode) or via digital interface (DB-25 mode), but recalculated into Watts using nominal laser parameters.
Read	Operating power [%]	34	Float, 1 digit after point	Read back operating power in [%] set by command 32 (in RS-232 mode) or via digital interface (DB-25 mode), but recalculated into [%] using nominal laser parameters.
Read	Operating pulse energy	36	Float, 2 digit after point	Read operating pulse energy in [mJ]. Values is calculated using nominal laser parameters and power settings.
Read	PRR monitor	38	Float, 1 digit after point	Read back operating PRR in [kHz] set by command 28 (in RS-232 mode) or applied via pin 20 of digital interface [in DB-25 mode)
Set	PRR	28	Float, 1 digit after point	Set operating pulse repetition rate in [kHz]
Read	PRR	29	Float, 1 digit after point	Read back operating pulse repetition rate in [kHz] set by command 28
Set	Laser emission ON	30		Command to switch ON laser emission
Set	Laser emission OFF	31		Command to switch OFF laser emission
Set	Operating power	32	Float, 1 digit after point	Set operating power in [%]. Range 0...100, resolution 255 for full scale.
Set	Guide laser ON	40		Switch ON guide laser
Set	Guide laser OFF	41		Switch OFF guide laser
Set	Reset alarms	50		Reset alarms, see alarm description for details
Set	Save parameters	54		Permanently save parameters to EEPROM
Read	Min/Max PRR	46	See description	Read back minimum and maximum operating PRRs. Return value is two float in [kHz] values separated by semicolon.
Read	Pulse duration	48	16Bit integer	Read back pulse duration in [ns] set by command 49
Set	Pulse duration	49	16Bit integer	Set optical pulse duration in [ns]. The set value should correspond to one from the list returned by the command 51.
Read	List of pulse durations	51		Read list of preset pulse durations in [ns]. List of 16Bit integers separated by semicolon.

Serial initialization + laser commands.

