Laser Measurement System **HPI-3D**

User

manual

Lasertex

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Laser measurements systems.

Measurement systems with data

acquisition.

Laser technique.

Laser Measurement System HPI-3D

User manual

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1. INTRODUCTION

Laser measurement system *HPI-3D* is a two frequency laser interferometer intended to be used mainly in machine geometry measurements. Its small size and low weight simplify transportation and make the instrument especially useful for service applications. Software version for Windows XP/Vista/7/8 and automation of many measurement processes make the interferometer easy to use. Software, compliant with ISO 230-2 and similar norms, enable making rapports and diagrams. It is possible to choose statistical results processing according to norms: ISO 230-2 (European), VDI/DGQ 3441 (German), NMTBA (USA), BSI BS 4656 Part 16 (British) and PN-93 M55580 (Polish).

Laser Measurement System HPI-3D is highly configurable device although already in its basic configuration it allows performing the complicated measurements at highest possible precision. Available options will be described below in this user manual.

Very good technical parameters of the interferometer allow using it in scientific laboratories, for precision

positioning, for scaling optical and magnetic measurement systems, etc.

a. Safety considerations

The Laser Interferometer *HPI-3D* is a Safety Class I product designed and tested in accordance with international safety standards. It is also a Class II Laser product conforming to international laser safety regulations. The instrument and the manual should be inspected and reviewed for safety markings and instructions before operation.

b. Warnings

Although the laser measurement system *HPI-3D* is design to be used in harsh environment, the following conditions **must** be met:

The Laser Head **must not** be put near strong magnetic fields.

The head should not be unscrewed from its base and if it is, it **may not** be put on a heat sink (e.g. thick metal plate).

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The head **must not** be thrown or dropped.

Keep the optical components clean and avoid scratching them.

When the optics is dusted, clean it with pure alcohol.

Do not use the system beyond its work conditions.

c. Compliance Information

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EC-DECLARATION OF CONFORMITY 2012

Wroclaw, 2012-04-20

Manufacturer

LASERTEX Co LTD.

Radzionkowska 17

51-506 Wrocław

Poland

Hereby certifies on its sole responsibility that the following product:

Laser Measurement System HPI-3D

which is explicitly referred to by this Declaration meet the following directives and standard(s):

Directive 2006/95/EC

Electrical Apparatus

Low Voltage Directive

- EN 61010-1:2011

Directive 2006/42/EU

Machinery Directive

- EN 60825-1:2007

Directive 2004/108/EU

Electromagnetic Comatibility:

- EN 61326-1:2006
- EN 61000-4-2:2011
- EN 61000-4-6:2007
- EN 61000-4-8:2010
- EN 61000-4-11:2007
- EN 55011:2007
- EN 55022:2011

Documentation evidencing conformity with the requirements of the Directives is kept available for inspection at the above Manufacture.

President, Janusz Rzepka PhD

2. QUICK START

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The information presented in this chapter is only for quick start. More detailed information can be found in the following chapters.

a. Main features

The **HPI-3D** is a device for contact measurement of the velocity of the moving object.

The device operates according to the laser interferometer principle (see *Principles of Operation* chapter). The Doppler shift phenomenon is used.

The basic measurement unit is the wavelength of the laser, i.e. 632nm.

The functionality of the instrument depends on the type of used optical components.

The *HPI-3D* is can be used either as a stand alone device or with a PC computer and the dedicated HPI Software.

b. How it works

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The *HPI-3D* measures shift of the moving element in relevance to the reference element as shown in the figure 2.1. It is important to notice, that the *relative* movement and not the absolute position of any of the elements is detected!

Reference element

—— Horizontal & Vertical polarization
----- Vertical polarization
----- Horizontal polarization

LASER HEAD

Moving element
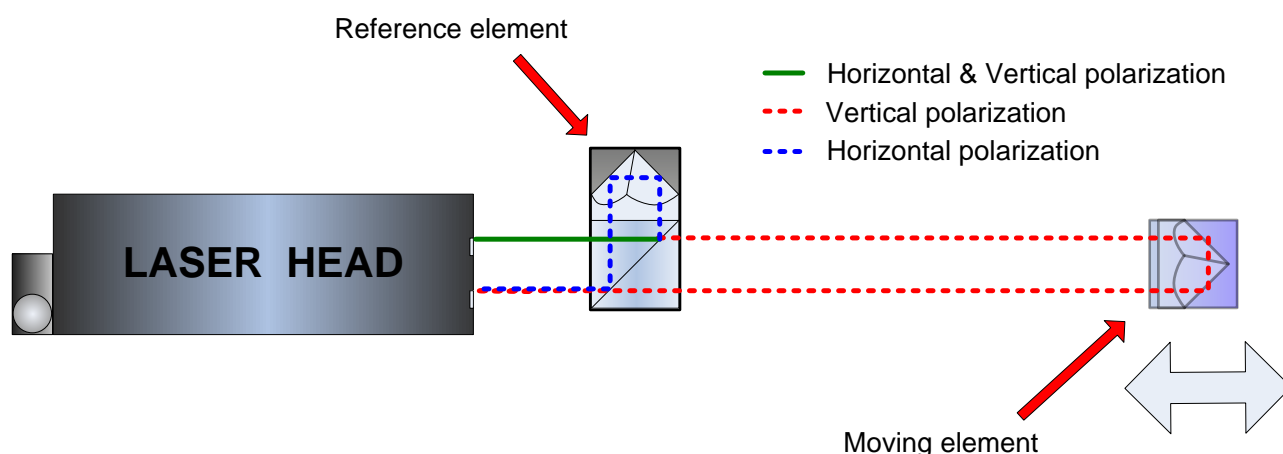
FIG. 2.1. ILLUSTRATION OF THE PRINCIPLE OF OPERATION - LINEAR OPTICS

i. Linear optics

i. To the linear optics belong Linear Interferometer IL1 and Linear Retroreflector RL1.

The operation of the HPI-3D with the linear optics used is shown in the figure 2.1. The laser outputs the laser beam

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consisting of two polarizations: Horizontal (H) and Vertical (V). The Reference element (IL1) splits the beam into two parts. The H polarized beam is reflected back to laser and the V polarized beam is directed into the measurement path. The frequency of the V beam is changed according to the Doppler Effect when the moving element is in motion.

The linear optics is mainly used for measurement of:

- Shift

- Velocity

- Acceleration

- Vibrations

- Straightness with 3D method

- Squareness with 3D method (RE3D element required)

- Parallelism with 3D method (RE3D element required)

ii. Angular optics

To the angular optics belong Angular Interferometer IK1 and Angular Retroreflector RK1.

The operation of the HPI-3D with the angular optics used is shown in the figure 2.2. The laser outputs the laser beam consisting of two polarizations: Horizontal (H) and Vertical (V). The IK1 splits the beam into two parts. Both beams are directed into the measurement path but are

parallel shifted by 50.8 mm. The frequency of both beams is changed according to the Doppler Effect when the RK1 element is in motion.

The frequency change of both beams is the same when RK1 and IK1 are shifted linearly. In this case no measured signal is detected by the laser head.

> ⚠️ The laser head with angular optics is insensitive to linear movements.

The laser detects movement only when the IK1 and RK1 are rotated against each other. In this case the frequency change of the H beam is different from the frequency change of the V beam.
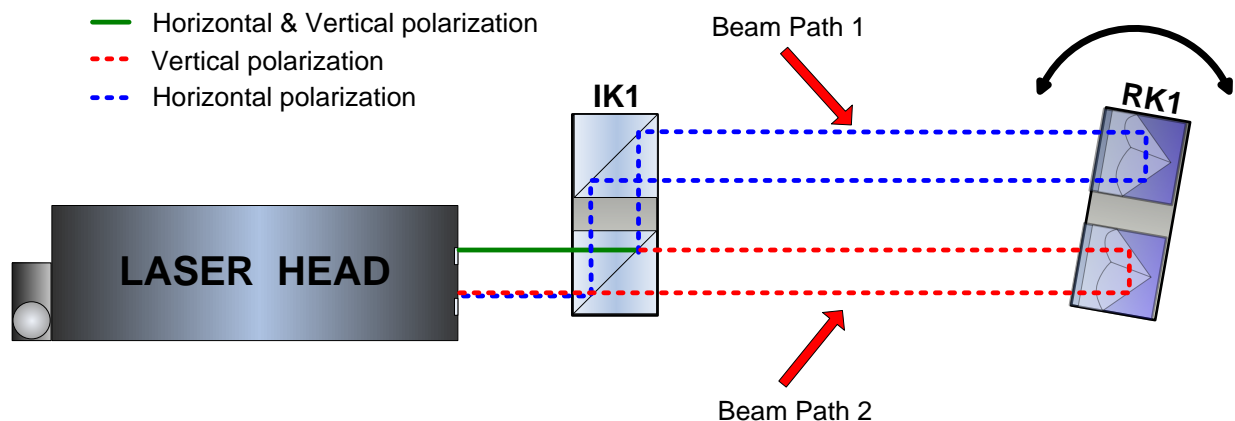
FIG.2.2. ILLUSTRATION OF THE PRINCIPLE OF OPERATION - ANGULAR OPTICS

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The angular optics is mainly used for measurement of:

- Small angles

- Straightness with Angular method

- Flatness

- Pitch

- Yaw

iii. Wollaston optics

To the angular optics belong Wollaston Prism WP2 and Wollaston Retroreflector WRP2.

The operation of the HPI-3D with the Wollaston optics used is shown in the figure 2.3. The laser outputs the laser beam consisting of two polarizations: Horizontal (H) and Vertical (V). The WP2 splits the beam into two parts. Both beams are directed into the measurement path. There is a certain angle between the beams. The frequency of both beams is changed according to the Doppler Effect when the WP2 element is in motion.

The frequency change of both beams is the same when WP2 and WP2 are shifted linearly. In this case no measured signal is detected by the laser head.

The laser head with Wollaston optics is insensitive to linear movements.

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The laser detects movement only when the WP2 is moved perpendicular to the beam from the laser. In this case the frequency change of the H beam is different from the frequency change of the V beam, because the lengths of beam paths 1 and 2 are different – see figure 2.3

A

WRP2

Beam Path 1

WP2

LASER HEAD

Beam Path 2

— Horizontal & Vertical polarization
- - - Vertical polarization
- - - Horizontal polarization

B

WRP2

WP2

LASER HEAD
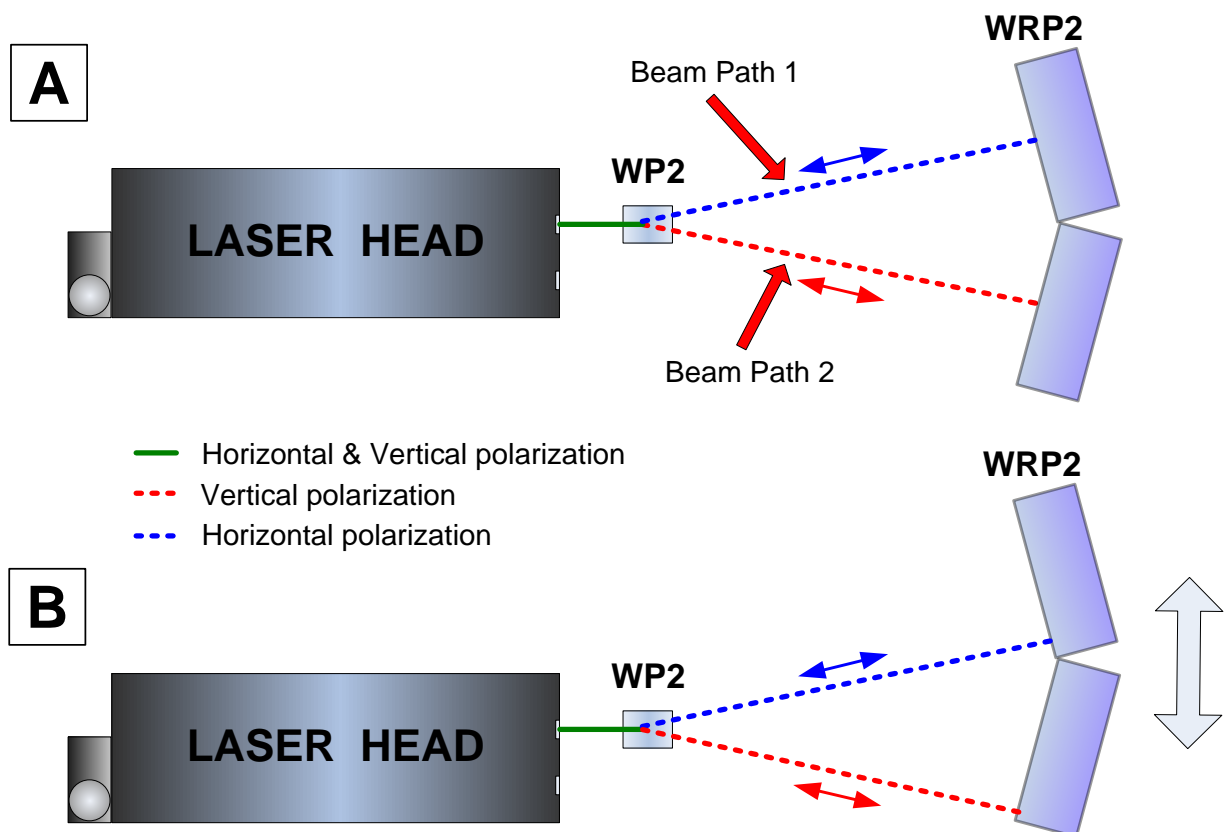
FIG.2.3. ILLUSTRATION OF THE PRINCIPLE OF OPERATION - WOLLASTON OPTICS. BEAMS RETURING TO THE LASER ARE IN THE PLANE OF THE DRAWING.

The Wollaston optics is mainly used for measurement of:

- Straightness with Wollaston method
- Axes squareness (with REW element)

- Axes parallelism (with REW element)

c. How to start
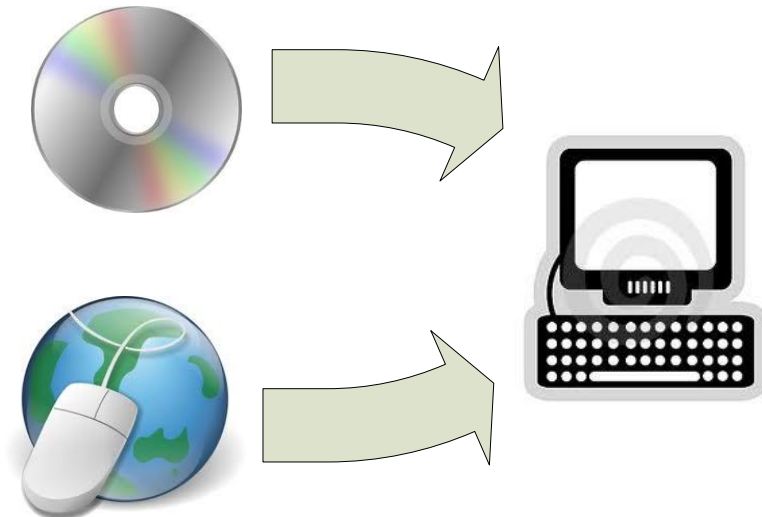
1. Install HPI software from CD or from www.lasertex.eu
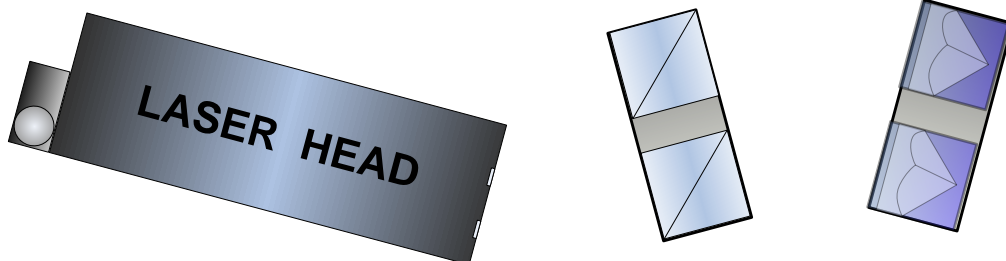
2. Mount Laser Head, and optical elements on the measured machine. Connect power supply to the Laser Head.

USB

Bluetooth

LASER HEAD
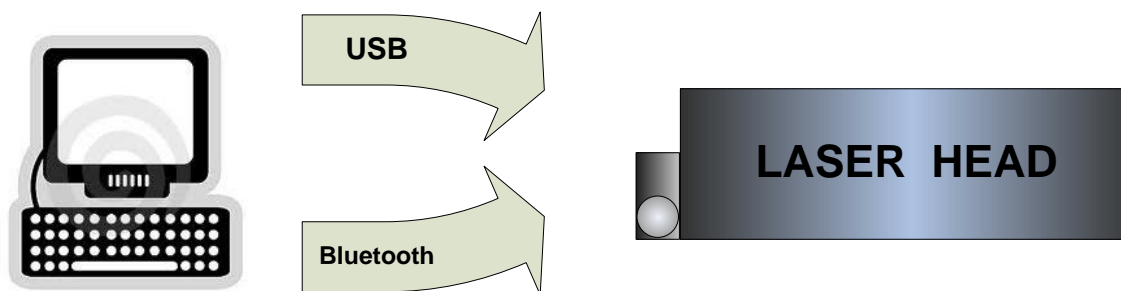
2

3. Run HPI Software and connect PC with laser over USB or over Bluetooth interface

LASER HEAD
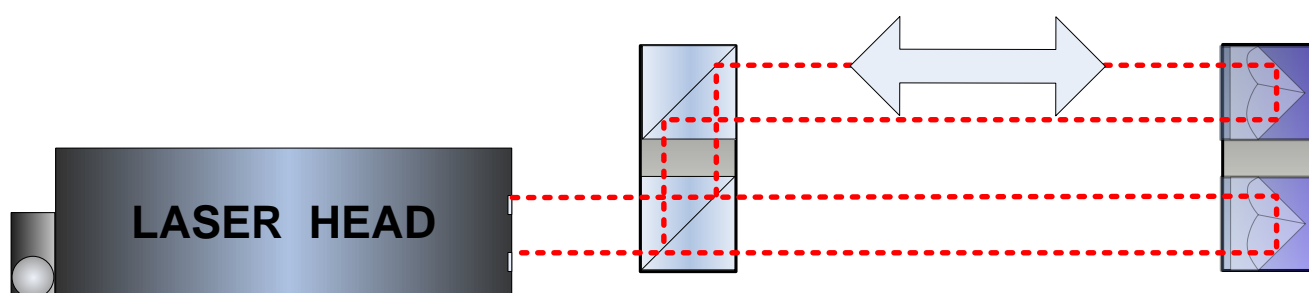
4. Align optical path
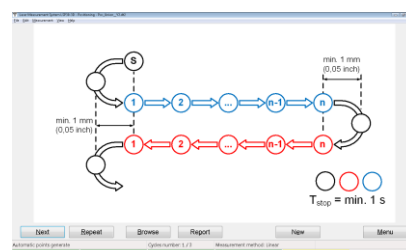
5. Start measurements

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3. PREPARATIONS

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The Laser Interferometer *HPI-3D* requires an installation of software "*HPI Software"* on a hard disc of a PC computer. The hardware requirements are:

Windows XP/Vista/7/8 system,

CR-ROM

Pentium processor, 1 GHz or better

SVGA graphic card

USB 2.0 or Bluetooth 2.0

a. Software installation

The software installation package is located on the USB memory stick that is included to the measurement system. *HPI_Software_Install* application can be launched from the USB memory. The installation process should start automatically.

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FIG. 3.1. ICON OF THE SETUP APPLICATION.

Following components have to be installed for proper operation of *HPI-3D* system:

– *HPI Software* application,

– Directory of the languages *Languages,*

– FTDI Driver for USB,

– documents folder with the manual and other documents (depending on a system version),

– Database BDE (Borland Database Environments)

During the installation process necessary parameters have to be set by the user. In the figure 3.2 there is shown a first windows that appears during installation. It allows choosing the installation language.
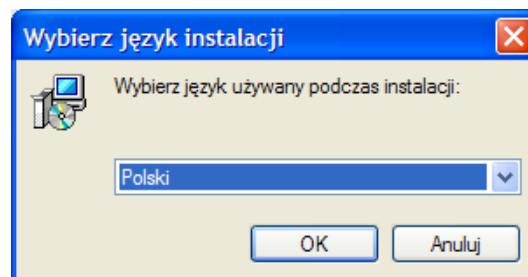
FIG.3.2. INSTALLATION LANGUAGE SETUP WINDOW.

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FIG.3.3. WELCOME WINDOW.
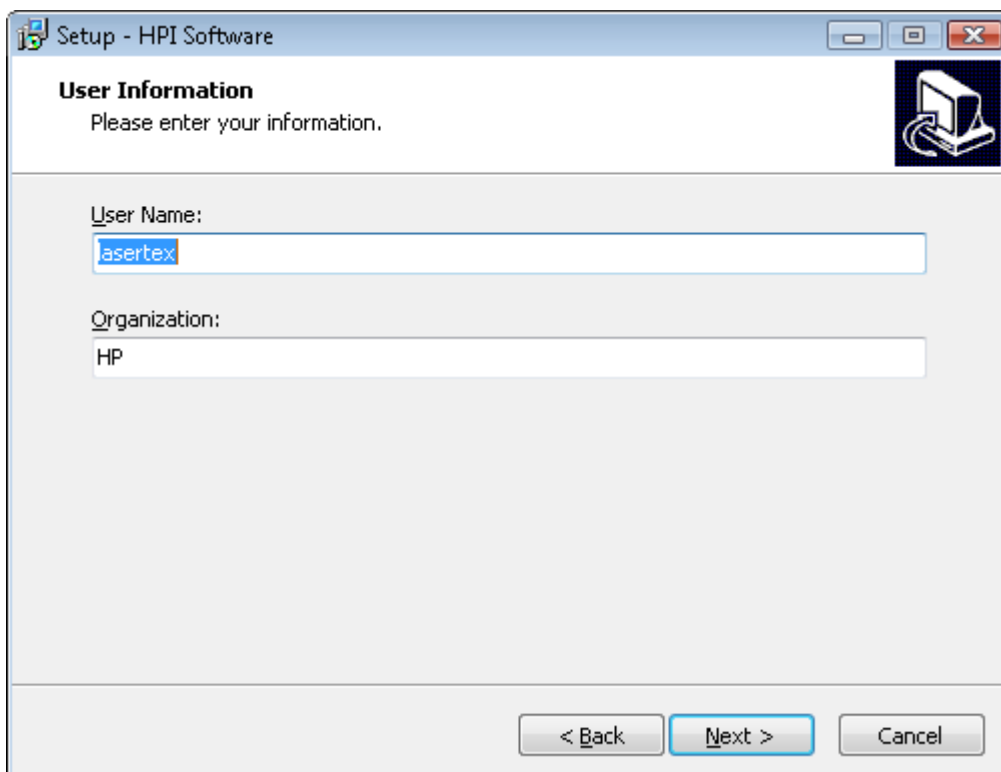
FIG.3.4. USER INFORMATION WINDOW.

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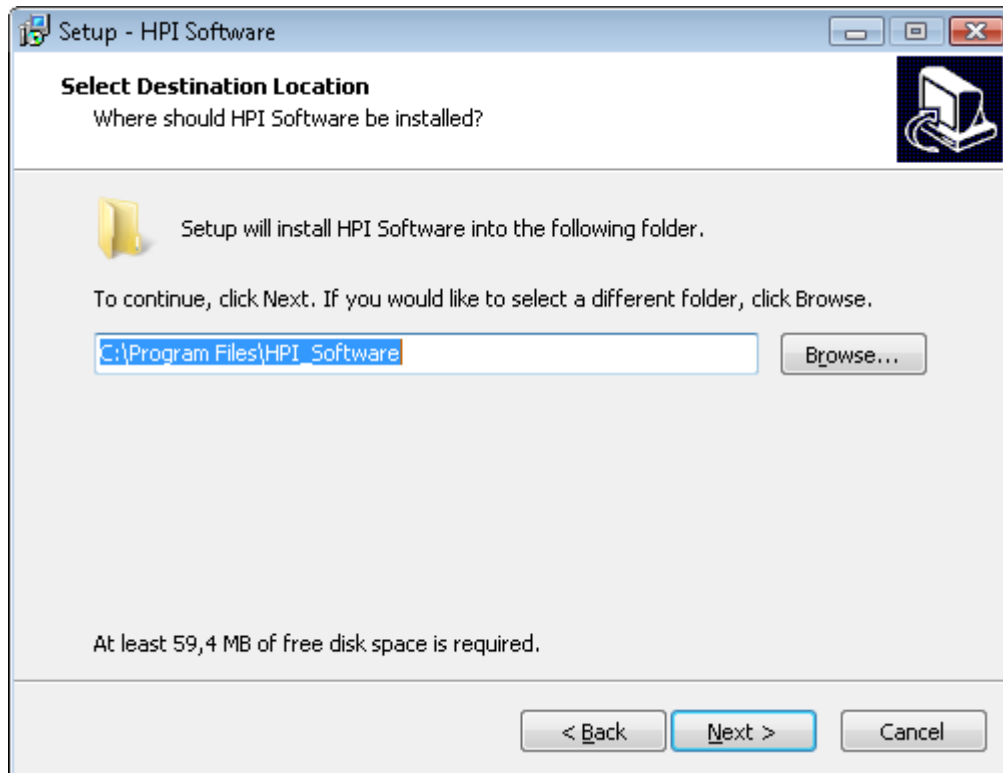
FIG.3.5. PROGRAM DESTINATION FOLDER WINDOW.
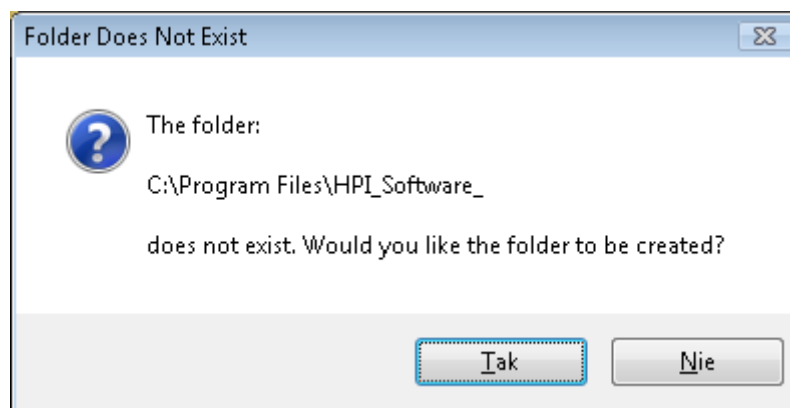
FIG.3.6. WINDOW APPEARING WHEN THE FOLDER NAME DOES NOT EXISTS IN THE

CURRENT INSTALLATION PATH.
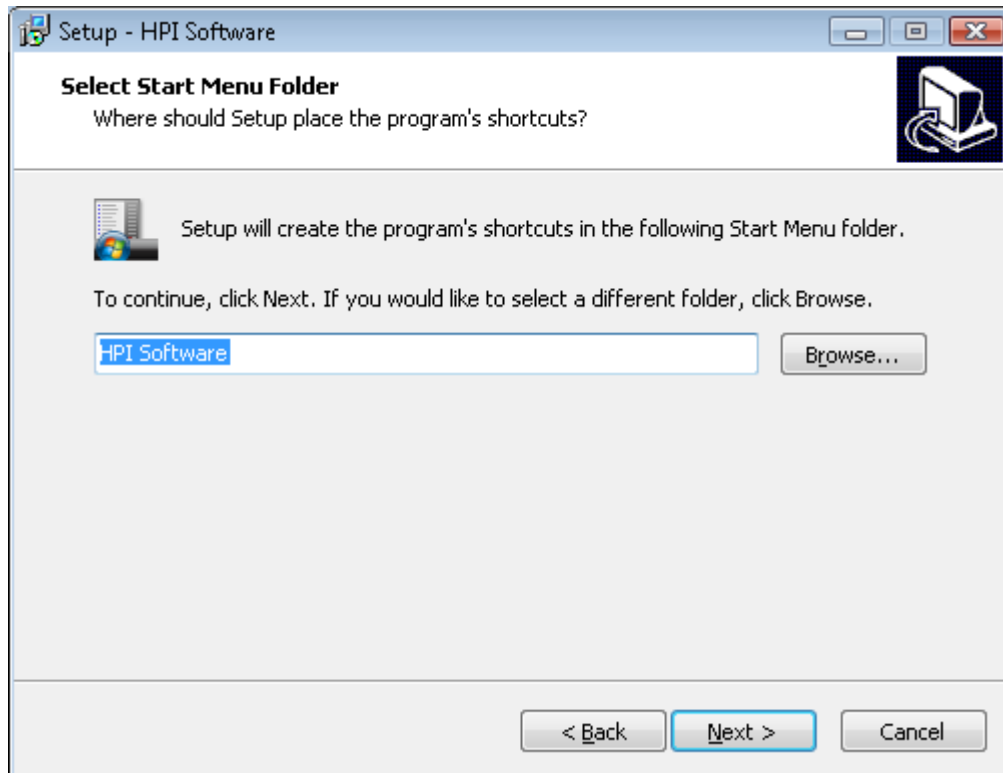
FIG.3.7. MENU START FOLDER SLECTION WINDOW.
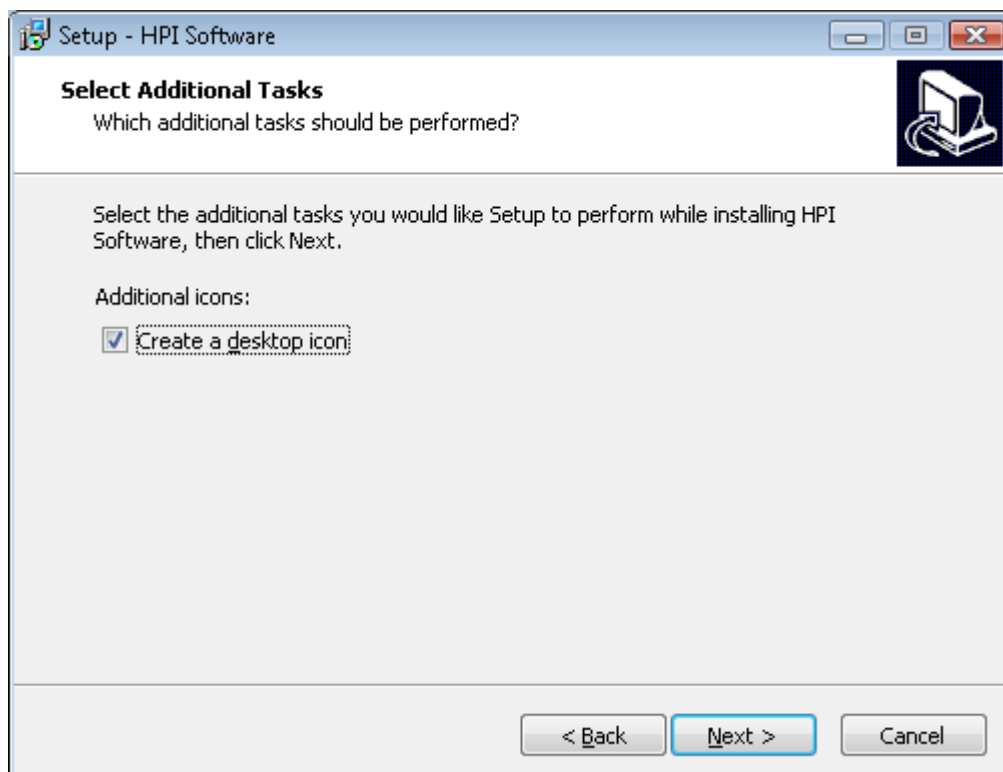
FIG.3.8. DESKTOP ICON SETUP WINDOW.
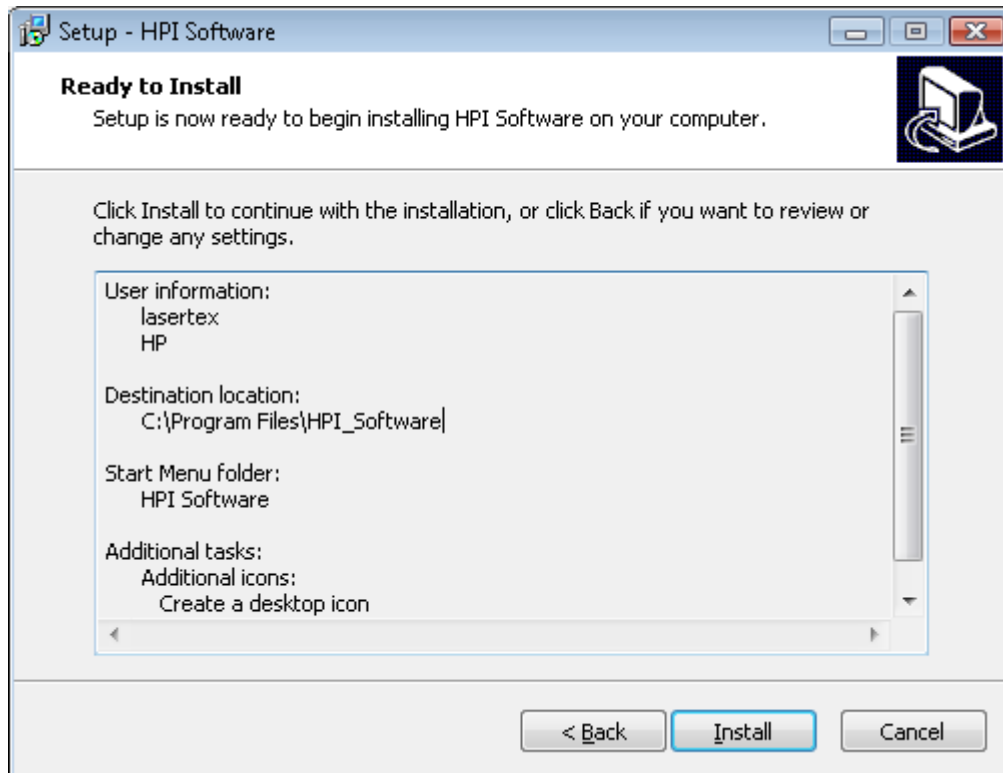
FIG.3.9. WINDOW WITH INSTALLATION INFORMATION.
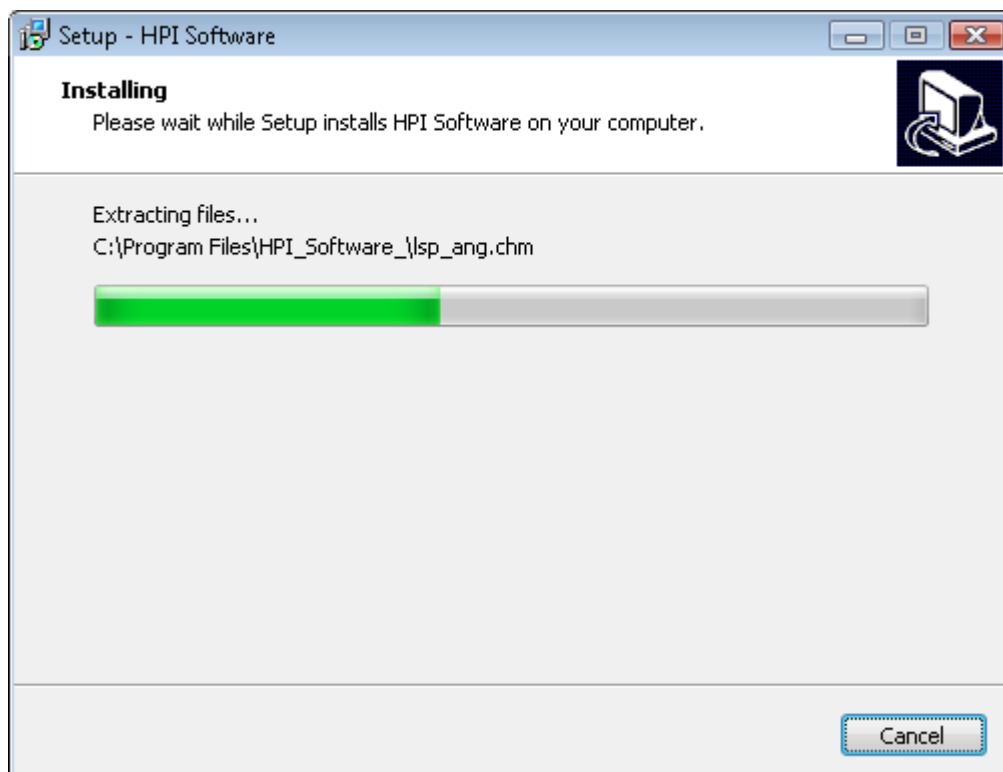
FIG.3.10. INSTALLATION WINDOW DURING DATA COPY OPERATION.
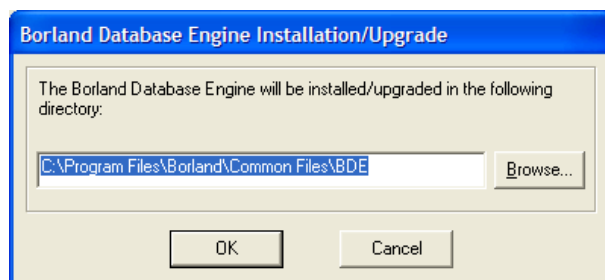
FIG.3.11. BDE (BORLAND DATABASE ENVIRONMENT) DESTINATION FOLDER WINDOW.
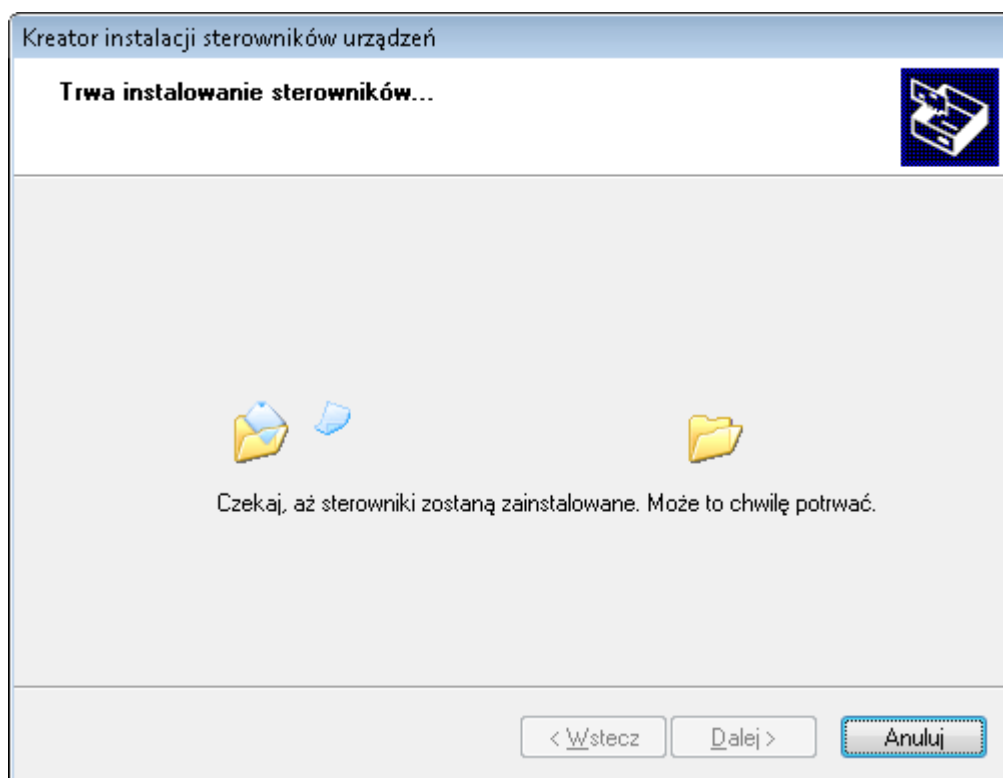
FIG.3.12. FTDI DRIVER INSTALLATION.

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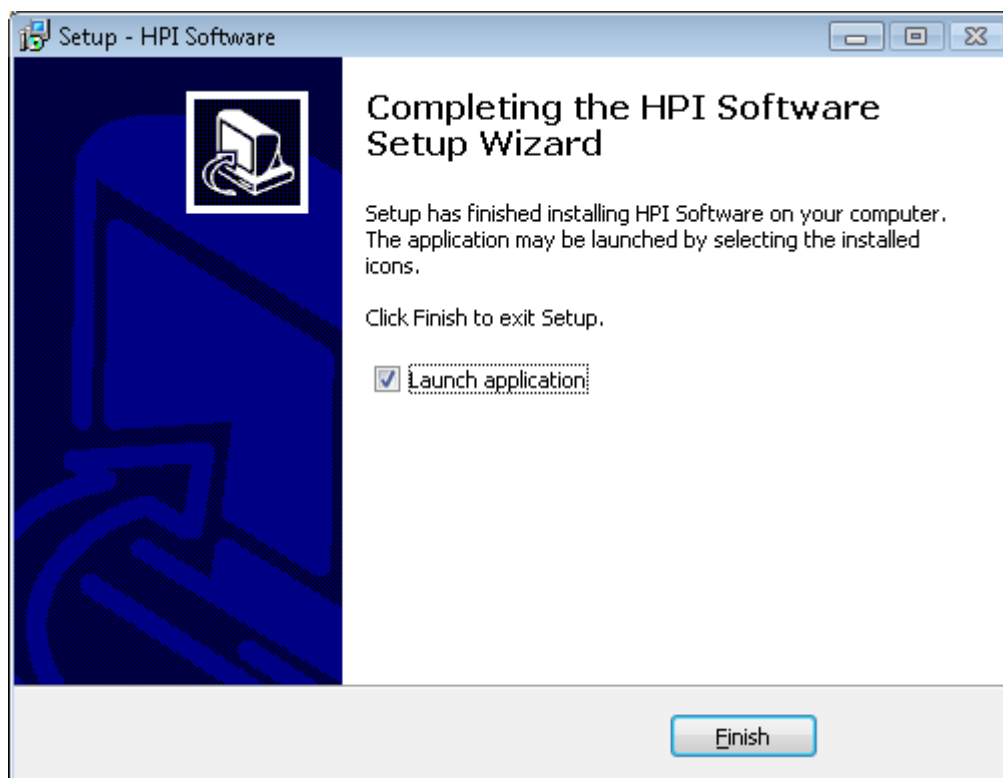
FIG.3.13. INSTALLATION SUMMARY WINDOW

In most cases, the installation is semi-automatic requiring only confirmation by the Enter key.

When the software is installed on the computer, also drivers should be installed. To complete this process, the system has to be connected by a USB cable to your PC. Driver installation is performed automatically by Windows.
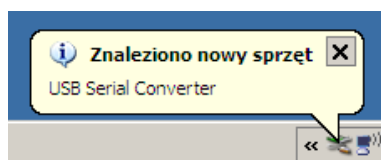
FIG.3.14. MESSAGE APPEARING WHEN THE NEW USB DEVICE IS FOUND.
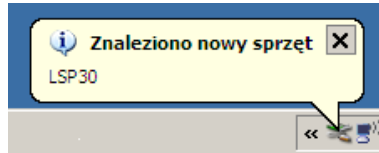
FIG.3.15. MESSAGE APPEARING WHEN THE DRIVER FOR HPI-3D DEVICE IS INSTALLED.

The *HPI Software* application can be launched from the HPI Software folder located in *Programs* tab in Windows *Start Menu* (assuming that the installation settings are not changed). The application can also be launched from the desktop, if the shortcut is created during installation.

FIG.3.16. ICON OF HPI SOFTWARE APPLICATION.

In order to uninstall the HPI Software application please choose *Uninstall HPI Software* from Menu Start.

FIG.3.17. ICON OF HPI SOFTWARE DEINSTALLATION APPLICATION

b. Elements of the Laser System

Number of the system elements is configurable and its configuration is related to the required application.

Following items are included in the standard set (for linear measurements):

1.	1 pcs	Laser head	
2.	1 pcs	Power Supply	
3.	1 pcs	Tripod stand	
4.	1 pcs	Linear retro-reflector **RL1**	
5.	1 pcs	Linear interferometer **IL1**	

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6.	3 pcs	Base temperature sensor	
7.	1 pcs	Air temperature sensor	
8.	1 pcs	Wireless strobe	
9.	2 pcs	Holding block **HB1**	
10.	2 pcs	Stainless rod **SR1**	
11.	2 pcs	Magnetic holder **UM2**	

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12.	1 pcs	USB Type B cable	

In the figure 3.18 there is shown a suitcase for transport and storage of the interferometer system.

FIG.3.18. THE SUITCASE FOR TRANSPORT AND STORAGE OF THE INTERFEROMETER SYSTEM.

Additional elements for angular measurements are:

1 x Angular Interferometer **IK1**,

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1 x Angular Retro-reflector **RK1**,

2 x Beam directing mirror **ZK1**,

1 x Rotary table **RE1**.

Additional elements for straightness measurements are:

1 x Wollaston Prism **WP2**,

1 x Wollaston Retroprism **WRP2**.

Additional elements for squareness measurements are:

1 x Right Angle Etalon for 3D measurements **RE3D**,

1 x Right Angle Etalon for Wollaston measurements **REW**.

c. Interferometer setup for measurement

The Laser Interferometer *HPI-3D* is supplied from autonomous 24VDC/5A Power Supply. Communication with a PC computer is performed by USB or Bluetooth interface. The USB connection is faster thus it gives more possibilities in some measurements (i.e. Vibration or Dynamic).

Before starting the measurements the *Laser Head* (**1**) should be placed on the *Tripod stand* (**3**) and connected to the Power Supply connector on the back of the laser head. The Laser Head can be also placed directly on the machine because it is equipped with magnetic base.

If the USB connection is used then the USB cable (**10**) should be connected to the male socket on the back panel of the Laser Head (fig. 3.19). The second end of the cable should be plugged into the USB socket of a PC computer. For the Bluetooth connection only power connection is necessary.

3

Power Button

Power Connector

USB Connector

Extension Connector
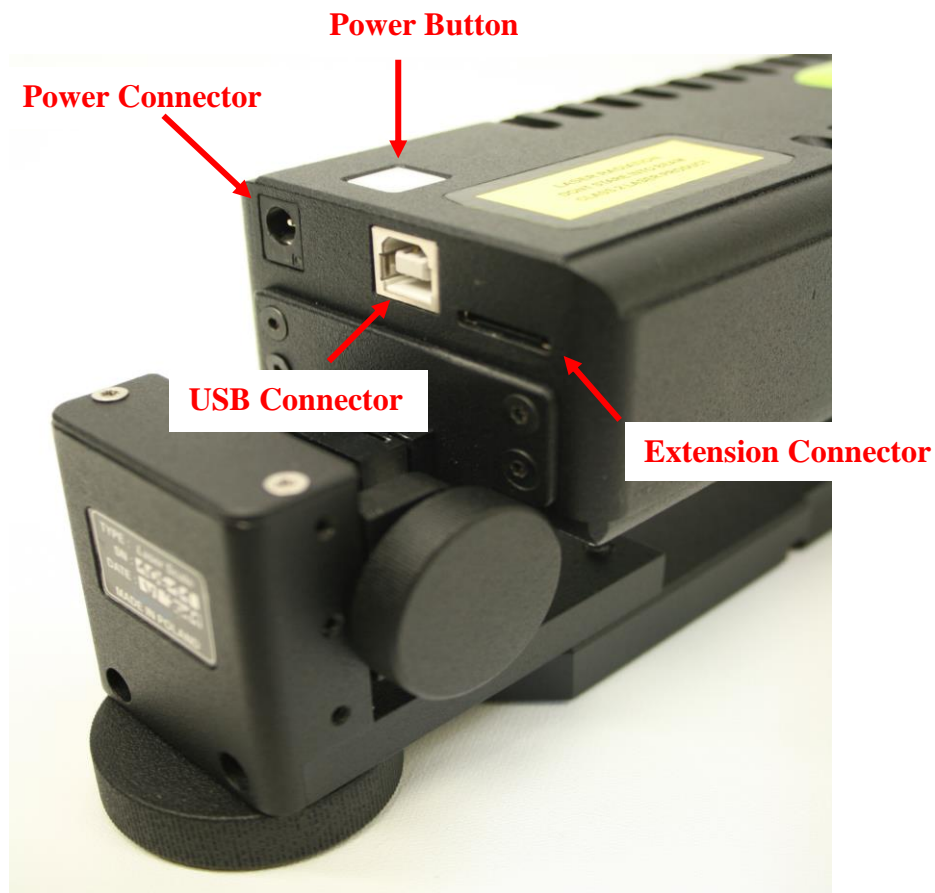
FIG.3.19. CONNECTIONS OF THE HPI-3D.

Through the Extension Connector it is possible to drive many peripherals directly from the laser head. This give huge possibilities of customization of the usage of the laser interferometer – e.g. in emulation of glass scales, driving

stepping motors, dynamic measurements, etc. Standard connector pinout is described in Technical Data at the end of this manual.

Environmental (**6**) and base temperature (**7**) sensors are connected to the Laser Head wirelessly. The sensors are maintenance free – they do require neither switching on/off nor charging. When the Laser Head is not powered they remain in power down mode. Sensors can only "wake up" and start to measure when the Laser Head is powered by the Power Supply unit.

Sensors are powered from 1/2AA 3.6V lithium battery (number 14250). It can be replaced, when the battery strength monitor on **Display** screen (see below in this Chapter) shows that it is depleted, after removing the cap of the sensor. The battery life time in the power down mode only is more than 30000 hours. The combined life time of the battery for the sensor is 10000 hours.

Wireless Strobe is used to manually capture points during measurements (see appropriate chapter).

The **Power Button** is used for switching the laser on or off and for signalization of the internal state of the laser. The meaning of the signaling of the Power Button is described in the table 3.1.

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Power Button state	State description
Red	Laser head powered on properly. Laser not working
Red – blinking fast	Laser head powered on properly but main CPU firmware is corrupted. Firmware programming necessary.
Orange / Green blinking slow	Laser switched on; Stabilization phase 1
Orange / Green blinking fast	Laser switched on; Stabilization phase 2
Green - blinking	Laser switched on; Stabilization phase 3
Orange	Laser stabilizes. Beam path unaligned.
Green	Laser stabilizes. Beam path aligned. System ready for measurements!

TAB.3.1. POWER BUTTON LED STATES

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d. Powering the system on

i. Starting hardware

The HPI-3D has only one soft-switch on the top of the laser head. Starting the laser is possible by holding the *Power Button* for 3 seconds (see figure 3.19) or from the HPI software by clicking on the bottom bar of the screen in "Laser" text (see fig. 3.20).
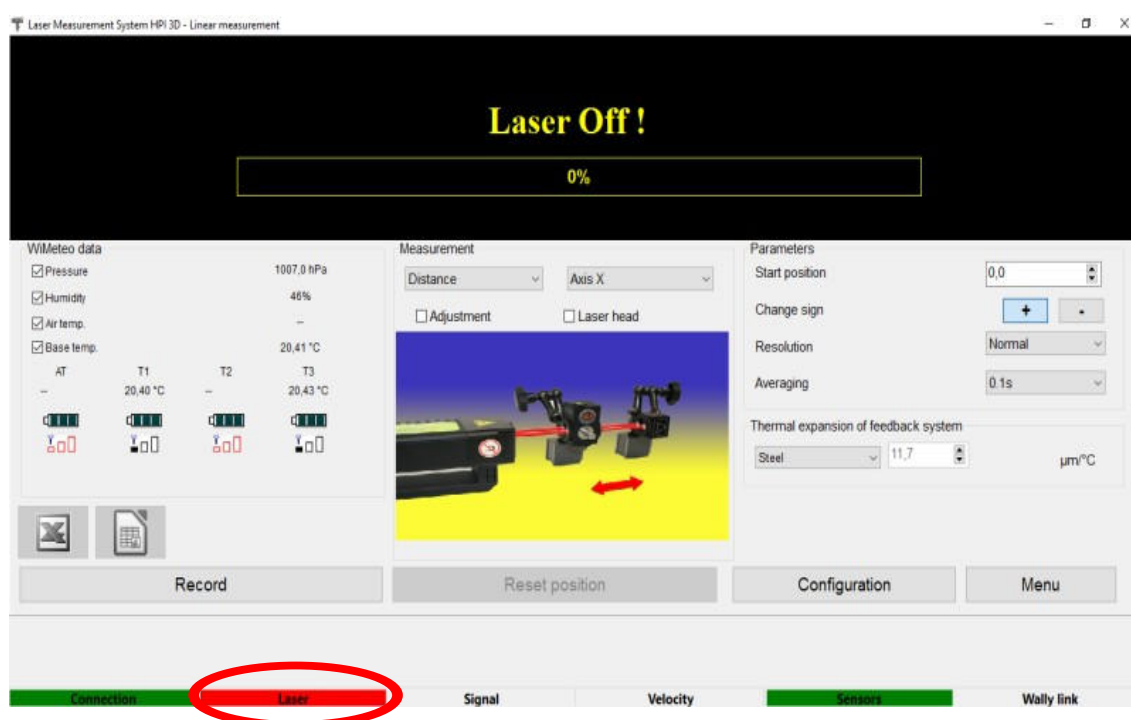
FIG.3.20. POWER SWITCH OF THE HPI-3D

ii. Starting software

When the software starts a splash screen appears (figure 3.21). Pressing F5 on the PC keyboard or the button marked

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Simulator causes the software to switch into simulation mode – connection to a HPI-3D device is emulated even if there is a real device connected to the computer!

In the bottom part of the splash screen there are shown all HPI-3D devices currently connected to the PC either by Bluetooth or USB interface. The devices paired up with the PC over Bluetooth are visible in blue. Devices connected over USB are shown in red.
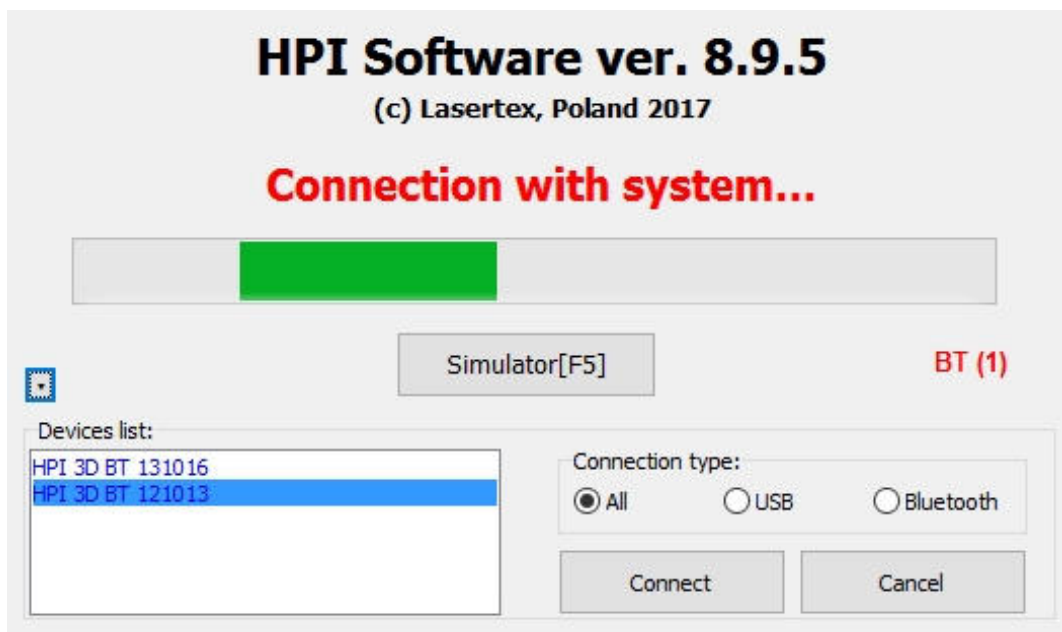
FIG.3.21. SPLASH SCREEN

After the splash screen a connection screen appears (figure 3.22) where the connection trials are shown. In the right bottom part there is shown the interface over which the software is actually trying to obtain a connection (see a red circle in the figure 3.22). After software installation, by default, the first trials are made over USB interface. When

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there is a successful connection made over other interfaces then the "successful" interface is taken as a first choice in next runs.

FIG.3.22. CONNECTION SCREEN

FIG.3.23. MAIN MENU

After the connection screen there the **Main Menu** appears as shown in the figure 3.23. There are two rows of buttons. Button **Display** opens the window with basic control of the laser operation. It is described in details later in this Chapter. Button **Configuration** opens configuration window. Pressing **Exit** button closes the application.

Other buttons open measurement screens. All options are described in details in following Chapters. Because of abundance of measurement types offered by the HPI-3D, some of the options are not visible and can be reached by using the buttons with arrows in the second row.

Connection problems troubleshooting is described in the *Troubleshooting* chapter.

e. Getting basic information from the system.

When the software is launched and the system is connected the option **Display** in the **Main Menu** should be chosen. The window shown in the figure 3.24 appears. If the output beam of the laser is properly redirected to the Laser Head (e.g. with the use of the retroreflector RL1) and laser maintain the stabilization (Laser status bar is green), the **Beam Strength** (a green indicator on the screen) shows 100% of the signal level. If the laser heats up to maintain the stabilization the **Beam Strength** appears and disappears. The speed of changes is related to the temperature of the laser. During the heating up the system is ready for the alignment of the optical path (see chapter 4).
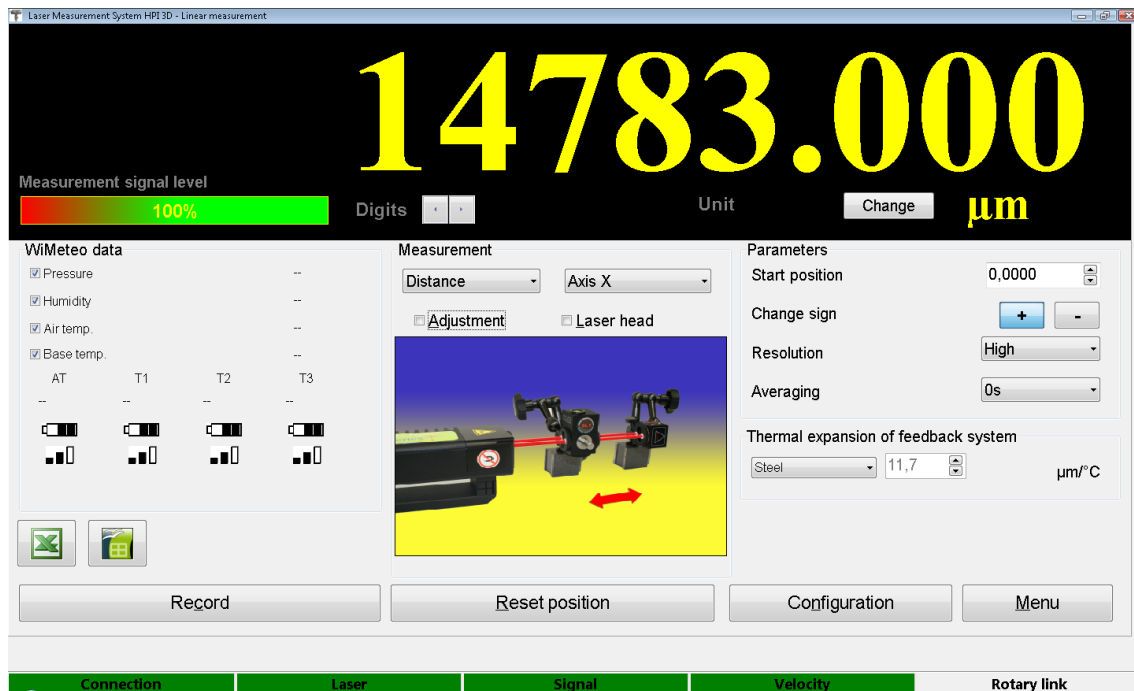
FIG.3.24. DISPLAY WINDOW

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On the Display screen there are a status bar and four panels:

- Panel (figure 3.25) where are presented a digital result of the measurement and the signal level. There are also located buttons for changing the **Units** and a number of displayed **Digits** in the result.

3

FIG.3.25. PANEL WITH MAIN DISPLAY

- Panel **Environment** (figure 3.26) where data obtained from the Environmental Compensation Unit (ECU) is shown. On the screen there are presented: temperature, pressure and humidity of the atmosphere (*Pressure, Humidity,* and *Air Temp.*) and temperature of the base which is measured by three base temperature sensors and averaged (*Average temp., T1, T2* and *T3*). For each sensor the battery voltage and signal strength are presented. Data from Environmental Compensation Unit can be also controlled by the user. It is possible switch off the data coming from ECU and insert parameters of the atmosphere manually. In the lower left corner there are icons setting up a link to Microsoft

Excel or OpenOffice Calc (if installed). This link allows registering measurement in Excel or Calc by each STROBE button press.
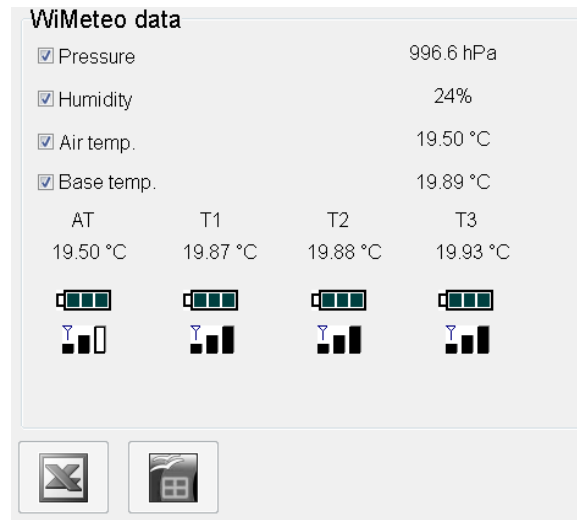
FIG.3.26. ENVIRONEMNTAL PANEL

- Measurement Panel (figure 3.27) contains basic information about current measurement. With the left drop-down list the type of the measurement is changed. Right drop-down list is used for an axis selection. If **Adjustment** or **Laser head** checkbox is not ticked, the pictorial view of optical configuration is presented. It reflects measurement type (i.e. distance, speed, angle, straightness) and axis (i.e. X, Y, Z). **Adjustment** and **Laser head** options are selected by the checkboxes located on the panel. However only one of them can be active, because they are mutually exclusive. Both options are very helpful in optical path alignment process (see chapter 4).
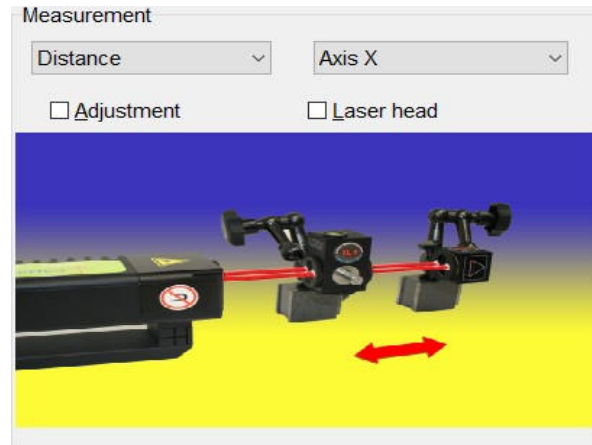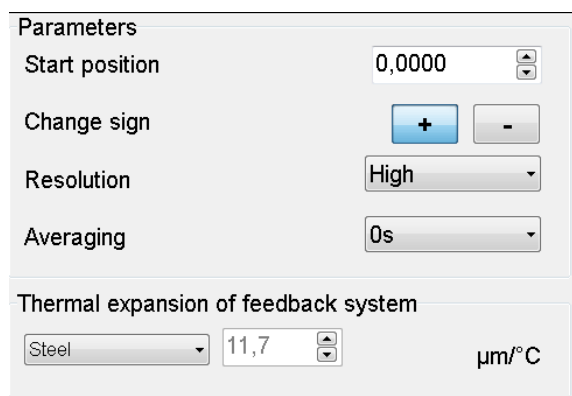
FIG.3.27. MEASUREMENT PANEL

- Panel **Parameters** (figure 3.28) is used for configuration of the measurement system. **Change sign** option selects whether enlarging distances between the retro-reflector and the interferometer gives positive (default "+") or negative result on the display. **Thermal expansion of feedback system** option is used to select the material from which a feedback measurement system of the measured machine is made of. Setting the proper value of the expansion coefficient is very important to obtain the highest accuracy of the system. Option **User** makes it possible to enter any value of the thermal expandability coefficient. **Resolution** enables to change between *High* (0.1 nm) and Normal (1 nm) system resolution.

FIG.3.28. PARAMETERS PANEL

3

Status Bar (figure 3.24) presents state of the Laser Head and state of the measurements. There are four fields: Connection, Laser, Signal and Velocity. In proper operation they should all be green. In table 3.2 there are shown the possible states of the fields.

Field	State description	Required action
Connection (red)	No connection to the Laser Head	Click on the field to open Configuration window. Restart the connection
Connection (green)	Laser Head is connected to the computer properly	No action necessary
Laser (red)	Laser Head off	Click on the field to switch the laser on
Laser (grey/red)	Laser Head on but not ready	Wait for the laser to become ready
Laser (yellow)	Laser Head near unstable region.	Finish performed measurements and click on the field to allow the head to find new stable point

3

Indicator	Condition	Action
Laser (green)	Laser Head works well	No action necessary
Signal (red)	Beam strength too week.	Using beam indicator adjust optical components to obtain satisfactorily beam strength, then click on the field to reset the error
Signal (yellow)	Beam strength fine but not calibrated	Beam path between IL1 and RL1 optical components should be obstructed for a while so the laser can calibrate beam parameters
Laser (green)	Beam strength fine	No action necessary
Velocity (red)	Velocity of the registered movement too high	Click on the field to reset the error
Velocity (green)	Velocity of the registered movement in range	No action necessary
Sensors (yellow)	No measuring sensors detected	At least 3 minutes after powering up the laser head: - Check if sensors are close enough to the laser head; - Check/replace sensors batteries;
Sensors (green)	At least one sensor is working	No action necessary
Rotary (gray)	Rotary encoder not detected	Check if rotary encoder is switched on

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Rotary (yellow)	Rotary encoder present. No link to rotary set.	Double click on the field for the laser to set the link to rotary
Rotary (green)	Rotary link set	No action necessary

TAB.3.2. STATUS BAR STATES

3

If measurements are performed with automatic compensation of the atmosphere parameters and the compensation of the base temperatures, one should:

- Place the air temperature and humidity sensors THS on the machine in the vicinity of the laser beam.

- place the sensors of the base temperature along the measured axis on the machine base

Measurements performed without automatic compensation are referred to normal conditions: temperature 20 °C, pressure 1013.25 hPa, humidity 50 %.

The measured machine is compensated to the temperature set in the *Reference temperature* edit box, located in the Configuration->Meteo panel (see figure 3.29). By default the reference temperature is set to 20 degrees C and should not be change unless necessary.
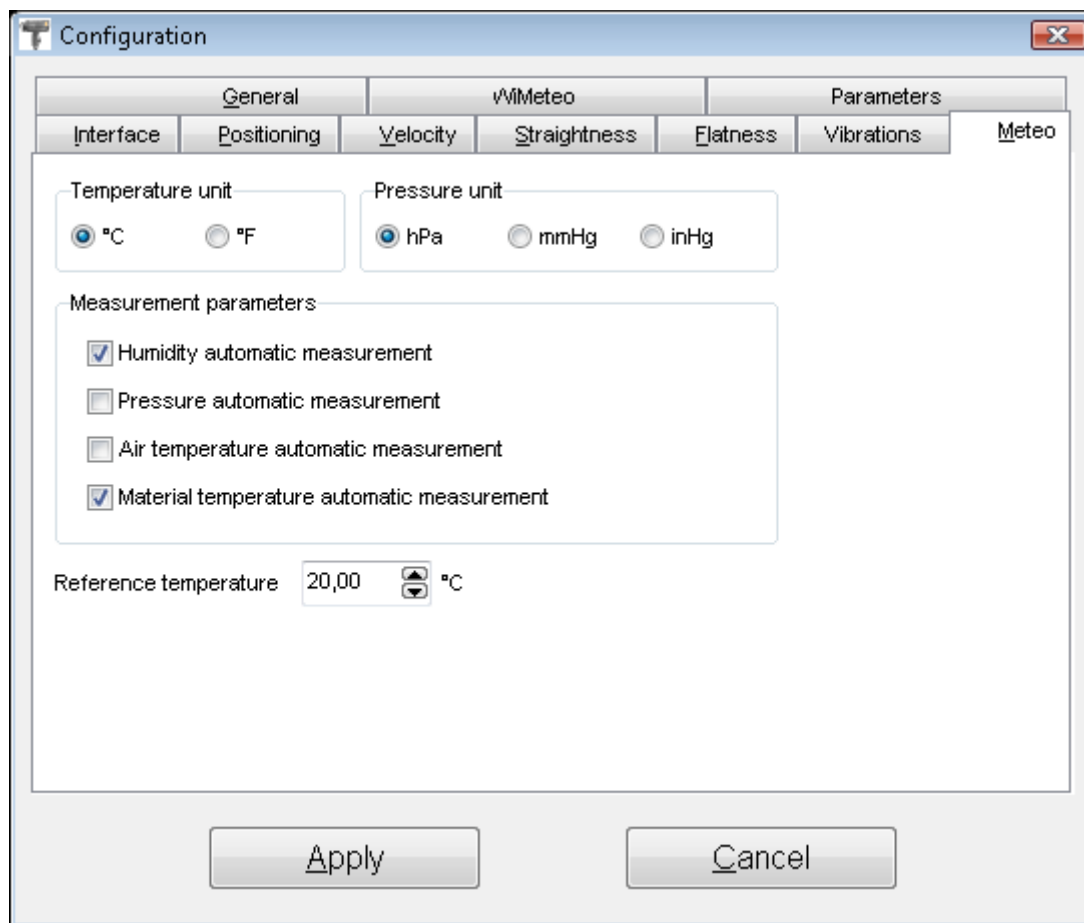
FIG. 3.29. CONFIGURATION WINDOW – METEO PANEL

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f. Recording mode

The long term changes of the length of machine axes under changes of temperature condition may give the information about thermal properties of the machine. This kind of measurements called "Recording mode" may be chosen by pressing RECORD button on the **Display** screen. This switches the system into the data recorder mode. The time interval of the records could be programmed from the computer by setting a required value.
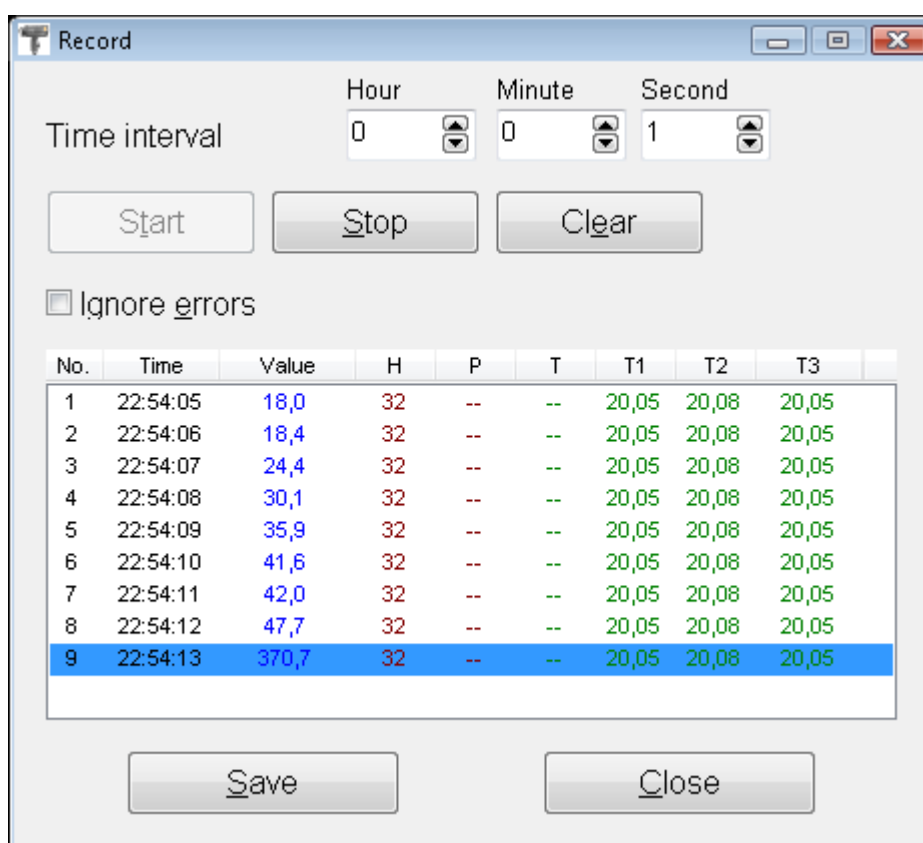
FIG.3.30. RECORDING DATA MODE WINDOW

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Pressing "End Recording" finishes the data recording. The results can be saved with the choice of "Save to file". In fig. 3.30 the example of Data Record is presented.

g. Flat mirror measurements - option

The flat mirror measurements option enables to measure the displacement, velocity, positioning, and vibrations of a flat surface. The surface should have a mirror quality (surface flatness $\lambda/8$) and the reflection coefficient not less than 50%. The aluminum, gold or dielectric mirror mounted to the moving part is suggested. There are two possible configurations: double pass setup Fig. 3.31 and single pass setup 3.32. The resolution of the double pass setup is two times bigger than the single pass. The setup consists of the laser head, the flat mirror interferometer **FMI** and the flat mirror. In order to obtain correct result of measurements with double-pass flat mirror configuration, the option *double-pass* in the *Configuration* window should be chosen (fig. 3.33).

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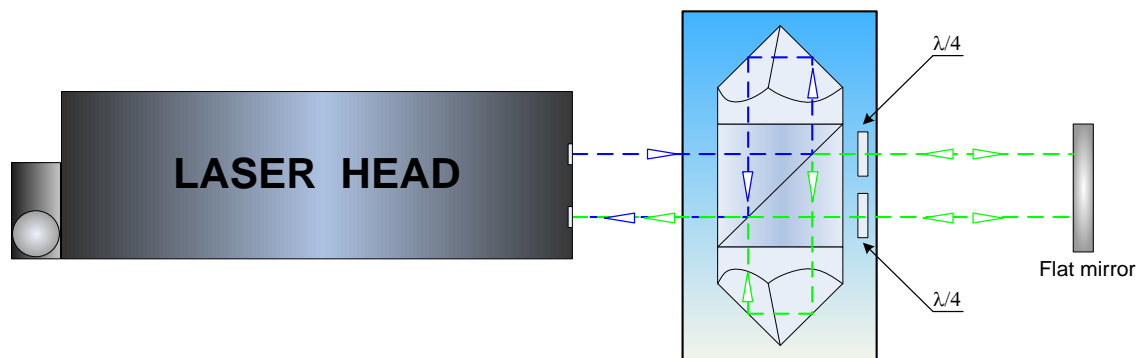
FIG. 3.31. DOUBLE PASS FLAT MIRROR INTERFREOMETER

3
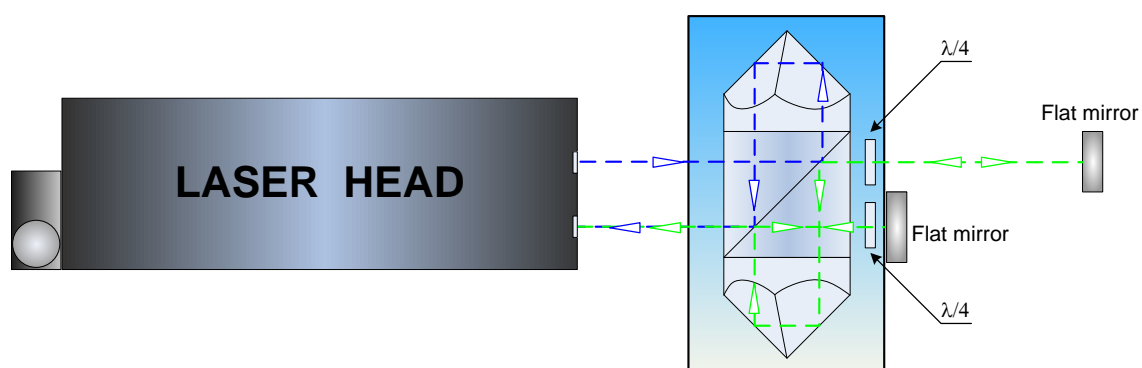
FIG. 3.32. SINGLE PASS FLAT MIRROR INTERFREOMETER
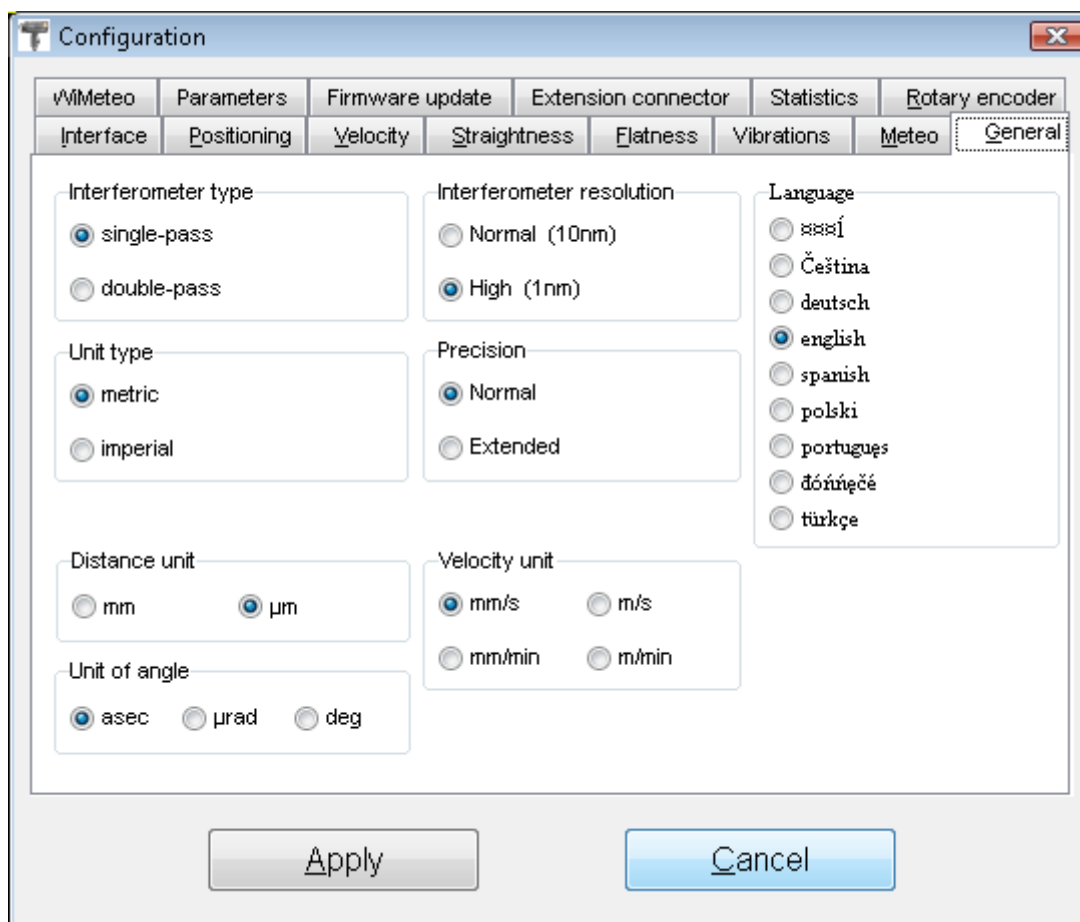
FIG. 3.39. CONFIGURATION WINDOW – INTERFEROMETER TYPR CHOICE

4.   BEAM ALIGNMENT

4

The alignment of the optical path **difficult** and **laborious** part of the whole measurement process. Be very **careful** reading this chapter!

a. Introduction

Beam alignment is a process in which the user, with the use of certain mechanical arrangements, makes the direction of the laser beam **parallel** to the direction of the movement in a measured axis. If the beam is not correctly aligned an effect like the one shown on Fig.4.1 may happen, i.e. the position of the beam returning on the detector in the Laser Head from the moving retroreflector may vary with the position of the retroreflector resulting in a cosine error (see chapter 17) and/or misalignment of the optical path (no *Beam Strength*).
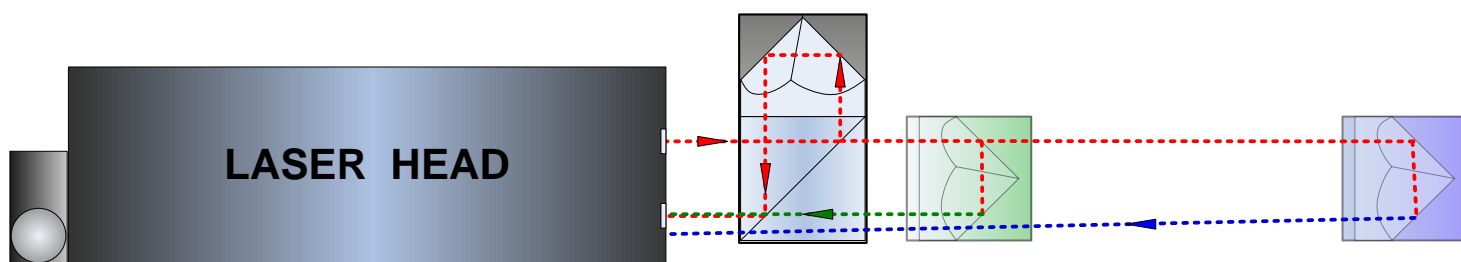
LASER HEAD

FIG.4.1. ILLUSTRATION OF BEAM MISALIGNMENT

The alignment of the optical set up should be conducted in the option **Display**. It can be done during Laser Head heating. Final check should be made when the system is ready to work.

b. Electronic alignment tools

The beam path alignment process is usually time consuming so in order to simplify and speed it up the HPI-3D provides, together with standard mechanical elements like diaphragms, three unique electronic tools.

The first is a function of electronic position of the laser head in space – **Display/Laser Head.** This option is a useful tool for the alignment of laser head position in space.

Another useful and unique tool supporting alignment is the *Electronic Beam Alignment* switched on in **Display/Alignment option.** With this tool the position of the beams returning to the laser can be controlled very accurately.

The third tool is the *Electronic Beam Indicator* showing if the beam returning to the laser is strong enough to make proper measurements. For indicating the beam strength the physical Power Button on the laser head is used. When the laser is ready for operation then this button stops blinking but turns orange or green. The second color means the proper value of beam level.

c. Basic rules of beam alignment

4

With the HPI-3D there are delivered three main types of optical components: linear optics, angular optics, Wollaston optics. Although the elements seem different the beam path alignment is similar for all cases. In the points below the process is described in more details with explanation of differences for the different types of optics.

In the Figure 4.2 there is shown a block diagram of the basic rules of beam path alignment. All points are covered in details in the paragraphs below.

Start

Set the laser head firmly on the tripod or on the machine bench

Switch the laser on and set the position of the laser so the beam is parallel to the measurement axis

Set proper optical components along the laser beam path.

Move the optical components along the measurement axis and regulate the position of the laser head so the beam always returns to the laser – use diaphragms

Repeat previous point with the use of Electronic Beam Alignment tool – (diaphragms in „work" position)

Control the strength of the returning beam either wirh Electronic Beam Indicator on the laser or with software beam indicator on the PC

Correct position of the laser if necessary

Stop

FIG.4.2. BASIC BEAM ALIGNMENT RULES

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d. Preparations

The Laser Head should be firmly attached to the tripod or put directly on the machine bench. The tripod should not touch the machine as it may cause vibration of the Laser Head and the optical path. Special attention should be paid not to move the legs of the tripod during the measurements. The alignment process would have to be repeated then.
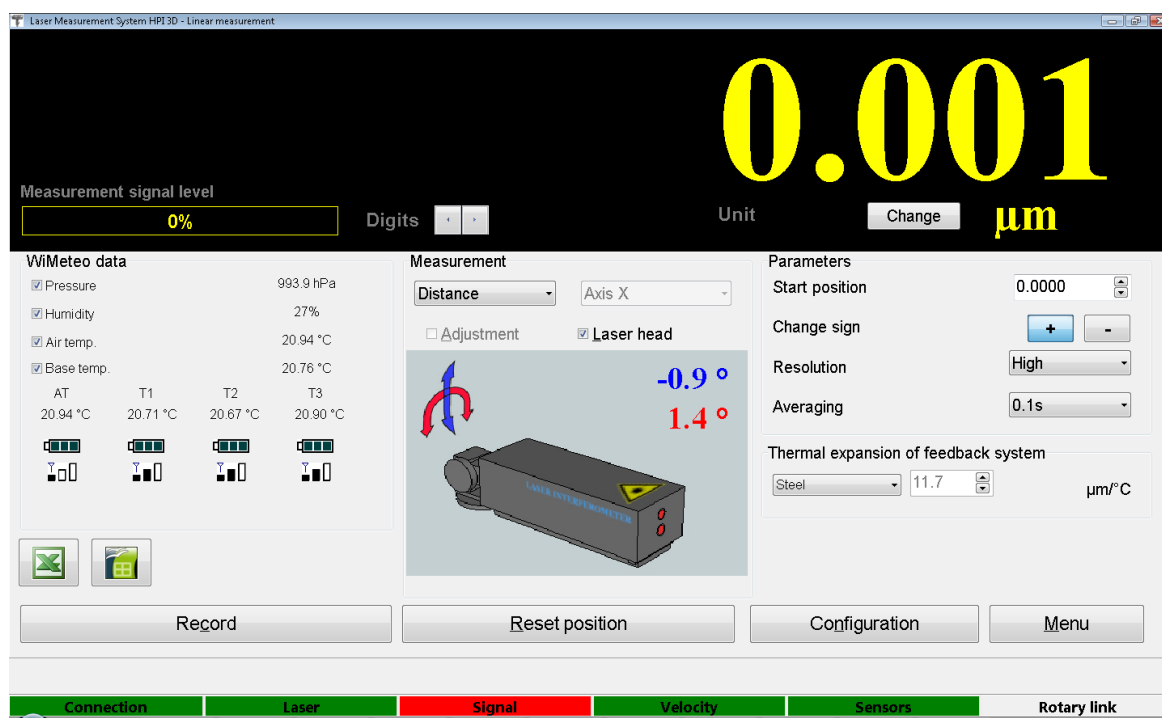
FIG. 4.3 ILUSTRATION OF THE FUNCTION LASER HEAD

The mechanical elements of the tripod help in the adjustment process. The tripod must be leveled, and after that with the function **Laser Head** the position of Laser Head must be set according to the angle of the measurement path.

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i. Diaphragm

The diaphragm of the laser beam on the front panel of the Laser Head (figure 4.4) helps in the process of alignment. The diaphragm can be placed in two positions:

" **Alignment**" – the laser beam goes out through opening in the diaphragm about 2 mm diameter,

" **Measurement**" from the Laser Head goes out beam about 8 mm diameter,

FIG.4.4. DIAPHRAGM POSITIONS. A) MEASUREMENT, B) ALIGNMENT

During transportation or when system is not used, correct position of diaphragm is **alignment** position. In this position optics is safe from getting dirty, covering with dust and accidental damage during transportation.

The Diaphragms are also used on most available optical components – see figure 4.5 – with the exception of Wollaston optics.
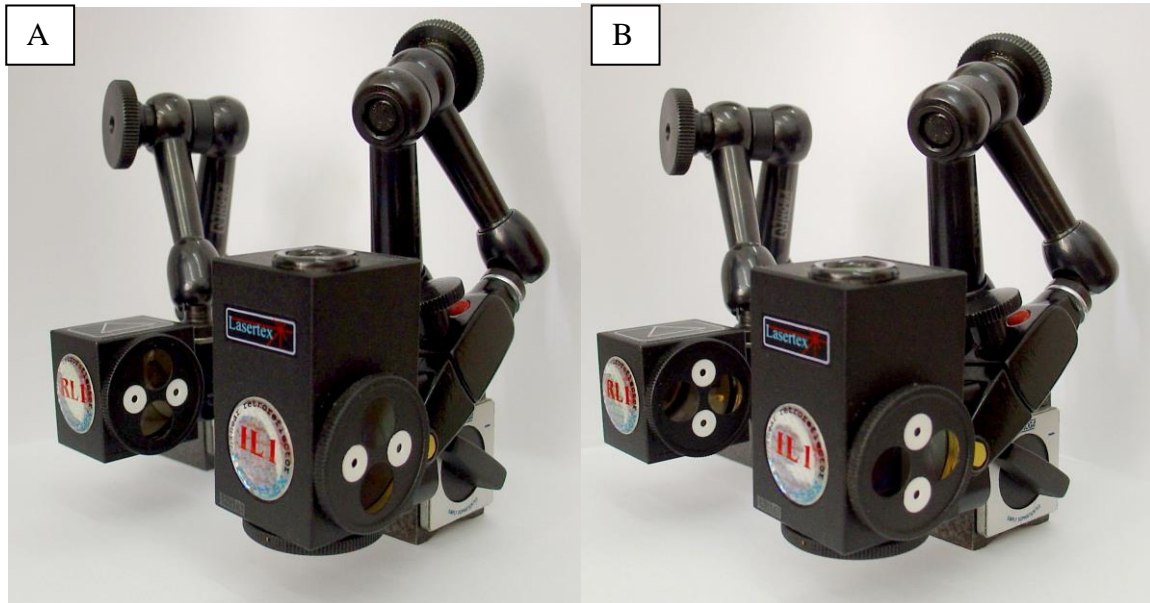
FIG.4.5. DAPHRAGMS: ALIGNMENT POSITION (A) AND WORK POSITION (B)

If it is required then the diaphragms can be taken off and put back later on.

4

ii. Laser head alignment elements

a)

b)

Vertical
movement
(axis Z)

Locking
screw

ball joint

Vertical
movement
(axis Z)

Horizontal
movement
(axis Y)

Vertical
rotation α

Horizontal
rotation β
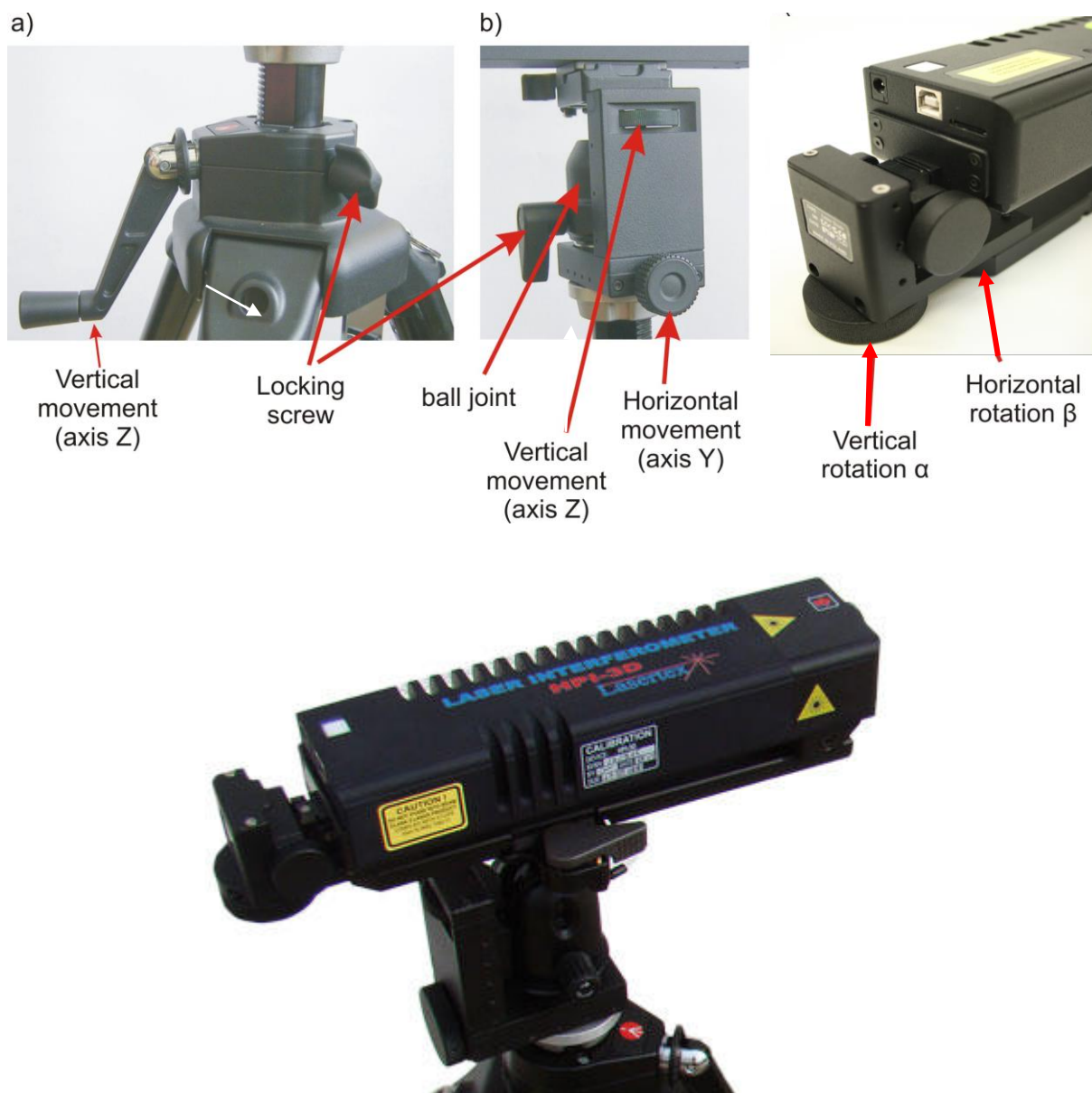
FIG.4.5. THE LASER HEAD ALIGNMENT ELEMENTS

In order to set the position of the beam in space properly the laser head has a few regulation elements as shown in the figure 4.5. The elements are placed on the swivel head of the tripod (figure 4.5a and 4.5b) and on the base of the laser head (figure 4.5c).

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Elements placed on the tripod are in general used for linear vertical and horizontal movement of the beam position, while the elements available on the laser head base are for angular vertical and horizontal movement of the beam.

iii. Electronic Beam Alignment tool

One of the unique features of the HPI-3D laser is the Electronic Beam Alignment tool. This is a software tool displaying the position of the beams returning to the laser. The tool can be activated in the **Display** option by checking **Adjustment** check box in the *Measurement* panel – see figure 4.6.
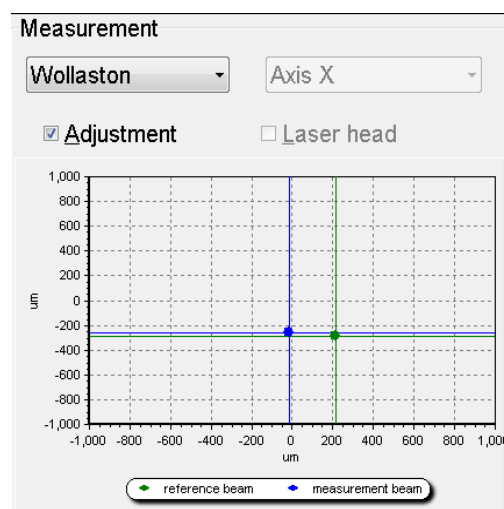
FIG.4.6. ELECTRONIC BEAM ALIGNMENT TOOL

The tool shows two crosses: green and blue. The green cross shows the position of the reference beam, while the blue one the position of the measurement beam.

The exact meaning of the crosses depends on the type of used optical components. The terms "reference beam" and "measurement beam" have sense only for linear optics. In this case the "reference beam" means the beam "from" IL1 element while "measurement beam" is the beam reflected back by RL1.

Each time the optical configuration of linear optics is changed it is required to stop the beam between IL1 and RL1 for 2-3 seconds. Laser needs this operation to conduct calibration procedures.

Attention! It is inadmissible to place one of optical elements (i.e. RL1 or IL1) outside the machine on an additional stand – the system measures then also displacements of the machine in relation to the stand!).

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e. Beam alignment process for linear optics
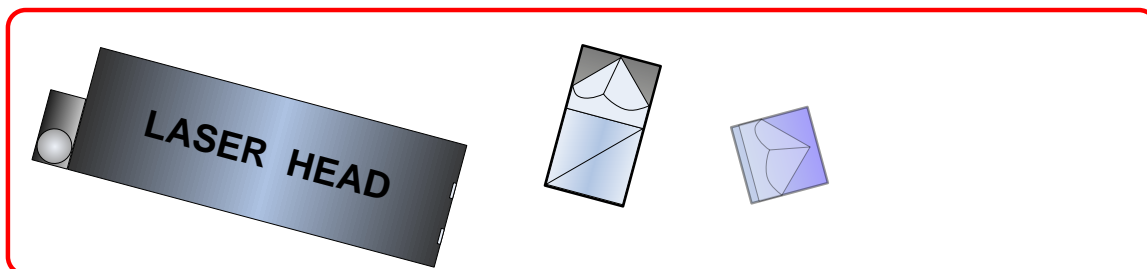
1. Mount Laser Head, IL1 and RL1 on the measured machine
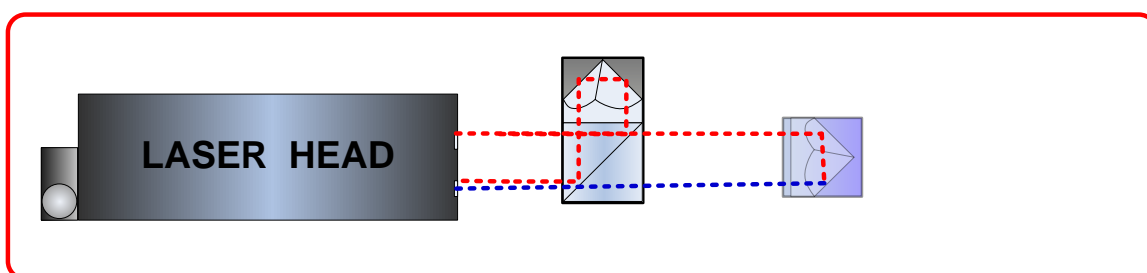
2. Turn on the laser and align all elements along the measurement axis
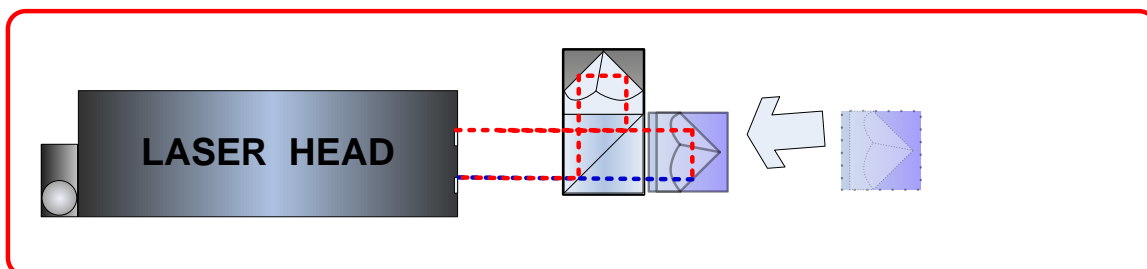
3. Move the RL1 very close to IL1 (they can touch each other). Set their initial position so the beam returns back to the laser.
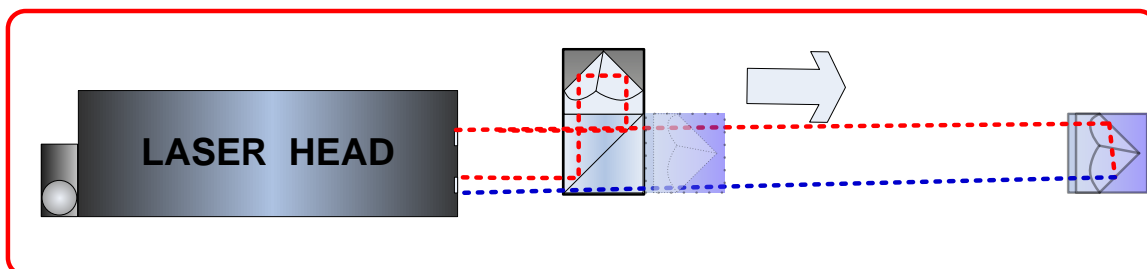
4. Move the RL1 from the IL1
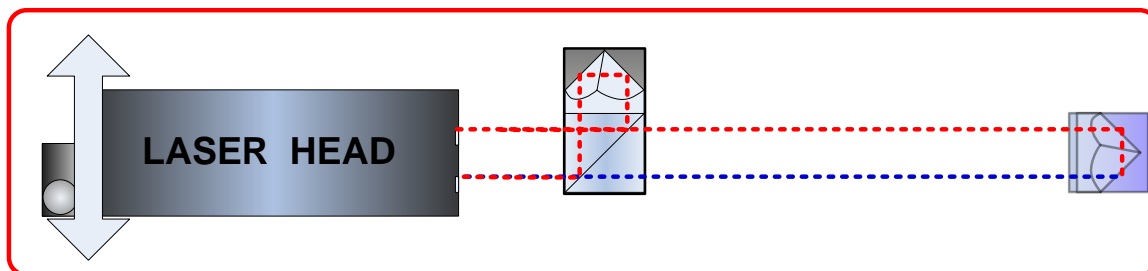
5. By regulation of the laser head position align the beam path so that both beam overlap on the input of the laser.

REMARK 1: With angular regulation the position of the beam from RL1 should be regulated. Position of the beam returning from IL1 should be regulated with mechanical components on the tripod.

REMARK 2: If the laser head is mounted directly on the machine then the position of the beam returning from IL1 should regulated by direct movement of the IL1 component.
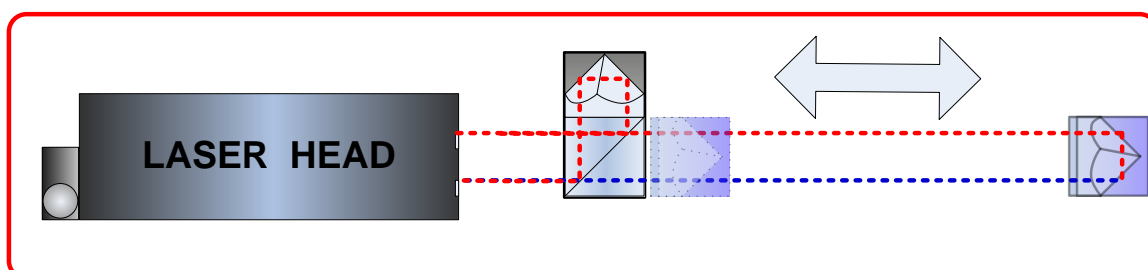
6. Move the RL1 back to IL1 (the components must not touch!) and check the quality of the beam path alignment. Use availble electronic tools – Beam Level Indicator and Electronic Beam Alignment Tool.

Attention! The position when the interferometer touches the retro-reflector can serve only to adjust. Be sure that during measurements in extreme nearest measuring position the retro-reflector does not touch the interferometer, because it can be a source of measuring errors.

f. Beam alignment process for angular optics

1. Mount Laser Head, IK1 and RK1 on the measured machine

2. Turn on the laser and align all elements along the measurement axis
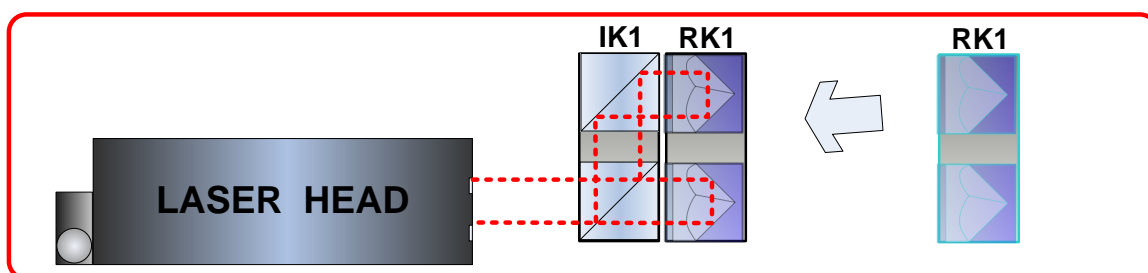
3. Move the RK1 very close to IK1 (they can touch each other). Set their initial position so the beam returns back to the laser.
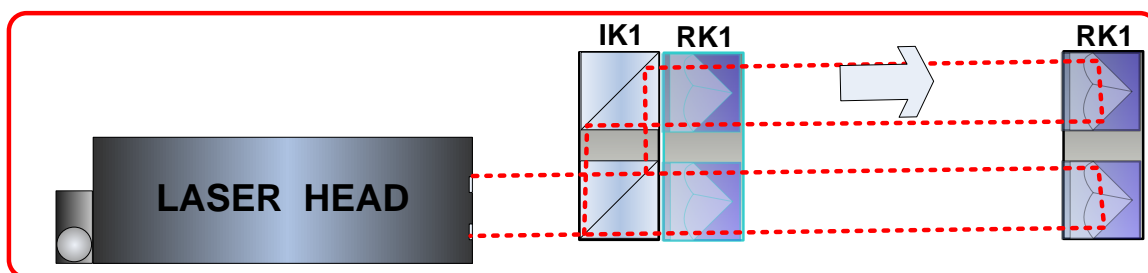
4. Move the RK1 from IK1.
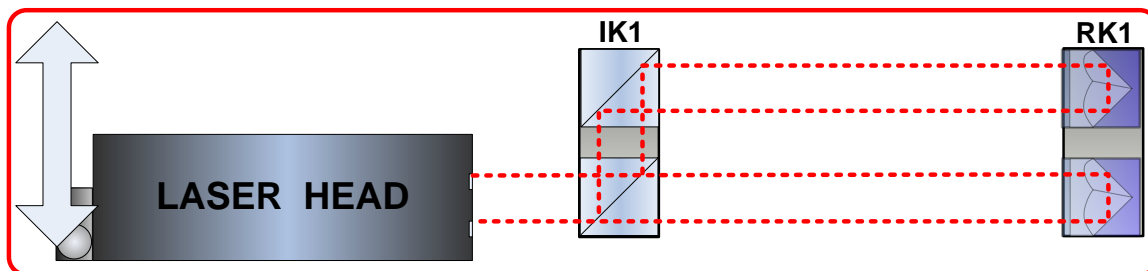
5. By regulation of the laser head position align the beam path so that both beam overlap on the input of the laser.
REMARK: If the beams do not overlap then it means that the IK1 is rotated against RK1. Check the roll of laser head against IK1 and RK1 – it should be zero!

6. Move the RK1 back to IK1 (the components must not touch!) and check the quality of the beam path alignment. Use available electronic tools – Beam Level Indicator and Electronic Beam Alignment Tool.