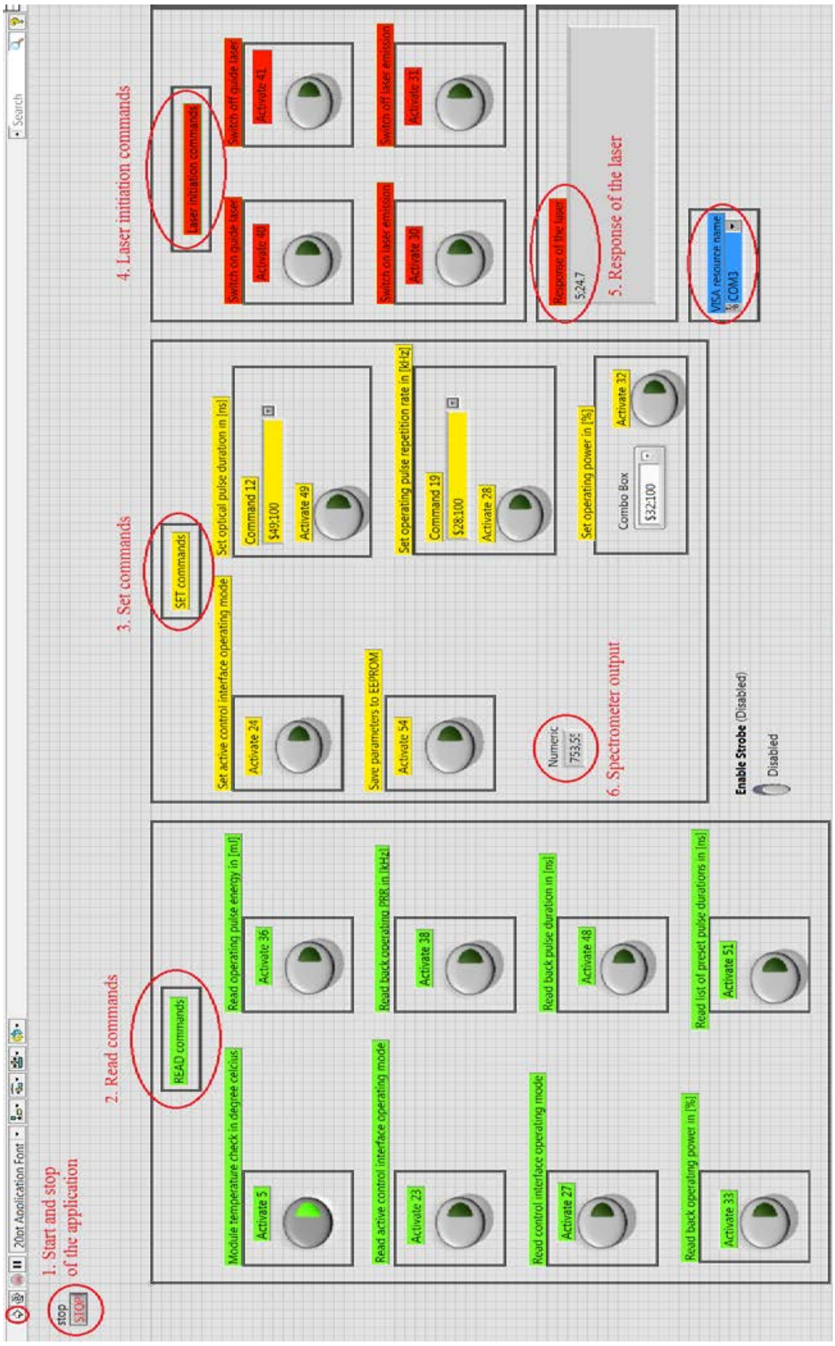


APPENDIX 20

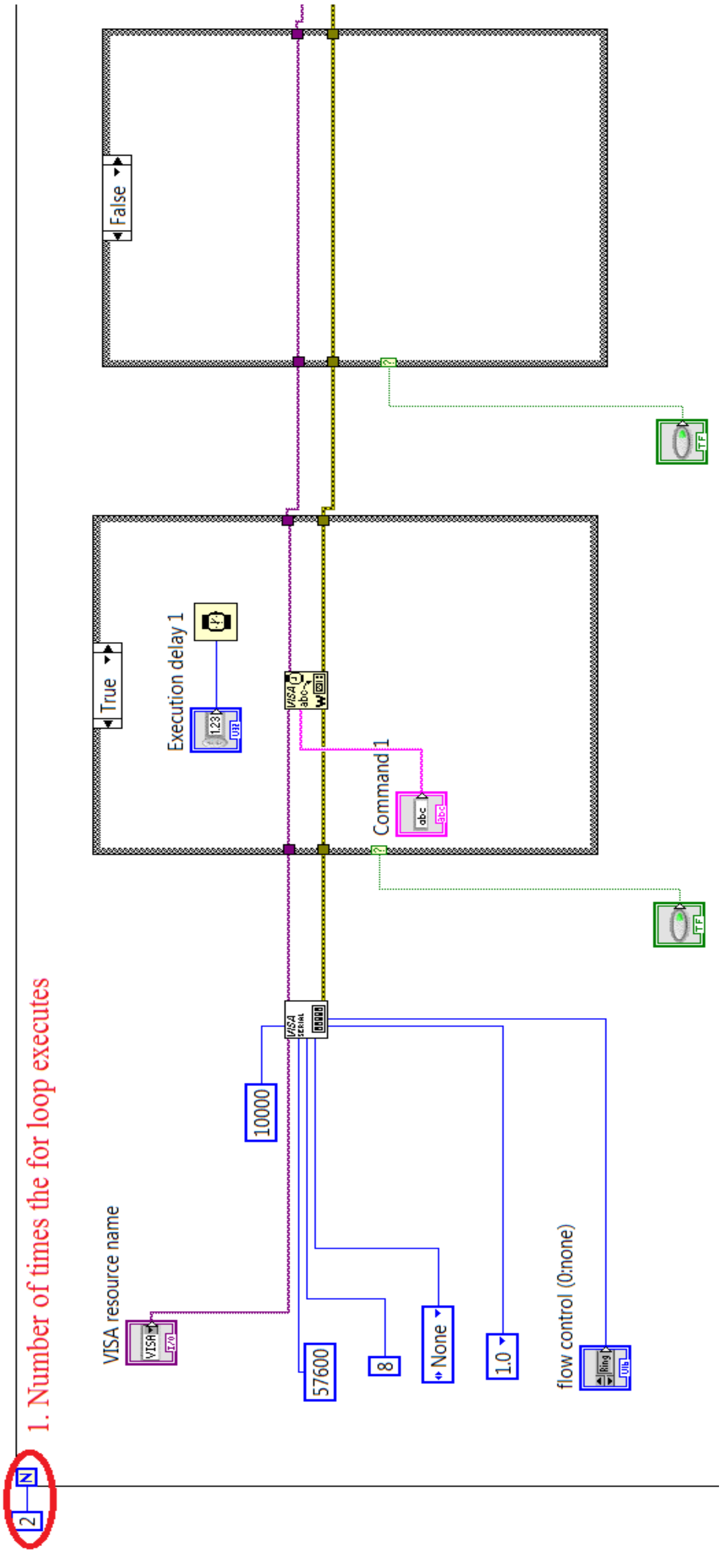
Spectrometer code + laser power control case structure connected.



User interface in LabVIEW.



For Loop structure enclosing the whole control code.



New user-interface.