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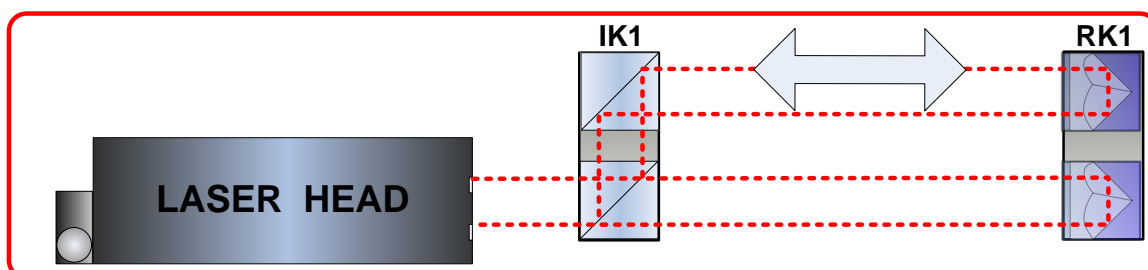
g. Beam alignment process for Wollaston optics
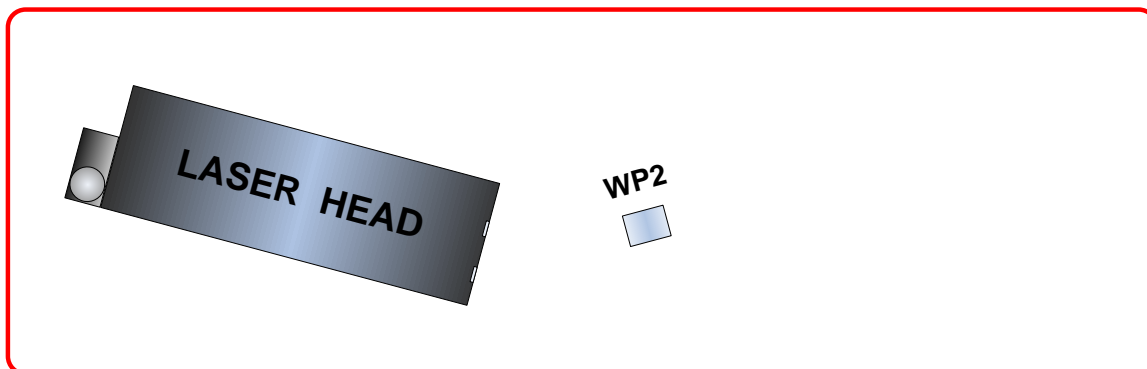
1. Mount Laser Head and WP2 on the measured machine
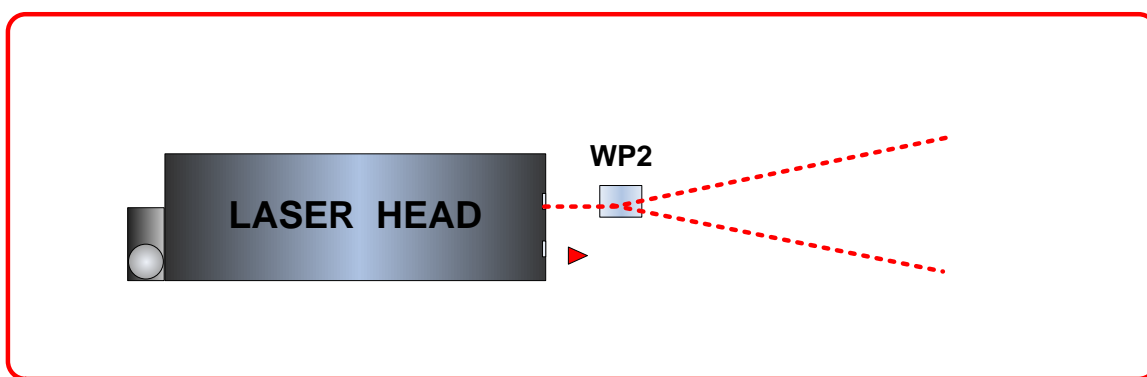
2. Turn on the laser. Switch diaphragms both on the WP2 and the laser head to the alignment position. Insert the WP2 in the laser beam path so that the beam passes through the middle of both diaphragms of the WP2
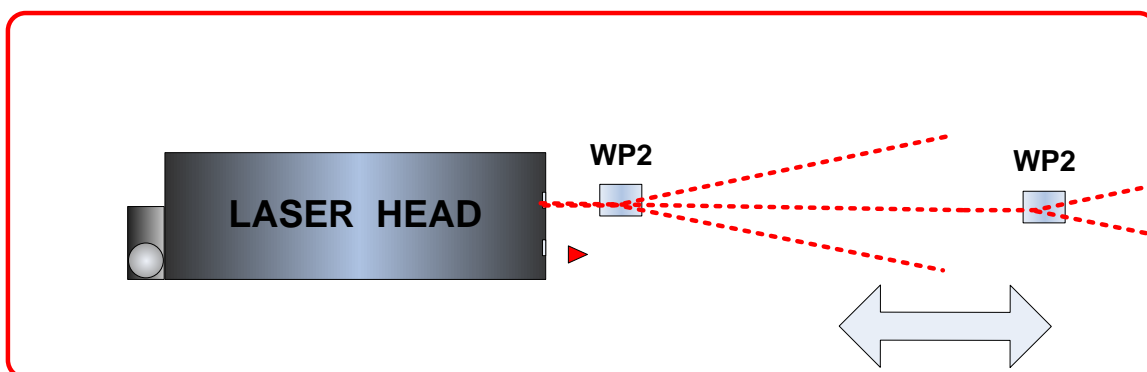
3. Move the WP2 along the measurement axis. Aling the laser position so that the beam passes always through the middle of the WP2 diaphragms.
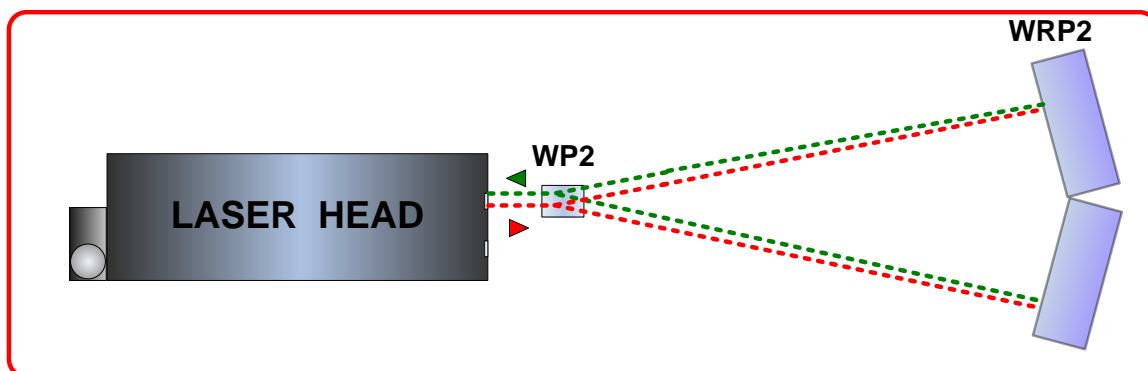
4. Insert WRP2 at the end of the measurement path.
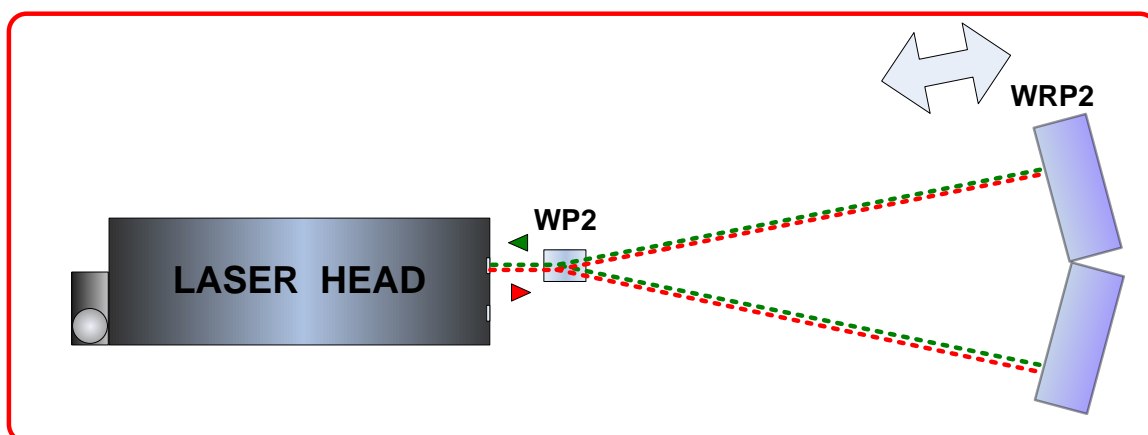
5. Regulate the angle of the WRP2 (with the large knob on the top) so that the reflected beam returns to the laser head
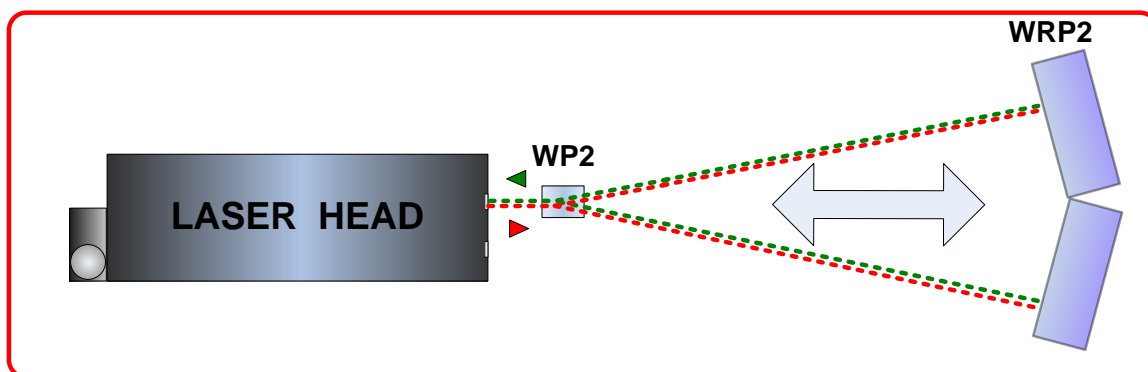
6. Move the WRP2 back to WP2 (not closer than 30 cm) and check the quality of the beam path alignment. Use available electronic tools – Beam Level Indicator and Electronic Beam Alignment Tool – the beams on the Alignment Tool have to overlap!. If they not over lap then rotate the WP2 so they are onto each other.

h. Beam alignment of linear optics with angle etalon
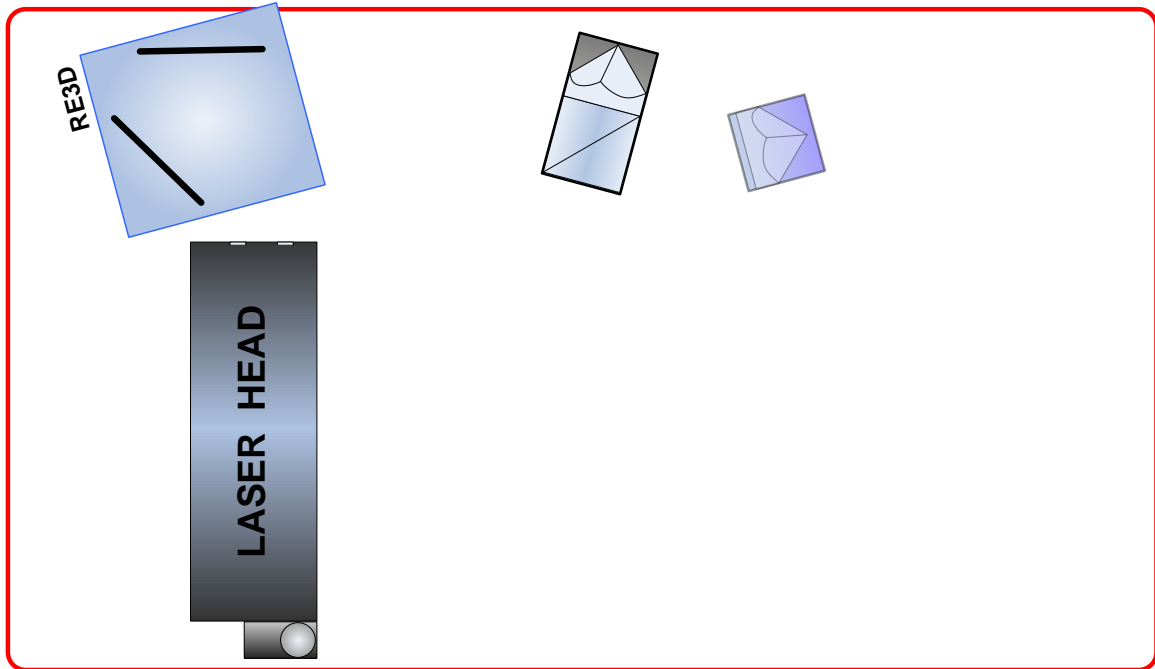
1. Mount Laser Head, IL1, RL1 and RE3D on the measured machine
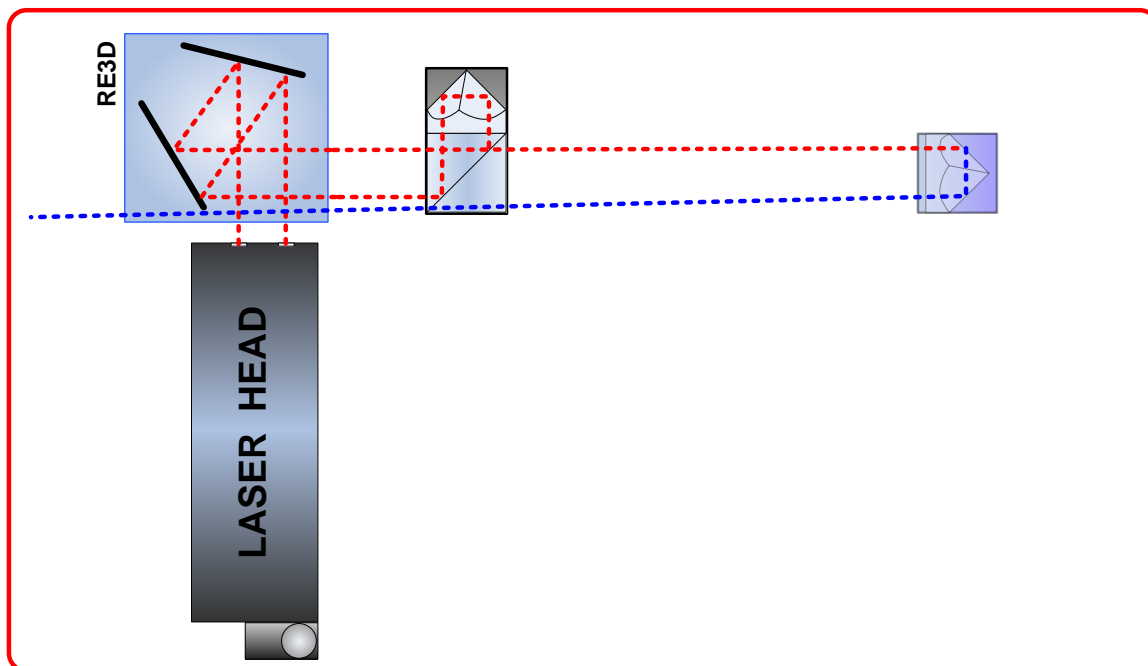
2. Turn on the laser and align all elements along the measurement axis

3. Move the RL1 very close to IL1 (they can touch each other). Set
   their initial position so the beam returns back to the laser.

4

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4. Move RL1 from IL1

5. By regulation of the laser head position align the beam path so that both beams overlap on the input of the laser.
REMARK 1: With angular regulation the position of the beam from RL1 should be regulated. Position of the beam returning from IL1 should be regulated with mechanical components on the tripod.
REMARK 2: If the laser head is mounted directly on the machine then the position of the beam returning from IL1 should be regulated by direct movement of the IL1 component.
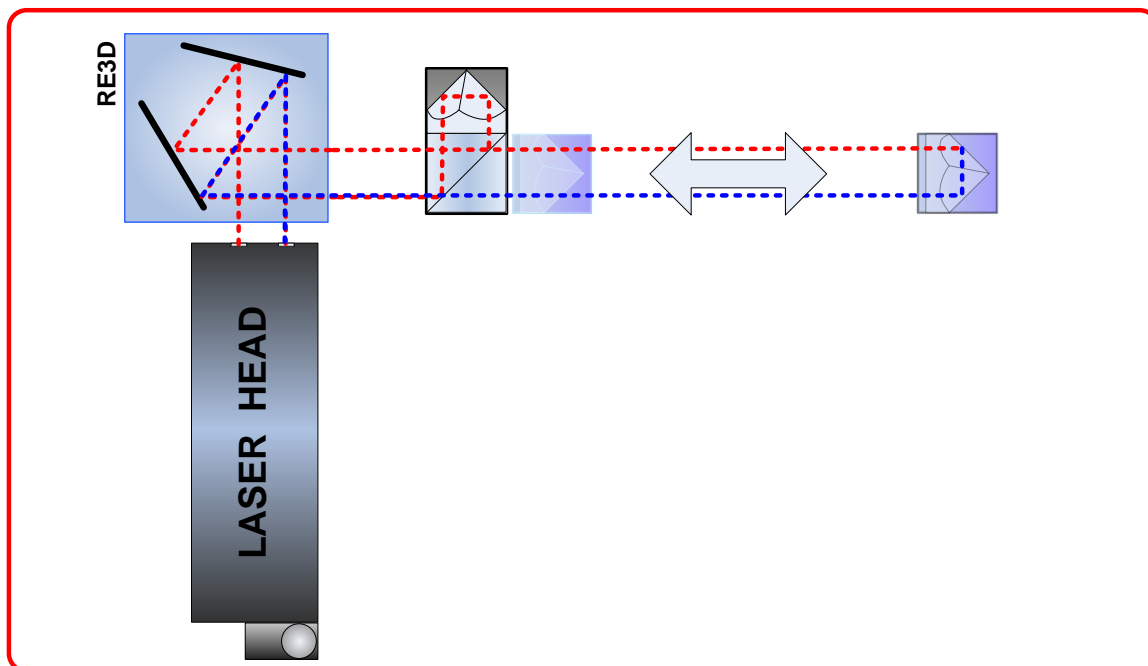
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6. Move the RK1 back to IK1 (the components must not touch!) and check the quality of the beam path alignment. Use available electronic tools – Beam Level Indicator and Electronic Beam Alignment Tool.

4

i. Beam alignment of angular optics with beam bender

i. *Laser Head initially not aligned*
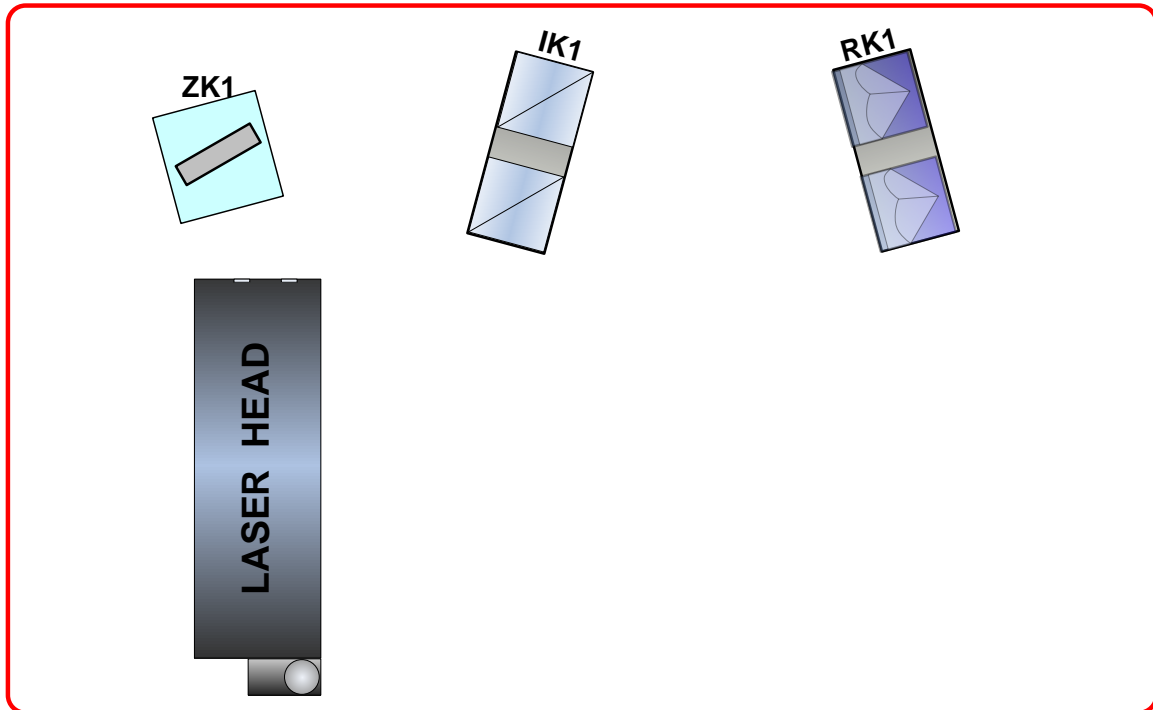

1. Mount Laser Head, IK1, RK1 and ZK1 on the measured machine
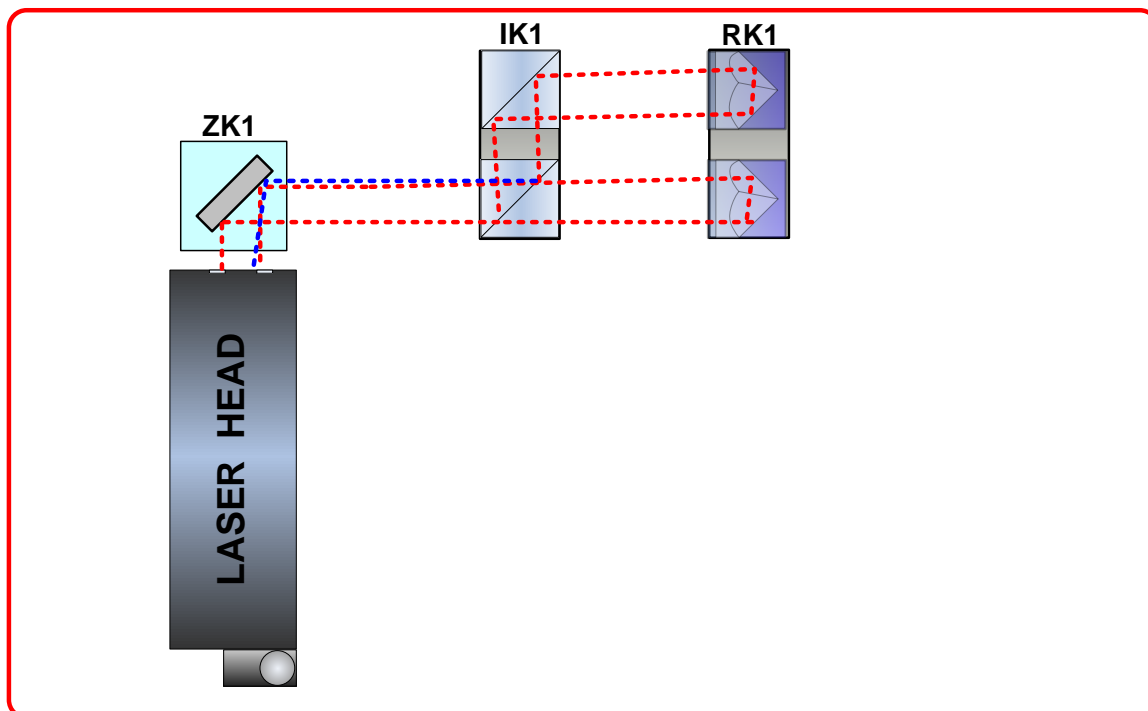
2. Turn on the laser and align all elements along the measurement axis


3. Move the RK1 very close to IK1 (they can touch each other). Set their initial position and the position of ZK1 so the beam returns back to the laser.

4. Move the RK1 from IK1.

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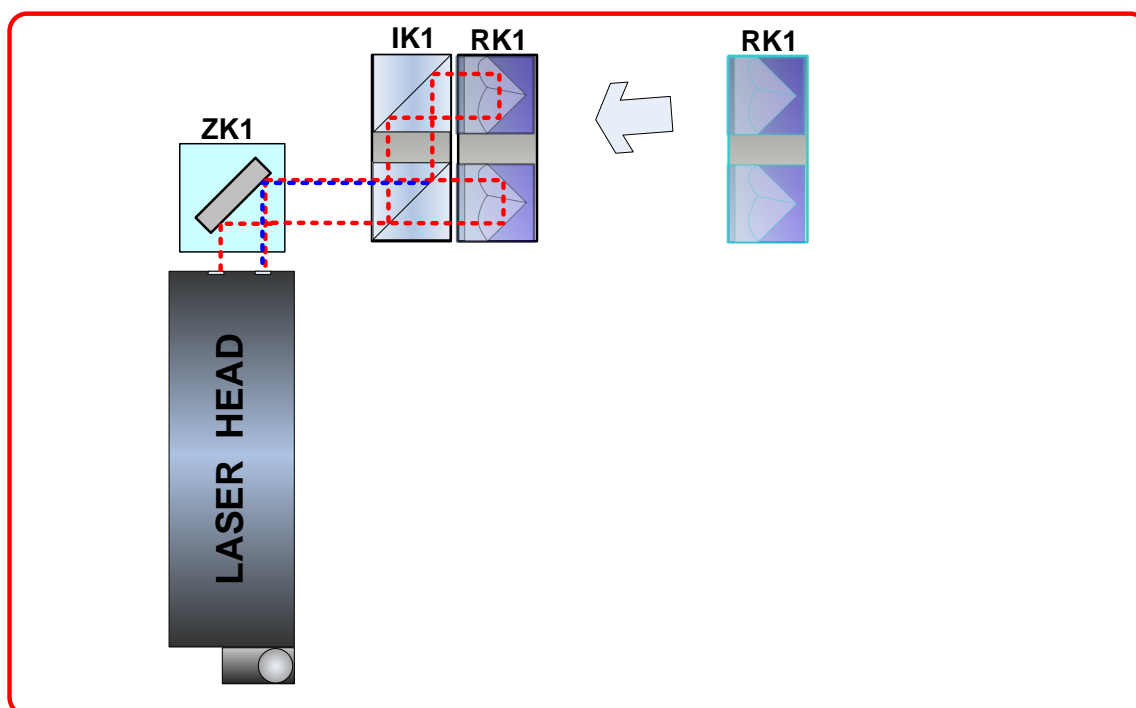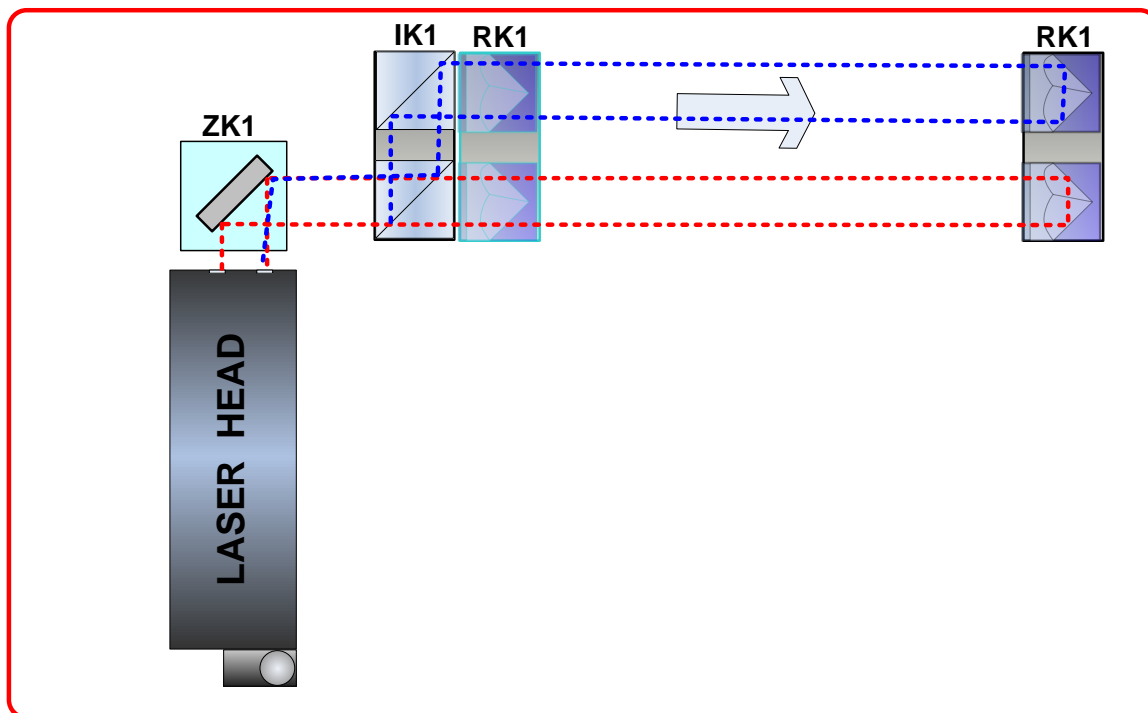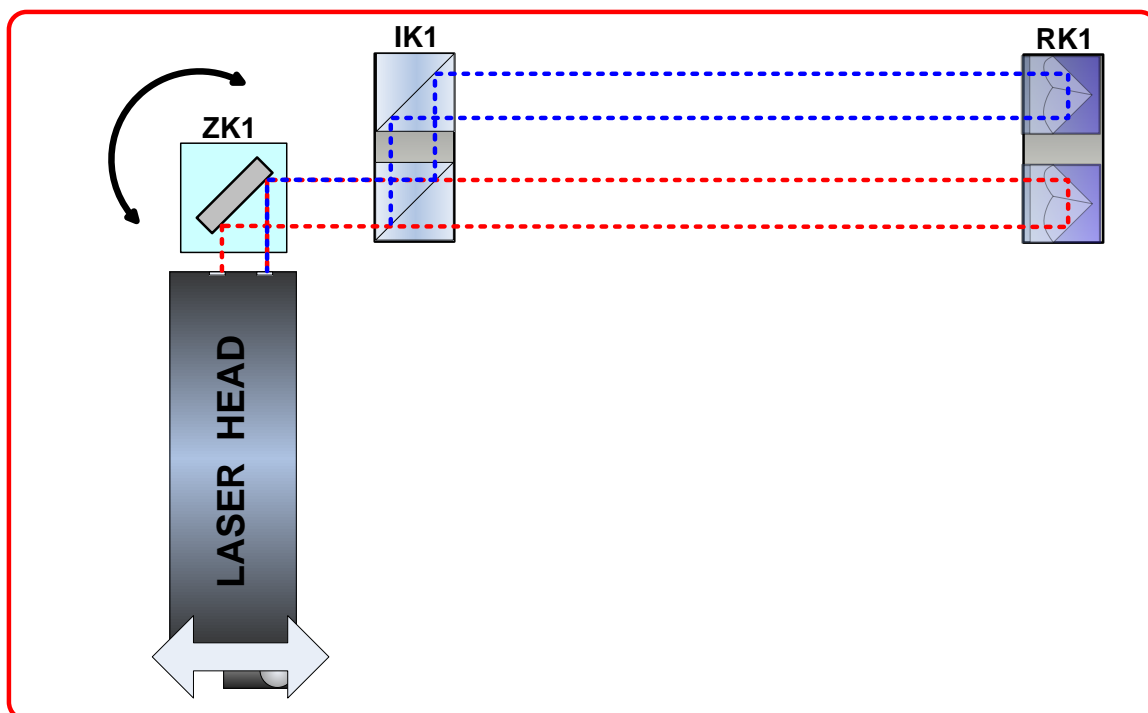
5. By regulation of the laser head position align the beam path so that both beams overlap on the input of the laser. Instead of regulating the position of the laser head it is possible to regulate the ZK1 – in many situations it would be faster!
REMARK: If the beams do not overlap then it means that the IK1 is rotated against RK1. Check the roll of laser head against IK1 and RK1 – it should be zero!
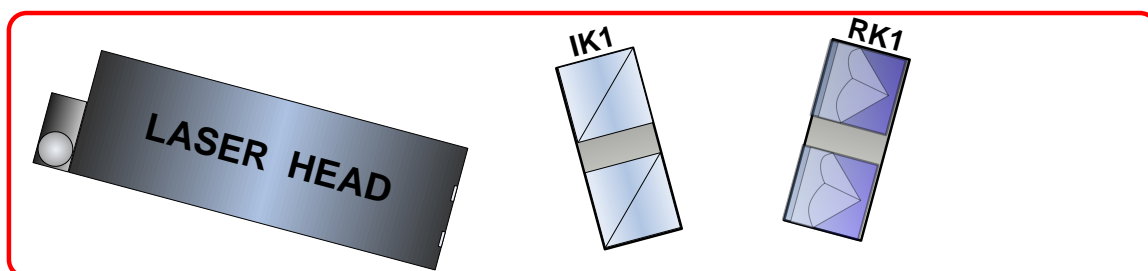

6. Move the RK1 back to IK1 (the components must not touch!) and check the quality of the beam path alignment. Use available electronic tools – Beam Level Indicator and Electronic Beam Alignment Tool.

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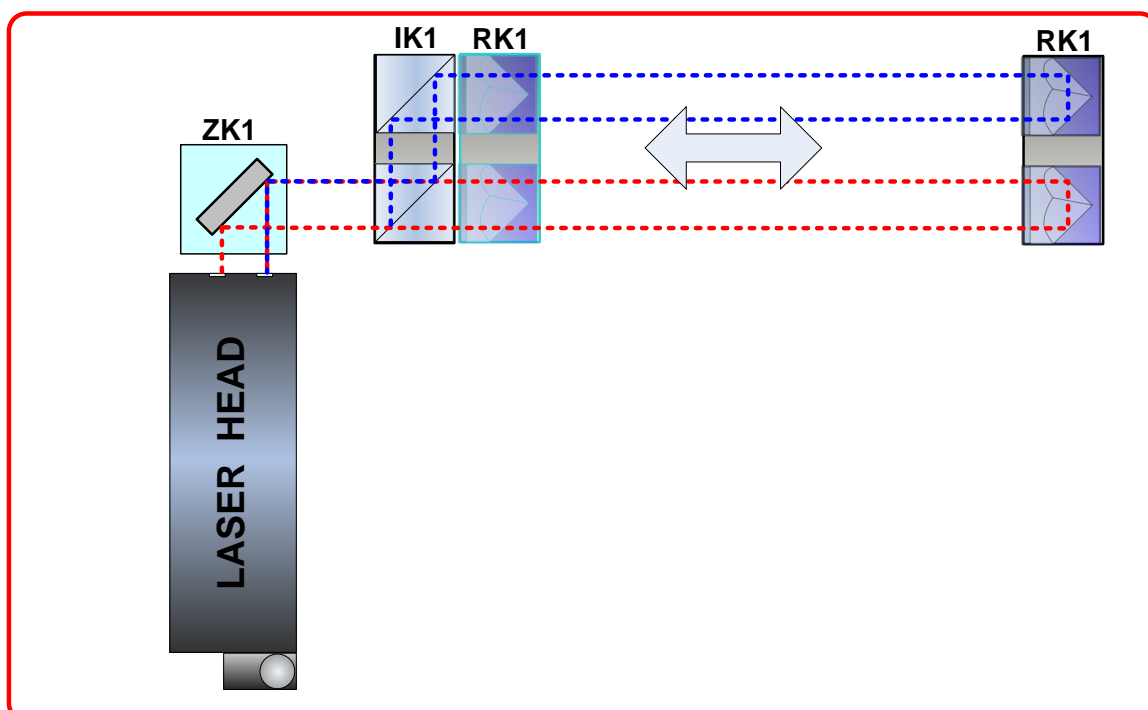
ii. Laser Head initially aligned
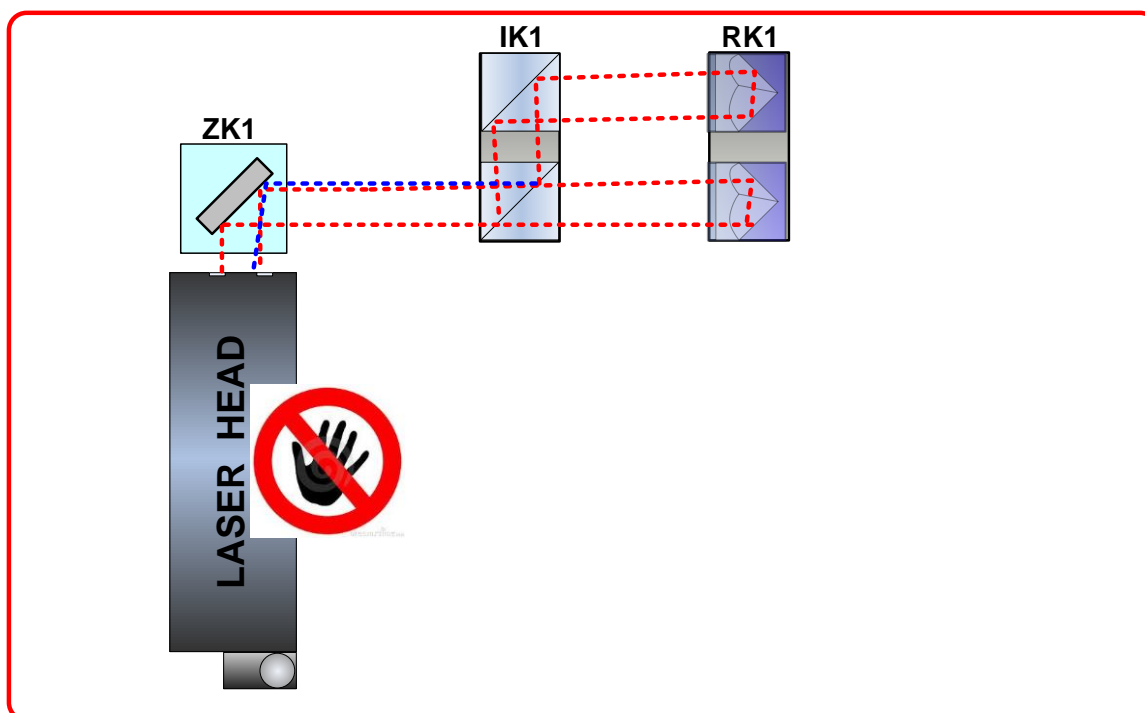
1. Align all elements (ZK1, IK1, RK1) along the new measurement axis.
DO NOT TOUCH the laser head
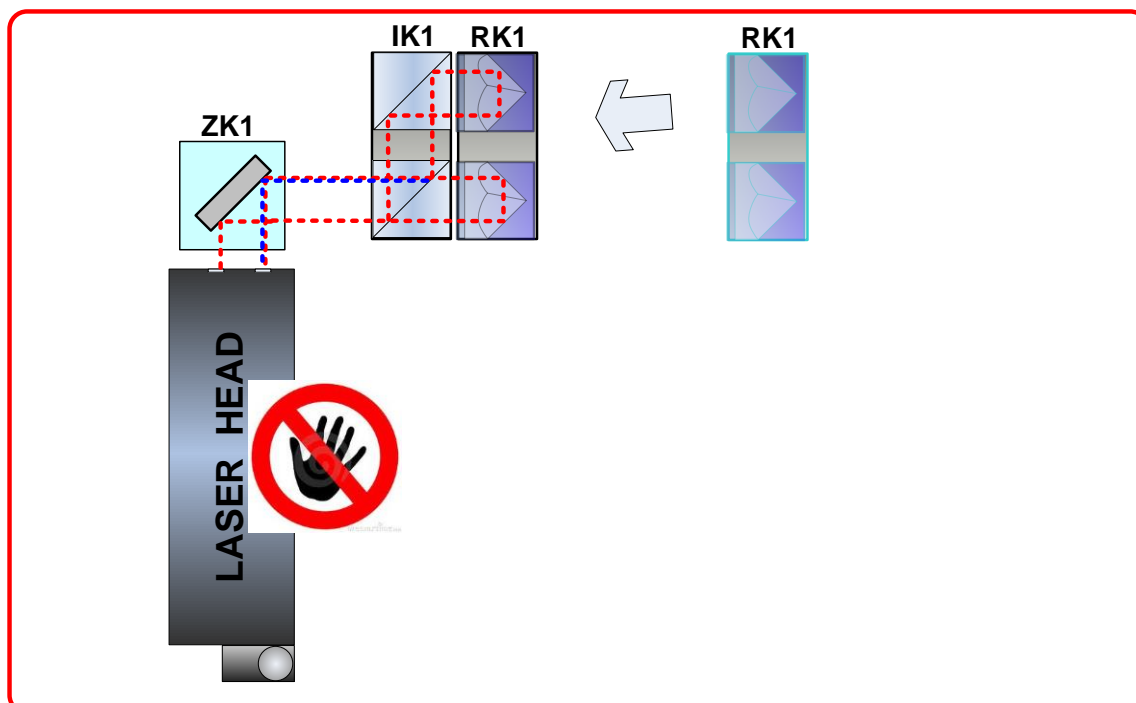
2. Move the RK1 very close to IK1 (they can touch each other). Set their
initial position and the position of ZK1 so the beam returns back to the laser.
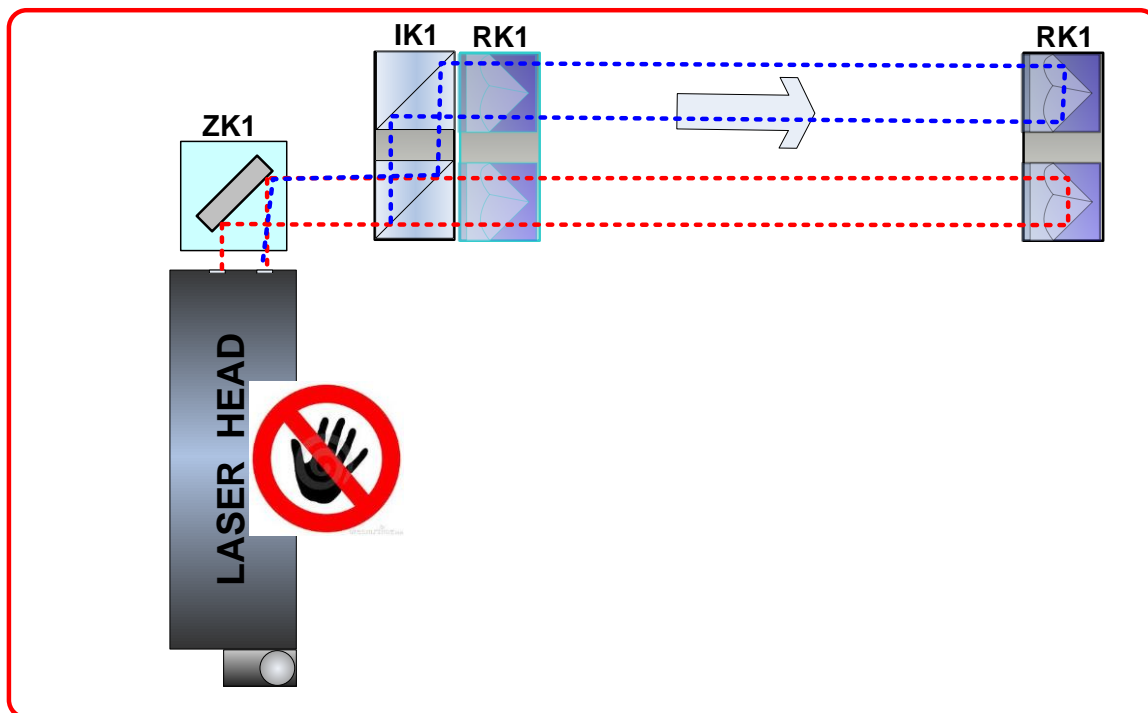
3. Move the RK1 from IK1.
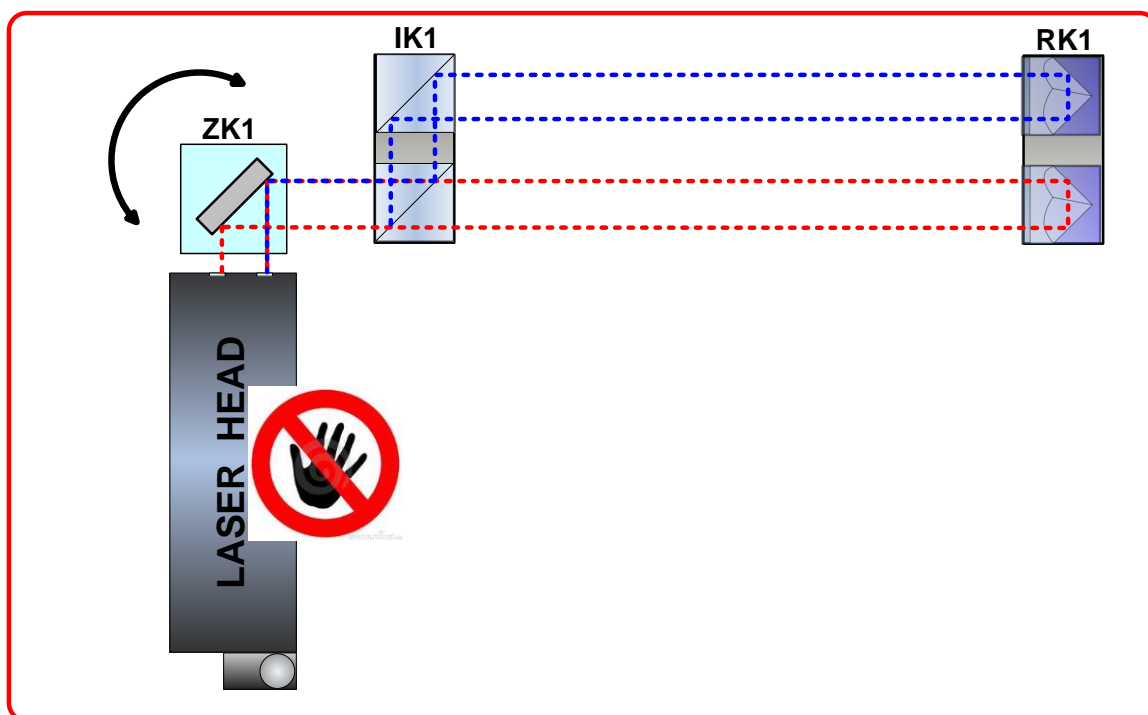
4. By regulation of the ZK1 position align the beam path so that both beam overlap on the input of the laser. DO NOT TOUCH the laser head.

REMARK: If the beams do not overlap then it means that the IK1 is rotated against RK1. Check the roll of laser head against IK1 and RK1 – it should be zero!
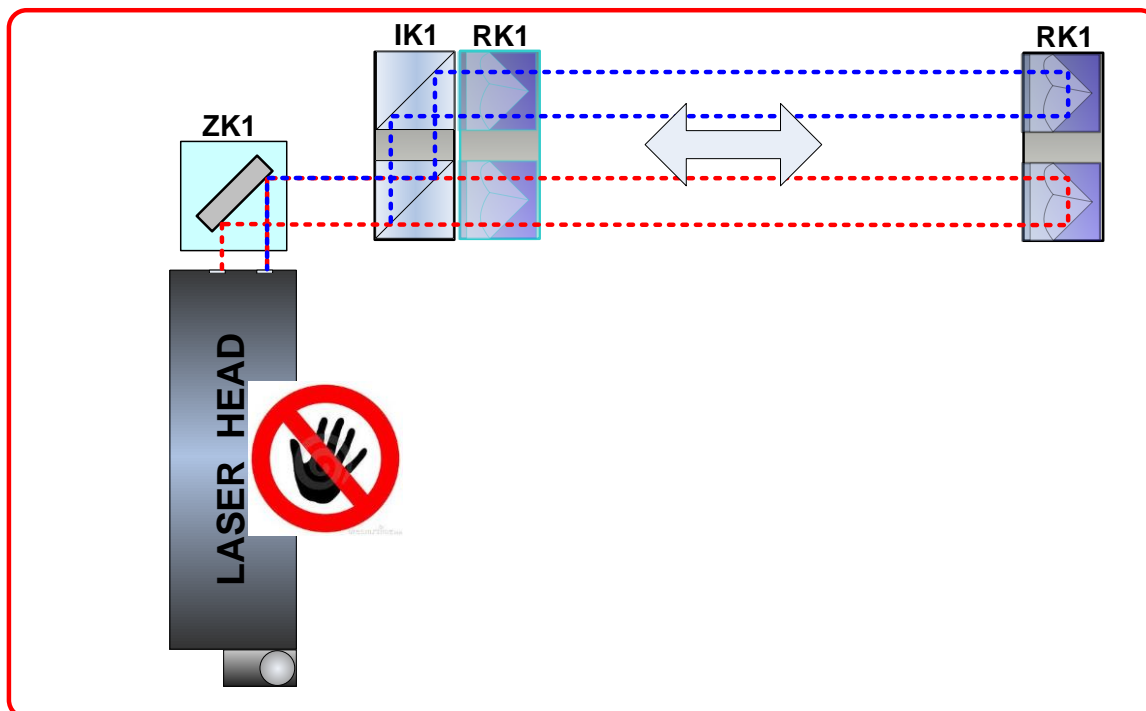
5. Move the RK1 back to IK1 (the components must not touch!) and check the quality of the beam path alignment. Use available electronic tools – Beam Level Indicator and Electronic Beam Alignment Tool.
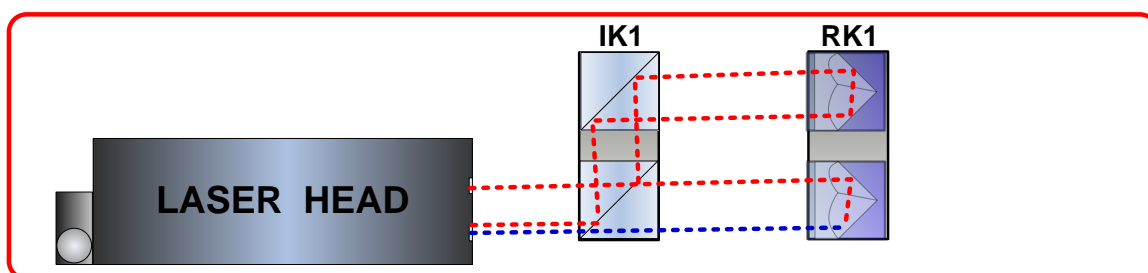
5. MEASUREMENTS - POSITIONING

a. General Description

The linear positioning measurement is the most advanced option of linear measurements. It is also the most common form of laser interferometer measurements performed on machines. The laser system measures linear positioning accuracy, repeatability and backlash by comparing the position to which the machine moves (i.e. the position displayed on the machine's readout) with the true position measured by the interferometer.

The HPI-3D device offers a unique feature of simultaneous measurement of positioning and estimation of straightness in horizontal and vertical planes. This 3D feature simplifies and significantly speeds up the process of machine geometry testing and improves measurement accuracy thanks to elimination of the cosine error.

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i. Positioning in brief

In the Figure 5.1 there is shown the block diagram of the linear positioning error correction algorithm. Following the presented algorithm it is easy to correct any numerically controlled machine.

In the first step there can be chosen some measurements options. In most cases this step can be omitted. Next in the software there should be generated the program for machine movement (G Codes). The generated program drives the machine in compliance with the ISO230-2 standard.

After starting the uploaded program on the tested machine the measurements can also be started in the *HPI Software*. No user attendance is necessary during measurement process.

After the measurement finishes there can be generated a special file for compensation of the machine control. After uploading the file, the machine positioning should be measured again to obtain the end results. The end results can be stored or printed.

All measurement steps are described in much greater detail inside the Chapter.

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Positioning method choice:
- linear
- pendulum
- pilgrim standard
- pilgrim effective

G-Codes program generation for CMM or CNC machines in LSP30-3D software

Loading G-Code program into machine

Performing linear positioning measurement by starting machine and pressing START in HPI Software (no user attendance during measurements necessary!)

0.2892

W oknie
Zaliczony

0.2857

Error report generation according to a chosen standard
(NMTBA, ISO, VDI/DGQ, BSI, PN, JIS)

Error compensation table generation in a format best suited the corrected machine
(linear, incremental, Siemes, HP, Fanuc)

Downloading corrections into machine (if necessary)

Printing error report according to a chosen standard
(NMTBA, ISO, VDI/DGQ, BSI, PN, JIS)

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FIG.5.1 LINEAR POSITION ERROR CORRECTION PROCEDURE

b. Measurement Setup

i. Principles

The Positioning measurement is the very basic measurement performed with the linear optical components: linear retroreflector RL1 and the linear interferometer IL1. Any change in the distance between IL1 and RL1 is detected by the laser head and shown in the HPI Software.

As it is illustrated in the Figure 5.2 both elements are normally aligned along the laser beam. Although IL1 is usually treated as a reference element with the movement of the RL1 measured but the configuration can also be reverse, i.e. RL1 can be stationary with IL1 being translated.

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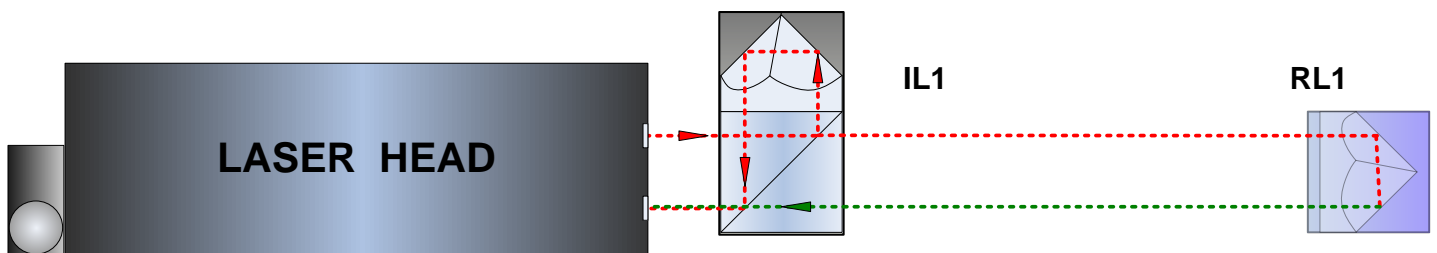
FIG.5.2 OPTICAL PATH SET UP FOR POSITIONING MEASUREMENTS-SCHEMATIC

The distance L measured in the linear configuration depends significantly on the actual wavelength λ_{air} of the laser beam with the formula

$$L = N * \lambda_{air} = N * \frac{\lambda_{vac}}{n(T,P,H)} \tag{5.1}$$

,where N denotes the number of interference fringes, λ_{vac} is the laser wavelength measured in vacuum and n(T,P,H) is the refraction coefficient of the air.

The wavelength changes with the fluctuations of the parameters of the air: humidity, pressure and humidity. From the experimental formulas (see Chapter 17) it may be obtained the refraction coefficient dependences on T, P and H in usual conditions (T=293K, P=1000hPa, H=50%):

$$\frac{\partial n}{\partial T} = -0,93*10^{-6}\left[\frac{1}{K}\right]$$

$$\frac{\partial n}{\partial P} = +0,27*10^{-6}\left[\frac{1}{hPa}\right]$$

$$\frac{\partial n}{\partial H} = -0,96*10^{-8}\left[\frac{1}{\%}\right]$$

The changes of the wavelength are compensated automatically by the HPI-3D laser head only if the TH sensor is used properly, i.e. placed near the laser beam path. The air pressure is measured inside the laser head.

ii. Principles – base temperature compensation

One of the important factors limiting the precision of every machine is the temperature. In the Figure {2} there is schematically shown a milling machine. On the machine

there is a work table with a workpiece. There is also schematically shown the measurement subsystem of the machine, i.e. the Scale. The position encoder (marked as Scale) is the part that is connected to the CNC control. It can be of different construction – magnetic, glass, laser, etc. Its expansion is corrected with positive sign in order to force the CNC control to leave the table in the same position despite the thermal expansion of the scale.

0

Workpiece

Table

Workpie. offset

workpiece

Scale
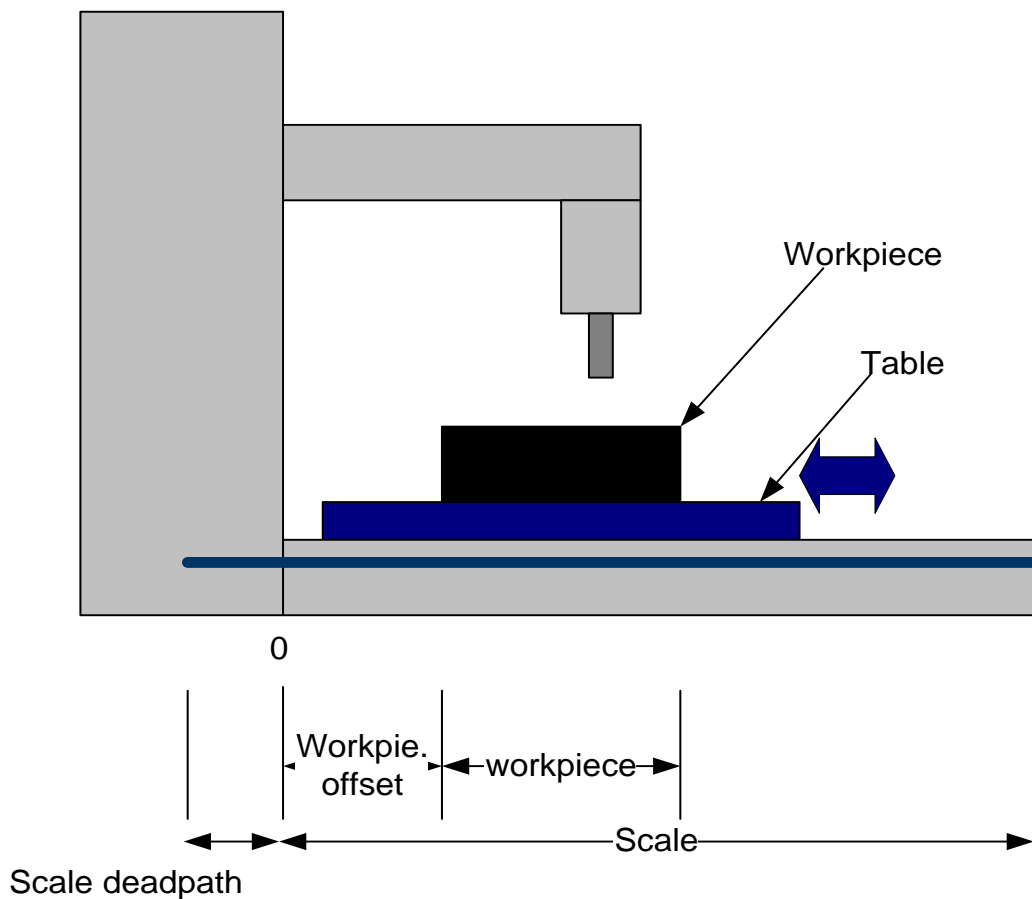
Scale deadpath

FIG.5.3 BASE EXPANDABILITY COMPENSATION - NOTATION

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The important parameters in the Scale length compensation are:

- scale thermal expandability factor in [ppm] or [μm/(m*K)] units; for glass scales it can have very low value

- scale deadpath – the length of the non-used scale part or the distance between the beginning of the scale and the Zero mark.

The HPI-3D is capable of automatic compensation of the thermal expandability of the Scale. The user has only to properly use Base Temperature sensors (i.e. place them as close to the machine measurement system as possible) and to set the thermal expandability value of the Scale.

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iii. Measurement Setup Preparations

For positioning measurements linear optics should be used. Necessary components are (see also figures 5.2 to 5.5):

- Laser Head
- Power Supply
- Linear interferometer **IL1**
- Linear retro-reflector **RL1**
- Air temperature sensor TH (Important!!!)
- At least one Base temperature sensor (T1, T2 or T3) (Important!!!)

Optional elements are:

- USB cable

- Manual Strobe

- Magnetic holder **UM2**

- Tripod stand

Positioning measurements require optical elements IL1 and RL1 to be aligned along laser beam as shown in the figure 5.2. Each of the elements can be moved.

During positioning measurements the Abbe, Dead Path and Cosine errors (for details – see the Chapter 17) have to be taken into consideration. The usage of the air temperature sensor and at least one base temperature sensor (T1 or T2 or T3) is **absolutely necessary**! More than one base temperature sensor should be used on long measurement axes, especially where a temperature gradient is possible.

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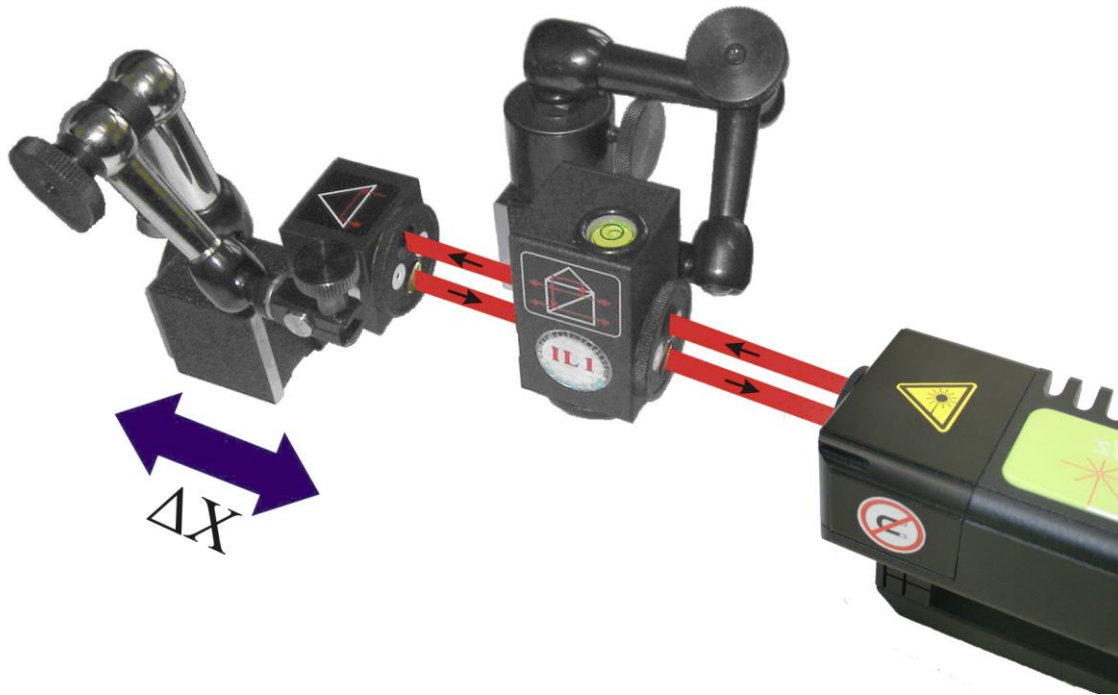
FIG.5.3 OPTICAL PATH SET UP FOR POSITIONING MEASUREMENTS IN X AXIS

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If only one base temperature sensor is used then all unused sensors should be switched off in the HPI Software. Otherwise the base temperature value would be false and the measurement would yield improper results. Switch singular sensors can be performed in the **Display** menu by clicking the value fields of the T1, T2 or T3 sensors in the WiMeteo panel.

Positioning measurements can be performed not only along the laser beam (as shown in figures 5.2 and 5.3) but also in directions perpendicular to the laser beam. These configurations are shown in figures 5.4 and 5.5. In those two

configurations the laser beam has to enter the IL1 from the bottom of the element. Only the retro-reflector RL1 can be moved.
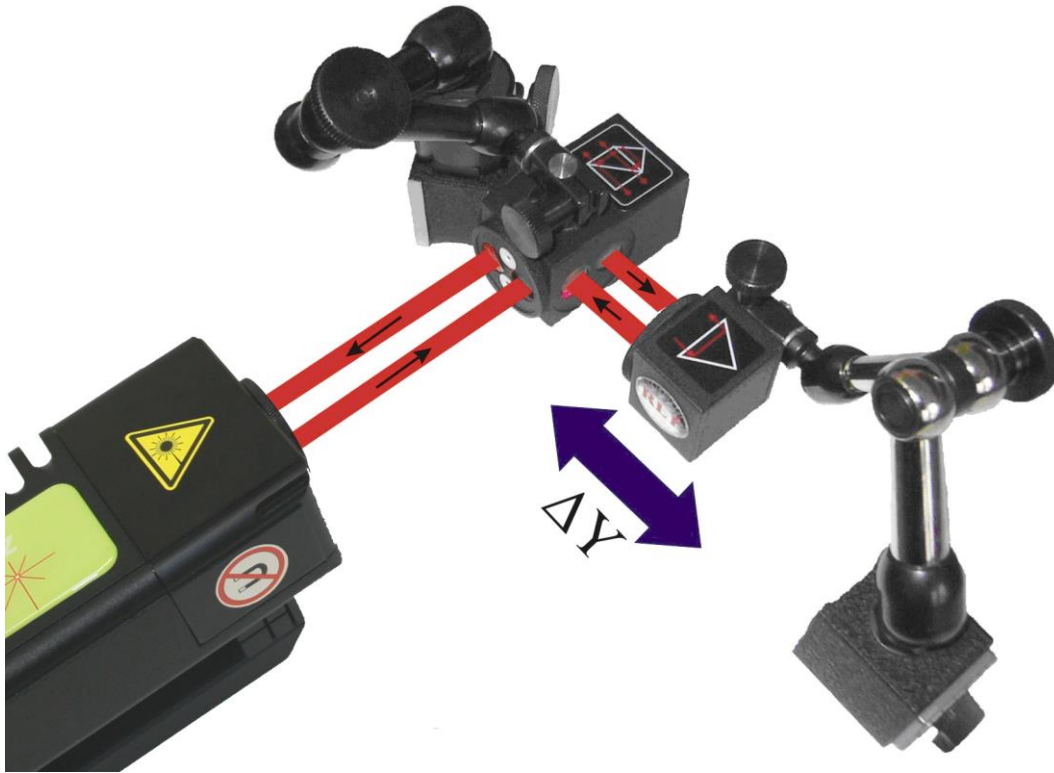
FIG.5.4. OPTICAL PATH SET UP FOR POSITIONING MEASUREMENTS IN Y AXIS
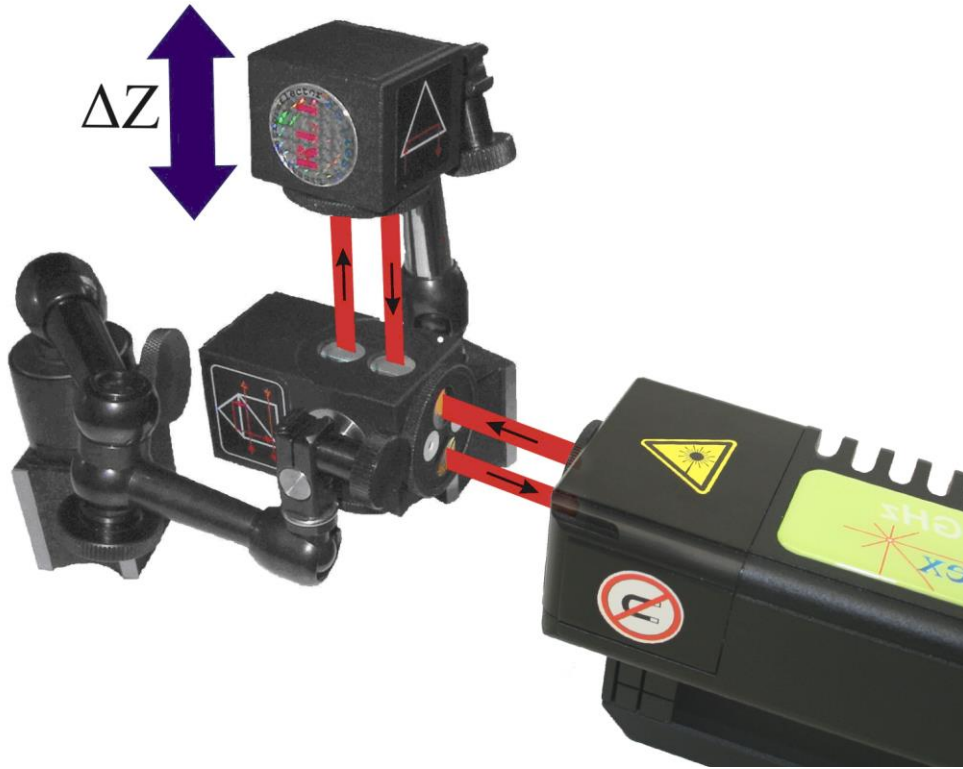
FIG.5.5. OPTICAL PATH SET UP FOR POSITIONING MEASUREMENTS IN Z AXIS

c. Software description

i. Introduction

In order to start *Positioning* measurements in the **Main Menu** the **Positioning** button should be pressed (Figure 5.6). On the screen there should appear a **Linear positioning** window as shown in the Fig. 5.7. The window consists of a pull-down menu and four panels:

- 1) Display panel – presents information about current distance, target distance and measurement signal level;
- 2) Positioning plot panel;
- 3) Positioning results panel
- 4) Panel with control buttons and status information.
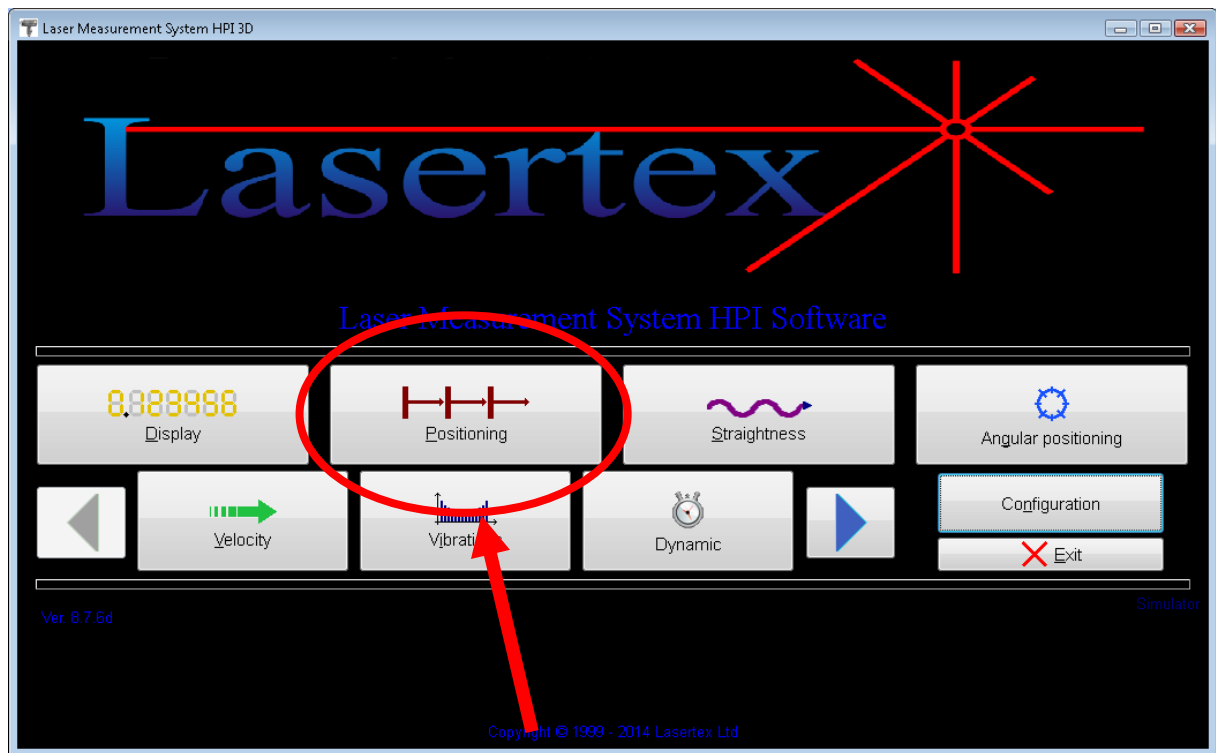
FIG.5.6 MAIN MENU

ii. Display Panel

The top part of the Display Panel (block 1 of figure 5.7) is used for basic control of the laser operation. Through this panel it is possible to monitor the quality of the input signal,

i.e. the beam strength and the current value measured by the laser. Number of displayed digits can also be modified.

FIG.5.7 LINEAR POSITIONING WINDOW

In the top left corner of the Panel there are two fields named *1st measurement point* and *2nd measurement point* allowing tying the coordinate system of the laser with the coordinate system of the measured machine. This option is described in more details below in the Chapter. Also later in the chapter there is described an option for switching between 1D and 3D positioning.

iii. Positioning Plot Panel

On the chart drawn in the Positioning Plot Panel there are shown information about the measured deviation between the real and the desired translation of the machine. On the plot the points are placed in two colors: the deviations measured during forward movement of the machine is shown with blue circles while the deviations measured during reverse movement are shown with red triangles. The points for the current measurement series are connected with the solid line (see Figure 5.8).
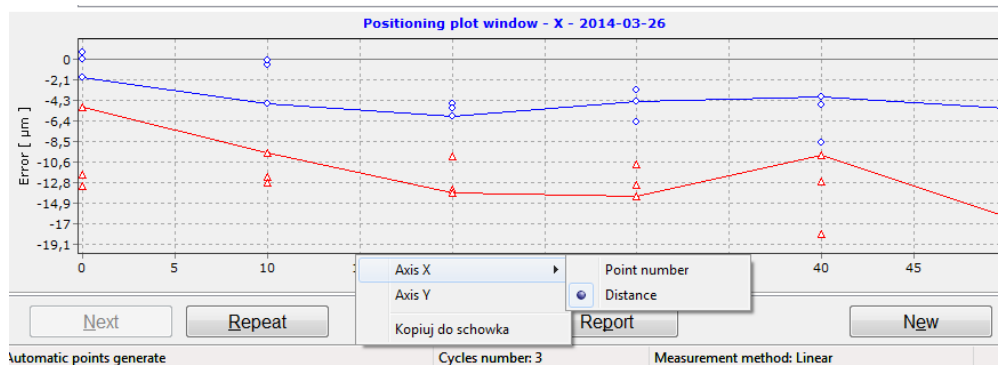
FIG.5.8. PLOT WITH POSITIONING MEASUREMENT RESULTS

Although the scale of the Y axis is set automatically by default but it is possible to set the display limits manually by choosing an *Axis Y* option from the pull-down menu (see Figure 5.8). Values in the axis X can be displayed either in the distance units or as numbers of measurement points.

iv. Positioning Measurement Values Panel

In the Values Panel there are displayed numerical values of the positioning measurements (Figure 5.11). These are the values from the current measurement series and these are shown on the Positioning Plot as points connected with the solid line.

The unit of the distance can be changed, independently on the unit of the chart, by clicking with the left mouse button on the distance (i.e. Ref.) column of the chart. There are two possibilities: true value of the distance or point number.

v. Positioning Control Panel

Positioning Control Panel is comprised of three main parts (Figure 5.11):

- Line with control buttons
- Line with measurement status information
- Line with laser status information.

The functionality of the line with the buttons changes with the current measurement state. In the Figure 5.9 there are shown various appearances of the control part of the Control Panel.

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A	Start	Reset position	Menu

B	Stop		Menu

C	Next	Repeat	Browse	Report	New	Menu
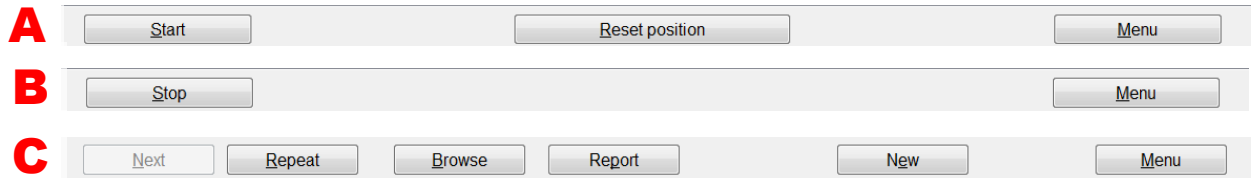
FIG.5.9 CONTROL PANEL – DIFFERENT MODES. CLARIFICATIONS IN TEXT

Case A appears when there is no measurement in progress and no data were read from a file. In this mode it is possible either to start the measurement ("Start"), to reset the main counter ("Reset position") or to return to the main menu of the program ("Menu").

Case B appears during measurements. The measurement can be stopped directly ("Stop") or indirectly ("Menu"). After pressing the "Menu" button the software always asks if the measurement is to be stopped first.

Case C is visible during analyses of the obtained results. If there are measured fewer series than the desired limit than the button "Next" becomes active. Pressing this button starts the measurement. The results obtained during the measurement will be added to the thus far registered results. Pressing "Repeat" button also starts new measurement but the results would supersede the results of the last measurement series. By pressing "New" button all registered results are cleared and a new measurement is started.
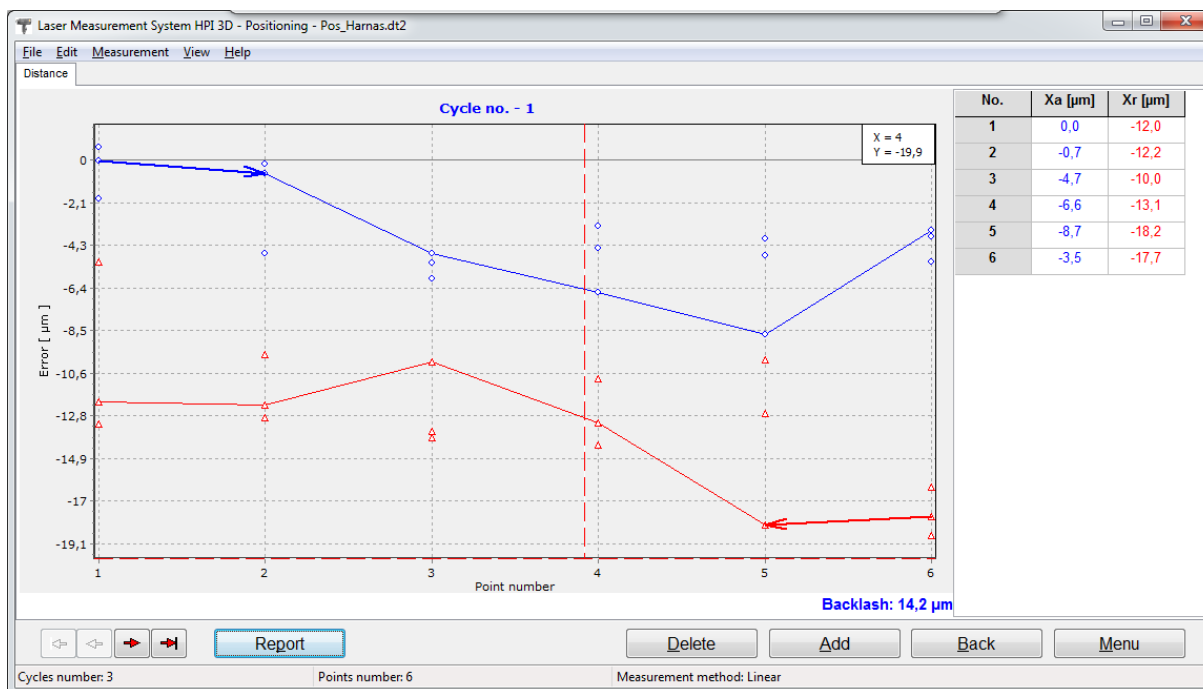
FIG.5.10. DATA BROWSING WINDOW

Button "Browse" opens the results browse window (Figure 5.10). The functionality of this window is show in more details later in the Chapter. Pressing "Report" opens Linear Positioning Report Window as shown in the Figure 5.34.
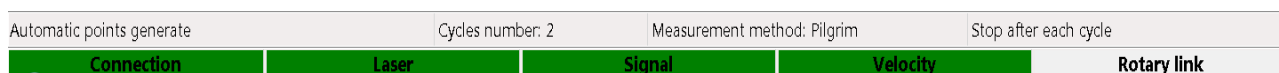
FIG.5.11. STATUS BARS IN POSITIONING WINDOW

In the bottom part of the Positioning Control Panel there can be found two status lines. The upper one is presenting a configuration of the positioning measurements, the lower the state of the laser system

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In the first field of the upper line there is an information about the points capture method (manual or automatic). The next field informs about number of cycles in series (number of cycles executed one after one, if not active is the option **Stop After Cycle**). In the third field there is shown the information about measurement method selected in the **Configuration**.

The bottom line shows information common to all options of the HPI Software, i.e. the state of Connection, Laser, Signal, Sensors and Rotary encoder. The functionality of the line is described in another Chapter.

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vi. Pull down menu - File

The menu bar consists of following options: File, Edit, Measurement, View, Help. In the File menu (figure 5.12) can be found commands for reading measured data from a file, saving the data to a file, printing measurements results or exporting them to a file.
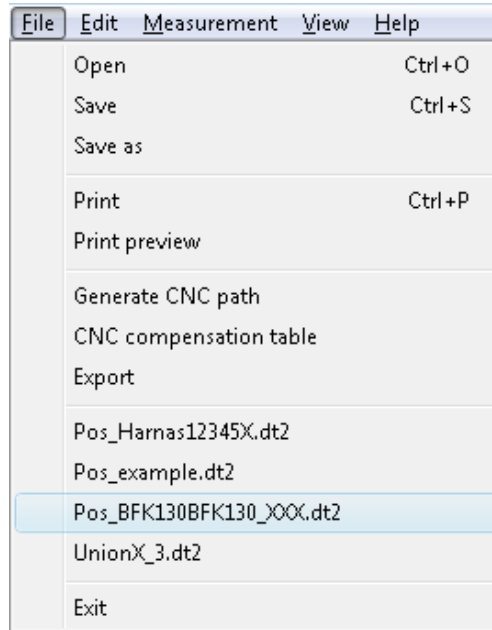
FIG.5.12. POSITIONING PULL-DOWN MENU *FILE*

Other important commands available in the *File* menu are options for generating CNC path and preparing compensation table.

vii. CNC path generation

CNC path generation options allows automatic preparation, by the HPI-3D software, the G-code program compatible with most CNC control systems. The options of the path generation are set in the separate window as shown in the figure 5.13.

In the upper part of the window the machine movement parameters are set. In the lower part the generated program

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can be viewed end edited. The results can be saved to a text file or previewed and printed.
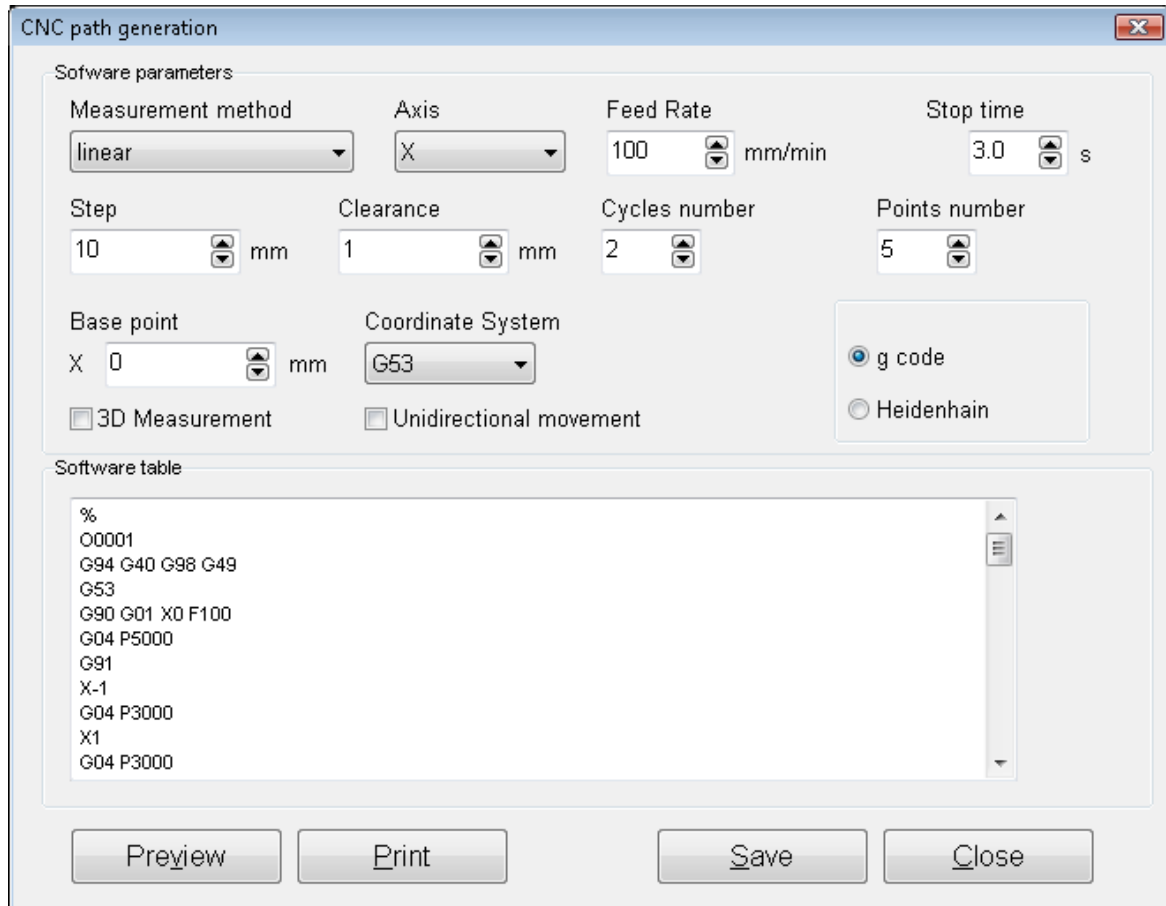
FIG.5.13. CNC PATH GENERATION WINDOW

Following parameters in *Software parameters* panel should be configured in order to generate the proper code:

- **Measurement method** - should be set accordingly with the chosen measurement method (see below). Choice must be made between linear, pendulum, pilgrim effective and pilgrim standard;

- **Axis** – the measured machine movement axis should be chosen (X, Y, Z, U, V, W, A, B, C).

- **Feed Rate** – the maximum machine feed rate in the chosen axis during measurements can be modified. The chosen value cannot be greater than machine limitations (see manual of the tested machine) and laser limitation (7 m/s = 420000 mm/min).

- **Stop Time** – the time the machine stops at every measurement point. This time is necessary for the HPI Software to capture measurement point. The proper value of this parameter depends on the tested machine and on *Point Capture* parameters of the laser (described later in this chapter).

- **Step** – the distance between measurement points.

- **Clearance** – additional machine movement used to compensate backlash. The chosen value should be large enough for the proper backlash compensation of the machine.

- **Cycles number** – sets the number of generated movement cycles. For proper calculation of statistical parameters in Report the number of measurement cycles should be not lower than three. The more measurement cycles is chosen the better characterization of the machine is done but

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the longer the measurement process lasts. The number of cycles should be the same with the value in *Configuration->Positioning->Cycles in series*.

- **Points number** – sets the number of measurement points.

- **Base point** – the initial position of the machine in its own coordinate system.

- **Coordinate system** – if used, the proper coordinate system should be chosen.

- **3D Measurement** – if checked then the **Stop Time** value is automatically increased to make the simultaneous 3D measurements possible (3D module requires additional 2 seconds stop time during each point capture).

- **Unidirectional movement** – if checked then the g-code program is generated only for machine movement in one direction. This option is useful for rapid estimation of machine geometry and for very long machines. Should not be used for normal measurements.

- **g code/Heidenhain** – it is possible either to generate the standard G-code program or a version compatible with Heidenhain machine controls.

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viii. Compensation table preparation
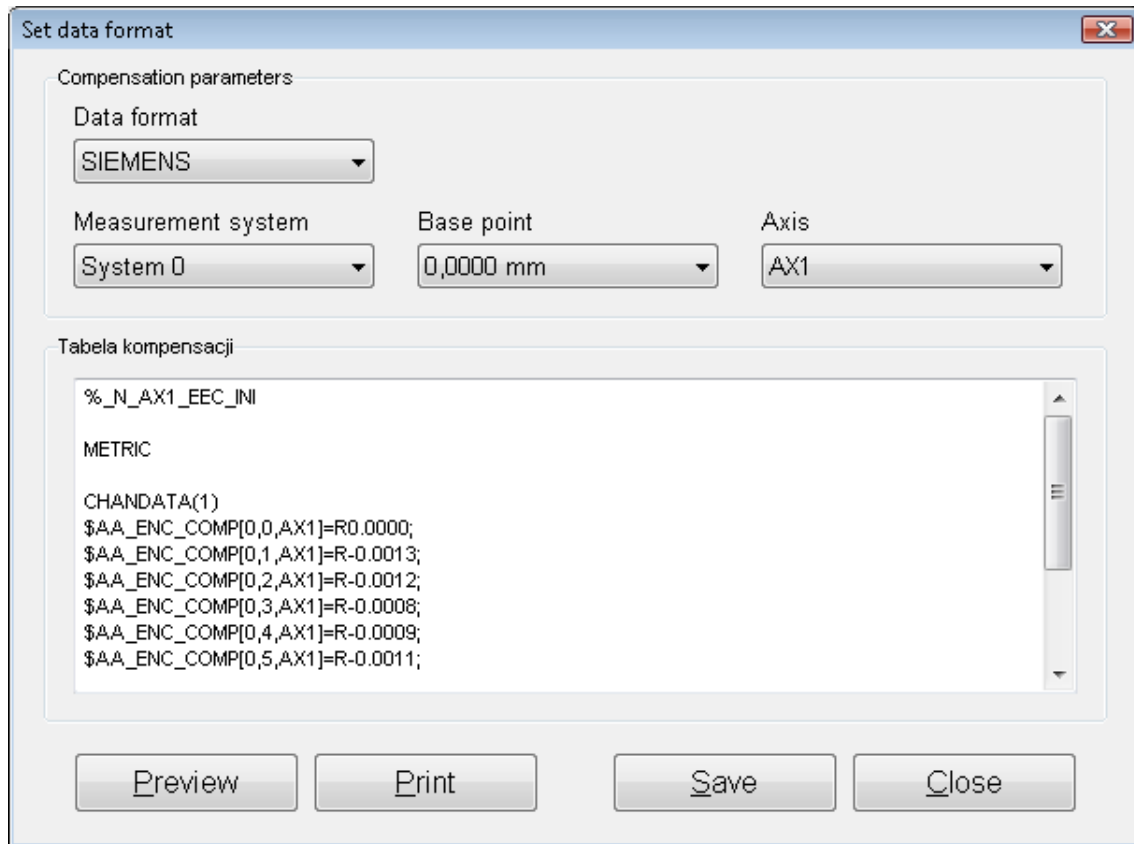
FIG.5.14. COMPENSATION TABLE PREPARATION WINDOW

Compensation table preparation (figure 5.14) is an option used when measurement is finished (before measurement start it is not enabled). The measurement results are used by the software to calculate errors and generate the compensation values for the machine control system. Suitable format of the compensation table for machine control system has to be selected from *Data format* drop-down list. Together with the data format additional parameters are configured.

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The option is described in more detail in the end of the chapter.

ix. Pull down menu - Edit

In the pull-down menu option **Edit** (fig. 5.15) there are options for setting measured machine data (Fig 5.16), defining machine error limits (fig. 5.17), previewing obtained positioning results, editing positioning points (when option **Target Points from List** from menu **Measurement** is active) and changing overall positioning configuration.
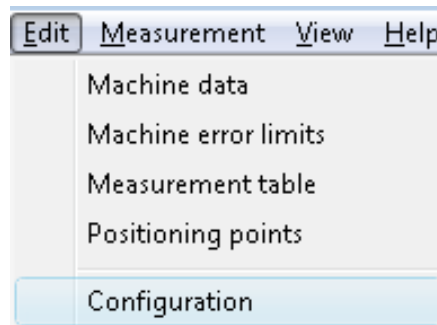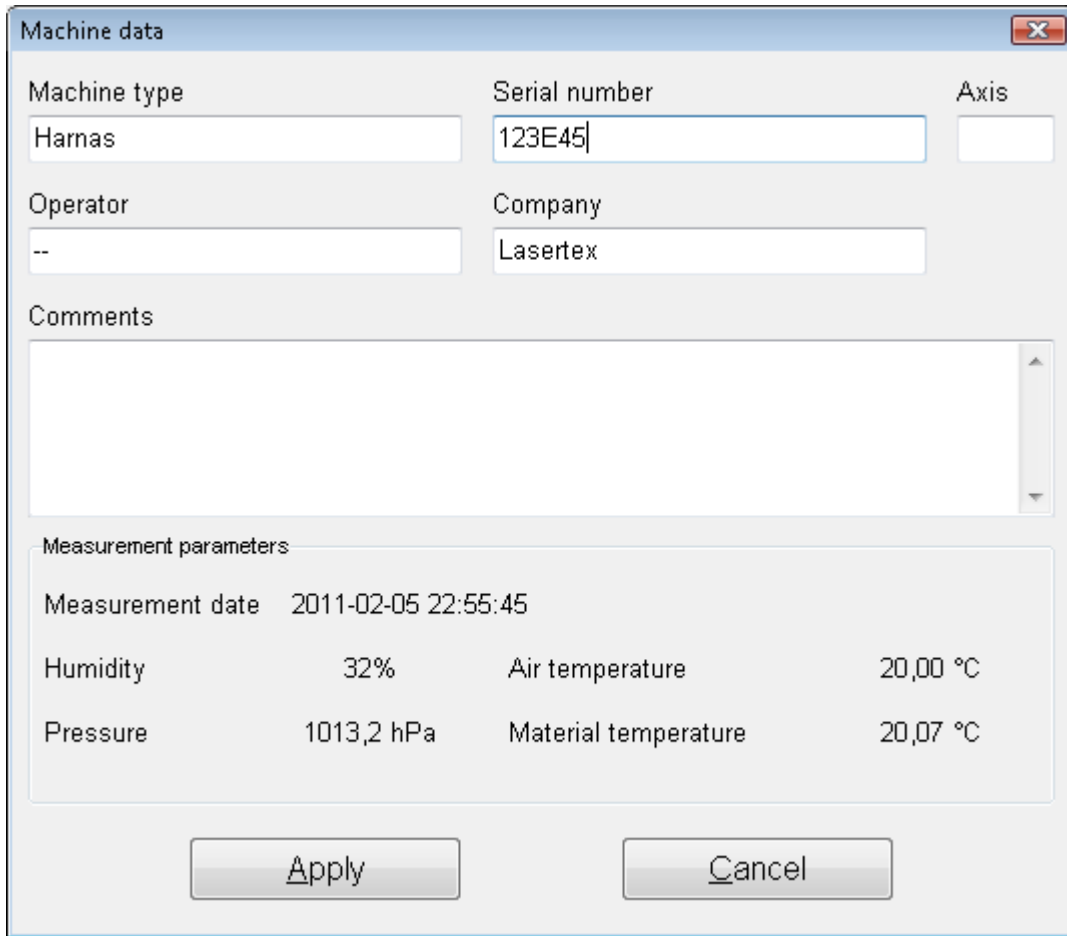
FIG.5.15. POSITIONING PULL-DOWN MENU *EDIT*

FIG.5.16 MACHINE DATAWINDOW

x. *Machine error limits*

In the **Edit** option the user can setup allowable error limits of the machine for different norms (option **Machine error** limits - Fig. 5.17). The results of the whole linear positioning measurements are compared with these limits (see Fig. 5.18). This option is especially useful when there are checked many machines of the same type and the same requirements on their accuracy are expected.
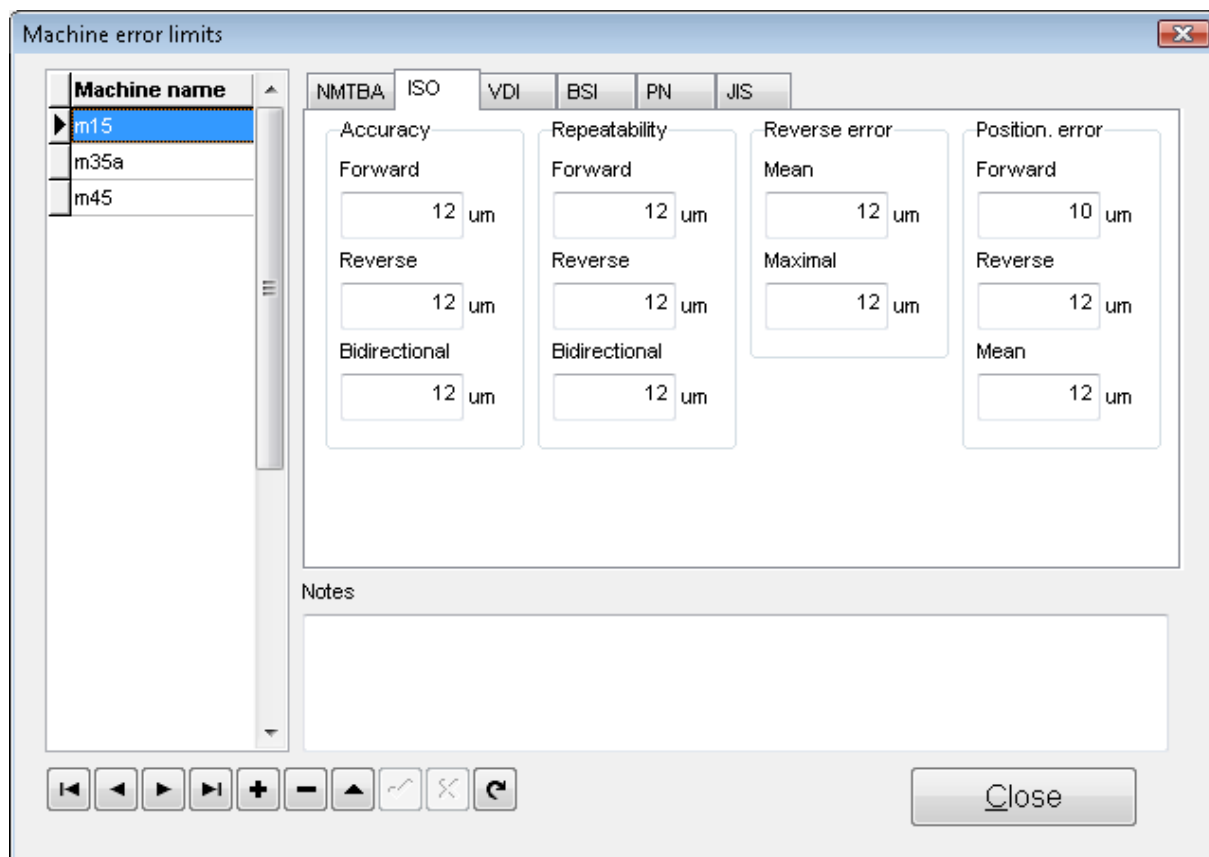
FIG.5.17. MACHINE ERROR LIMITS WINDOW

FIG.5.18. MACHINE ERROR LIMITS COMPARATION PANEL

xi. Positioning points generation
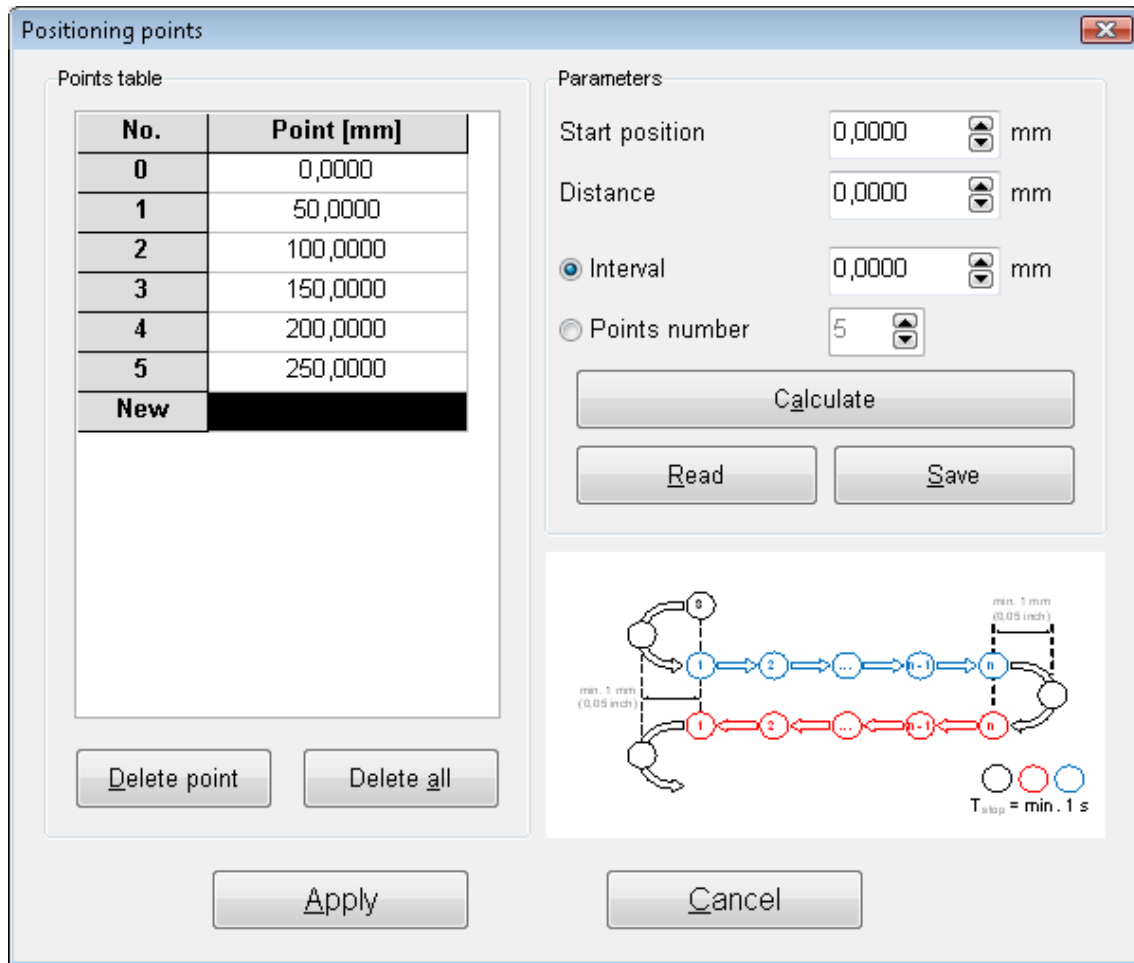
FIG.5.19. POSITIONING POINTS GENERATION WINDOW

If option **Target Points from List** from menu **Measurement** is active, then the program expects the measured machine to stop in points defined in the Positioning points window as shown in the figure 5.19. Points can be entered manually or can be generated from the input parameters: start position (can be negative), distance (must be positive) and interval (must be positive) or number

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of points. The points are calculated when *Calculate* button is pressed. Obtained points can be saved to a file.

xii. Configuration of Positioning measurement
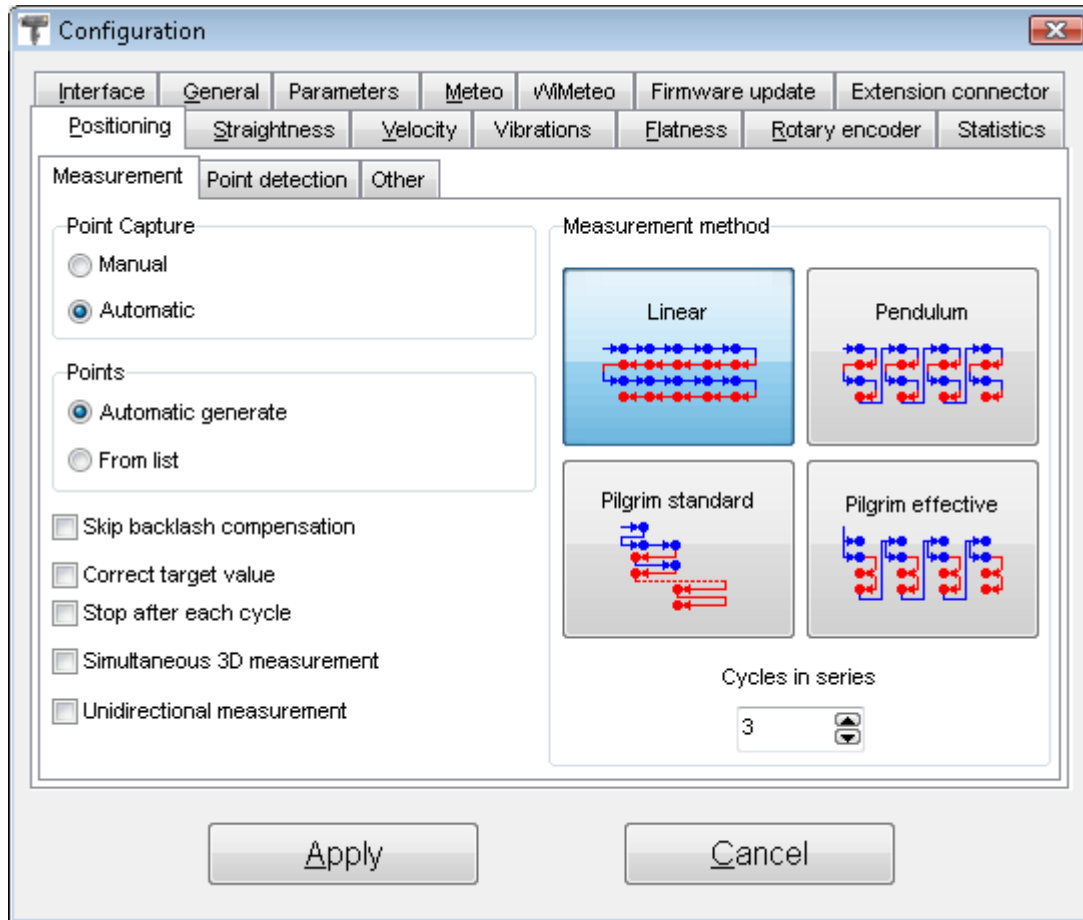
FIG.5.20 LINEAR POSITIONING COFIG WINDOW

In the **Positioning** tab in the **Configuration** window the important options of the linear positioning measurements (Fig. 5.20) can be set.

In the **Measurement** tab the user can choose the main parameters of the positioning measurement. The parameters

grouped in the **Point detection** tab change the behavior of the software during point capture process.

There are four available methods for checking machine's positioning: Linear, Pendulum, Pilgrim Standard and Pilgrim Effective (buttons in *Measurement method* panel). The directions of the expected movement of the machine are shown in the pictograms and in figures 5.21, 5.22, 5.23 and 5.24. Usually the *Linear* method is used.

In the *Cycles in series* field the number of complete measurements cycles is set. The greater number of cycles is used the better result is achieved. At least three cycles are recommended for proper calculation of statistics.
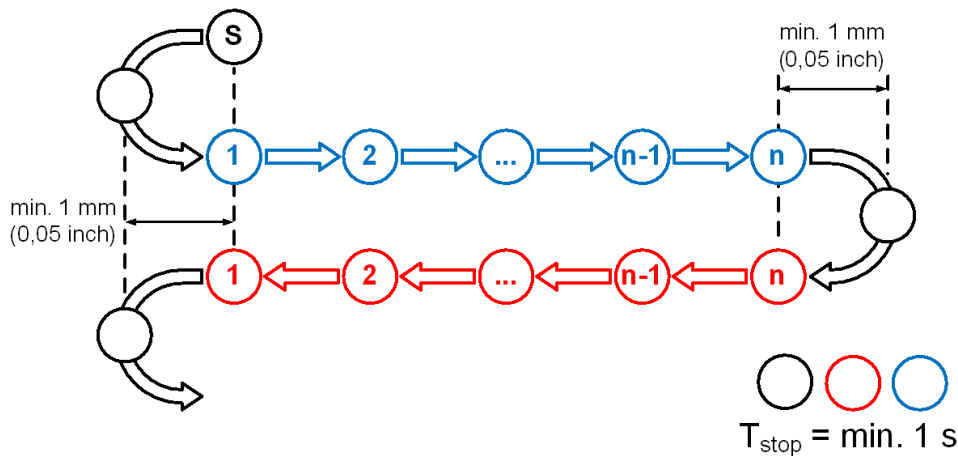
FIG.5.21. MACHINE MOVEMENT IN THE **LINEAR** MODE (S – STARTING POINT)
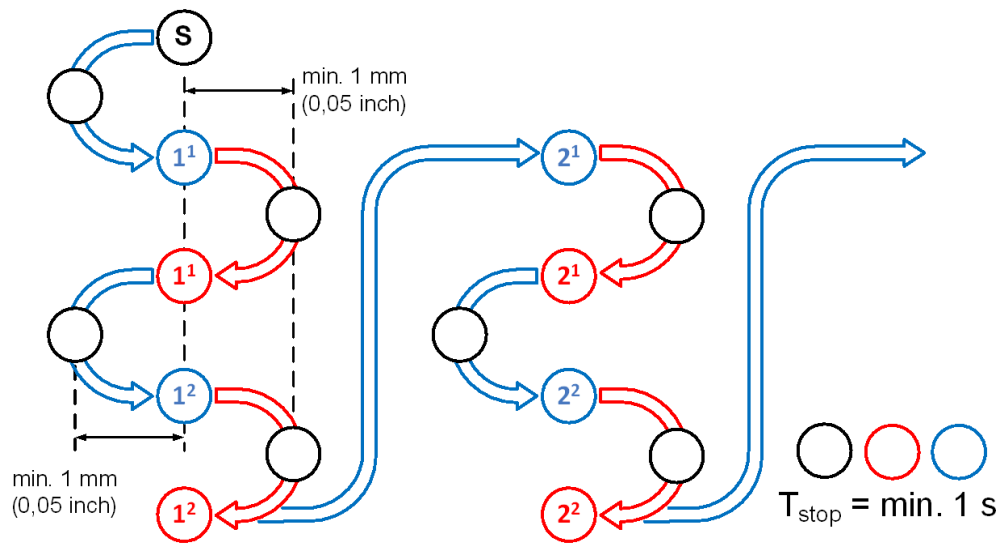
FIG.5.22. MACHINE MOVEMENT IN THE **PENDULUM** MODE (S – STARTING POINT)
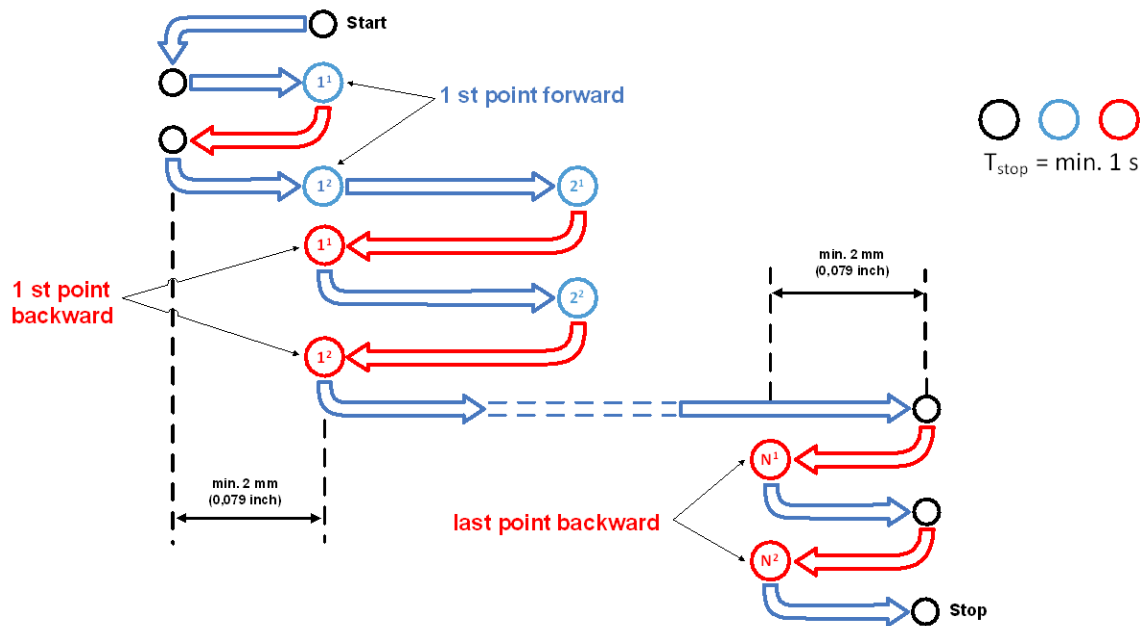
FIG.5.23. MACHINE MOVEMENT IN THE **PILGRIM STANDARD** MODE (S – STARTING POINT)

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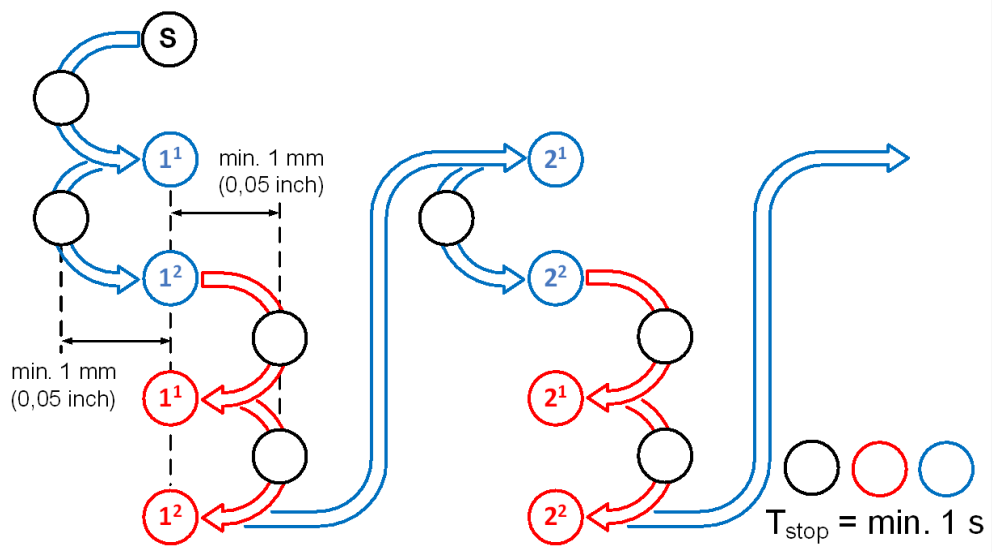
FIG.5.24. MACHINE MOVEMENT IN THE **PILGRIM EFFECTIVE** MODE (S – STARTING POINT)

Measurement points can be either captured manually (with keyboard space or Strobe button) or captured automatically by the software. For automatic capture parameters set in the **Point detection** tab are used.

For numerically controlled machines the Automatic point capture and Automatic point generation should be chosen.

Measurement points can be automatically detected by the software during measurement process or can be edited manually. The manual point list edition is described later in this chapter.

Set of checkboxes allow further modification of the positioning process

- **Skip backlash compensation** – if checked then the software does not expect the machine to make the backlash compensation movement (from point S to point 1 in the figures 5.21 – 5.24). When manual point capture option is chosen then there is no backlash compensation at the first measurement point!

- **Correct target value** – if checked then the software confirms laser measured distance value of each captured point. Option usable for non-numeric machines.

- **Stop after each cycle** – if checked then the measurements is stopped automatically after full measurement cycle (i.e. when machine returns back to position 0). The option is useful when intermediate results are to be viewed and analyzed.

- **Simultaneous 3D measurement** – if checked then, during positioning measurements also a 3D straightness measurements are performed. Longer machine stop time in measurement points is required.

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- **Unidirectional measurements** – if checked then the measurement is finished when machine return movement is detected and not when the machine returns back to zero.
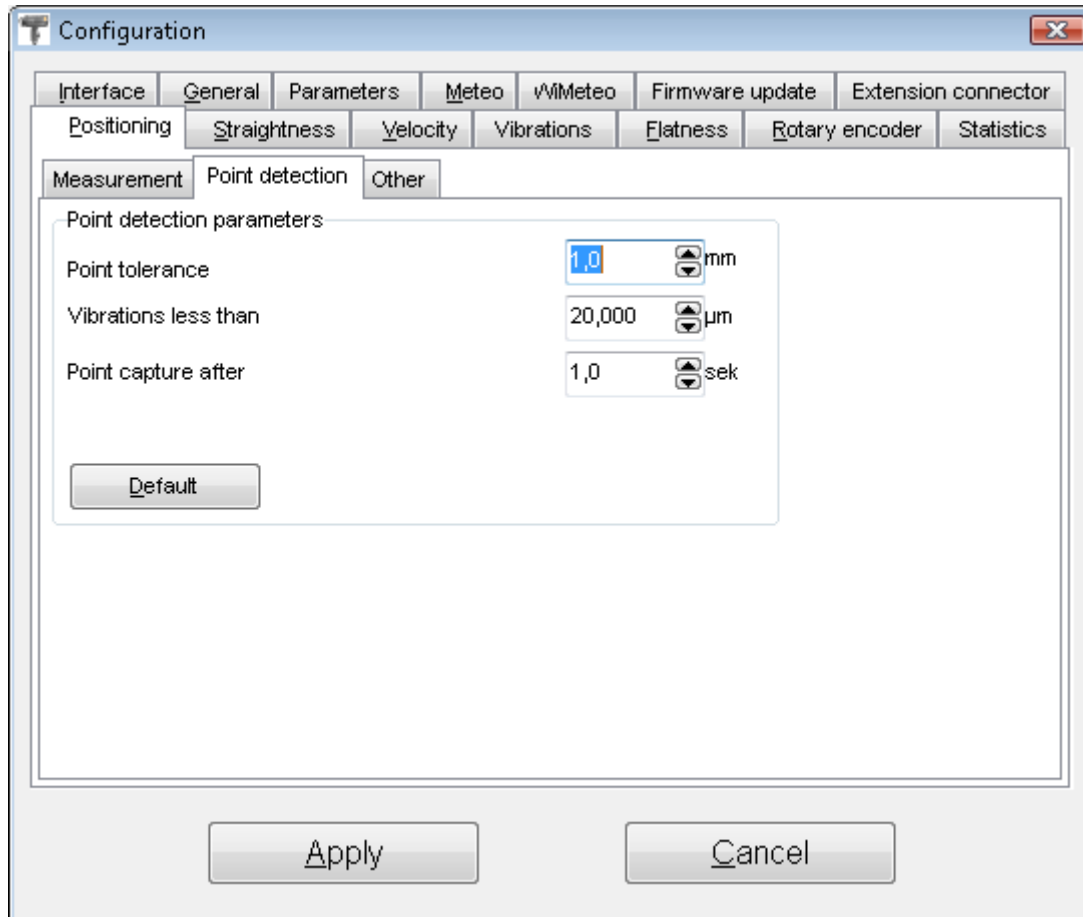
FIG.5.25. LINEAR POSITIONING COFIG WINDOW – POINT DETECTION

The options available in the **Point detection** tab are usable only when Automatic Point Capture option is chosen. They define the conditions under which the software captures the measurement points.

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A point is captured when the measured distance vibrations are lower than *Vibration less than* value after time defined in *Point capture after*. The measurement point value is rounded with tolerance set in *Point tolerance*.

For example if the *Point tolerance* is set to 1.0 mm and laser measures 50.11mm, then a desired measurement point of 50.00 mm is taken with machine error of 0.11 mm. In the case when laser measures 60.61 mm the measurement point of 61.00 mm is taken with machine error of -0.39 mm.

In the case when the *Point tolerance* is set to 0.2 mm and laser measures 50.11mm, then a desired measurement point of 50.20 mm is taken with machine error of -0.09 mm. In the case when laser measures 60.61mm the measurement point of 60.60 mm is taken with machine error of 0.01 mm.

xiii. Pull down menu – Measurement
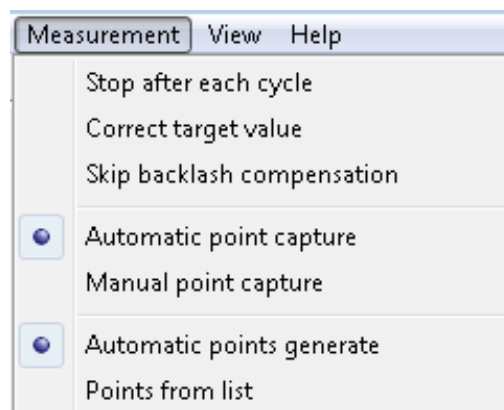
FIG.5.26. POSITIONING PULL-DOWN MENU *MEASUREMENT*

Measurement menu includes the options related to the measurement process:

Stop after each cycle – if this option is active program breaks the measurement when a measuring cycle is completed; if it is not active the configured number of cycles is executed.

Correct target value – setting this option enables to change an earlier defined distance value of a measuring point during the measurement process. Before the point is captured, appears a window in which a new distance value can be written. In the edit field there are only marked places after comma what causes that it is not necessary to write the whole distance.

Skip backlash compensation – if checked then the software does not expect the machine to make the backlash compensation movement (from point S to point 1 in the figures 5.21 – 5.24).

Automatic point capture – program captures measurement points automatically using settings from *Configuration*. In this mode the system itself recognizes the moment of stop, the value of target point, the direction of movement and the series number. Option exclusive with "Manual point capture".

Manual point capture – measured points are captured by the program when a **Manual Capture** button, *Space* key or

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a remote *Strobe* button is pressed. Option exclusive with "Automatic point capture".

Automatic points generate – positioning points are calculated automatically by the program. Points calculation is performed in first measuring cycle. Option exclusive with "Points from list".

Points from list – when this option is selected on the screen appears a window for positioning points edition. This window enables to write or calculate distance values for positioning points which are compared to measured points during positioning measurement. Option exclusive with "Automatic points generate".

FIG.5.27. POSITIONING PULL-DOWN MENU *VIEW*

View menu is used to switch on or off a **Deviation table** and to switch on drawing on the graph points from **All cycles** (active cycle is drawn using solid line but remaining cycles are illustrated using only points). **Show pictogram** command is used to present a schematic diagram of selected measurement method.

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d.Preparations for measurement

i. Measurement window
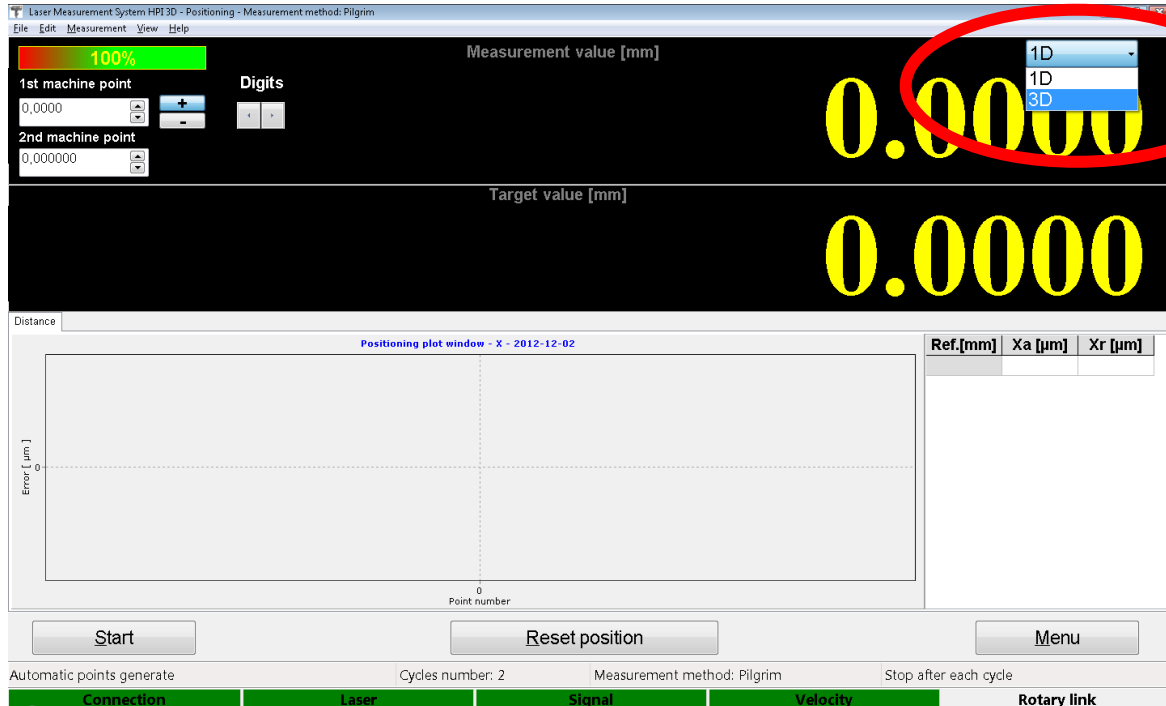
FIG.5.28 CHOICE BETWEEN 1D AND 3D POSITIONING

If the system is ready to work, then two digital displays and the gauge of measuring signal level appear on the screen. On the upper display the measured value is shown. On the bottom display the value of the target position (read from data points table or appointed automatically) is shown. Under the displays on the left side there is shown a graph on which the results of measurements are shown. On the right side an **Error Table** can be found. Under the graph three buttons can be found:

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- **Start** - beginning of the measurement,

- **Reset Position** – resetting the measured value and the button

- **Menu** - allowing returning to the Main menu.

ii. 1D and 3D measurements

In the right upper corner of the main positioning window (see figure 5.28) there is placed the button for choosing if the laser measures only the positioning ("1D") or if the 3D axes straightness is measured simultaneously ("3D"). If the "3D" option is chosen, together with the positioning data, the straightness data in horizontal and vertical planes are gathered.
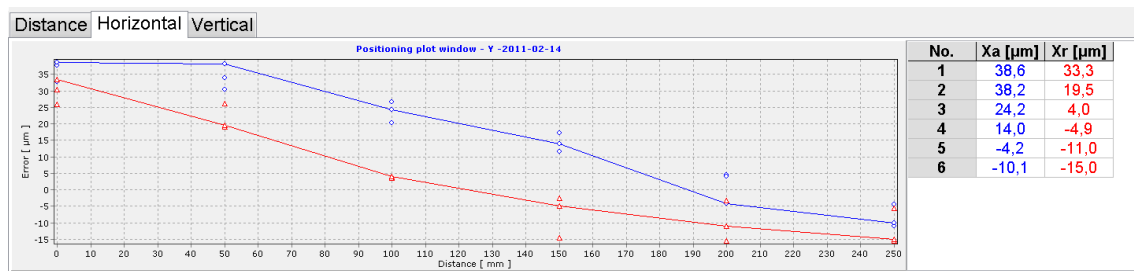
FIG.5.29. 3D DATA BROWSING

All measured data can be browsed during measurements by changing data panels (figure 5.29). The data from actual measurement series are shown in the table and on the chart connected with lines. Points from previous

obtained series are visible on the chart as blue circles or red triangles.

iii. Measurements in machine coordinate system

It is possible to obtain positioning measurements directly in the machine coordinate system. To do this the *1st machine point* and *2nd machine point* fields have to be filled (see figure 5.31). In these fields the position of first two measurement points in the machine coordinate system has to be entered. After modification of these fields the measurement results is shown in the machine coordinate system. Also the error compensation files are changed appropriately.
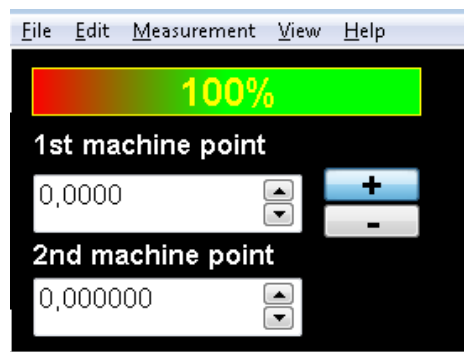
FIG.5.31. CONNECTING COORDINATE SYSTEMS OF LASER AND MACHINE

iv. Setting measurement points

The linear positioning measurement requires target positions which define the points where positioning errors are calculated. The target points can be automatically defined during the first cycle in the measurement, or manually written to the list or calculated (**Target Points From List**). Points are detected with 1.0 mm tolerance in automatic mode (if other point tolerance value is required, then *Configuration->Positioning->Point detection->Point tolerance* value should be changed). The positioning points can be also written or calculated after marking an option **Target Points From List** (see figure 5.19). After activating this option the positioning points can be defined with any accuracy.

Measurement can be performed in an **Automatic** option or in a **Manual Capture** option as described earlier in this chapter. In the automatic mode the system itself recognizes the moment of stop, the value of target point, the direction of movement and the series number.

e. Rules of automatic positioning measurement

For correct operation of the automatic positioning measurement option below rules should be followed:

1) The time of machine stand still duration in the positioning point must be no less than 1 second – default value (this can be changed in the *Configuration->Positioning->Point detection->Point capture after*),

2) Vibrations of the target should be less than 10 μm - default value (this can be changed in the *Configuration->Positioning->Point detection->Vibrations less than*),

3) Backlash compensation move of the machine should exceed 1.0 mm.

If vibrations are too large and system does not capture points – then the option Manual Capture should be switched on in the Measurement menu.

f. Remarks on measurements and on data analysis

Examination of linear positioning of machine consists of at least 2 measuring cycles.

In every cycle the measured the machine moves the retro-reflector for programmed distance forward and back.

After each shift the machine should stop for a time of at least one second.

From practical point of view, because of machine vibration, the stop time should exceed 3 seconds.

The measured distance by the laser system is saved in the table of results.

After one cycle, if **Stop after each cycle** is set or after the whole measurement process the window with results appears (figure 5.32).
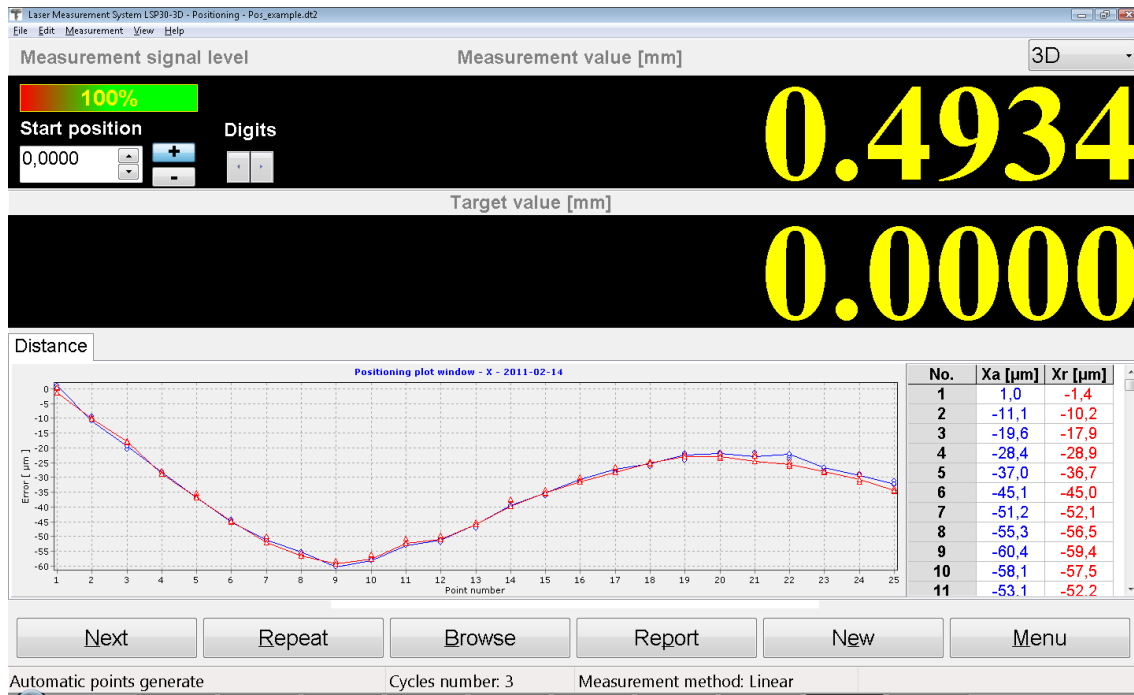
FIG.5.32. POSITIONING WINDOW AFTER FINISHING A FULL MEASUREMENT CYCLE

Buttons **Remove** and **Add** can be used to remove or add the measurement cycle. It is possible to change the measuring cycle in which accidental error is suspected. Button **Browse** opens data browsing window (figure 5.33) where each data cycle can be viewed and analyzed.
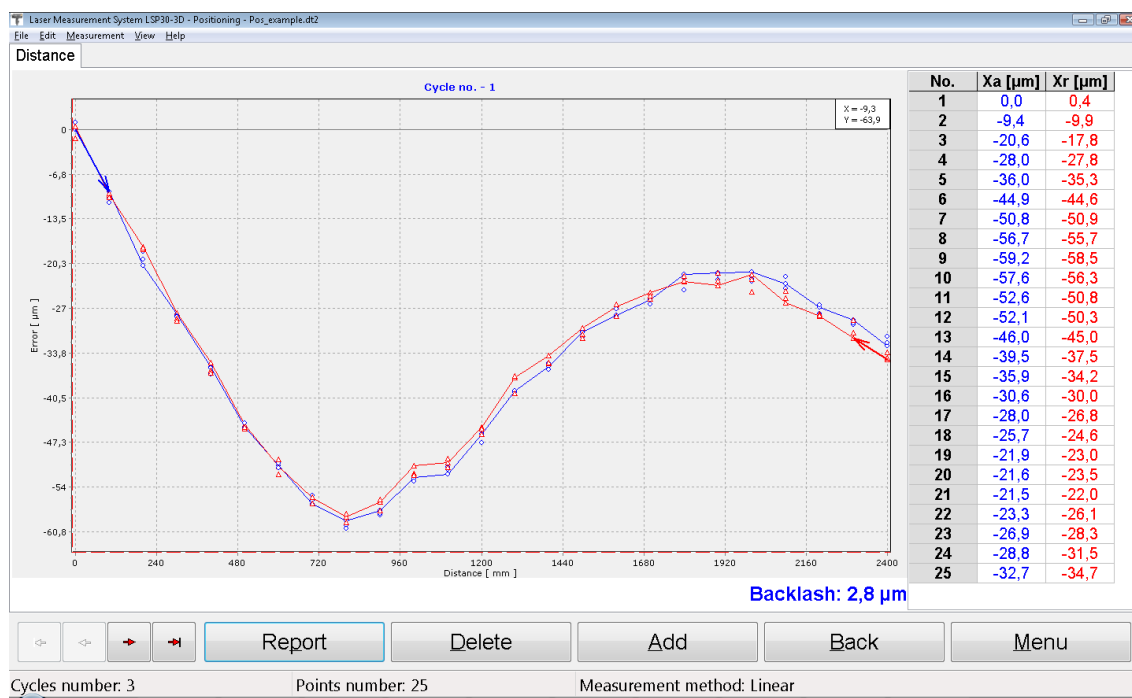
FIG.5.33. DATA BROWSING WINDOW

Both from main positioning window and from data browsing window the measurement report can be generated. If at least two series of measuring cycles are completed, statistical calculations can be performed and the report can be generated. In order to get the final report the **Report** button has to be pressed. The screen of the computer after pressing the button **Report** is presented on fig. 5.34.
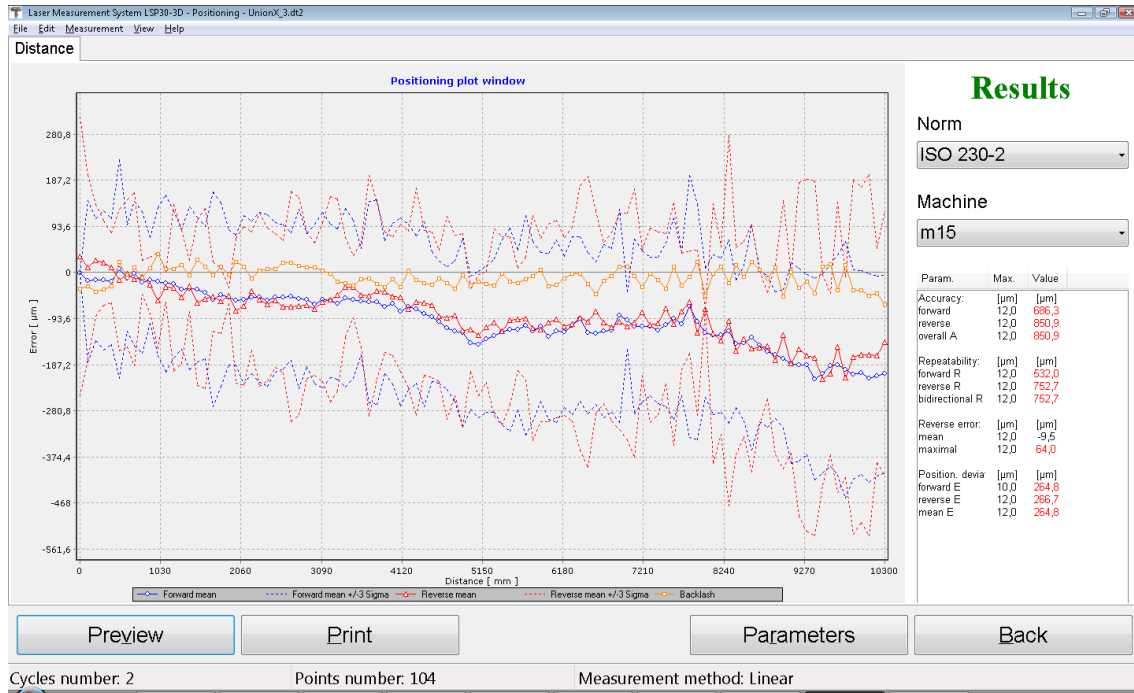
FIG.5.34. LINEAR POSITIONING REPORT WINDOW

The positioning results are presented on the graph and in the **Results** panel. This panel is also used to set measurement data processing parameters. The norm defines a statistical method used in calculations and can be chosen from a pull-down list. Norm selection causes recalculation of the results. Limit values for measured machine parameters are presented in this panel. They are assigned to the machine that is chosen from **Machine** pull-down list. If the error value exceeds limits for the machine, this error is displayed in red.

Under the graph there are: buttons used for report **Preview**, **Print** the report, change of the graph **Parameters**, and return to the previous window.

The axis scale can be changed using **Axis Scale** (automatic scaling or assignment, minimum and maximum values) option available by right mouse click on the graph.

FIG.5.35. LINEAR POSITIONING REPORT EXAMPLE

The generated report can be simplified or extended. The selection window is shown each time the **Preview** or **Print** buttons are pressed. The simplified version consists of three pages: the title page, the results page and the chart page – see also figure 5.35. The logo on the title page can be changed in the **Configuration->Parameters**. In the Extended Report additional pages with measurement results are added. The number of additional pages depends on the number of gathered measurement points.

g. Machine error compensation

When the measurement is finished the data can be saved to a file or exported as a text file (pull down menu *File->Export*). Text file export gives possibility of further analysis of obtained data in mathematical tools like Matlab, Mathematica or Excel.

The HPI Software from the positioning results generates also the text compensation file for the machine control (figure 5.35). At this moment there are available eight different formats of the output files. Format should be selected according to the type of the control of the machine.

Depending on the chosen output data format different set of parameters appears in the Error Compensation

window (figures 5.37-5.39). Below there are described most commonly used data formats.
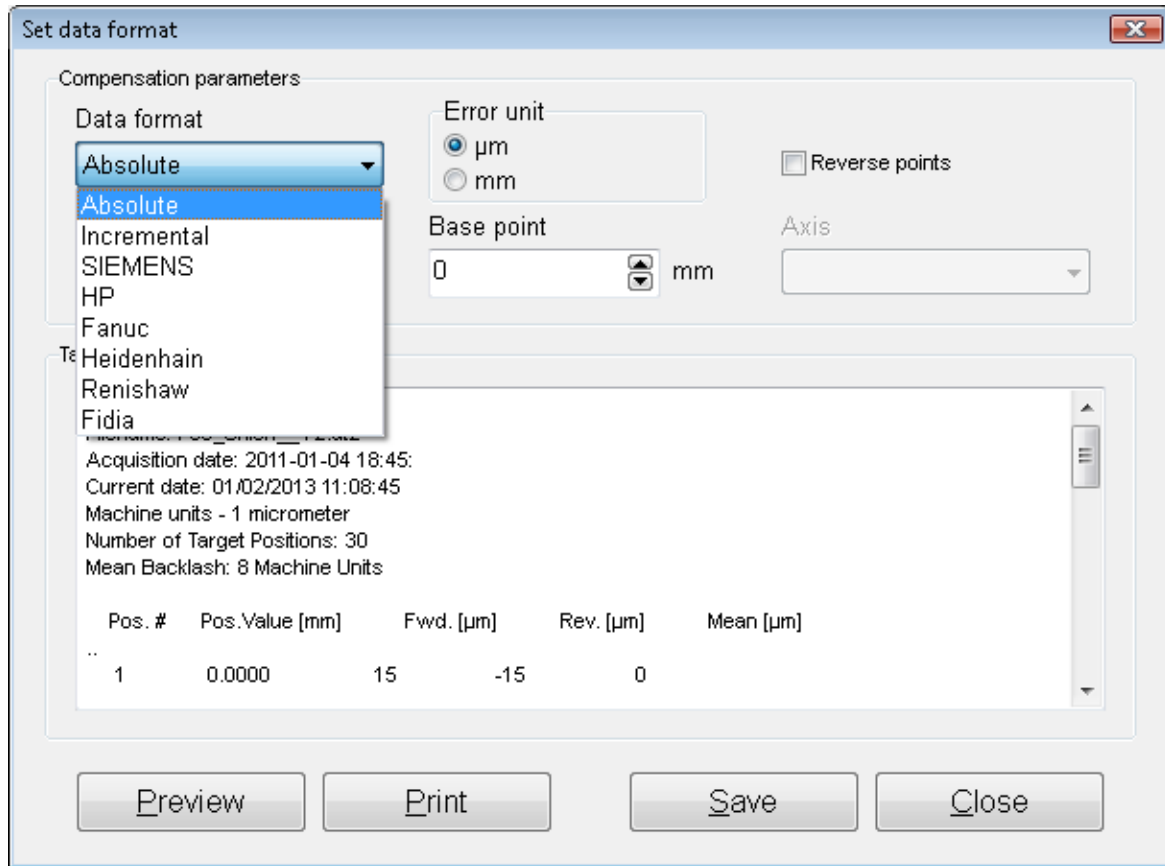
FIG.5.36. MACHINE ERROR COMPENSATION

i. *Absolute and Incremental data formats*

The basic and most universal error correction file formats are *Absolute* and *Incremental*. In this case the data are formatted as a simple table with five columns (figure 5.37):

- number of positioning point

- distance value in the positioning point

- error in forward direction

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- error in reverse direction

- mean error

In the case of the absolute format the values of errors are absolute, non-relative. In the case of the incremental format the errors in the certain point are calculated relative to the errors in the previous point, taking error in the first measurement point as zero.
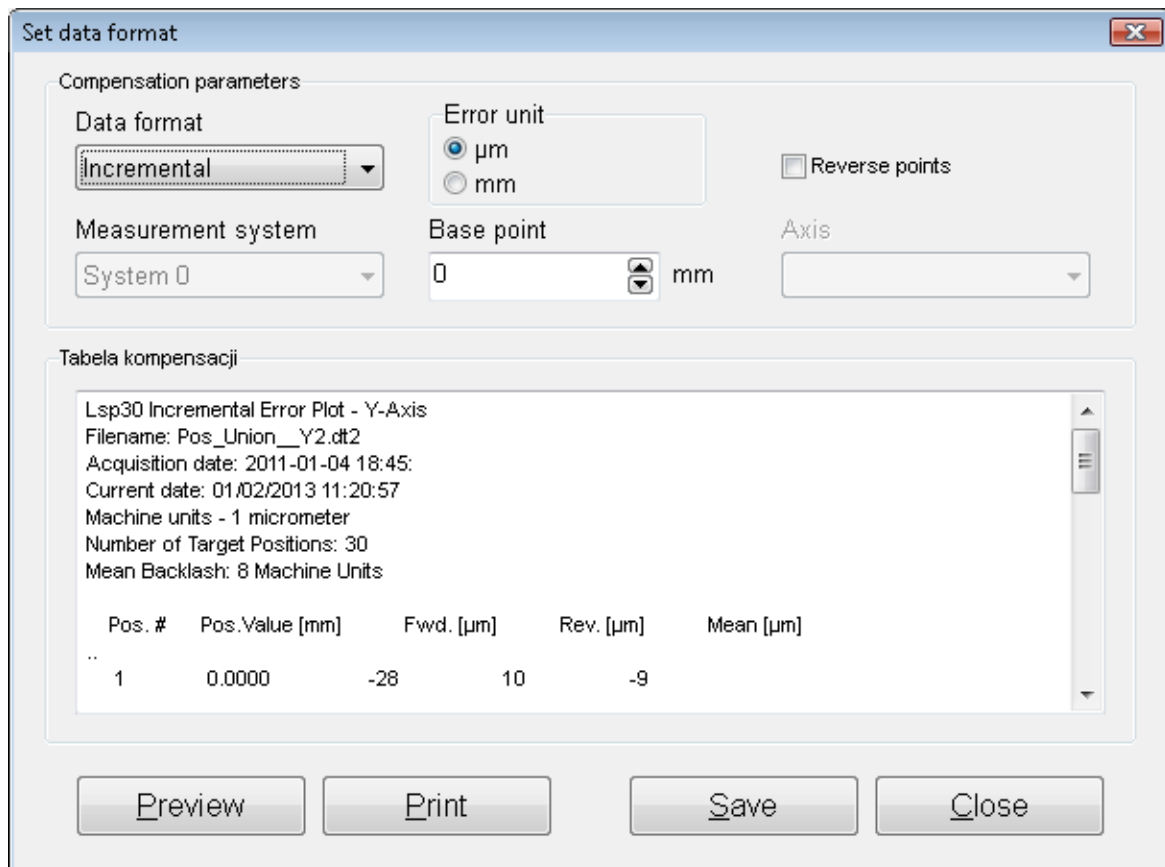
FIG.5.37. MACHINE ERROR COMPENSATION – LINEAR AND INCREMENTAL DATA FORMAT

The compensation window for those formats is shown in the figure 5.37. The user can change the *Error unit* between

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μm and mm and the *Base point*. The base point value is added to all position values in the second column.

ii. Siemens data format

The Siemens data format file is usable in most commonly used machine control units produced by Siemens. The choice is between types 828 and 840. For older control units the incremental data format should be used.
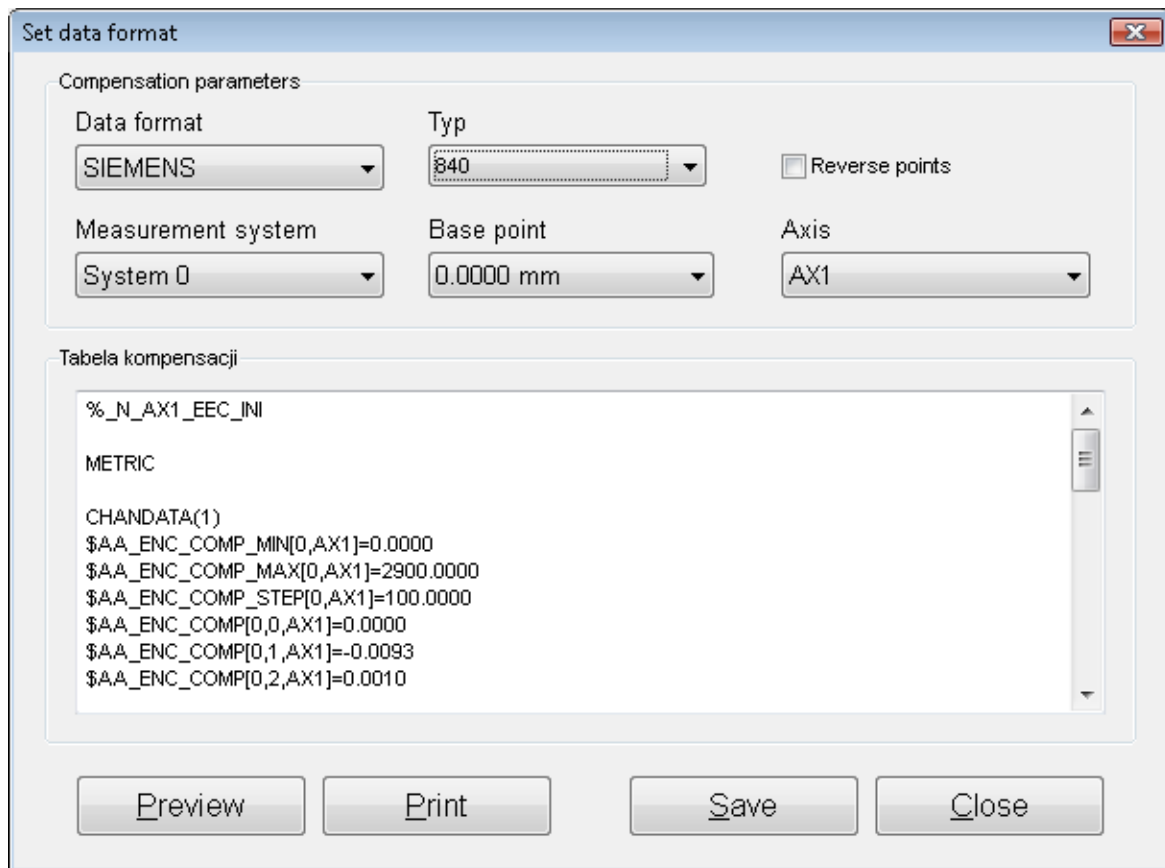
FIG.5.38. MACHINE ERROR COMPENSATION – SIEMENS DATA FORMAT

As shown in the figure 5.38 the format of the Siemens file differs greatly from the absolute/incremental format.

The Siemens type file can be stored to a file and uploaded directly to the corrected machine (with 828 or 840 drives).

It is possible to set proper *Measurement system,* change the machine *Base point* (not necessary when the machine coordinate system is used) and change the compensated *Axis* name.

iii. Fanuc data format
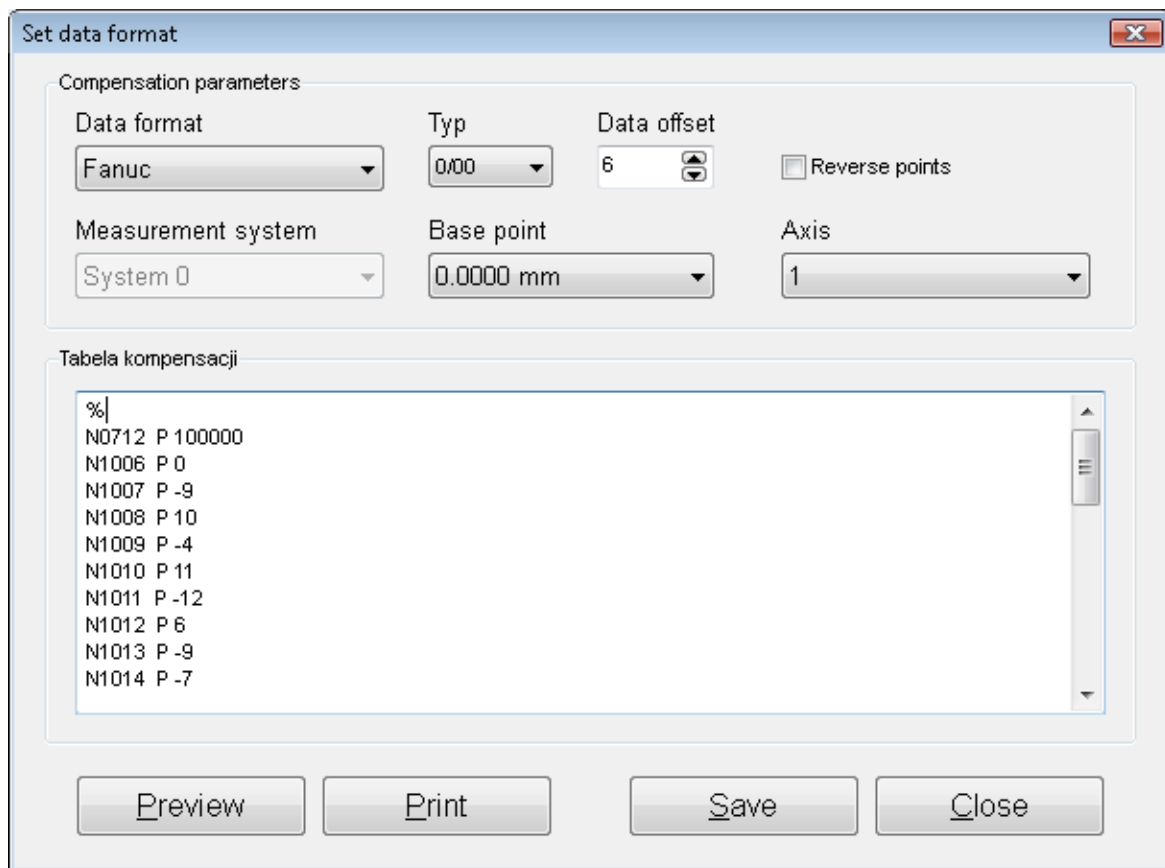
FIG.5.39. MACHINE ERROR COMPENSATION – FANUC DATA FORMAT

The Fanuc data format file is usable in most commonly used machine control units produced by Fanuc. The choice is between different types of Fanuc control units.

As shown in the figure 5.39 the format of the Fanuc file differs greatly from the absolute/incremental format. The Fanuc type file can be stored to a file and uploaded directly to the corrected machine.

It is possible to set proper *Data offset* (should be in 0-1023 range), change the machine *Base point* (not necessary when the machine coordinate system is used) and change the compensated *Axis* name.

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6.   MEASUREMENTS - VELOCITY

a. General Description

Velocity measurements are performed with the use of linear optics. This measurement can be used, for example, for characterization of motor movement. The System enables to measure velocity in different units. It can be configured in *Configuration->Velocity* option. The value of velocity is sampled every 40ms.

b. Measurement Setup

For velocity measurements linear optics should be used. Necessary components are (see also figures 6.1 to 6.4):

- Laser Head
- Power Supply
- Linear interferometer **IL1**

- Linear retro-reflector **RL1**

Optional elements are:

- USB cable

- Manual Strobe

- Magnetic holder **UM2**

- Tripod stand

- Base temperature sensor

- Air temperature sensor

Velocity measurements require optical elements IL1 and RL1 to be aligned along laser beam as shown in the figure 6.1. Each of the elements can be moved.

During velocity measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

6
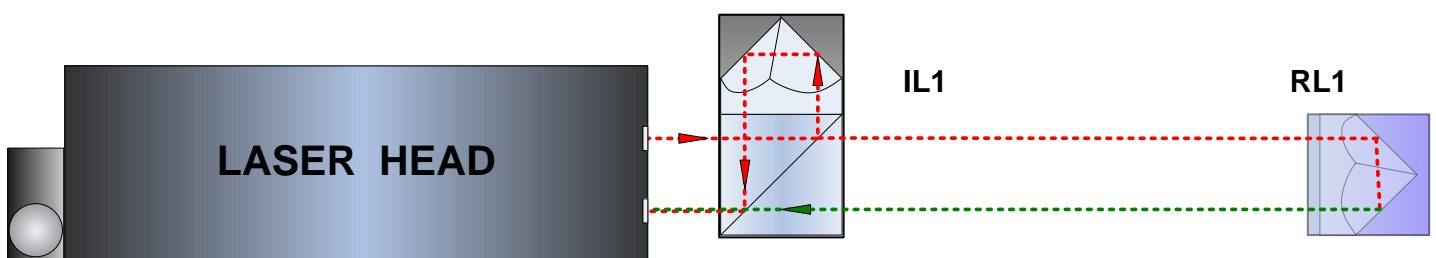
FIG.6.1 OPTICAL PATH SET UP FOR VELOCITY MEASUREMENTS-SCHEMATIC.

Velocity measurements can be performed not only along the laser beam (as shown in the figures 6.1 and 6.2) but also

in directions perpendicular to the laser beam. These configurations are shown in the figures 6.3 and 6.4. In those two configurations only the retro-reflector RL1 can be moved.
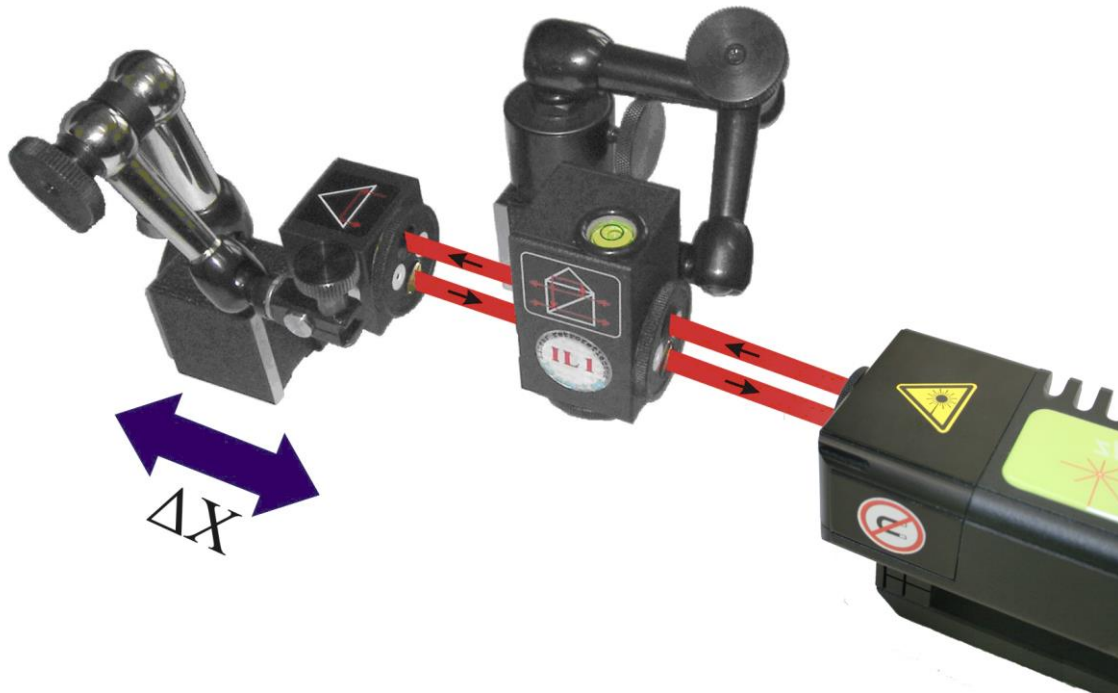
FIG.6.2 OPTICAL PATH SET UP FOR VELOCITY MEASUREMENTS IN X AXIS.
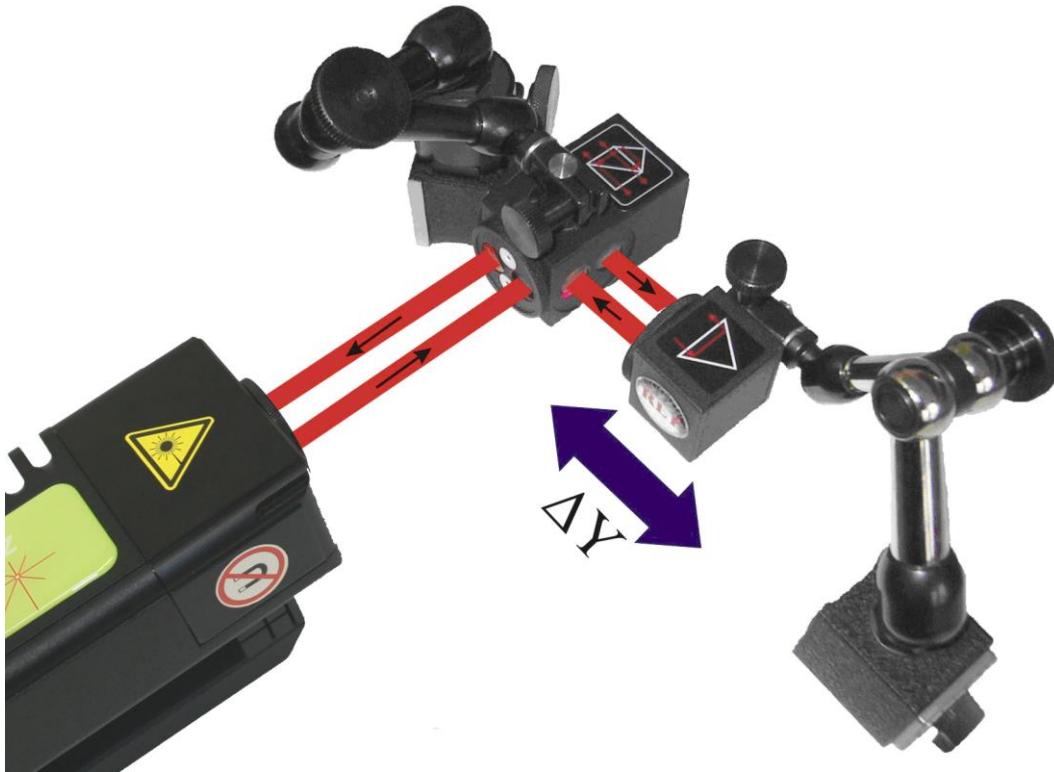
FIG.6.3. OPTICAL PATH SET UP FOR VELOCITY MEASUREMENTS IN

Y AXIS.
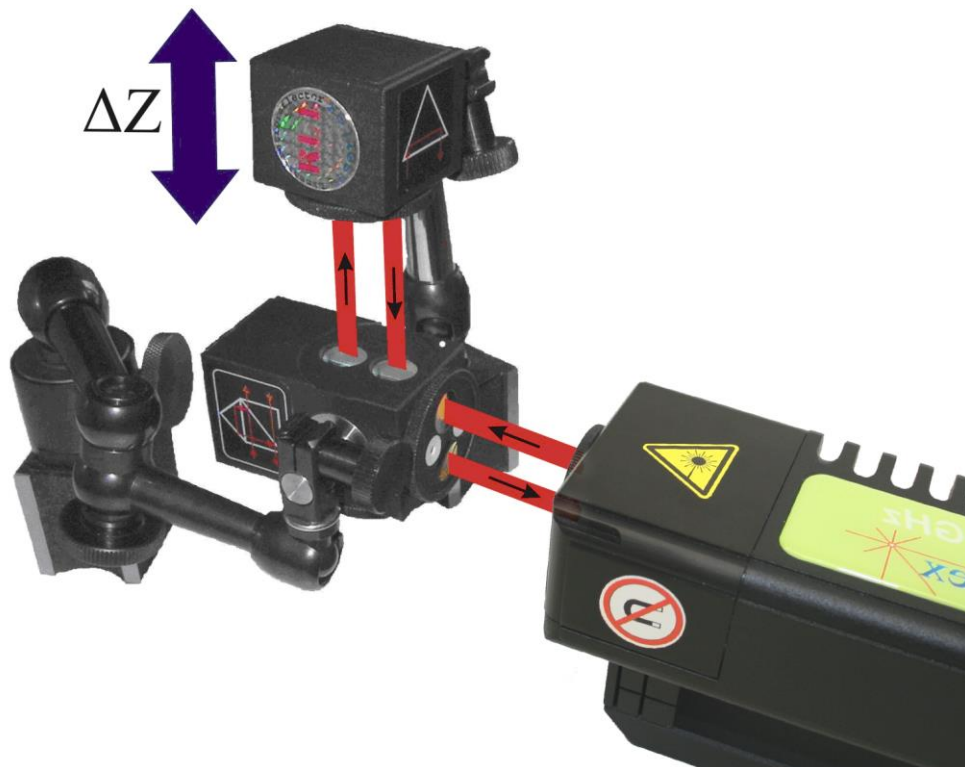
FIG.6.4. OPTICAL PATH SET UP FOR VELOCITY MEASUREMENTS IN

Z AXIS.

c. Software description

Velocity is measured in the **Velocity** option, chosen from the **Main Menu**. In the Fig. 6.5. there is presented a main window of the **Velocity** option in the *HPI Software.* The window consists of four main parts:

- Display – presents a current velocity and measurement signal level;
- Velocity plot – blue line is a plot of the measured velocity, red line is a plot of the averaged velocity;
- Velocity value table – a table containing consecutively numbered samples, time elapsed from start, and current velocity value;
- Panel with buttons
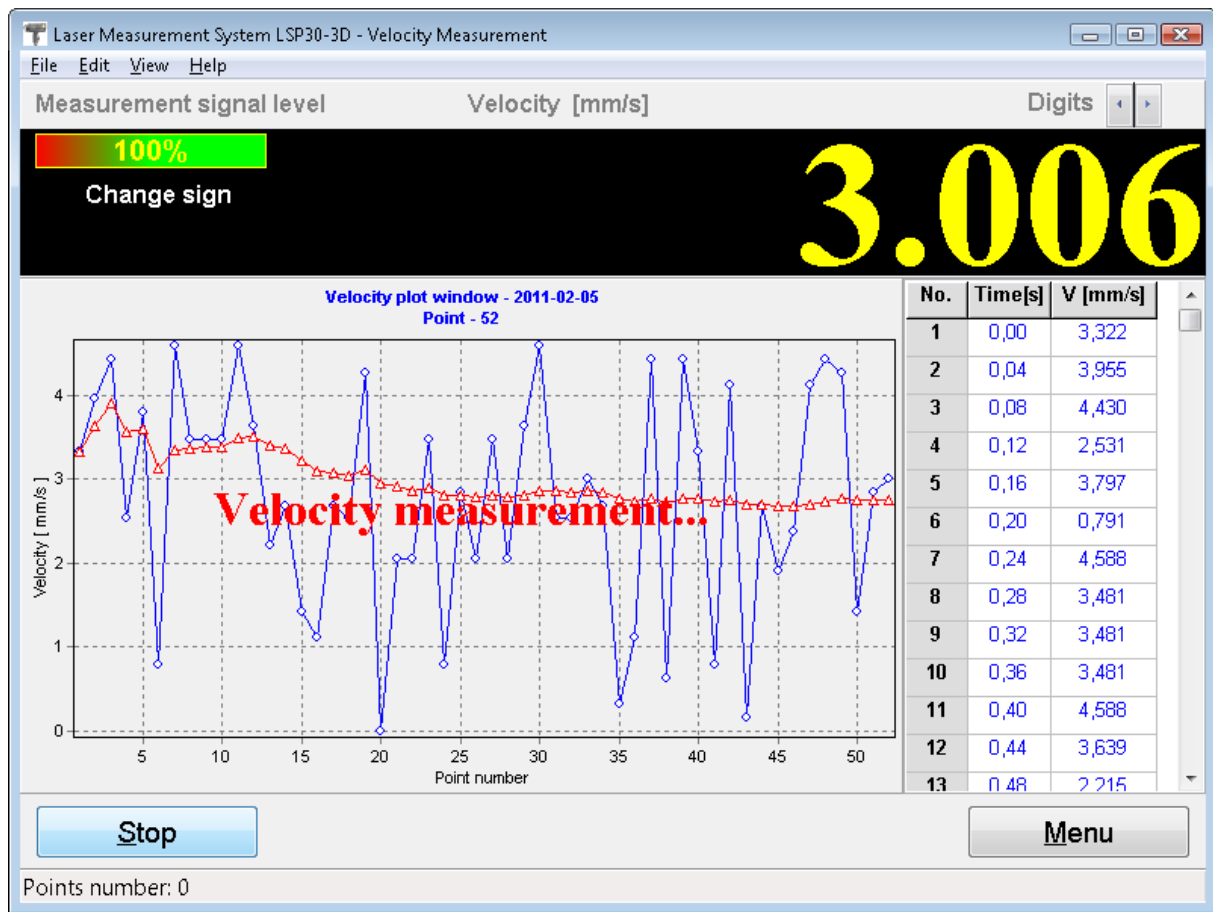
FIG.6.5. VELOCITY MEASUREMENT WINDOW.

Velocity measurement is launched by the **Start** button and software performs a continuous velocity data acquisition of the measured object. The measurement is finished by the **Stop** button. During measurements the velocity graph will be constantly updated on the screen. By clicking on a part of the graph and moving the mouse rightwards the graph can be zoomed. By clicking on a part of the graph and moving mouse leftwards the zoom is cancelled. The graph can be printed or saved to a file. Those commands are available from the **File** menu (i.e. Save, Save as, Print – see figure 6.6).
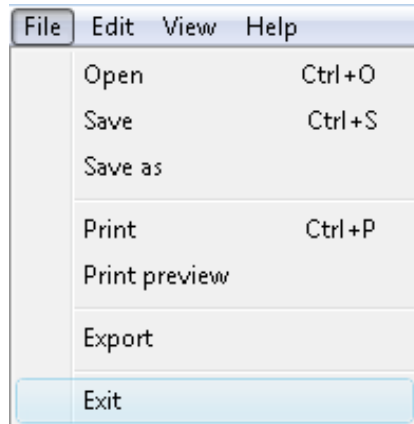
FIG.6.6. VELOCITY PULL-DOWN MENU *FILE.*

Before saving the file the program asks about machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator (see figure 6.7). Those values allow describing performed measurement for later analysis and they are also present on the printed report.

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FIG.6.7. MACHINE DATA WINDOW.

Measurement report can also be generated from obtained data, either by pressing *Print* or *Preview* in the measurement analysis window (fig. 6.8). The report can be generated in the basic form where only the plot of the measured values is shown (fig. 6.9) or in the extended version, which contains tables with measured data.
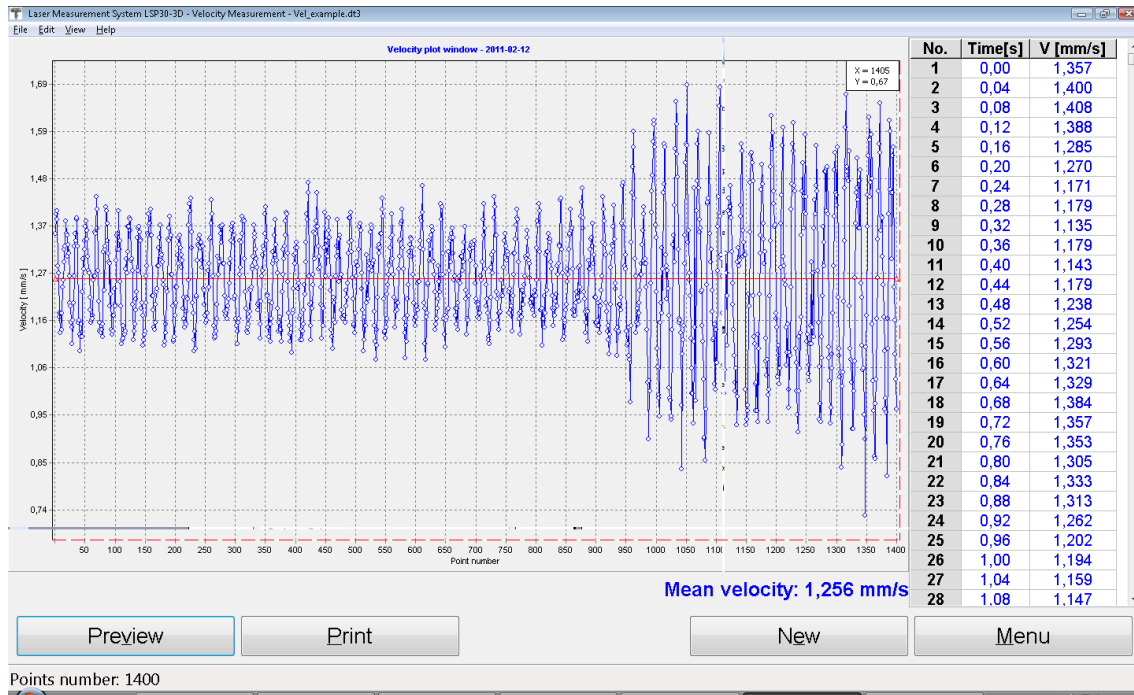
FIG.6.8. VELOCITY MEASURED DATA ANALYSIS WINDOW.
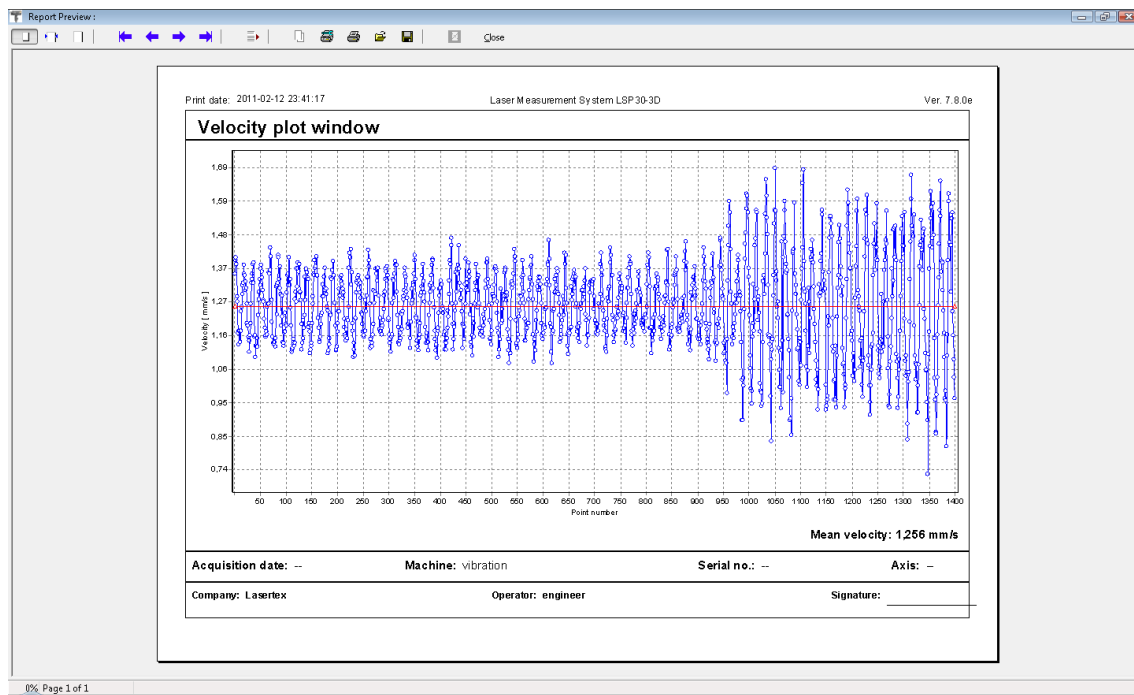
FIG.6.9. VELOCITY REPORT PREVIEW WINDOW.

It is also possible to copy the velocity graph to the clipboard and then paste it for example to a Word editor

document. **Copy to clipboard** command is available from popup menu that appears after right-click on the area of the graph.

The velocity unit can be set in the **Configuration**, **Velocity** tab (see figure 6.10). **Configuration** is available from **Edit** menu.
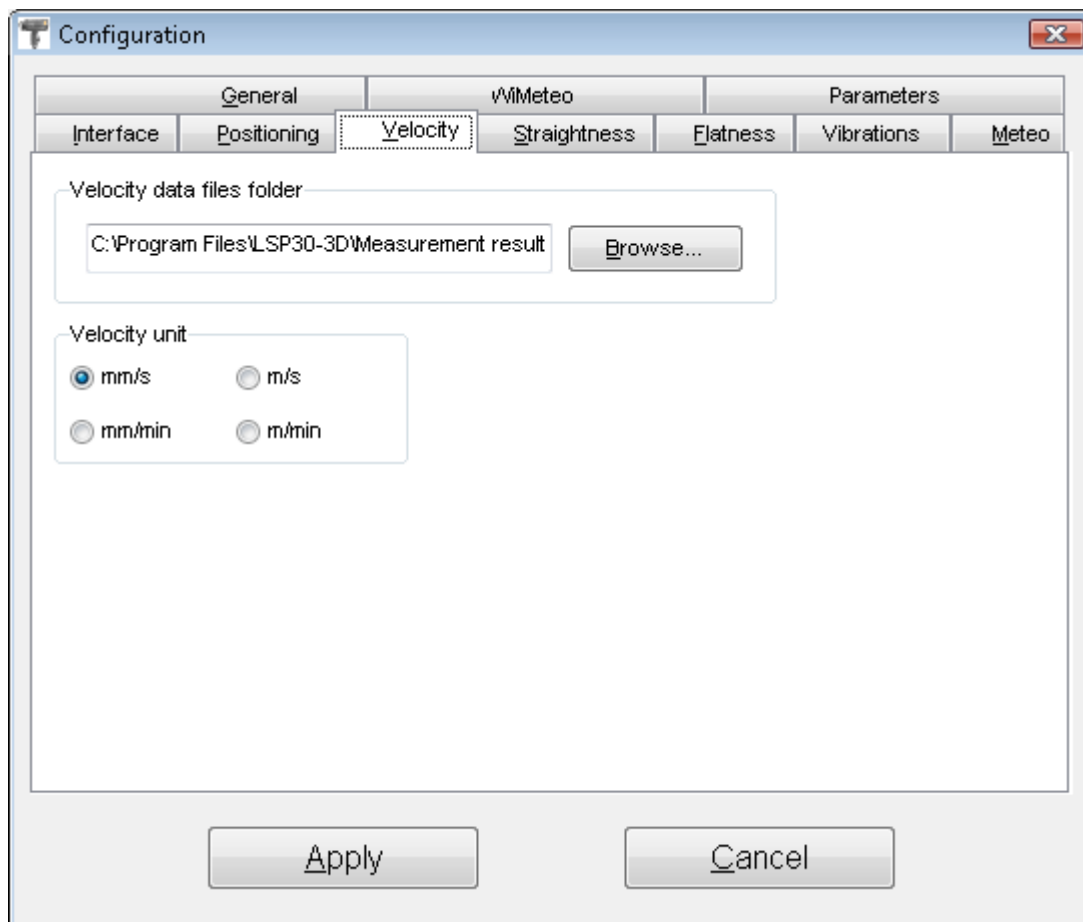
FIG.6.10. VELOCITY CONFIGURATION OPTIONS.

d. Measurement procedure

1. Set up the laser on the measured machine and align optical path.

2. Start the HPI-3D software and select Velocity option.

3. Choose desired Velocity unit in the Configuration window (optional).

4. Press Start button and run the machine.

5. When the machine stops, press Stop button, save the results and/or print the measurement report.

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7. MEASUREMENTS - STRAIGHTNESS

a. General Description

Straightness measurements is a measurement usually used to gain basic information about the machine axis geometry. With this option the user can measure machine base straightness on all important surfaces of the base or check the movement of e.g. the measured machine's element in space.

In the HPI-3D device the straightness measurements can be performed with three different methods: Angular, Wollaston and 3D. *Angular* method is designed to be used in base straightness measurements (like optical autocollimator); Wollaston method is designed for "movement in space" measurements – e.g. the movement of a machine table or working tool can be characterized; *3D* method is used for rapid estimation of "movement in space" – like Wollaston method but the measurement is performed in the three axes at once. The main parameters of those methods are described in the Technical Data chapter.

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b. Measurement Setup – Angular optics

i. Principles

The operation of the HPI-3D with the angular optics used is shown in the Figure 7.1. The laser outputs the laser beam consisting of two polarizations: Horizontal (H) and Vertical (V). The IK1 splits the beam into two parts. Both beams are directed into the measurement path but are parallel shifted by 1'' or 2'' distance (depending on the version).
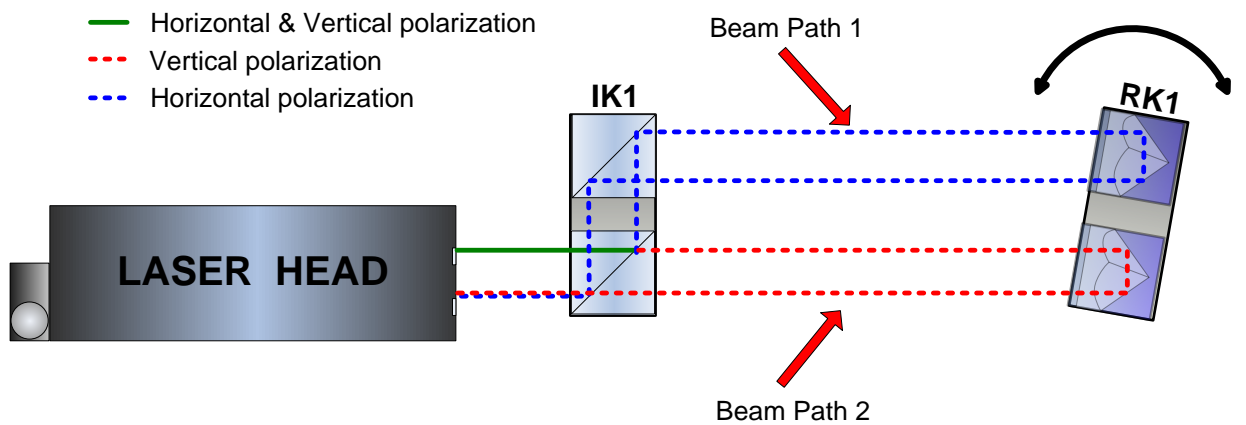
FIG.7.1. ILLUSTRATION OF THE PRINCIPLE OF OPERATION - ANGULAR OPTICS

When the distance between optical elements altered then the frequency of both beams is changed according to the Doppler Effect. The laser head does notice a movement only

if there is a rotation of IK1 versus RK1, i.e. when there is difference in lengths of beam paths. The measured distance can then be used to obtain either the rotation angle (pitch or

The laser head with angular optics is **insensitive** to linear movements.

yaw of the machine) or the vertical movement of the optical component (IK1 or RK1).

FIG.7.2. CALCULATION OF STRAIGHTNESS DURING ANGULAR MEASUREMENTS - NOTATION

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In the Figure 7.2 there is shown schematically an RK1 on a carriage with all parameters important for calculation. For the clarity the position of IK1 is treated as a reference. The meaning of the parameters is:

L – base length;

s – distance between beams on IK1 and RK1 elements;

x – distance measured by the Laser Head

α - angular rotation of RK1 element

h – difference in height between two measurement points

The Laser Head measures the parameter **x** while the distance between beams **s** and the base length **L** must be set in the parameters of the HPI Software. Then the rotation angle α and the movement in the vertical direction **h** can be calculated from:

$$\alpha = \arctan \frac{x}{s}$$

$$h = x * \frac{L}{s}$$
(7.1)

ii. Application Notes

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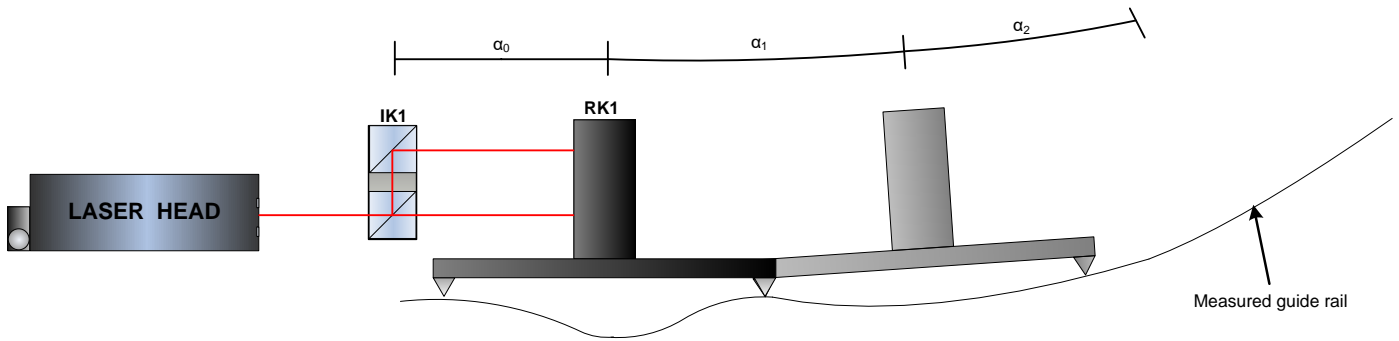
FIG.7.3. MEASUREMENT OF STRAIGHTNESS - PRINCIPLES

The angular optics can be used for:

- Measurement of pitch or yaw of a machine
- Measurement of straightness of a machine bed
- Measurement of small angles

The explanation of the first two applications is shown in the Figure 7.3. The RK1 mounted on a carriage is translated over the measured guide rail. Every length of the carriage (usually 100mm) a measurement is performed. Formulas 7.1 are then used for calculation of the angles (for pitch/yaw measurements) or the vertical translations (for straightness measurements).

It is worth to notice that such straightness measurement method requires proper choice of measurement points. Choosing points denser than the carriage size results in excessive values of the straightness errors (the shape of the error is proper).

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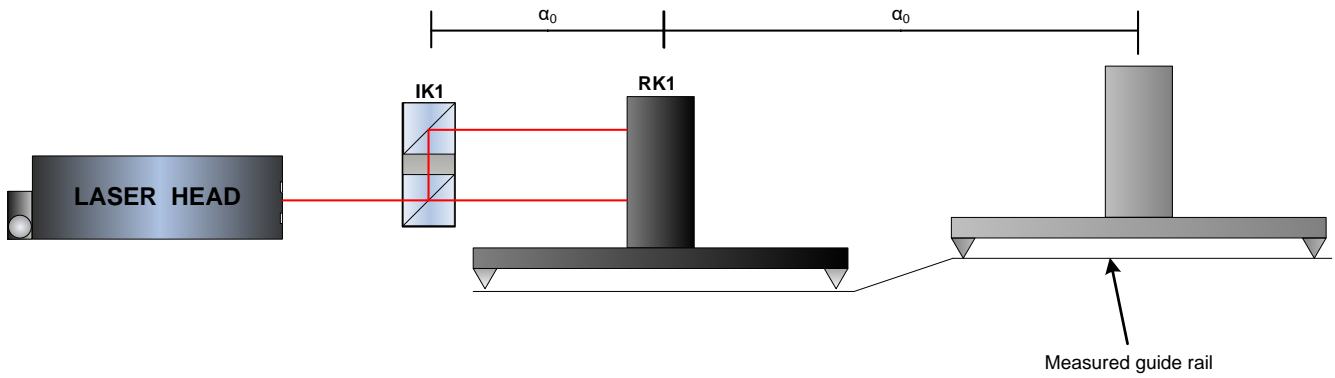
FIG.7.5. MEASUREMENT OF STRAIGHTNESS WITH TOO SPARSE MEASUREMENT POINTS

Choosing points too sparse may effect both the shape and the value of the error as shown in the Figure 7.5. In this special case because of too sparse measurement points the laser will not notice the change in the shape of the guide rail – the measured distance between beams will not change!

The measurement of small angles allows very accurate measurements of small rotations if two conditions are met:

1. measured angle is within ±5 degrees
2. distance between RK1 and the laser head does not change more than a few centimeters.

The second limitation comes from the heterodyne effect present in the HPI-3D laser. This effect influences the angle according to (Δl is the change of distance between the laser and RK1 during measurements) :

$$\alpha = \arctan \frac{x + \Delta l * 2.260 \mu m}{s}$$ (7.2)

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The above effect is present also in the normal straightness measurements but it is taken care by the HPI Software.

iii. Measurement Setup Preparations

For **Angular** straightness measurements the angular optics should be used. Necessary components are:

- Laser Head
- Power Supply
- Angular Interferometer **IK1**
- Angular Retro-reflector **RK1**

Optional elements are:

- USB cable
- Manual Strobe
- Magnetic holder **UM2**
- Tripod stand
- Air temperature sensor
- Base temperature sensor

Angular straightness measurements require optical elements IK1 and RK1 to be aligned along laser beam as shown in the figure 7.6. Each of the elements can be moved.

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During Angular straightness measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.
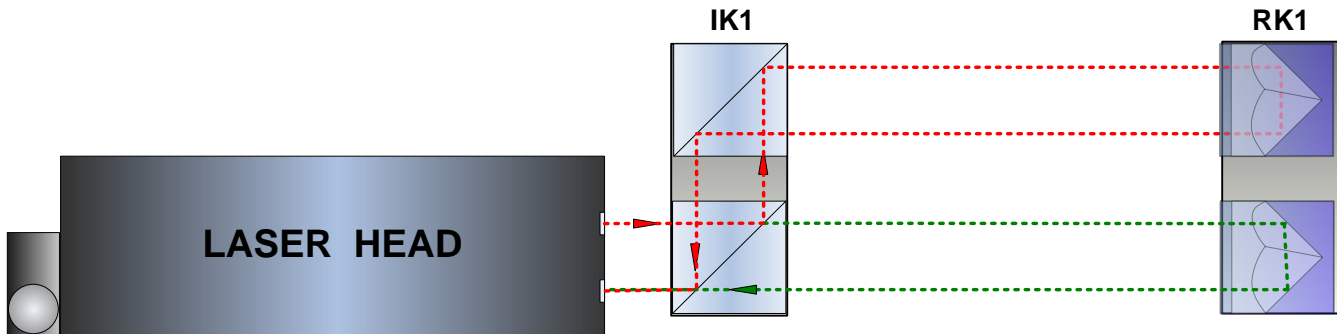
FIG.7.6 OPTICAL PATH SET UP FOR ANGULAR STRAIGHTNESS MEASUREMENTS- SCHEMATIC.
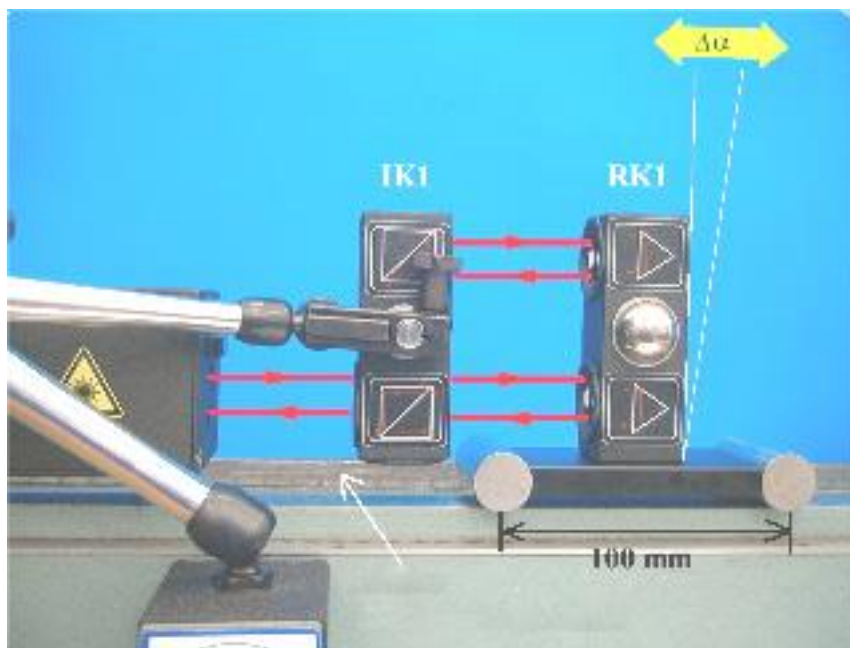
FIG.7.7 OPTICAL PATH SET UP FOR ANGULAR STRAIGHTNESS MEASUREMENTS IN X AXIS.

Angular straightness measurements can be performed not only along the laser beam (as shown in figures 7.7 and

7.8) but also in directions perpendicular to the laser beam. Such configuration is shown in figure 7.9. In this configuration only the retro-reflector RK1 can be moved.
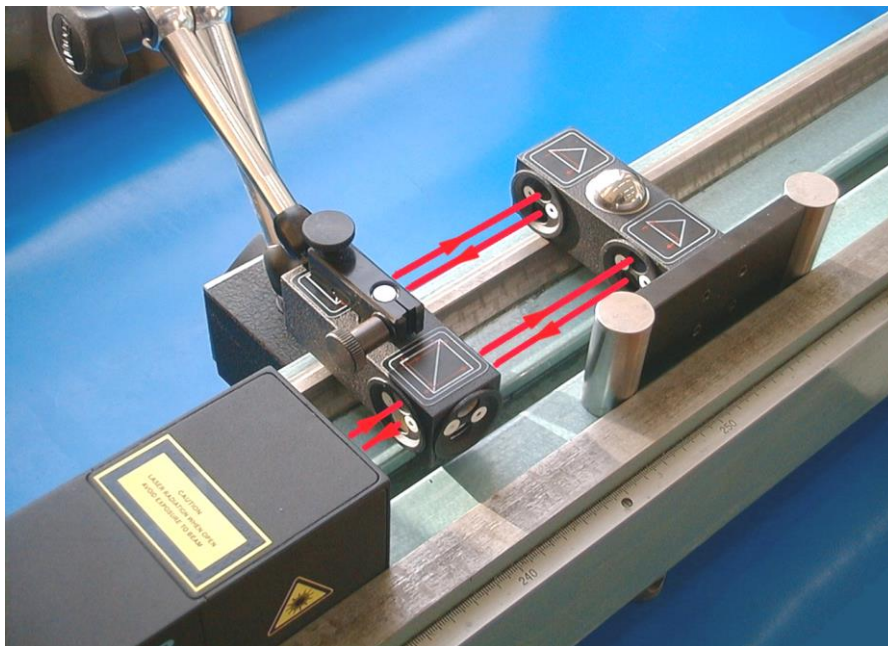
FIG.7.8 OPTICAL PATH SET UP FOR ANGULAR STRAIGHTNESS MEASUREMENTS IN Y AXIS.
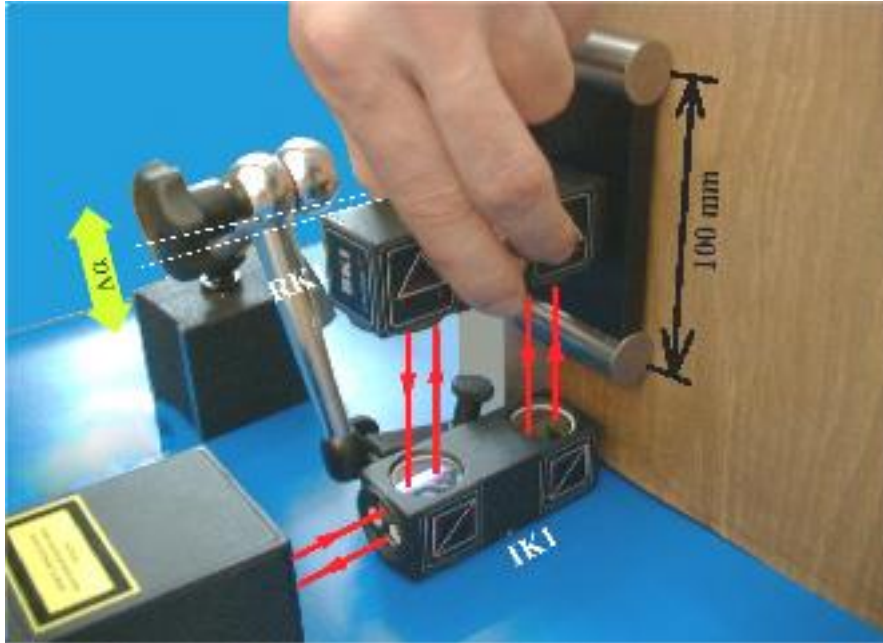
FIG.7.9 OPTICAL PATH SET UP FOR ANGULAR STRAIGHTNESS MEASUREMENTS IN Z AXIS.

During beam alignment it is important first to set up the position of IK1 aligned with the position of the laser head. Then the diaphragms on both optical components should be switched into the alignment position. The IK1 and RK1 should be set in such a way that the beam passes the centers of diaphragms.

After successful setup the diaphragms are to be set into work position and final alignment should be done with the use of electronic beam alignment tool. In order to keep the highest precision of the measurement the position of both beams on the alignment tools should stay within 200μm window for the whole linear movement range.

c. Measurement Setup – Wollaston optics

i. Principles
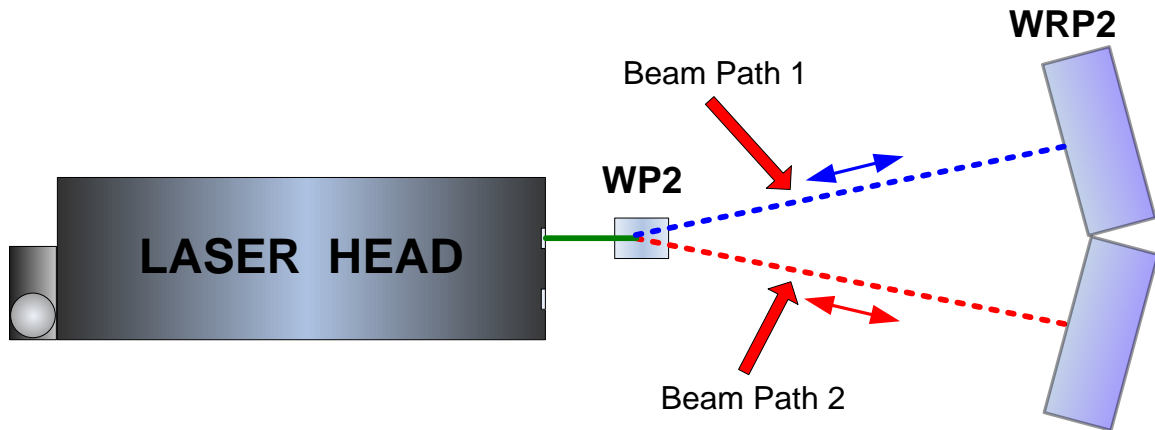
FIG.7.10 WOLLASTON PRISM OPTICS - PRINCIPLES

Another way of measuring straightness, parallelism and squareness with the laser interferometer requires the use of Wollaston type optics. The optics consist of two elements: Wollaston polarizing prism WP2 and a paired reflector WRP2 – see Figure 7.10. The laser beam, consisting of two perpendicular polarizations, is split by the WP2 element into two beams. The beams are leaving the WP2 at a certain angle and then, after being reflected back by the reflector WRP2 are returning to the laser head. The laser measures the difference between beams' paths lengths.
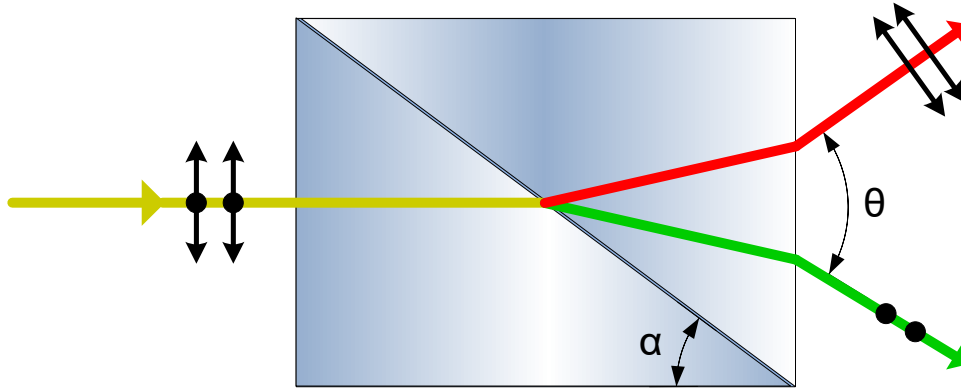
FIG.7.11 WOLLASTON PRISM POLARIZER WP2

In the Figure 7.11 there is shown the explanation of the operation of the WP2 element. This prism is constructed of two birefringent triangle prisms cemented together. Both prisms are built from the same material but their ordinary and extraordinary axes are perpendicular to each other, i.e. refraction coefficient of the ordinary axis of the left prism n_{ol} equals to the coefficient value of the extraordinary axis of the right prism n_{er}.

Because of this the orthogonally polarized laser beams entering the Wollaston element are deflected at different angles on the middle boundary layer and on the right boundary layer. This behavior can be easily proven with the use of the Snell's law. The angle between the exiting beams is often denoted as Θ.

X

Y
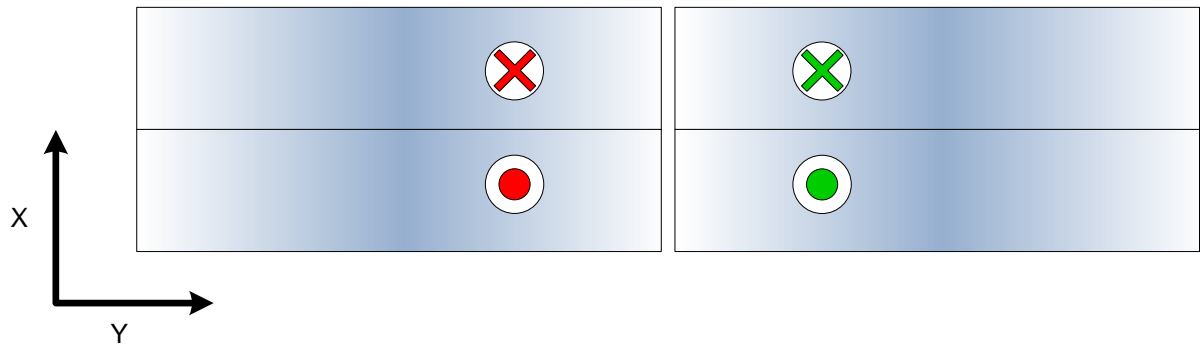
FIG.7.12A WOLLASTON REFLECTOR WRP2 – FRONT VIEW

180 - θ
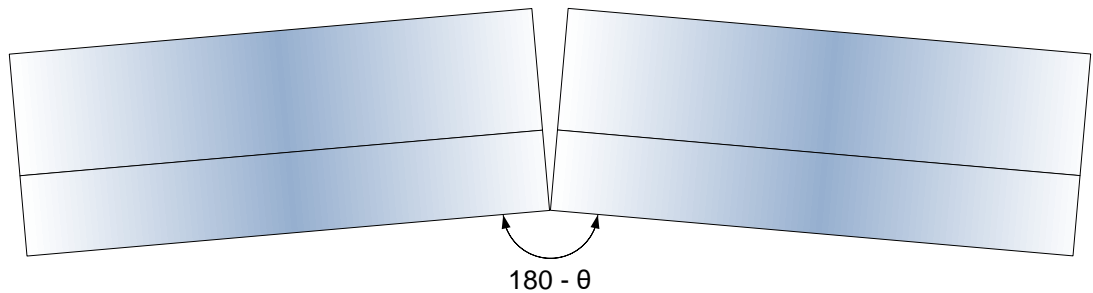
FIG.7.12B WOLLASTON REFLECTOR WRP2 – TOP VIEW

Unlike in the angular optics (see previous part of this Chapter) the distance between beams are changing with distance, thus making the construction of the reflecting element difficult. In the figure {7} there is shown the construction of the reflection element for the Wollaston optics WRP2. It consists of two special glass prisms glued very precisely at 180-Θ angle. The prisms used in the WRP2 in *y* axis reflect the beam with ½′′ translation (like the retroreflector RL1). In the *x* axis the beam is reflected with no translation (like in a mirror).

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The use of Wollaston optics makes possible the measurement of relative movement of WP2 element in the axis perpendicular to the laser beam. As it is shown in the Figure 7.13 the measurements are possible ONLY with the WP2 movement.
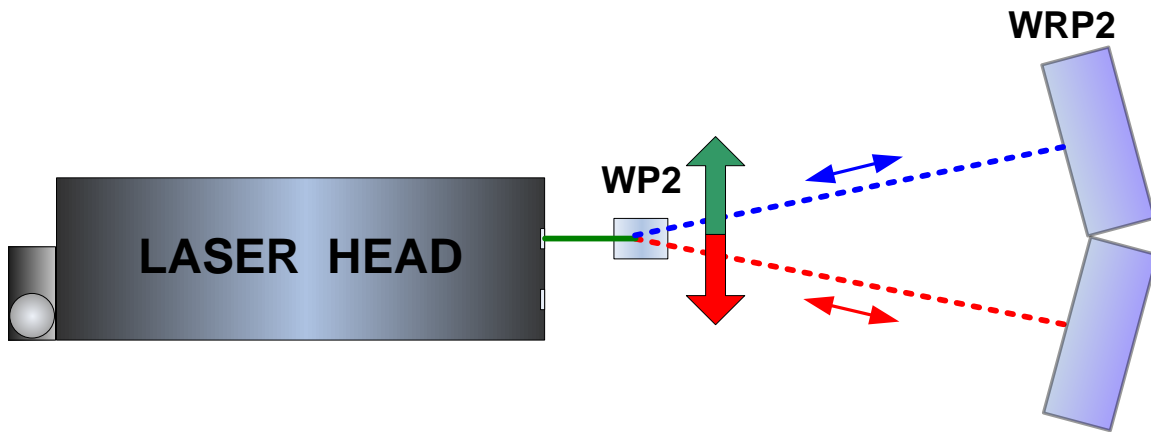
FIG.7.13 MEASUREMENTS WITH WOLLASTON OPTICS

Because of the sensitivity of the laser readout on the angular movement of the WRP2 it is important that during measurements the WRP2 element is neither touched nor moved. In more details it is described in the next section.

ii. Application Notes

Although it is possible to measure the straightness either with movement of the WP2 or WRP2 element but there are certain differences. The WRP2 this element should be stationary during measurement (i.e. should not be moved along the laser beam). As the WRP2 behaves in one of the axis like a mirror thus any angular movement of the WRP2

in this axis may result in the laser beam not returning to the laser head and will influence significantly the measurement results!

> The laser head with Wollaston optics is **sensitive** to angular movements of the reflector!

There are no such problems when the WP2 is moved instead. The only disadvantage is the smaller measurement range. WP2 can be moved ±2mm while maximal measurement range of the WRP2 is ±30mm (but only when the distance between WP2and WRP2 is 4.5 m).

iii. *Measurement Setup Preparations*

For **Wollaston** straightness measurements the Wollaston optics should be used. Necessary components are:

- Laser Head
- Power Supply
- Wollaston prism **WP2**
- Wollaston retro-reflector **WRP2**

Optional elements are:

- USB cable

- Manual Strobe

- Magnetic holder **UM2**

- Tripod stand

- Air temperature sensor

- Base temperature sensor

Wollaston straightness measurements require optical elements WP2 and WRP2 to be aligned along laser beam as shown in the figure 7.14. The beam alignment procedure is described in the fourth chapter.

During measurement the WRP2 element should be stationery, i.e. its distance from the laser head should not change.

During Wollaston straightness measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

FIG.7.14 OPTICAL PATH SET UP FOR WOLLASTON STRAIGHTNESS MEASUREMENTS- SCHEMATIC.

Wollaston straightness measurements can be performed in two configurations – horizontal X (figure 7.15) and vertical Z (figure 7.16). In configuration X only the straightness of path in X axis is measured. The same situation is with Z setup. In both configurations the measurements should be performed with the moving of WP2 element.

FIG.7.15 OPTICAL PATH SET UP FOR WOLLASTON STRAIGHTNESS MEASUREMENTS IN X AXIS.

FIG.7.16 OPTICAL PATH SET UP FOR WOLLASTON STRAIGHTNESS MEASUREMENTS IN Z AXIS.

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d.Measurement Setup – 3D method

i. Principles

The HPI-3D laser head is capable of detecting the position of the returning beam. The position of the returning beam changes with the movement of the retroreflector RL1 perpendicular to the laser beam axis. This phenomena for one axis is shown in the Figure 7.17. The beam returning from the linear interferometer IL1 is treated as a reference while the beam reflected by RL1 as measuring beam. The laser simultaneously registers information about the changes of position of an optical component in both axes perpendicular to the laser beam.
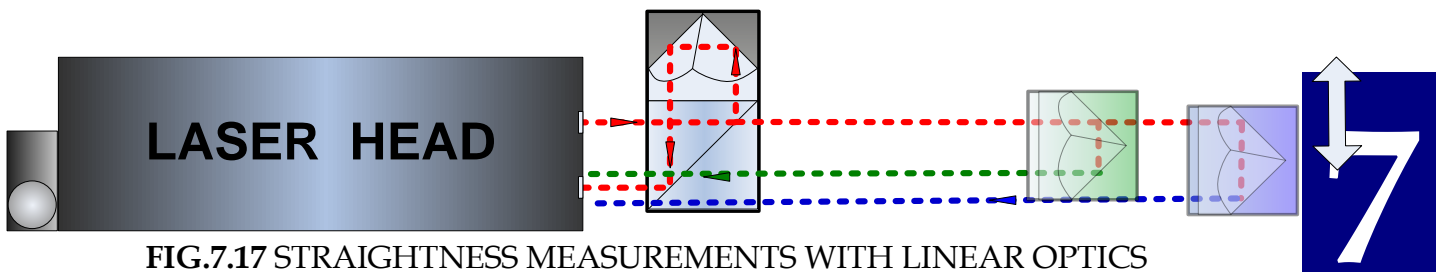
FIG.7.17 STRAIGHTNESS MEASUREMENTS WITH LINEAR OPTICS

The measured position is then used either for precise control of the laser beam path alignment or for the straightness, squareness or parallelism measurements.

The 3D measurement returns absolute values of the beam position. This is different from the main,

interferometric measurement axis where obtained results are incremental.

ii. Application Notes

The 3D option can be used for rapid estimation of straightness simultaneously in two axes but with some limitations resulting from physical nature of the measurements.

Unlike in all interferometric measurements, the laser head takes active part in the measurements, i.e. its position and its vibrations influences the measurement results. For this reason it is **important** to avoid using the tripod stand and to fix the laser head directly on the measured machine.

The 3D measurement bases on the position of the returning beam on the position sensitive device. Thus it is **important** that the beam stays within the measurement range of the device, i.e. ±1 mm. Using 3D option outside this range would produce unreliable results.

Similarly to all laser based straightness measurements the air turbulences have an influence on the results. Small wandering of the laser beam can be accommodated by the

signal processing circuit inside the laser with the change of averaging time (see Software Description for more details). If the air movements are too large – i.e. when the beam returning to the laser wanders outside ±1 mm window - then the results of the 3D measurements may become unusable. In such situation either some shielding from the air movement or a fan forcing the air movement have to be used. The problem with air turbulences is more troublesome for larger distances between the laser head and RL1 element.

iii. Measurement Setup Preparations

For 3D straightness measurements linear optics should be used. Necessary components are (see also figures 7.18 to 7.21):

- Laser head – *Laser Interferometer*
- Power supply - *Laser Interferometer Power Supply*
- Linear interferometer **IL1**
- Linear retro-reflector **RL1**

Optional elements are:

- USB cable
- Manual Strobe
- Magnetic holder **UM1**
- Tripod stand (not recommended)

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- Air temperature sensor

- Base temperature sensor

3D straightness measurements require optical elements IL1 and RL1 to be aligned along laser beam as shown in the figure 7.18. Only the retro-reflector RL1 should be moved.

During 3D straightness measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.
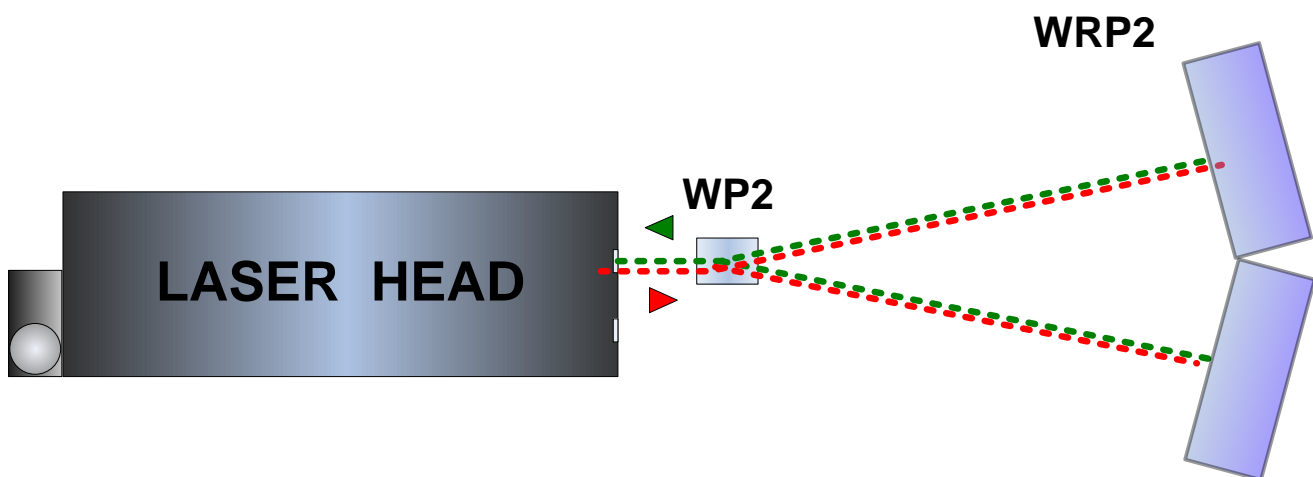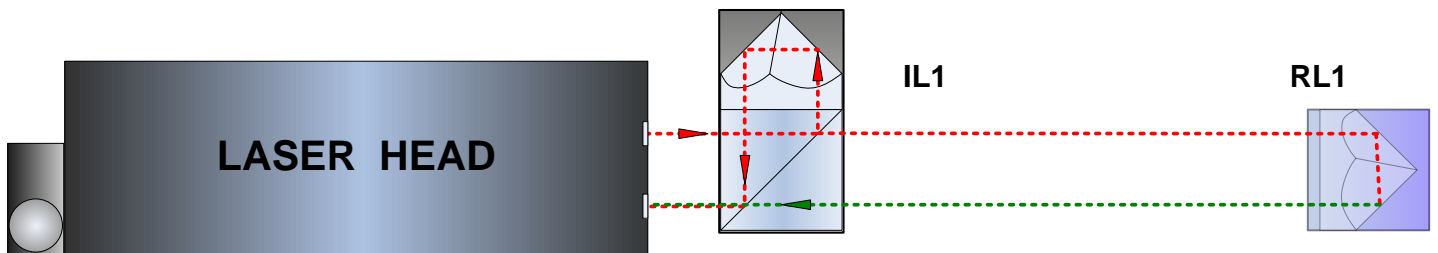

FIG.7.18 OPTICAL PATH SET UP FOR 3D STRAIGHTNESS MEASUREMENTS-SCHEMATIC.

3D straightness measurements can be performed not only along the laser beam (as shown in figures 7.18 and 7.19) but also in directions perpendicular to the laser beam. These configurations are shown in figures 7.20 and 7.21. Also in those two configurations only the retro-reflector RL1 can be moved.

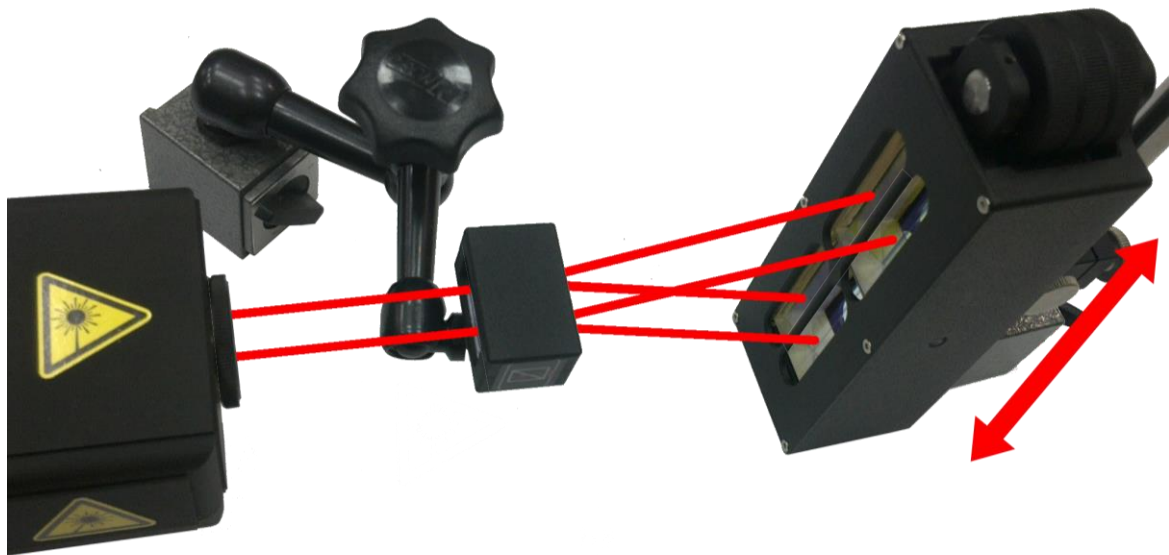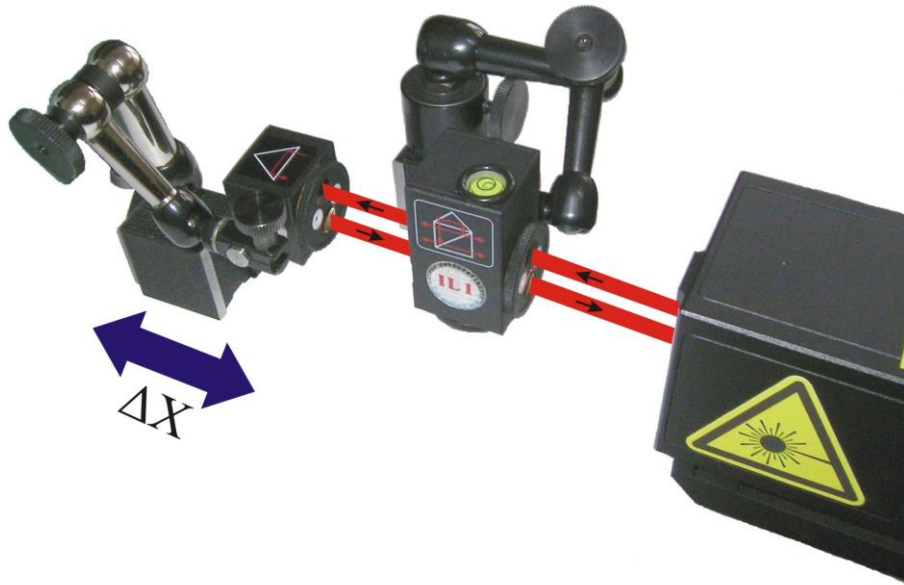**FIG.7.19** OPTICAL PATH SET UP FOR 3D STRAIGHTNESS MEASUREMENTS IN X AXIS.
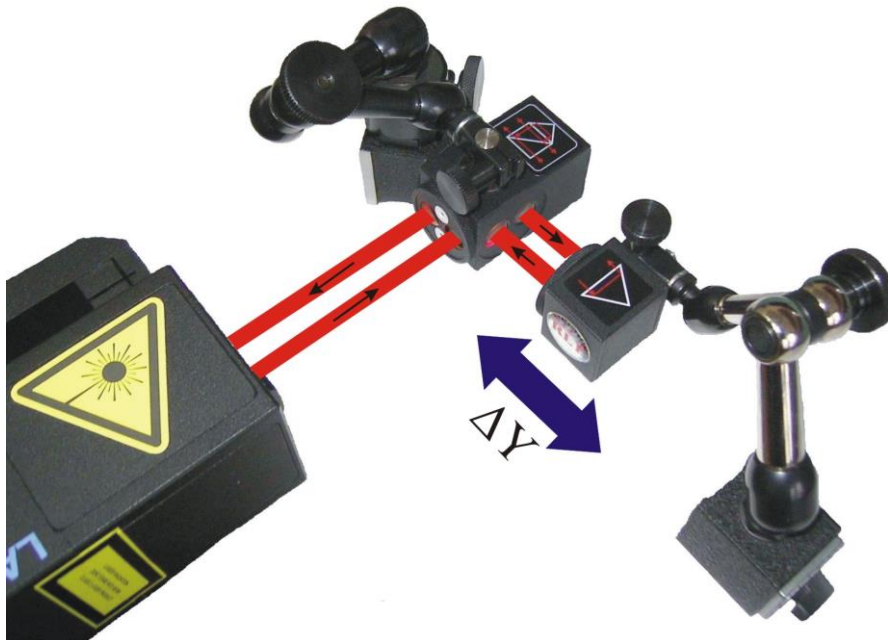
FIG.7.20. OPTICAL PATH SET UP FOR 3D STRAIGHTNESS MEASUREMENTS IN Y AXIS.
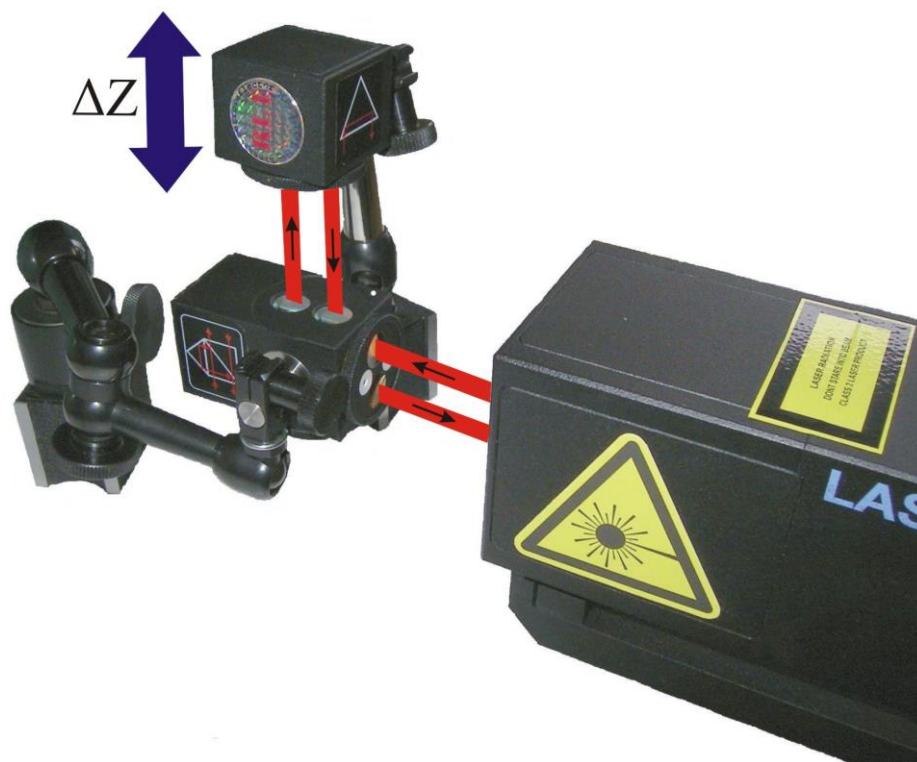
FIG.7.21. OPTICAL PATH SET UP FOR 3D STRAIGHTNESS MEASUREMENTS IN Z AXIS.

e. Software description

i. Introduction

Straightness measurement are performed in the **Straightness** option, chosen from the **Main Menu** (fig. 7.22).

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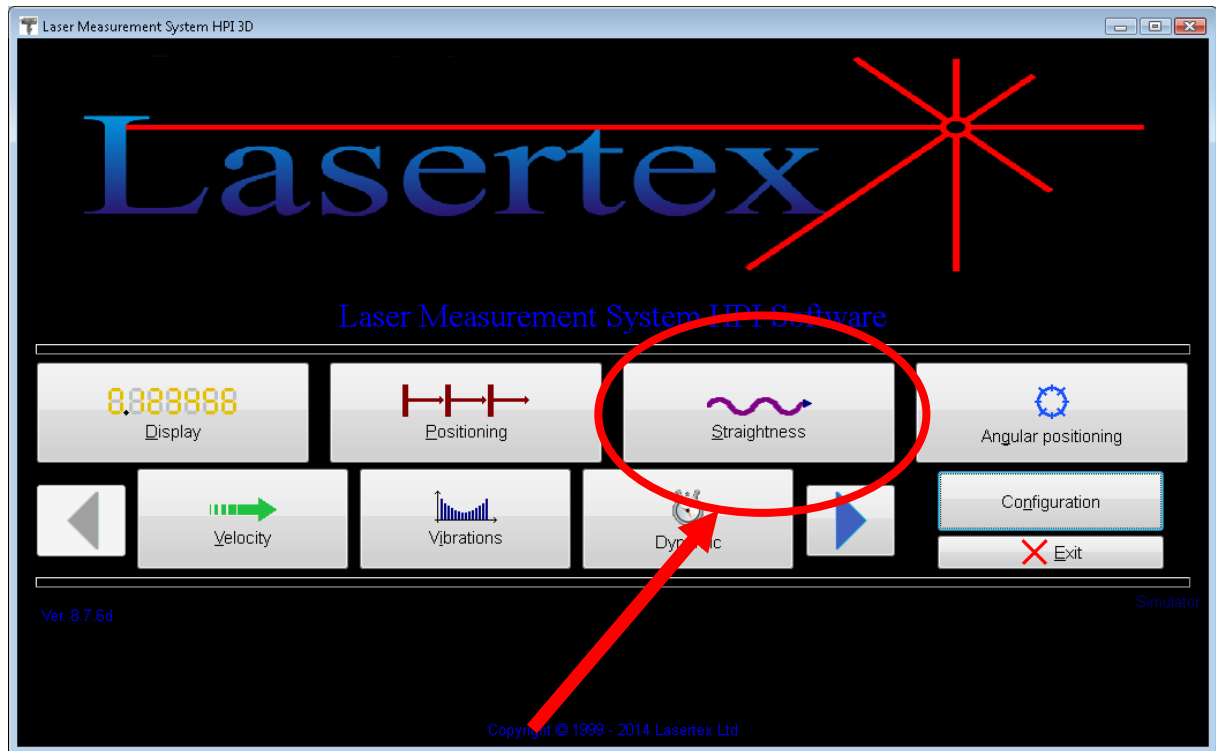
FIG.7.22 MAIN MENU

The Straightness HPI Software program window is shown in the Fig. 7.23. The window consists of a pull-down menu and five panels:

- 1) Display – presents current distance and measurement signal level;
- 2) Straightness Plot – in the 3D mode there are visible plots for vertical and horizontal axis, in the Angular and the Wollaston mode only one plot is visible;
- 3) Panel for changing the operation mode;
- 4) Straightness value table – a table containing consecutively numbered samples and measured straightness value (or two values in 3D mode);

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- 5)   Panel with control buttons and status information.
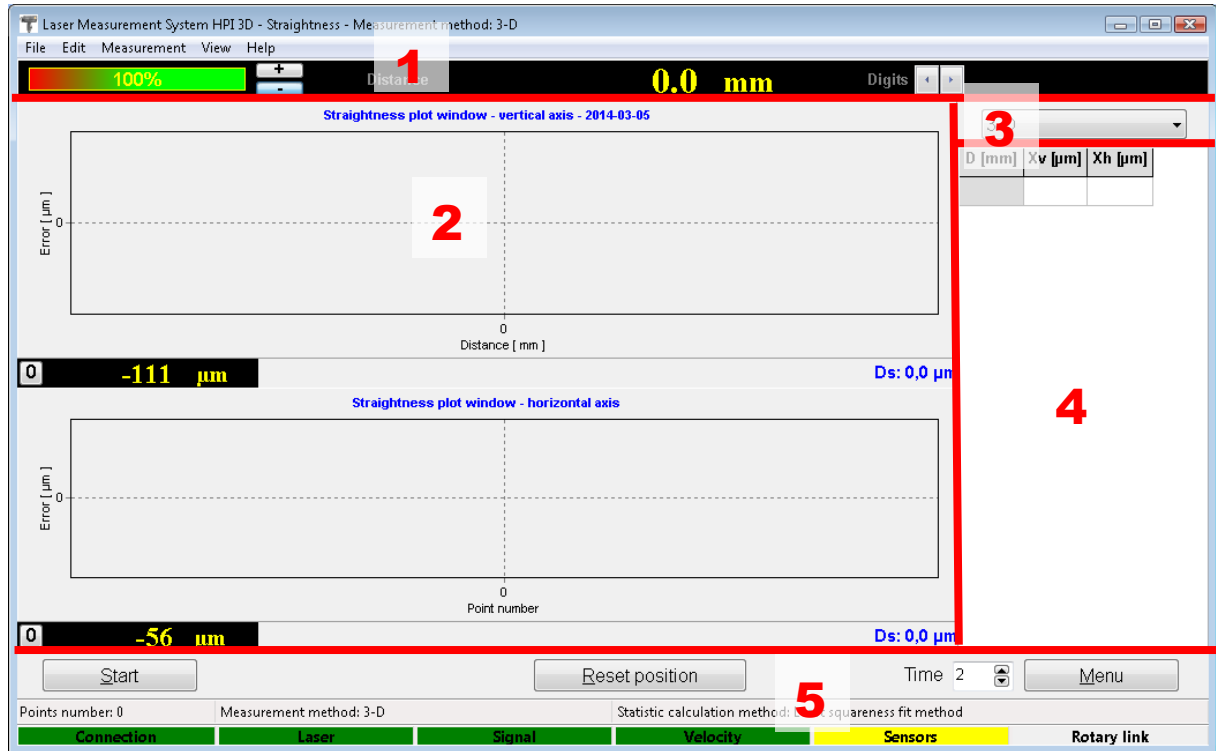
FIG.7.23. STRAIGHTNESS MEASUREMENT WINDOW WITH PANELS.

ii. Display Panel

The Display Panel (figure 7.24) is used for basic control of the operation of the interferometric part of the laser. Through this panel it is possible to monitor the quality of the input signal, i.e. the beam strength and the current value measured by the laser. Depending on the chosen

measurement type the values are displayed in different units (figures 7.24A,B and C): for angular and pitch/yaw measurement types it is arcseconds, for Wollaston it is micrometers and for 3D it is millimeters. For the 3D option the value displayed on the panel is only an auxiliary one – the straightness readouts are shown on the Straightness Plot panel described below.
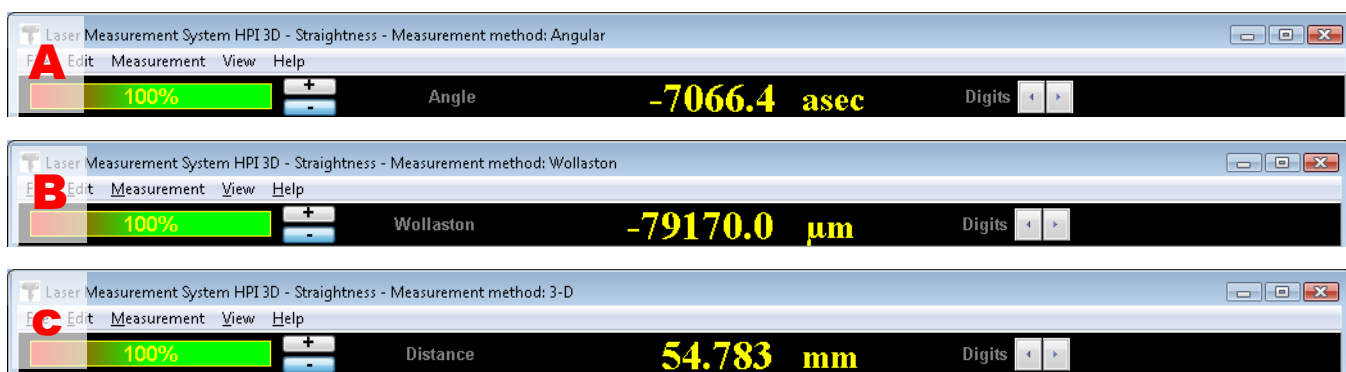
FIG.7.24 DISPLAY PANEL DURING (A) ANGULAR, (B) WOLLASTON, (C) 3D TYPE MESUREMENTS

Through the buttons available on the Display Panel it is possible to change either the sign or the displayed resolution of the current measurement result. The setting of the sign influences the values registered in Straightness Plot and Values Table. Changing number of digits have no influence on the measurement.
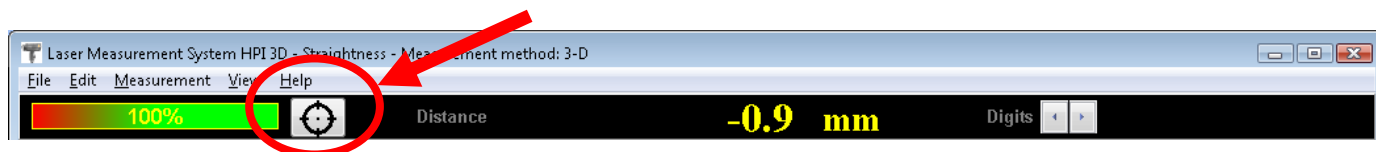
FIG.7.25 DISPLAY PANEL AFTER 3D TYPE MESUREMENTS

After the 3D measurements are finished then on the Display Panel appears additional button. This is shown in the Figure 7.25. Pressing this button makes possible retaking any measurement point. The remeasurement procedure is described further in the Chapter.

iii. Straightness Plot Panel
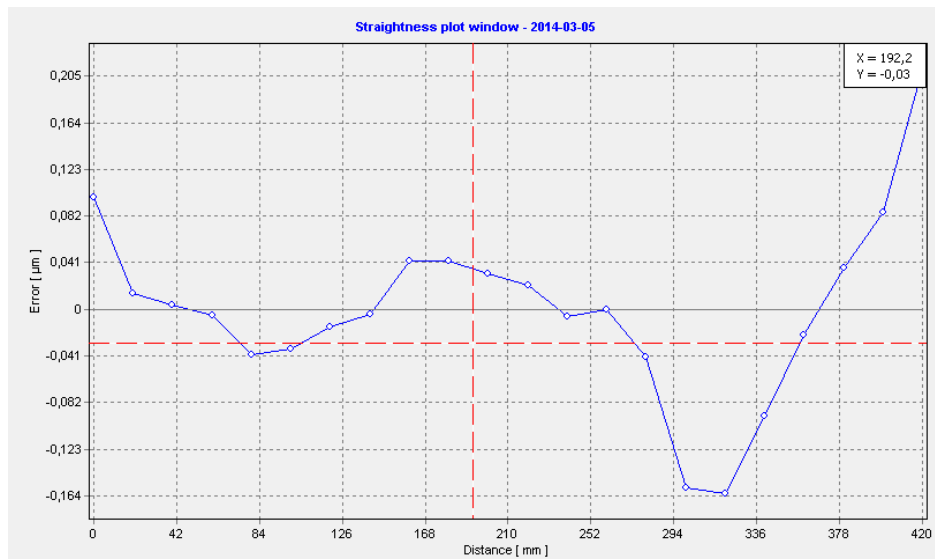
FIG.7.26 STRAIGHTNESS PLOT PANEL IN THE ANGULAR AND WOLLASTON OPTIONS

The Straightness Plot panel is the place where measurement results are displayed. The measurement results are placed on the plot(s) as soon as they are registered by the laser head. There can be one or two plots displayed in dependence on the measurement type. For angular and Wollaston type measurements there is only one plot (fig.

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7.26) because with this optics it is possible to measure straightness only in one axis at a time.
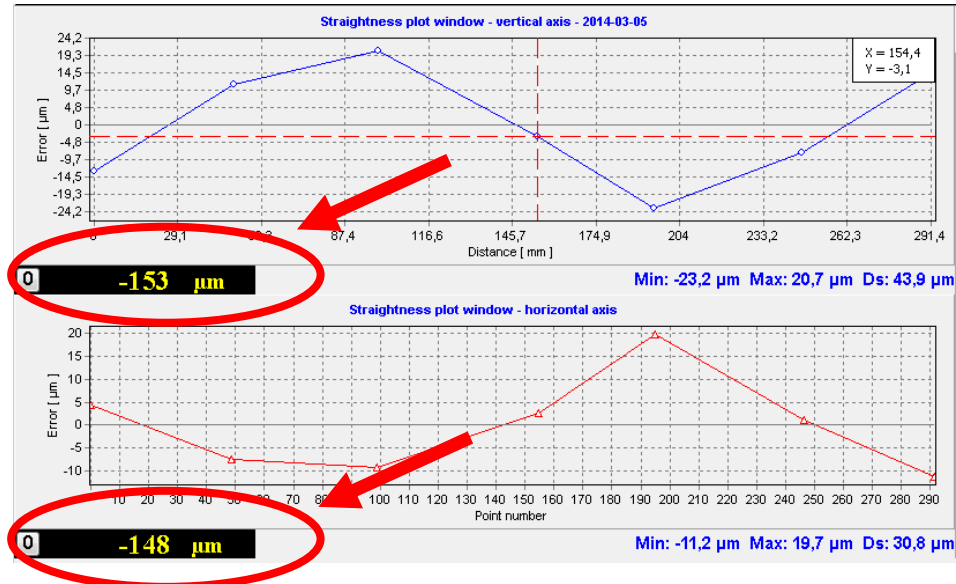
FIG.7.27 STRAIGHTNESS PLOT PANEL IN THE 3D OPTION

The Straightness Plot during the 3D measurement looks differently (fig 7.27) because simultaneously there are measured: the distance between RL1 and IL1 (shown in the Display Panel) and the position of the RK1 in the axes perpendicular to the laser beam (denoted as horizontal axis and vertical axis).

Both straightness values can be resetted by pressing *0* button on the small displays. It has to be remembered that this resetting is valid only for the current measurement – 3D straightness values are absolute and not incremental like in the interferometric channel.

In the bottom right corner of the panel there are displayed the edge values of the straightness, i.e minimal

value *Min*, maximal value *Max*, amplitude of the straightness *Ds=Max-Min*. In the case of 3D measurements those values are shown for each axis.
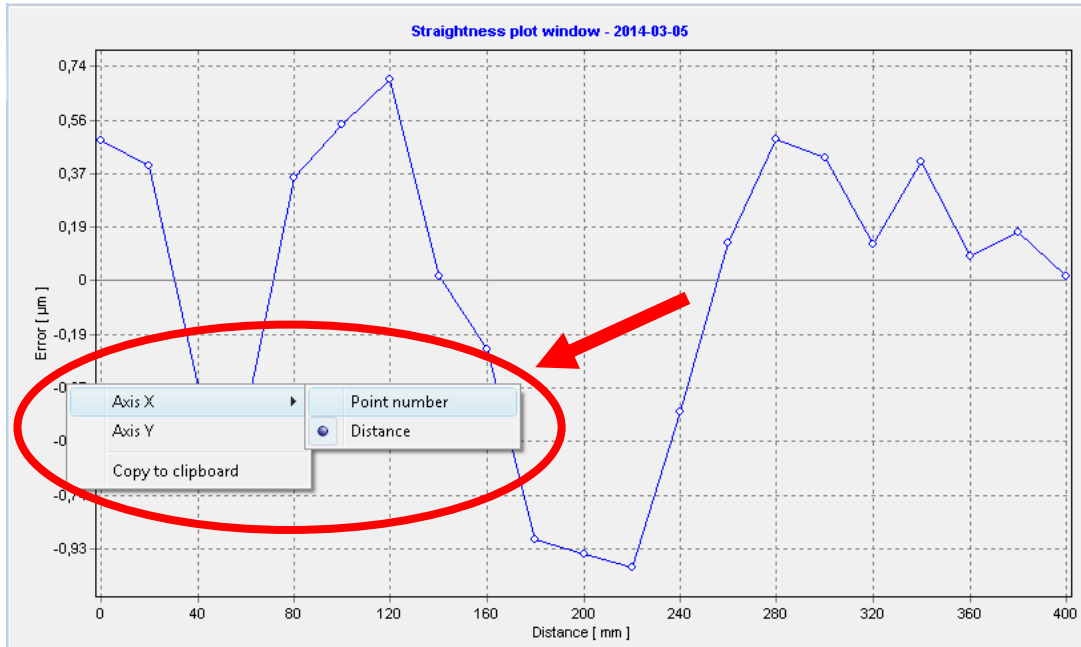
FIG.7.28 POP UP MENU ON THE STRAIGHTNESS PLOT PANEL

The units on the vertical axis of the straightness plot depend on the actual configuration set in the Configuration->General option. For straightness measurements these are usually micrometers while for pitch/yaw measurements arcseconds. The displayed range is set automatically but it can be set also manually. On the horizontal axis there can be displayed either the distance or measurement points numbers.

After the right mouse button click on the chart axis the pop-up menu as shown in the Figure 7.28 will appear. The

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options in this menu are used for modification of displaying of horizontal and vertical axes of the chart. The chart can also be copied to clipboard ("Copy to clipboard" option) for further pasting into a document editing software (like Microsoft Word or OpenOffice Write).
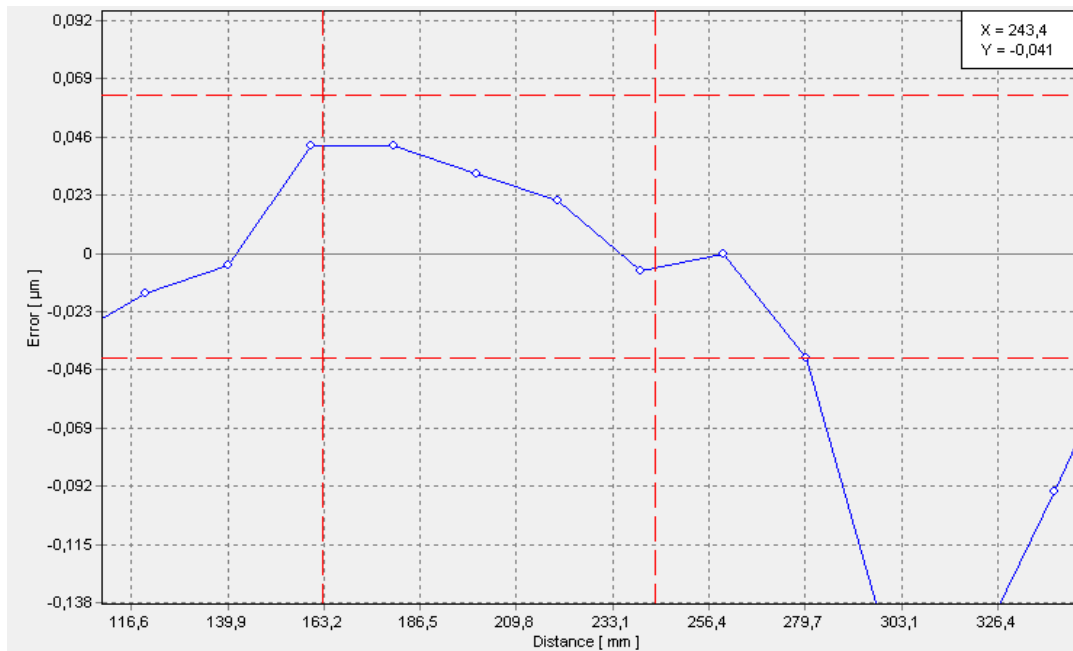
FIG.7.29 CHART ZOOMING

The displayed chart can be zoomed in and out with the use of the mouse. Zooming in requires marking the top left corner of the desired area by pressing the left mouse button. The button has to be held and the mouse pointer should be moved to the bottom right corner of the desired are. The auxiliary red dashed lines as shown in the Figure 7.29 should appear. Zooming out is done by moving the pressed left

mouse button from the bottom right corner to the top left corner.

Zoomed chart view can be shifted by pressing the right mouse button on the chart (and not on the axes as the pop-up menu would appear!) and moving the mouse pointer in the desired direction.

iv. Operation Mode Panel
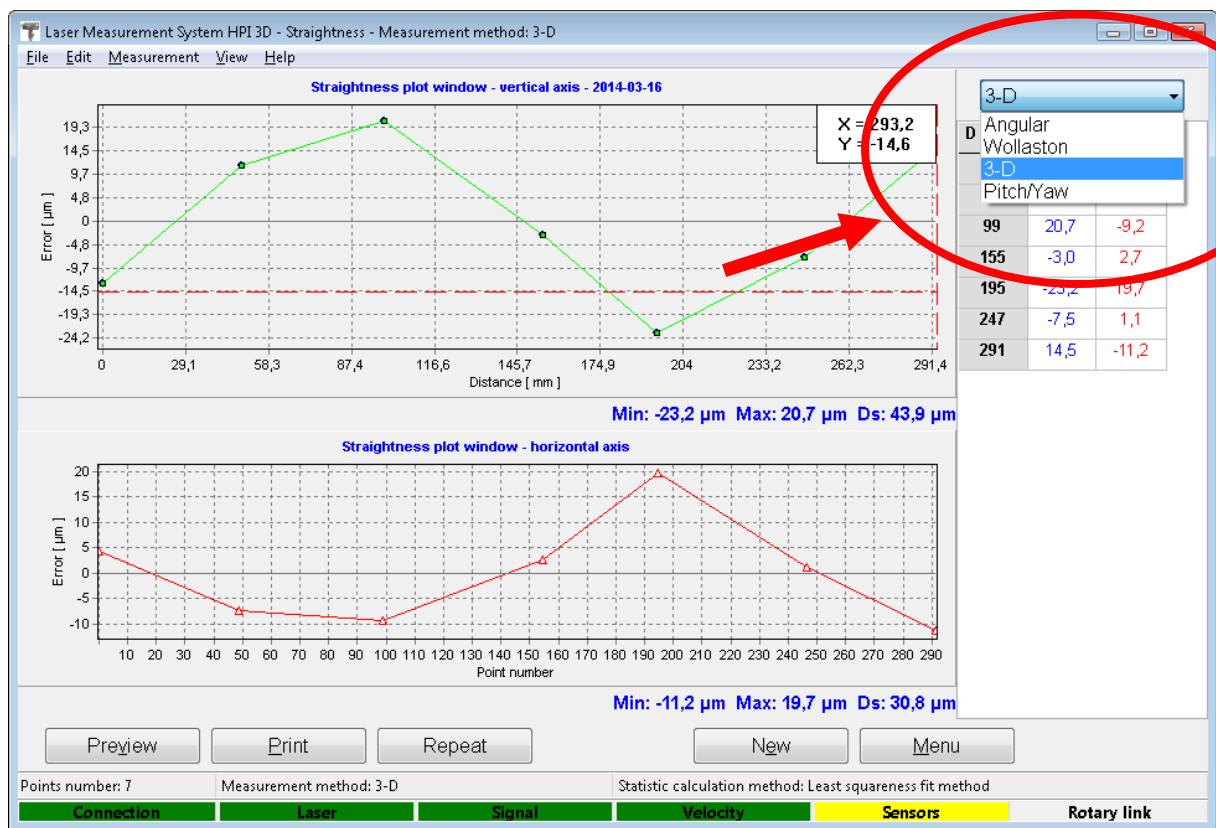
FIG.7.30 OPERATION MODE PANEL

In the upper right corner a button for changing measurement mode is placed (Fig. 7.30). There are four options available: Angular, Wollaston, 3D and Pitch/Yaw.

The last mode is described in another Chapter of this document.

v. Straightness Measurement Values Panel

In the Values Panel there are displayed numerical values of the straightness measurements (Figure 7.31). These are the same values that are shown on the chart(s).
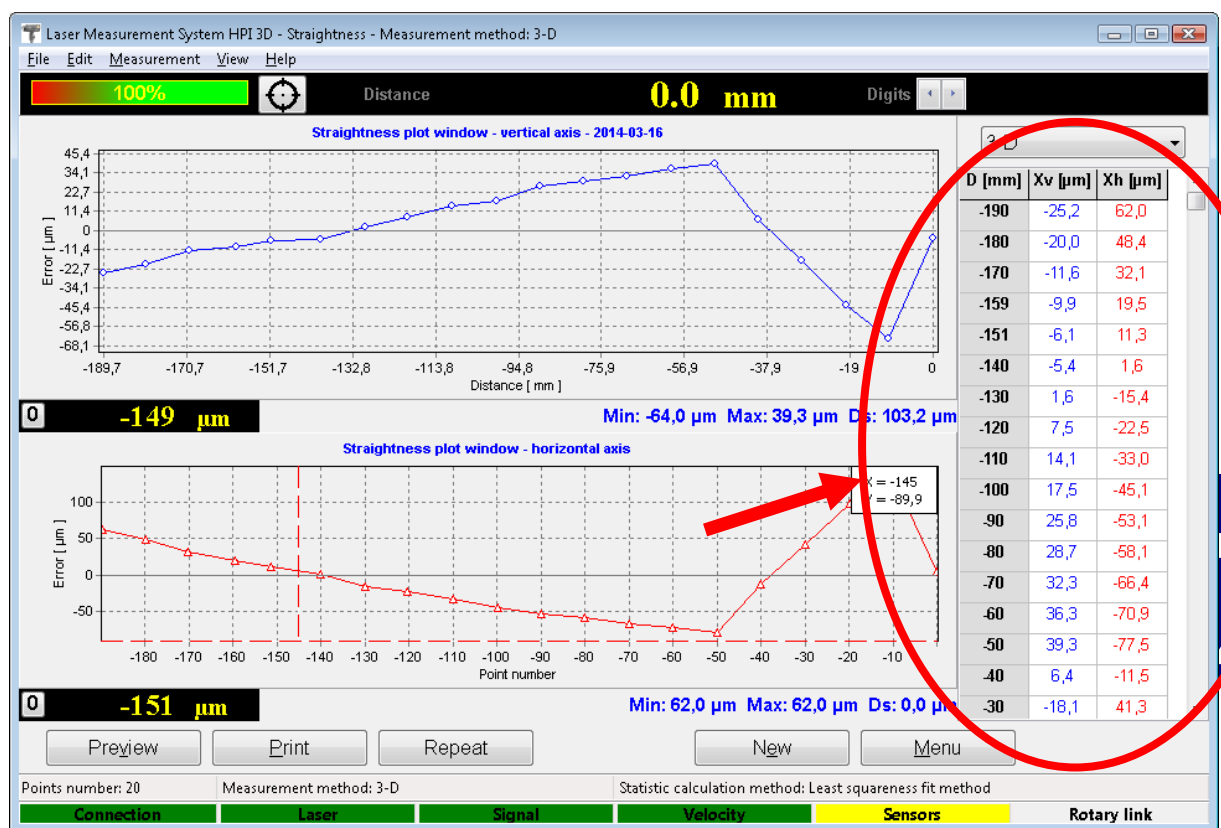
FIG.7.31 VALUES PANEL

The unit of the distance D can be changed, independently on the unit of the chart, by clicking with the left mouse button on the distance column of the chart. There

are three possibilities (see Figure 7.32): rounded values of the distance (A), true value of the distance (B) and number of points (C).

D [mm]	Xv [µm]	Xh [µm]	D [mm]	Xv [µm]	Xh [µm]	No.	Xv [µm]	Xh [µm]
-190	-25,2	62,0	-189,6714	-25,2	62,0	0	-25,2	62,0
	-20,0	48,4	-17__17	-20,0	48,4	1	-20,0	48,4
-170	-11,6	32,1	-170,1226	-11,6	32,1	2	-11,6	32,1
-159	-9,9	19,5	-159,4504	-9,9	19,5	3	-9,9	19,5
-151	-6,1	11,3	-151,4330	-6,1	11,3	4	-6,1	11,3
-140	-5,4	1,6	-139,9930	-5,4	1,6	5	-5,4	1,6
-130	1,6	-15,4	-129,9343	1,6	-15,4	6	1,6	-15,4
-120	7,5	-22,5	-120,2265	7,5	-22,5	7	7,5	-22,5
-110	14,1	-33,0	-109,9312	14,1	-33,0	8	14,1	-33,0
-100	17,5	-45,1	-99,8334	17,5	-45,1	9	17,5	-45,1
-90	25,8	-53,1	-89,9977	25,8	-53,1	10	25,8	-53,1
-80	28,7	-58,1	-79,9685	28,7	-58,1	11	28,7	-58,1
-70	32,3	-66,4	-69,9203	32,3	-66,4	12	32,3	-66,4
-60	36,3	-70,9	-59,9563	36,3	-70,9	13	36,3	-70,9
-50	39,3	-77,5	-50,0096	39,3	-77,5	14	39,3	-77,5
-40	6,4	-11,5	-39,9974	6,4	-11,5	15	6,4	-11,5
-30	-18,1	41,3	-29,9376	-18,1	41,3	16	-18,1	41,3

FIG.7.32 VALUES PANEL – DIFFERENT MODES. CLARIFICATIONS IN TEXT

vi. Straightness Control Panel

Straightness Control Panel is comprised of three main parts (Figure 7.23):

- Line with control buttons
- Line with measurement status information
- Line with laser status information.

The last line shows information common to all options of the HPI Software, i.e. the state of Connection, Laser, Signal, Sensors and Rotary encoder.

The measurement status line shows the information of the current measurement like the number of the registered

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measurement points, the measurement type and the statistical method used for data fitting.

The functionality of the line with the buttons changes with the current measurement state. In the Figure 7.33 there are shown various appearances of the control part of the Control Panel.

Case A appears when there is no measurement in progress and no data were read from a file. In this mode it is possible either to start the measurement ("Start"), to reset the main counter ("Reset position") or to return to the main menu of the program ("Menu"). It is possible also to set a time between automatically captured measurements ("Time").
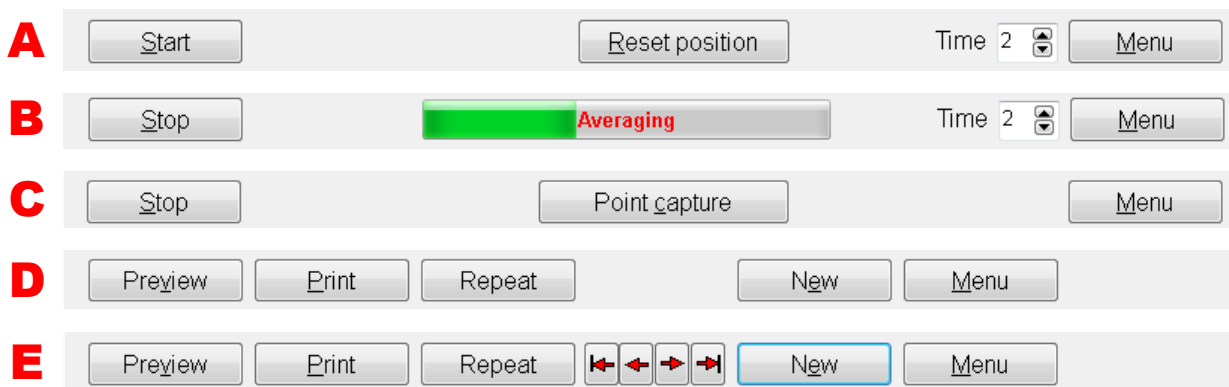
FIG.7.33 CONTROL PANEL – DIFFERENT MODES. CLARIFICATIONS IN TEXT

Cases B and C appear during measurements. The former is during the Automatic Point Capture mode, while the latter during the Manual Point Capture mode. The measurement can be stopped directly ("Stop") or indirectly ("Menu").

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After pressing the "Menu" button the software always asks if the measurement is to be stopped first.

Cases D and E are visible during analyses of the obtained results. If there is only one measurement series performed than the panel D appears, otherwise pane E. From those panels it is possible either to view measurement report ("Preview" or "Print") or to redo the measurements ("Repeat" or "New"). In case D (single series) the functionality of "Repeat" and "New" is the same. When there are more than one series measured then it is possible to repeat only one series ("Repeat") or to start completely new measurements ("New").

vii. Straightness pull-down menus

Viewed graph can be printed or saved to a file. Those commands are available from the **File** menu (i.e. Save, Save as, Print – see figure 7.34).
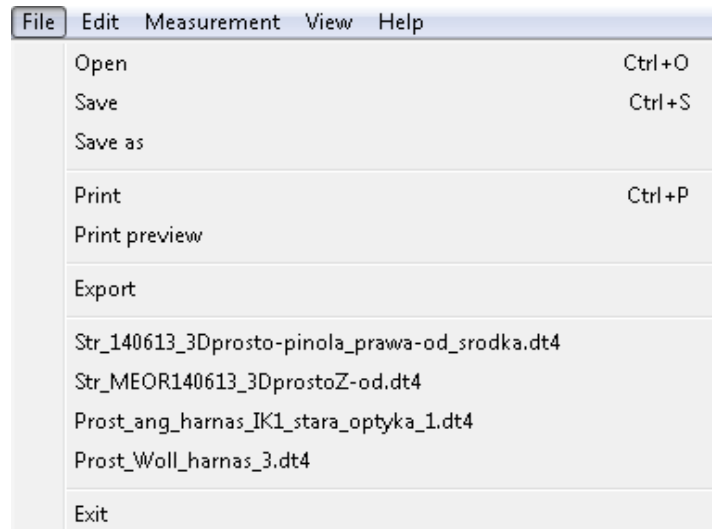
FIG.7.34. STRAIGHTNESS PULL-DOWN MENU *FILE*.

Before saving the file the program asks about changing machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator. Those values allow describing performed measurement for later analysis and they are also present on the printed report.
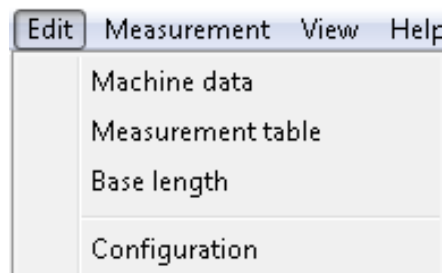
FIG.7.35. STRAIGHTNESS PULL-DOWN MENU *EDIT*.

Other options available in *Edit* menu are:

- **Measurement table** – raw data are shown for analysis, export and print;

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- **Base length** – angular retro-reflector RK1 base length can be set (default is 100mm); the option available also in *Configuration->Parameters*;

- **Configuration** – opens Configuration window as shown in the figure 7.36.
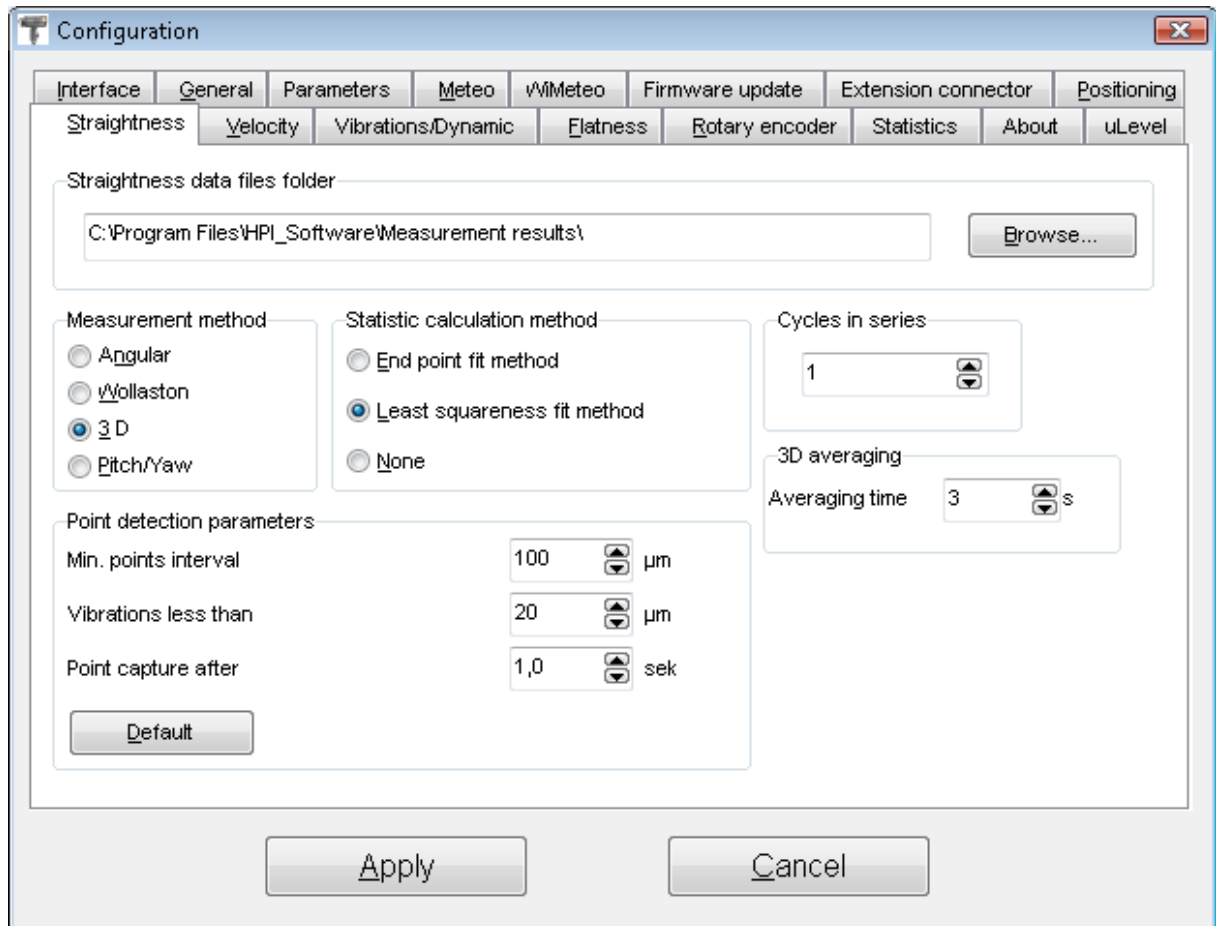
FIG. 7.36. STREIGHTNESS CONFIGURATION OPTIONS.

In the Configuration it is possible to set:

1. Straightness data file folder – place where the operating system will point to during the measurement data save;

2. Measurement method – the same functionality with the operational mode panel;

3. Statistic calculation method – measured data can be viewed either as a raw or line fitted data. For the raw data *None* option should be chosen. Line fitting can be done according either to the *End point fit* or *Least squareness fit* method. Which method is used depends on personal preferences.

4. Cycles in series – defines how many measurement series are to be expected by the software. It is possible to perform fewer cycles then set in this parameter;

5. 3D averaging time – as the 3D straightness measurement is an amplitude type measurement thus, depending on the measurement condition, the device requires certain time for averaging the results. The longer is the distance between the laser head and the reflecting element RL1 and the larger airflow is tangible the larger value of the *Averaging time* should be set;

6. Point detection parameters – parameters not used in the current version of the software. Applicable only in customized version of the HPI Software.
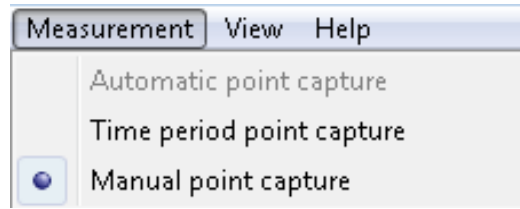
FIG.7.37. STRAIGHTNESS PULL-DOWN MENU *MEASUREMENT.*

In the *Measurement* pull-down menu it is possible to change the method of capturing measurement points. Either a manual method (PC keyboard or the manual Strobe can be used) or a semi-automatic (time) one can be used.
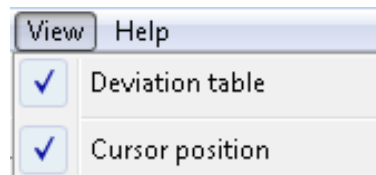
FIG.7.38. STRAIGHTNESS PULL-DOWN MENU *VIEW.*

The options in the *View* pull-down menu can be used for switching on or off the view of the deviation (error) table and for switching on or off the cursor position field on the straightness charts.

viii. Reports

Measurement report can also be generated from obtained data, either by pressing Print or Preview on the measurement analysis window (fig. 7.39). The report can be generated in the basic form where only the plot of the

measured values is shown (fig. 7.40) or in the extended version, which contains tables with measured data.
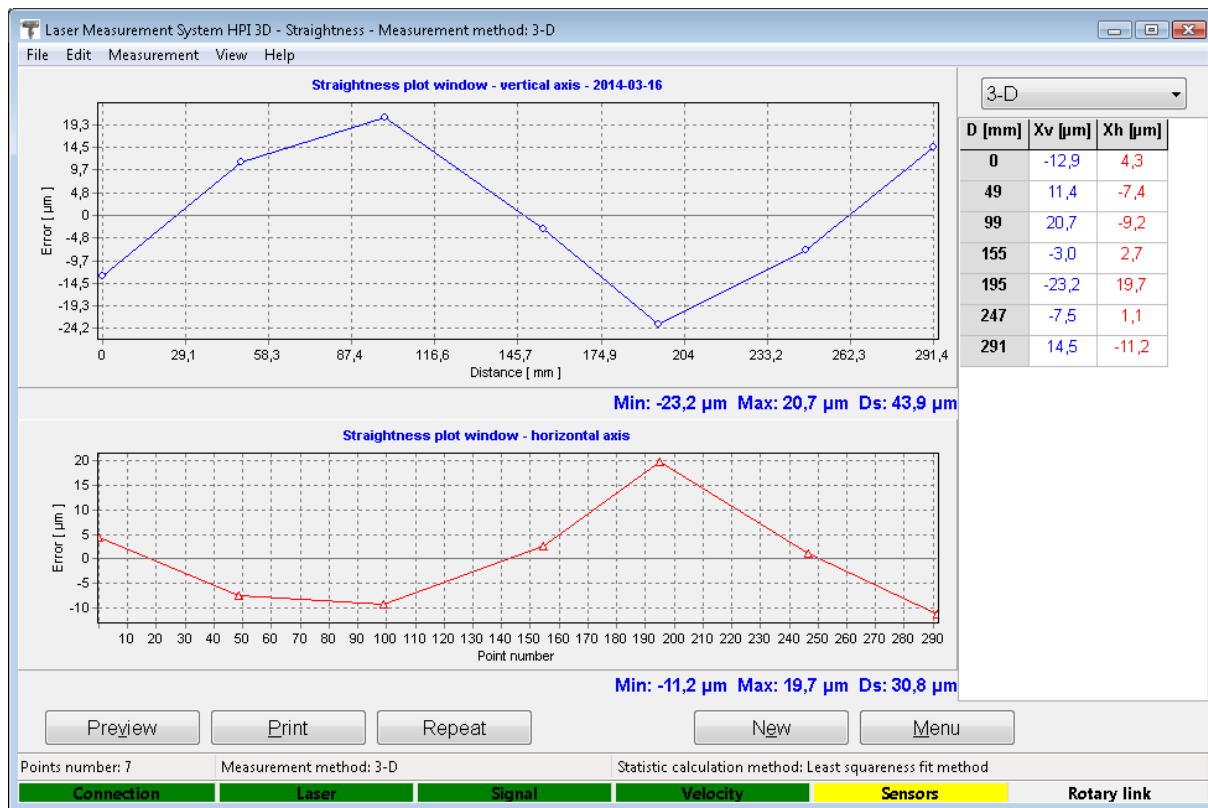
FIG.7.39. STREIGHTNESS MEASURED DATA ANALYSIS WINDOW.
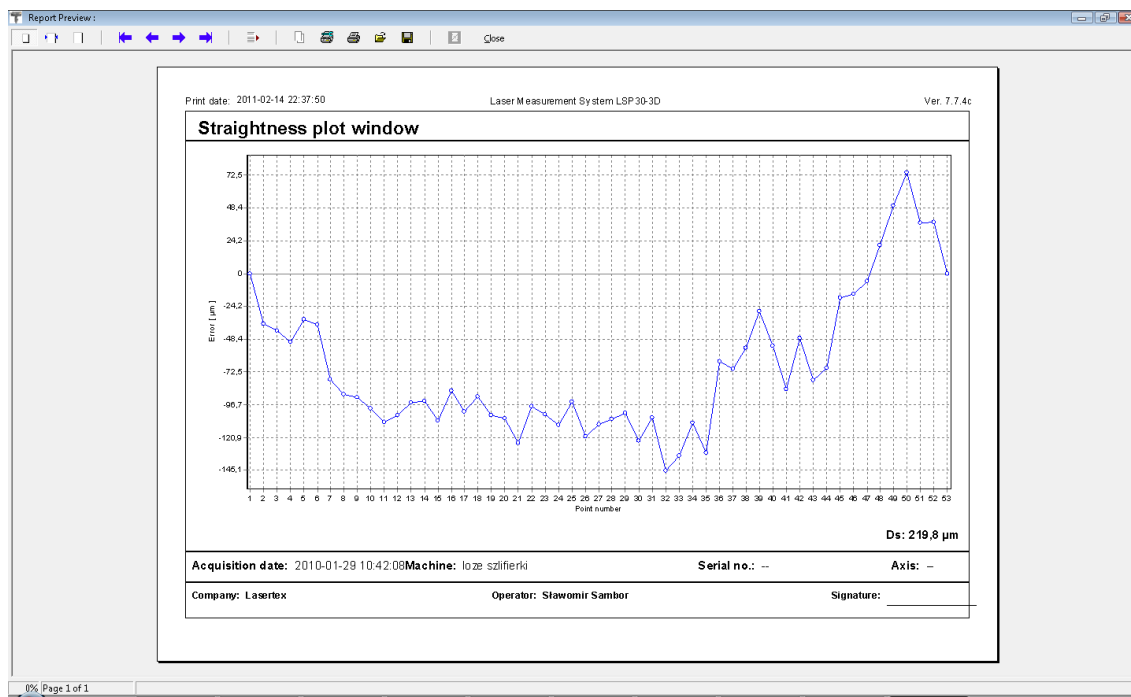
FIG.7.40. STREIGHTNESS REPORT PREVIEW WINDOW.

It is possible to copy the straightness graph to the clipboard and then paste it for example to a Word editor document. **Copy to clipboard** command is available from popup menu that appears after right-click on the area of the graph.

f. Straightness measurements procedure

Straightness measurements are started by pressing the **Start** button. During the measurement points are collected by the software and the straightness graph is constantly updated. The measurement is finished by pressing the **Stop** button.

The straightness measurements are driven along a straight line pointed by the laser light. The actual measurement procedure depends slightly on the measurement mode: angular, Wollaston or 3D.

i. Measurement procedure – Angular optics - preparations

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The Straightness measurement in Angular mode is based on moving angular Retro-reflector RK1 by an interval set in the Base Length parameter (usually 100 mm) and measuring the angular deviation of the RK1.

It is **very important** to set before the measurements with the angular optics the distance between measurement points and the actual optical configurations, i.e. whether RK1 or IK1 is moved and in which direction. This can be done in the special pop-up window (Figure 7.41). This window appears always after pressing the **Start** button.
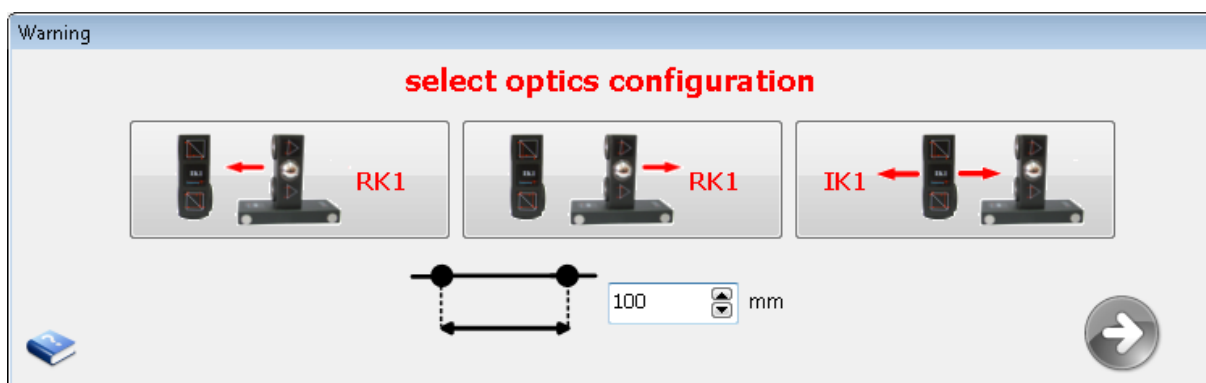
FIG.7.41. SELECTION OF CONFIGURATION OF THE ANGULAR OPTICS

If the RK1 is moved manually then the distance between points should be marked on the leading ruler or on the examined surface before the measurement begins. It is recommended to use the ruler with the scale – see Figure 7.42.

During the measurement points can be captured either manually by the user or automatically by the software in the

constant time intervals. The time period between points captures is used to move the retro-reflector about a distance of 100 mm (**RK1** base length). The time interval should be tailored to the experience of the user. It is suggested to set the time to 10 s and to decrease it if needed. The time interval is increased and decreased by pressing ↑, ↓ keys on the computer screen.
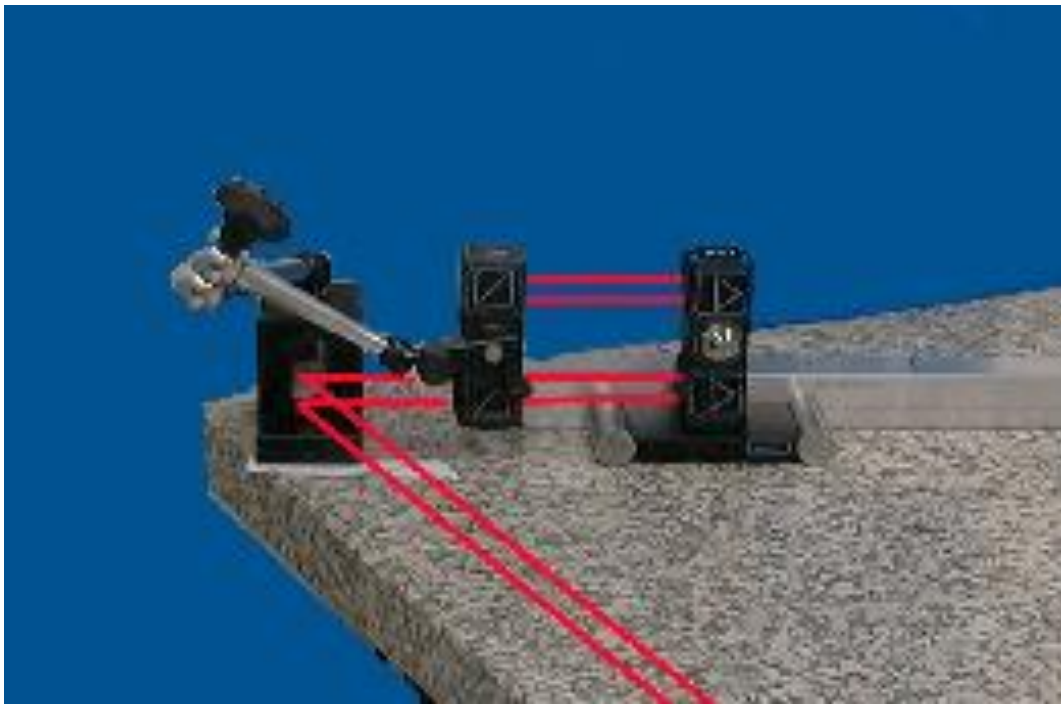
FIG.7.42. AN EXAMPLE OF OPTICAL COMPONENTS SETUP IN ANGULAR STRAIGHTNESS MEASUREMENT.

ii. Measurement procedure – Angular optics

1. Set up the laser on the measured machine and align the optical path.

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2. Start the HPI Software and select Straightness option.

3. Choose the measurement method: Angular.

4. Choose whether the points are to be captured manually or automatically

5. Press Start button

6. Choose the right optical configuration

7. Wait for the program to capture the first point (in time capture mode) or capture the point manually.

8. Move the **IK1** or the **RK1** by the distance set in the *Edit->Base length* option (default 100mm) and wait on the next point capture.

9. Continue the measurement until the last point is reached.

10. Stop the measurement.

iii. Measurement procedure – Wollaston optics – preparations

The Straightness measurement in the Wollaston mode is based on moving Wollaston prism WP2 by an interval set in the Base Length parameter (usually 100 mm) and measuring the movement of the WP2 in the direction perpendicular to the laser beam.

iv. Measurement procedure – Wollaston optics

1. Set up the laser on the measured machine and align the optical path.

2. Start the HPI Software and select Straightness option.

3. Choose the measurement method: Wollaston.

4. Choose whether the points are to be captured manually or automatically

5. Press Start button

6. Wait for the program to capture the first point (in time capture mode) or capture the point manually.

7. Move the **WP2** by the distance set in the *Edit->Base length* option (default 100mm) and wait on the next point capture.

8. Continue the measurement until the last point is reached.

9. Stop the measurement.

v. Measurement procedure – 3D method - preparations

The Straightness measurement in the 3D mode is based on moving linear optics elements (IL1 or RL1) by any distance and measuring the relative movement of the IL1 and RL1 in both directions perpendicular to the laser beam.

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vi. Measurement procedure – 3D method

1. Set up the laser on the measured machine and align the optical path.

2. Start the HPI Software and select Straightness option.

3. Choose the measurement method: 3D.

4. Choose whether the points are to be captured manually or automatically

5. Press Start button

6. Wait for the program to capture the first point (in time capture mode) or capture the point manually.

7. Move the **IL1** or the **RL1** by the distance set in the *Edit->Base length* option (default 100mm) and wait on the next point capture.

8. Continue the measurement until the last point is reached.

9. Stop the measurement.

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8. MEASUREMENTS - FLATNESS

a. General Description

The flatness measurement is performed using the angular straightness measurement principal. In order to obtain a surface flatness the measurement of angular straightness in eight axes is necessary. From obtained axes straightness data a flatness map is calculated and drawn (fig.8.1.).

b. Measurement Setup

For flatness measurements the angular optics plus additional mirrors should be used. Necessary components are:

- Laser Head
- Power Supply
- Angular Interferometer **IK1**

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- Angular Retro-reflector **RK1**

- Two Beam Benders **ZK1** (see figure 8.2)
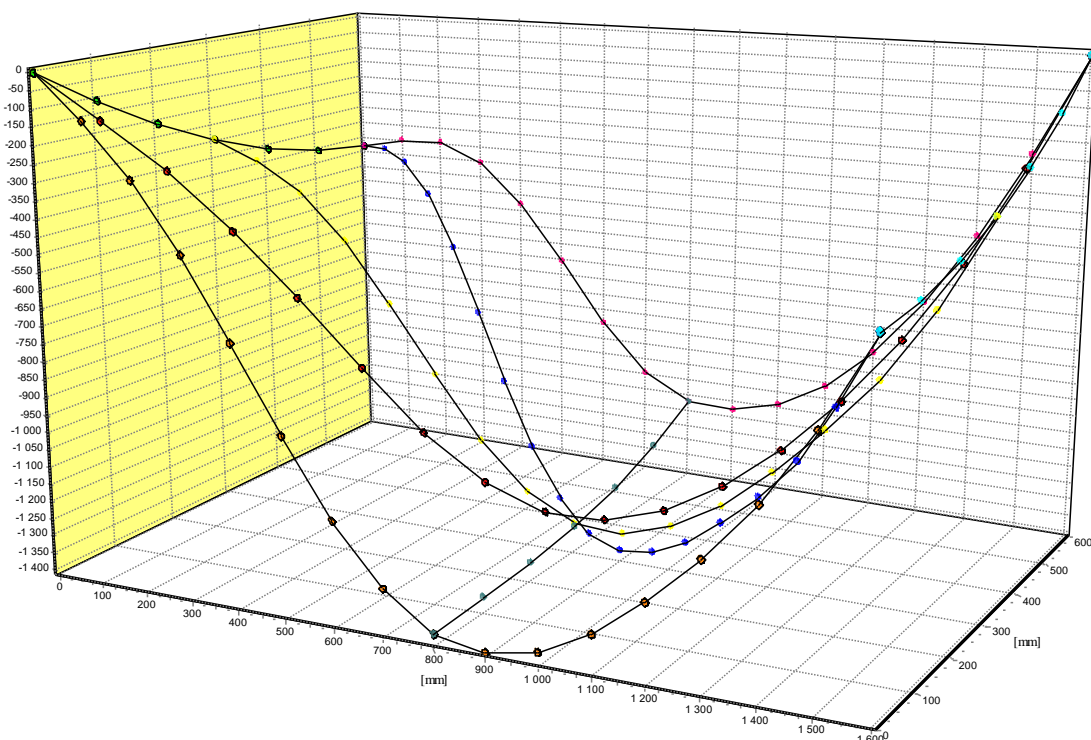
FIG.8.1. FLATNESS MAP OF AN EXEMPLE SURFACE.

Optional elements are:

- USB cable

- Manual Strobe

- Magnetic holder **UM2**

- Tripod stand

- Air temperature sensor

- Base temperature sensor

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FIG.8.2. THE ELEMENT SET FOR THE FLATNESS MEASUREMENTS (**IK1, RK1** AND **ZK1**).

Flatness measurements require that optical elements IK1 and RK1 are aligned along laser beam as shown in the figure 8.3 for the first axis. Element IK1 is stationary and element RK1 is moved.

Other axes can be measured with the use of one or two beam benders with constant position of the laser head, or by moving the position of the laser head. In both cases realignment of the IK1 and RK1 components is required. It is recommended to use the option with constant position of the laser head because it simplifies the realignment process.

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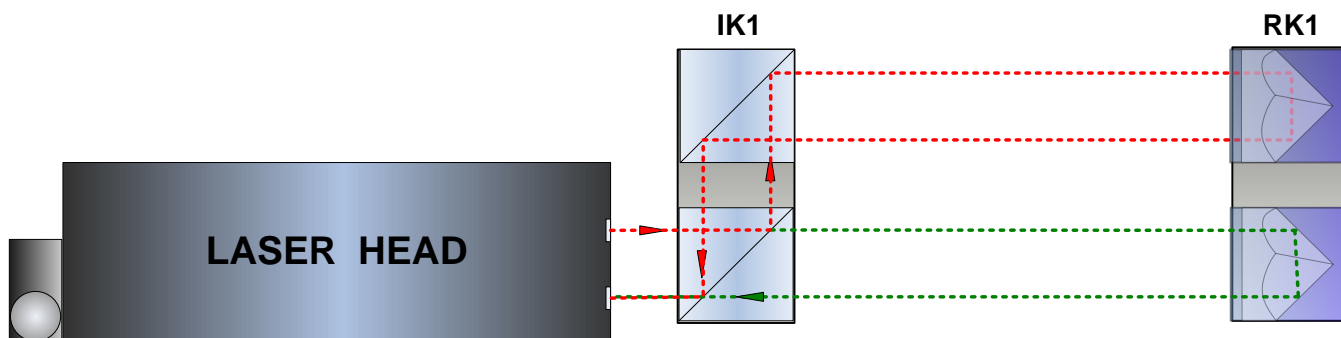
FIG.8.3 OPTICAL PATH SET UP FOR FLATNESS MEASUREMENTS –
SCHEMATIC.

During flatness measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.
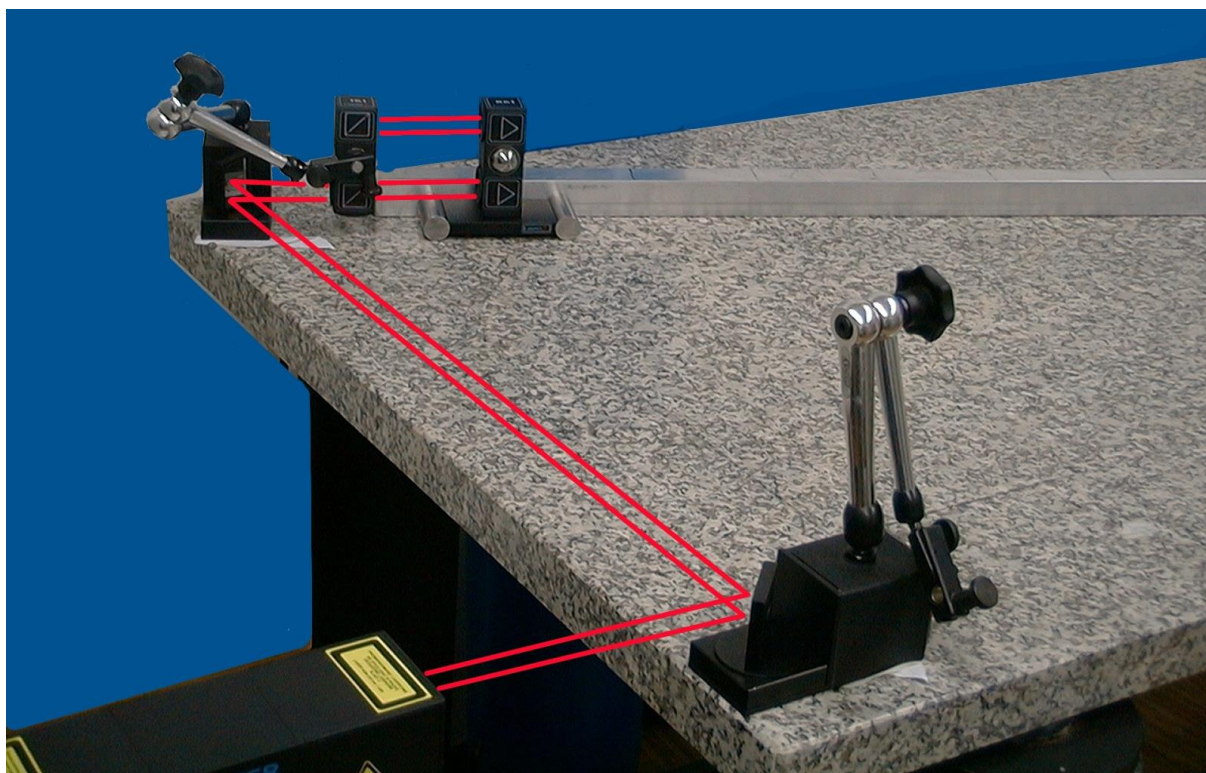
FIG.8.4. OPTICAL PATH SET UP FOR FLATNESS MEASUREMENTS IN ONE
OF AXES.

c. Software description

Flatness is measured in the **Flatness** option, chosen from the **Main Menu**. The *HPI Software* program window looks like it is shown in the Fig. 8.5. The Flatness Measurement Summary window consists of three main parts:

- Display – presents flatness of the surface calculated according to straightness measurements for axes;
- Schematic chart – allows to select axis;
- Panel with buttons.
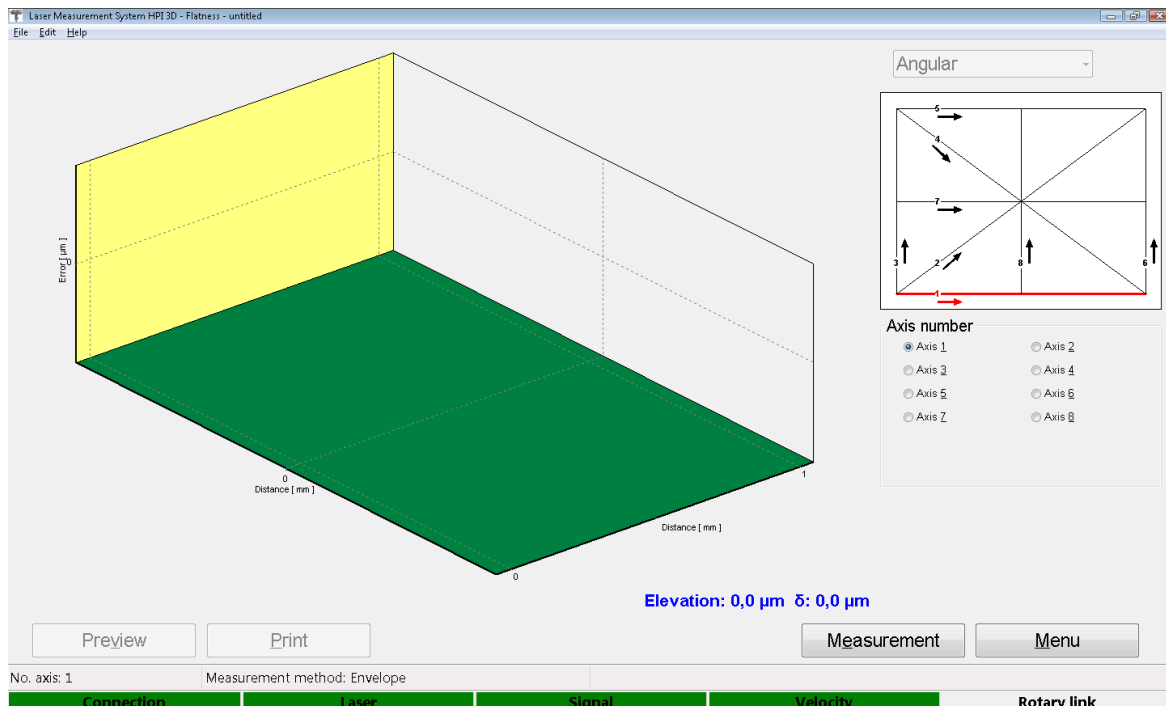
FIG.8.5. FLATNESS MEASUREMENT SUMMARY WINDOW.

Measurements of the axes are performed in the *Flatness Measurement* window that is launched by the **Measurement** button from *Flatness Summary* window. The window as shown in the figure 8.6 appears. In this window it is also possible to change the measured axis and analyze the straightness results of each individual axis. The axis can be selected by clicking the proper axis on the axes chart or by choosing it from the *No. axis* pull down list.
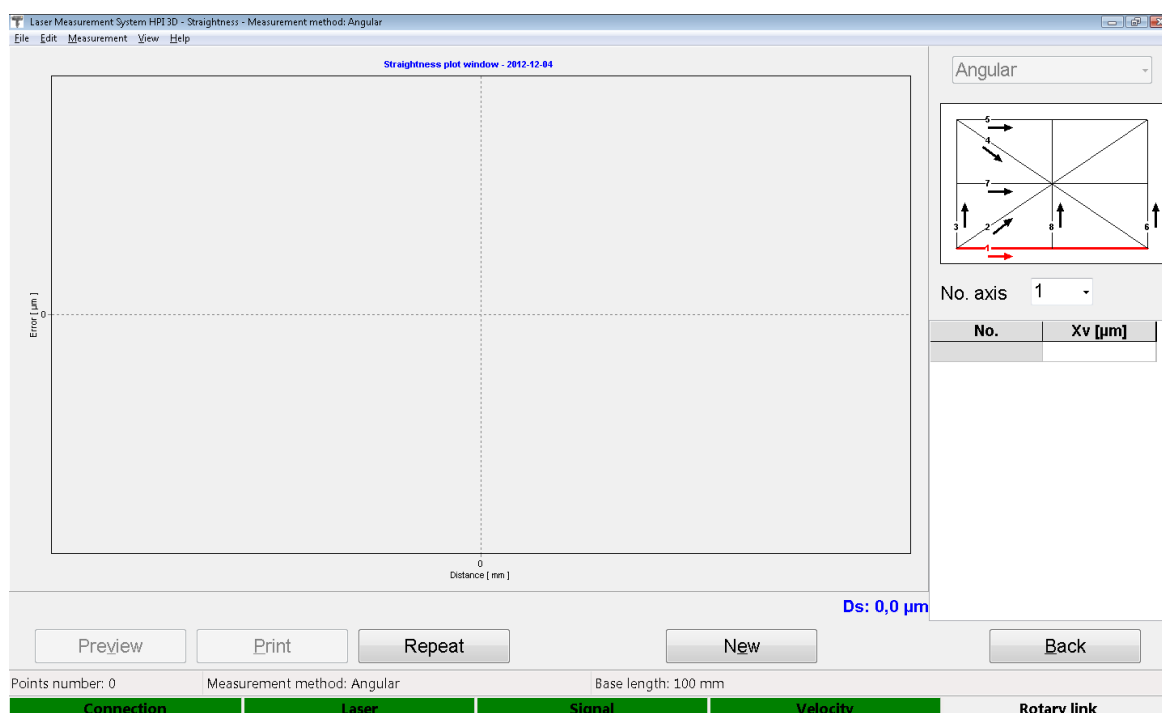
FIG.8.6. FLATNESS MEASUREMENT WINDOW.

The options available in the flatness measurement window allow also for repeating the single straightness measurement (**Repeat** button) or printing the results (of a single measurement) in the form of the Report (**Preview** or **Print** button).

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The graph can be printed or saved to a file. It can be chosen from the **File** menu (i.e. Save, Save as, Print – see figure 8.7).
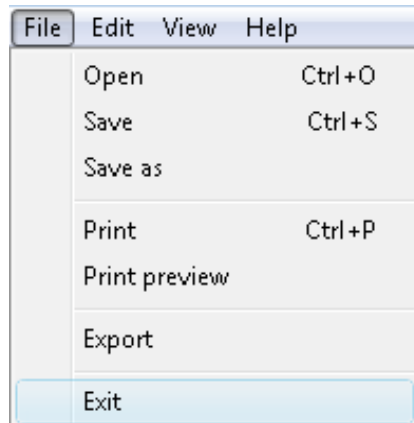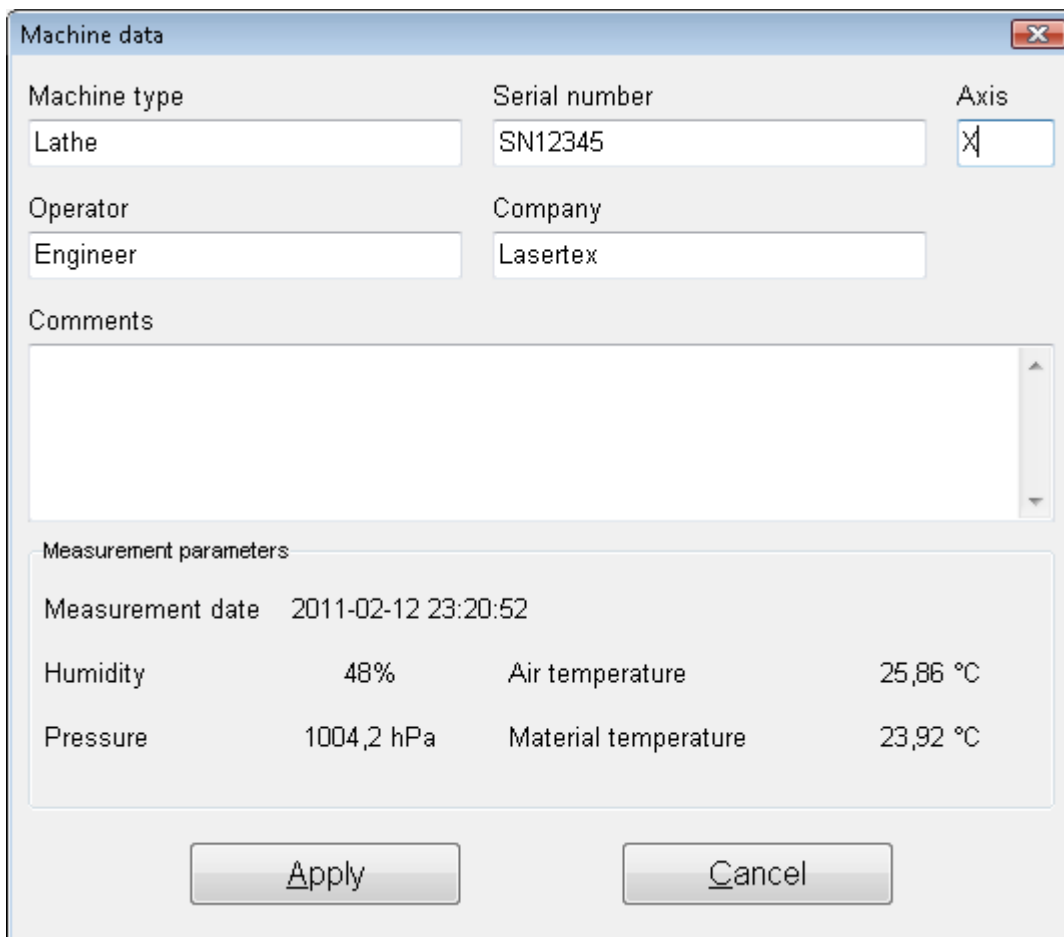
FIG.8.7. FLATNESS PULL-DOWN MENU *FILE*.

Before saving the file the program asks about changing machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator (see figure 8.8). Those values allow describing performed measurement for later analysis and they are also present on the printed report.

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FIG.8.8. MACHINE DATA WINDOW.

Measurement report can also be generated from obtained data, either by pressing Print or Preview on the measurement analysis window. The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.

It is also possible to copy the straightness graph to the clipboard and then paste it for example to a Word editor document. **Copy to clipboard** command is available from

popup menu that appears after right-click on the area of the graph.

The flatness option can be configured in the **Flatness** tab (Fig. 8.9.) located in the **Configuration** window accessible from the **Main Menu** or from pull down menu *Edit->Configuration*.
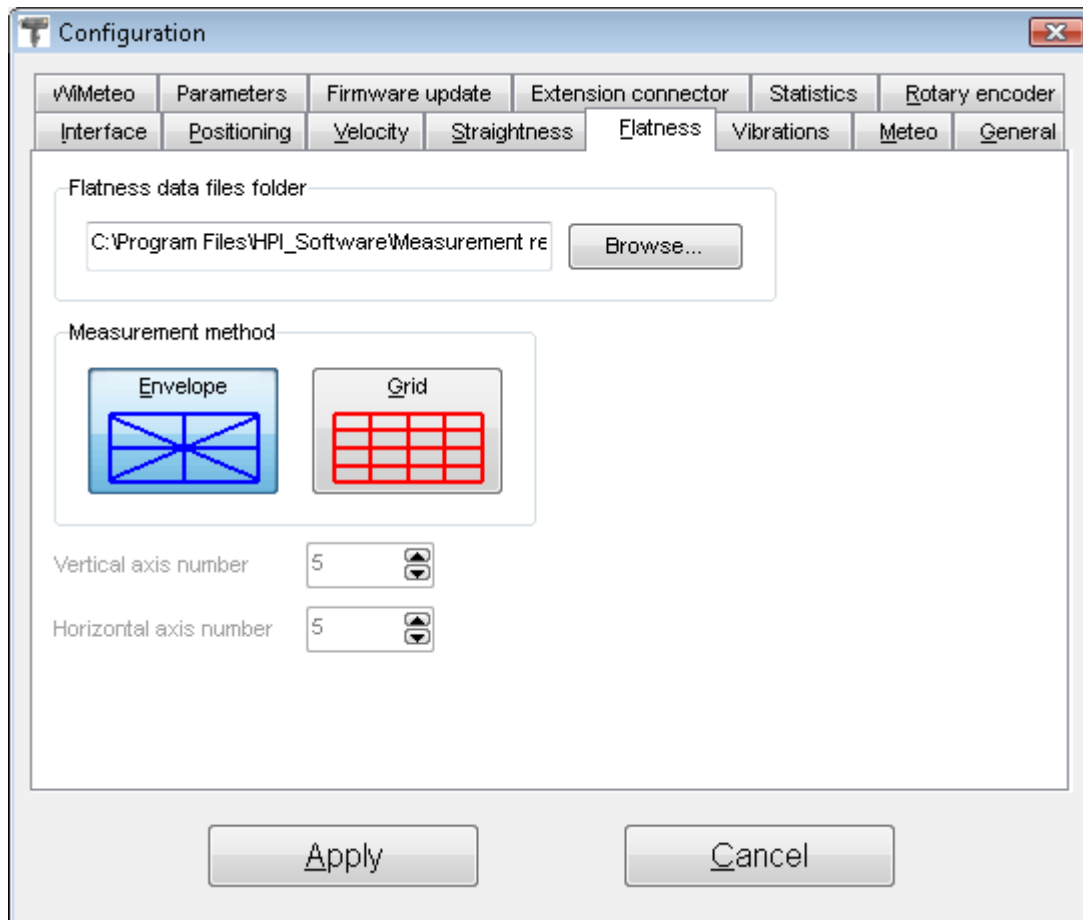
FIG.8.9. FLATNESS CONFIGURATION OPTIONS.

In the Flatness Configuration Tab it is possible to change the destination data folder or to choose the measurement method. The standard one is the Envelope that uses Moody

method for flatness calculation. For Grid method the number of vertical and horizontal axes can be set from 3 to 8.

d. Alignment of optics for the flatness measurements

The flatness measurement consists of the straightness measurements performed along 8 axes. The axis can be selected by clicking the proper axis on the axes chart or by choosing it from the list (Fig. 8.10.). There are also shown: directions of measurements in the axes and margins that must be kept during measurements.
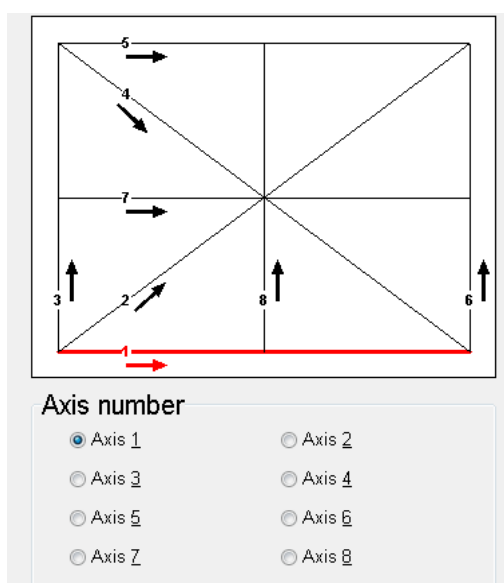
FIG.8.10. AXES CHOICE CHART.

Straightness measurements are made with angular optics as it is described in the Chapter *Measurements -*

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Straightness. Depending on the measurement axis, a different set of optical components is used and the alignment of the optical path is done in slightly different way. As mentioned earlier the measurements can be made either with or without changing the position of the laser head. In both cases the measurements have to be performed in accord with the directions pointed by arrows on the schematic graph on the main screen of flatness measurement (Fig. 8.10).

Below there is described the procedure of flatness measurements in the constant laser head position configuration.

i. Optical path alignment of the axis "1".

The straightness measurement of the axis "1" is performed in the same way as described in Chapter 7, *Straightness measurements*.

ii. Optical path alignment of the axes: "3", "6", "8".

During flatness measurements of the axes "3", "6" and "8" an additional beam directing mirror **ZK1** is used. The way of using it is shown in the Figure 8.11. The alignment procedure is the same as described in Chapter 4 for angular optics with an additional beam directing element (**ZK1**) in the path.

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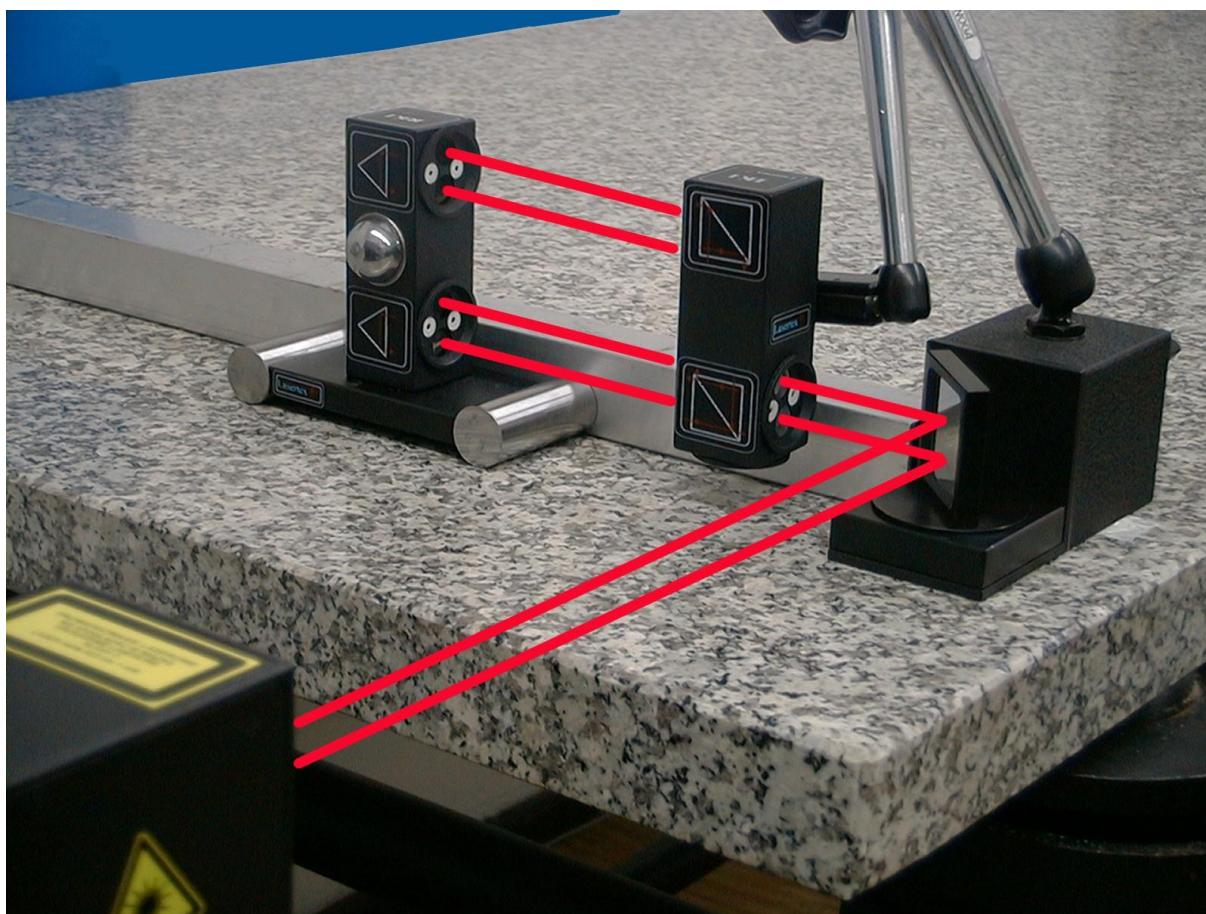
FIG.8.11. THE SET OF THE OPTICAL COMPONENTS USED IN STRAIGHTNESS MEASUREMENTS IN THE AXES: "3", "6:" AND "8".

iii. Optical path alignment of the axes: "5" and "7"

During flatness measurements of the axes "5" and "7" two beam directing mirrors **ZK1** are used. The way of using them is shown on Figure 8.12. The alignment procedure is the same as described in Chapter 4 for angular optics with an additional beam directing element (**ZK1**) in the path.
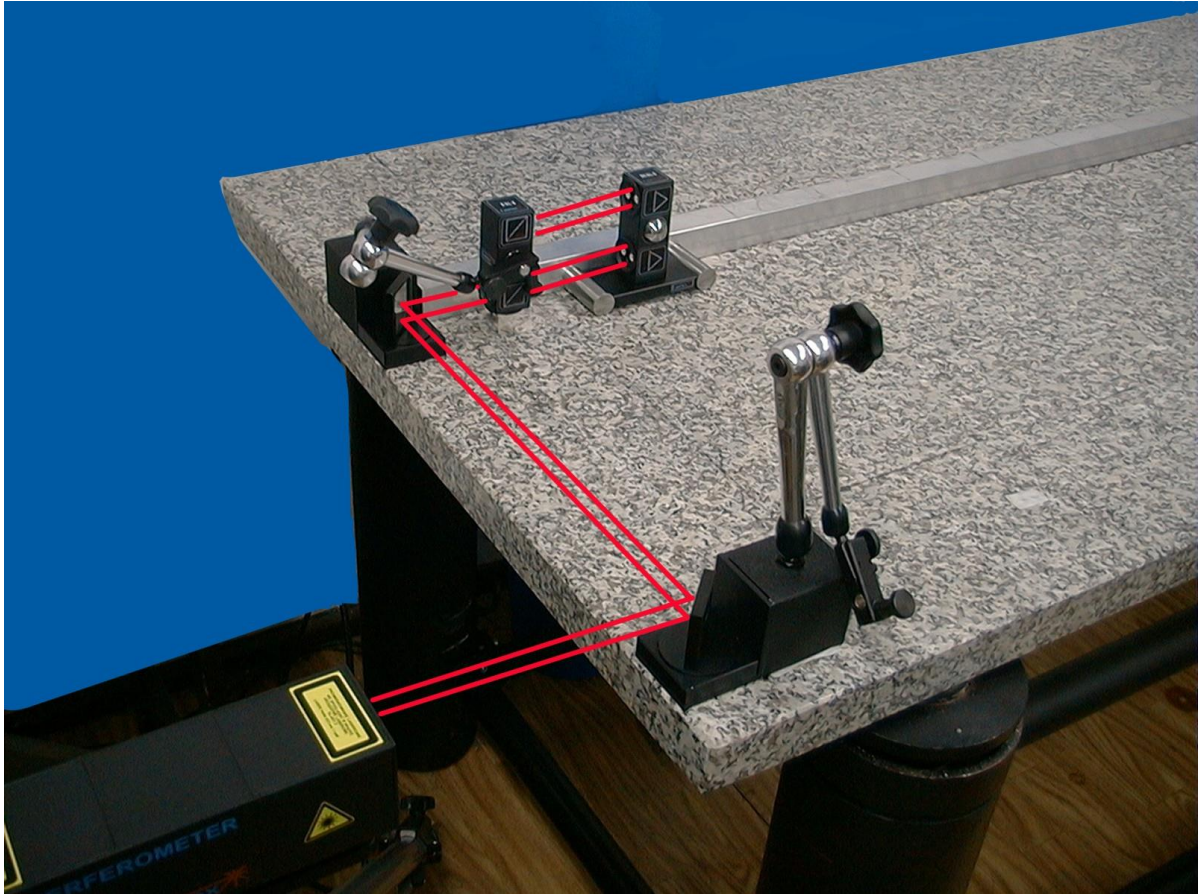
FIG.8.12. THE SET OF THE OPTICAL COMPONENTS USED IN STRAIGHTNESS MEASUREMENTS IN THE AXES: "5" AND "7".

iv. Optical path alignment of the axes: "2" and "4"

Similarly to previously described axes "5" and "7", during flatness measurements of the axis "4" two beam directing mirrors **ZK1** are used. The difference is that the angle of the second mirror usually differs from 45°. The alignment of the axis "4" is shown in the Figure 8.13. In case of the axis "2" only one beam directing mirror **ZK1** is used, but alignment procedure is quite similar to the axis "4". The alignment procedure is the same as described in Chapter 4

for angular optics with an additional beam directing element (**ZK1**) in the path.
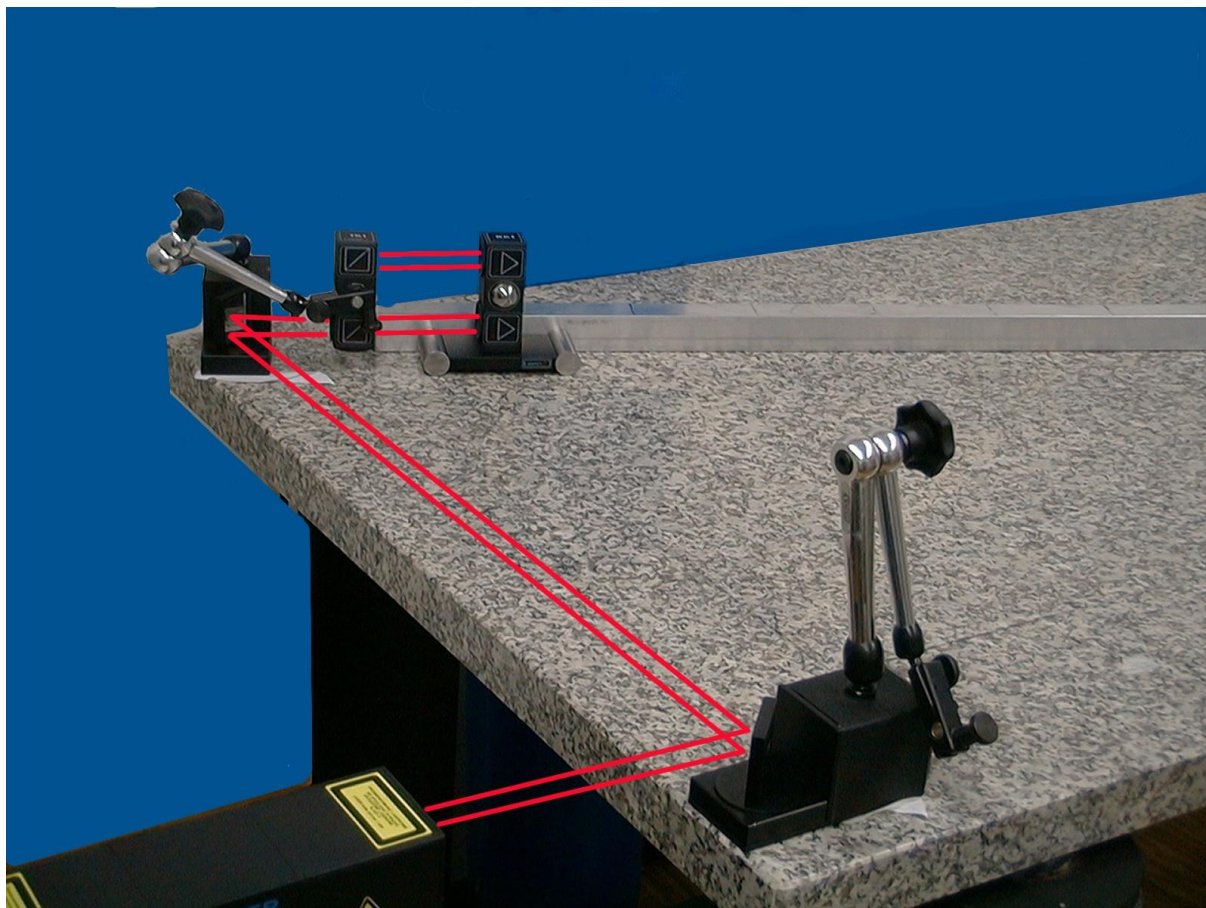
FIG.8.13. THE SET OF THE OPTICAL COMPONENTS USED IN STRAIGHTNESS MEASUREMENTS IN THE AXES: "2" AND "4".

e. Measurement procedure

1. Set up the laser on the measured machine and align first optical path.

2. Start the HPI Software and select Flatness option.

3. Press Measurement button on the Flatness summary screen

4. Choose the proper axis on the axis choice chart and press Start, New or Repeat button.

5. Move the **RK1** by the distance set in the *Edit->Base length* option (default 100mm) and wait on the next point capture (or capture it manually).

6. Continue measurements until all points on the path are measured.

7. Stop the measurement.

8. If not all axes are measured then repeat points 4-7.

9. When straightness measurements of all axes are completed then the Back button should be pressed. The software returns to the Flatness Summary screen – see figure 8.14
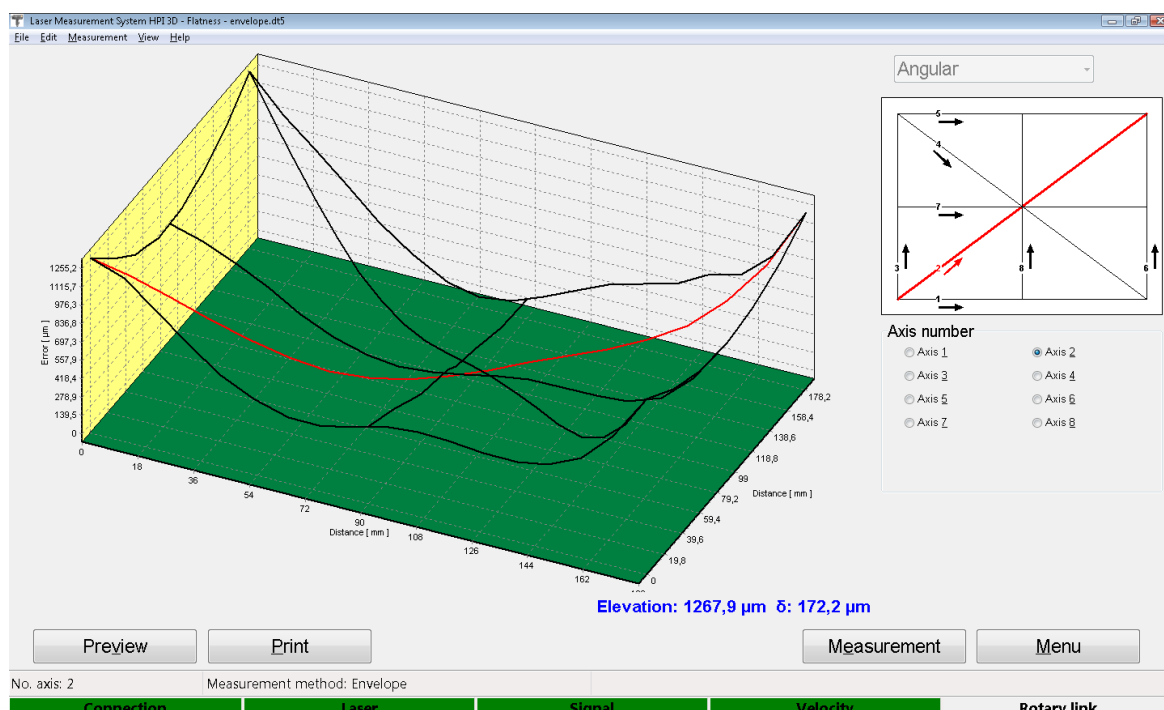
FIG.8.14. A RESULT OF FLATNESS MEASUREMENT.

In order to perform the measurement in the manual capture mode, the *Measurement->Manual point capture* should be selected. The measurement begins by pressing **Start/New/Repeat**. The point can be captured by pressing *Space* key, clicking the **Point capture** button, or pressing the remote Strobe button. When the last point is captured the **Stop** button should be pressed.

Measurement report can also be generated from obtained data, either by pressing Print or Preview on the measurement analysis window. The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.

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9. MEASUREMENTS – PITCH/YAW

a. General Description

Pitch/Yaw measurement enables to better characterize the measured machine axis geometry. With this option the machine base straightness on all important base surfaces can be measured or the quality of movement of the measured element can be checked. The measured errors are known in the literature as pitch and yaw errors. Pitch/Yaw option is very similar to the Angular Straightness option which is described in another Chapter of this document. The only difference is a method used for measurement result calculation.

b. Measurement Setup

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For **Pitch/Yaw** measurements the angular optics should be used. Necessary components are:

- Laser Head
- Power Supply
- Angular Interferometer **IK1**
- Angular Retro-reflector **RK1**

Optional elements are:

- USB cable
- Manual Strobe
- Magnetic holder **UM2**
- Tripod stand
- Air temperature sensor
- Base temperature sensor

Pitch/Yaw measurements require optical elements IK1 and RK1 to be aligned along laser beam as shown in the figure 9.1. Each of the elements can be moved.

During Pitch/Yaw measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

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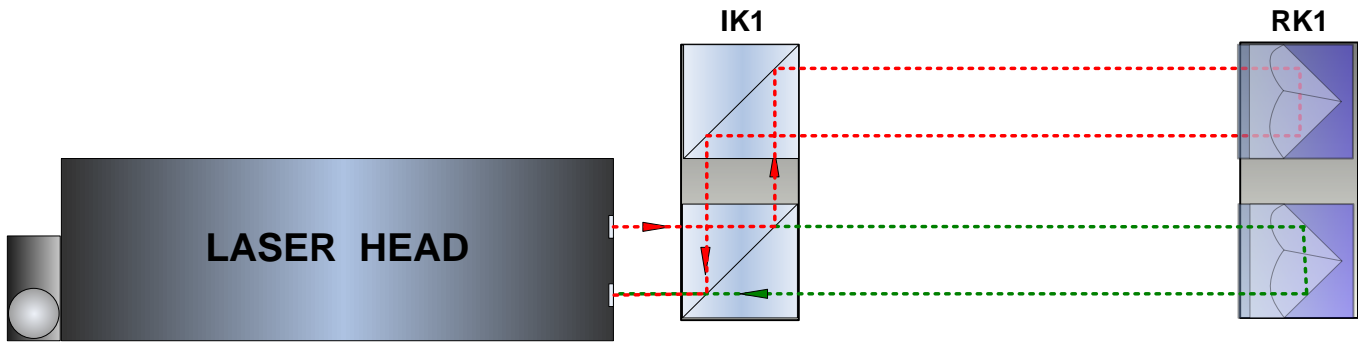
FIG.9.1 OPTICAL PATH SET UP FOR PITCH/YAW MEASUREMENTS-SCHEMATIC.
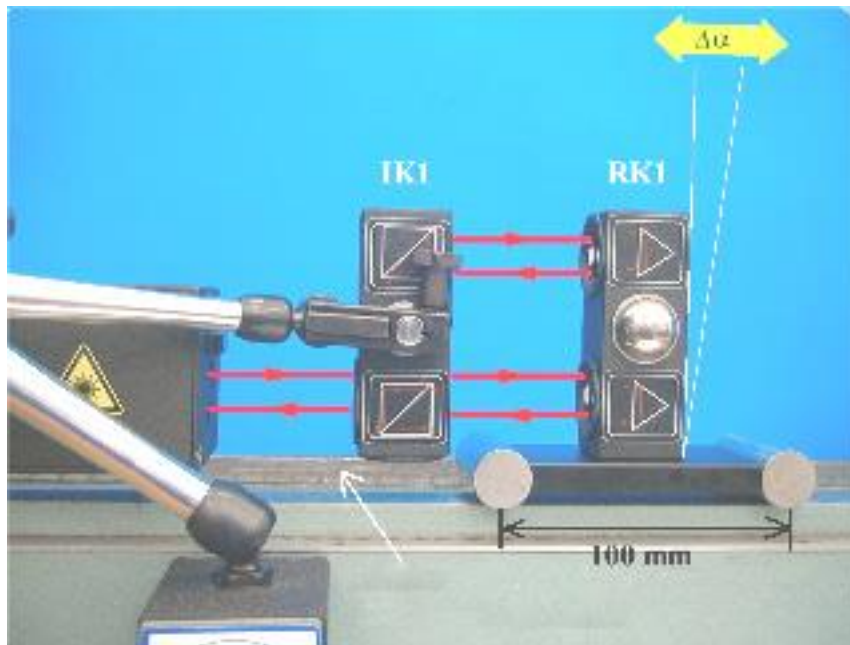
FIG.9.2 OPTICAL PATH SET UP FOR PITCH/YAW MEASUREMENTS IN X AXIS.

Pitch/Yaw measurements can be performed not only along the laser beam (as shown in figures 9.1 and 9.2) but also in directions perpendicular to the laser beam. These configurations are shown in figures 9.3 and 9.4. In those two configurations only the retro-reflector RK1 can be moved.

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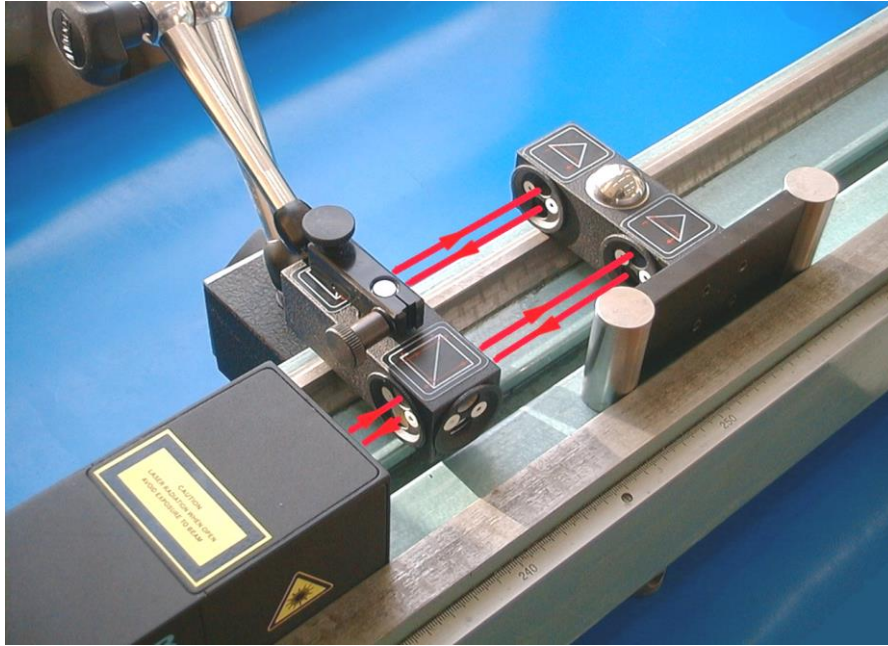
FIG.9.3 OPTICAL PATH SET UP FOR PITCH/YAW MEASUREMENTS IN Y AXIS.
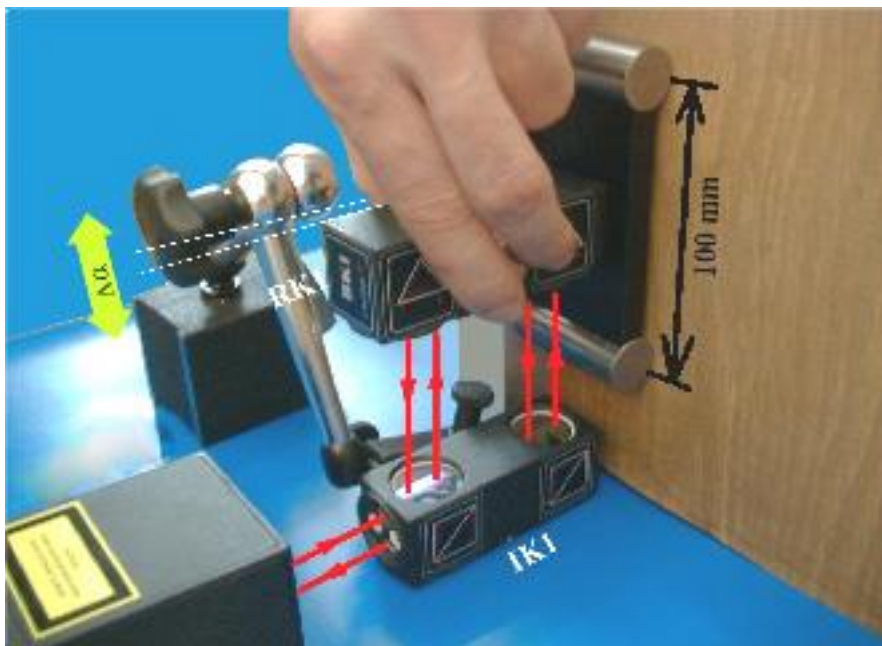
FIG.9.4 OPTICAL PATH SET UP FOR PITCH/YAW MEASUREMENTS IN Z AXIS.

c. Software description

Pitch and Yaw errors can be measured in the **Pitch/Yaw** option, chosen from the **Main Menu**. The HPI-3D program window looks like it is shown in the Fig. 9.5. The window consists of four main parts:

- Display – presents recent measured angle and measurement signal level;

- Obtained results plotted on a graph;

- Obtained results displayed in the measurement table;

- Panel with buttons.
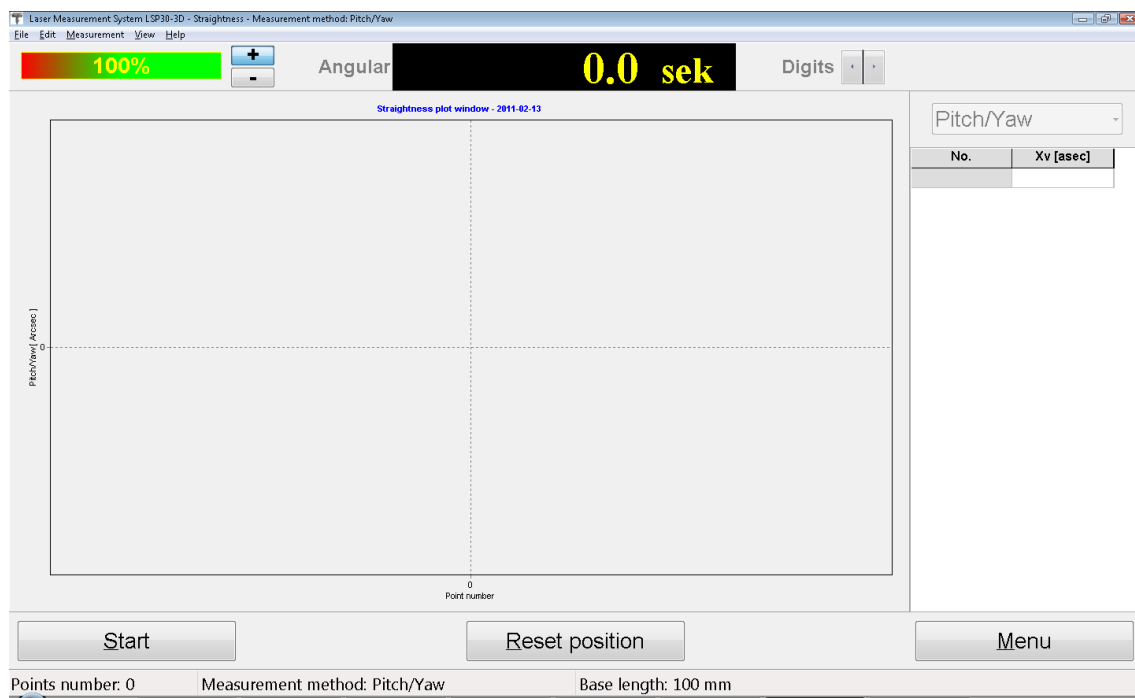
FIG.9.5. PITCH/YAW MEASUREMENT WINDOW.

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Before the measurement is started the right point capture method from the *Measurement* menu should be chosen (see figure 9.6). There are two methods available:

Time period point capture – points are captured automatically by the software in constant time intervals. Time interval is configured on the panel with ↓ and ↑ buttons.

Manual point capture – points are captured when the *Point capture* button on the panel, *Space* key on the keyboard or Manual Strobe button is pressed.
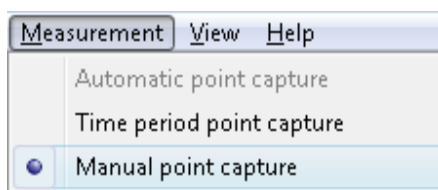
FIG.9.6. PITCH/YAW PULL-DOWN MENU *MEASUREMENT.*

Measurement is started by the **Start** button. Depending on the chosen point capture method the points are captured automatically or have to be captured by the user. During the measurement the graph on the screen is constantly updated. The measurement is finished by the **Stop** button.
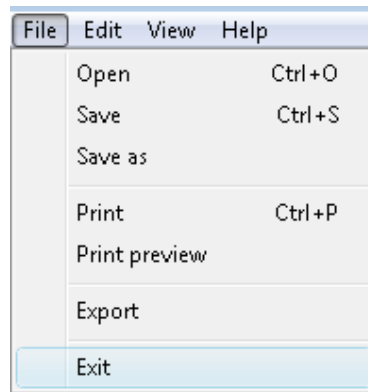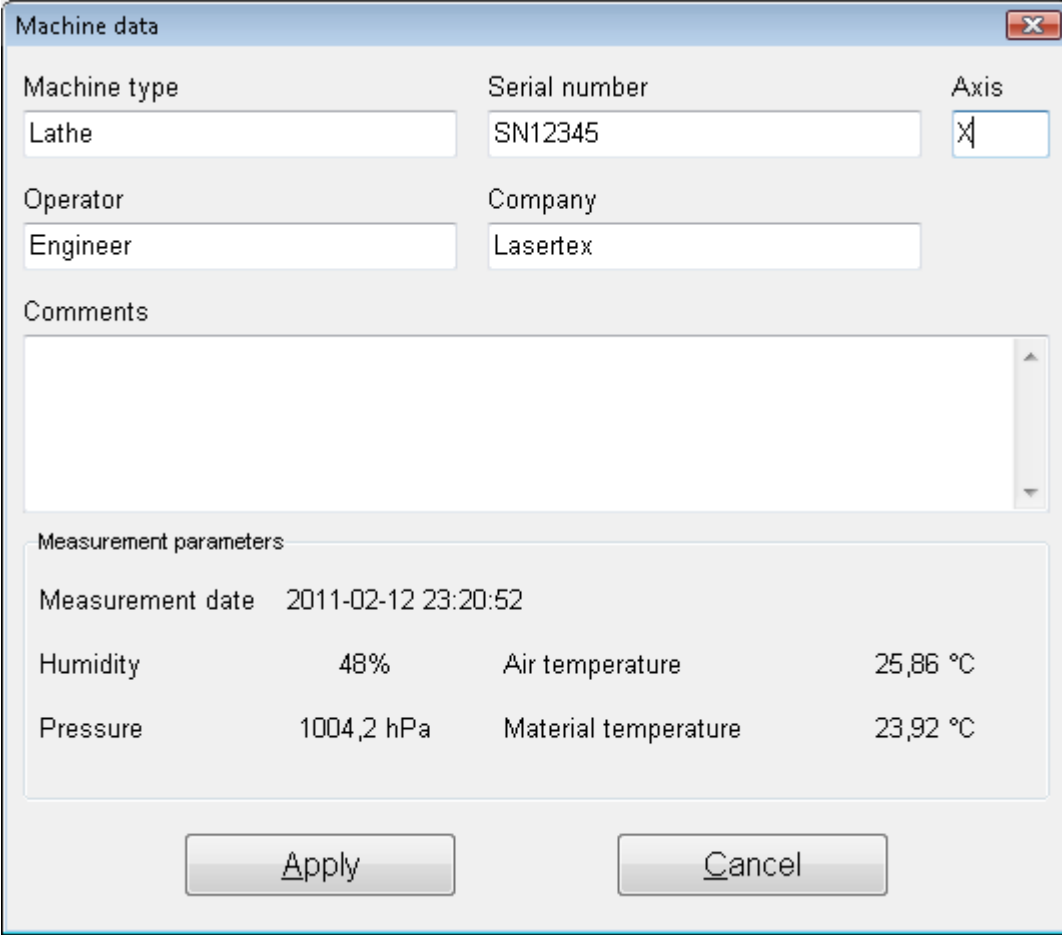
FIG.9.7. PITCH/YAW PULL-DOWN MENU *FILE.*

Obtained results can be saved, printed or exported (menu File). Before saving the file the program asks about changing machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator (see figure 9.8). Those values allow describing performed measurement for later analysis and they are also present on the printed report.

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FIG.9.8. MACHINE DATA WINDOW.

Measurement report can also be generated from obtained data, either by pressing Print or Preview on the measurement analysis window (fig. 9.9). The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.
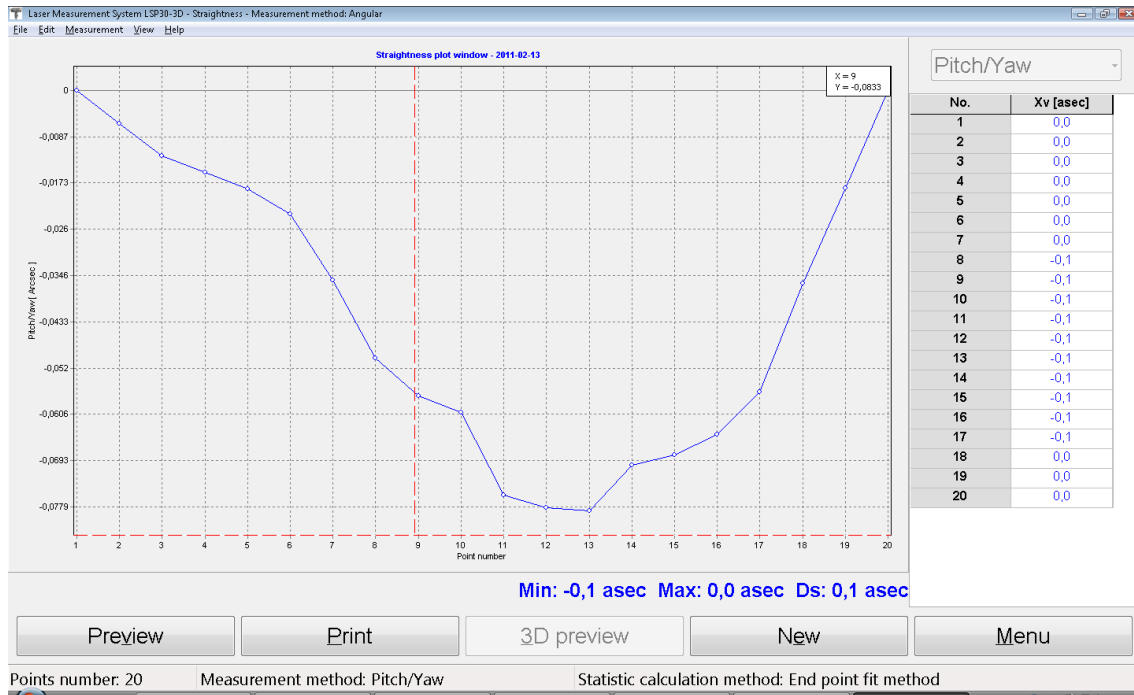
FIG.9.9. PITCH/YAW MEASURED DATA ANALYSIS WINDOW.

It is also possible to copy the straightness graph to the clipboard and then paste it for example to a Word editor document. **Copy to clipboard** command is available from popup menu that appears after right-click on the area of the graph.

Configuration of Pitch/Yaw measurement option is available in the *Configuration->Straightness* window. There is performed a configuration of statistic calculation method (fig. 9.10) which is used for measurement data processing. End point fit or Least squareness fit can be chosen to use statistical methods. The None option enables to perform an analysis of raw results.

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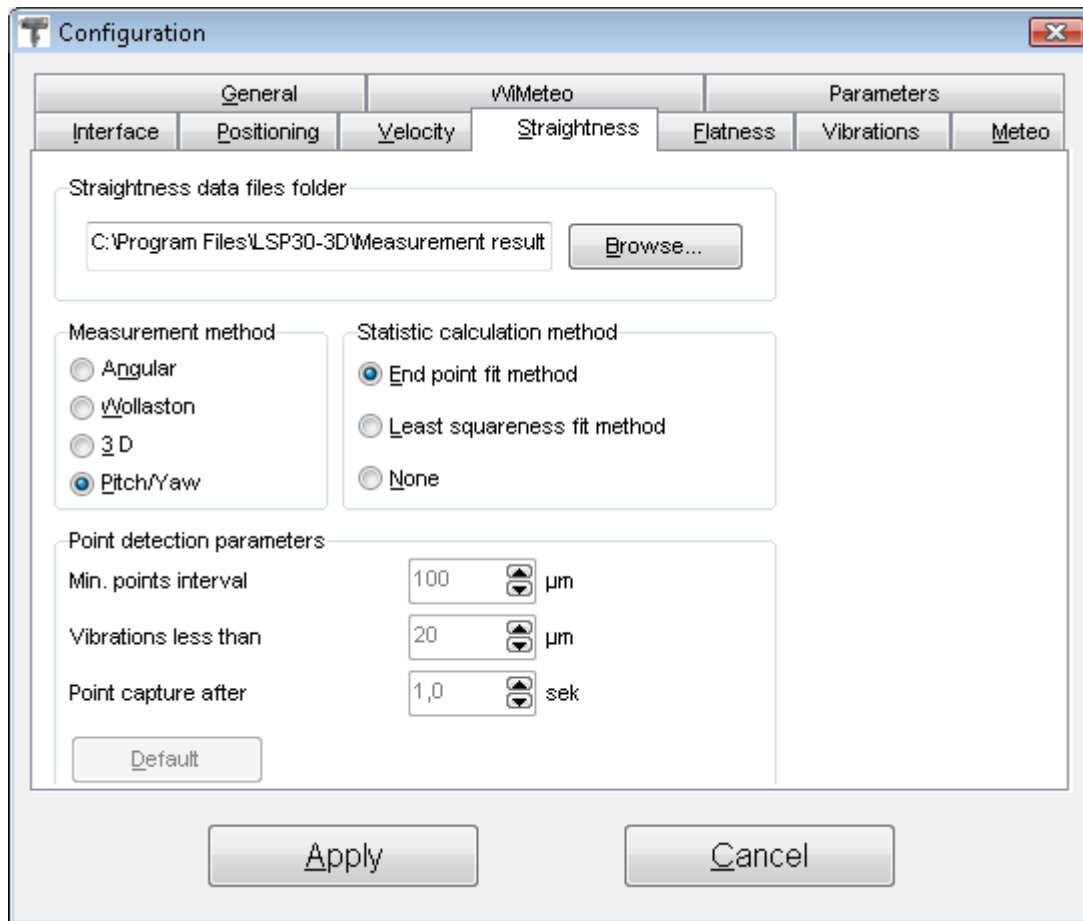
FIG. 9.10. PITCH/YAW CONFIGURATION OPTIONS.

d.Measurement procedure

1. Set up the laser on the measured machine and align optical path.

2. Start the HPI-3D software and select Pitch/Yaw option.

3. Choose the desired point capture method.

4. Press Start button and run the machine.

5. In the manual mode capture points using the most appropriate method; in the automatic mode points

are captured by the software in constant time intervals.

6. Stop the measurement.

7. Save the results and/or print the measurement report.

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10. MEASUREMENTS - SQUARENESS

a. General Description

The squareness measurement is used to characterize the measured machine geometry, i.e. the squareness of axes. The measurement is performed using either 3D or Wollaston straightness measurement technique. In order to obtain the proper results, two measurements with the use of a right angle etalon are necessary. From obtained axes straightness data the squareness is calculated and drawn (fig.10.1.).

b. Measurement Setup

The choice of optical elements necessary for squareness measurements depends on the selected measurement method: i.e. 3D or Wollaston. If 3D method is used then the linear optics plus right angle etalon should be used. In this case the necessary components are:

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- Laser Head

- Power Supply

- Linear Interferometer **IL1**

- Linear Retro-reflector **RL1**

- Right angle etalon **RE3D or REW**
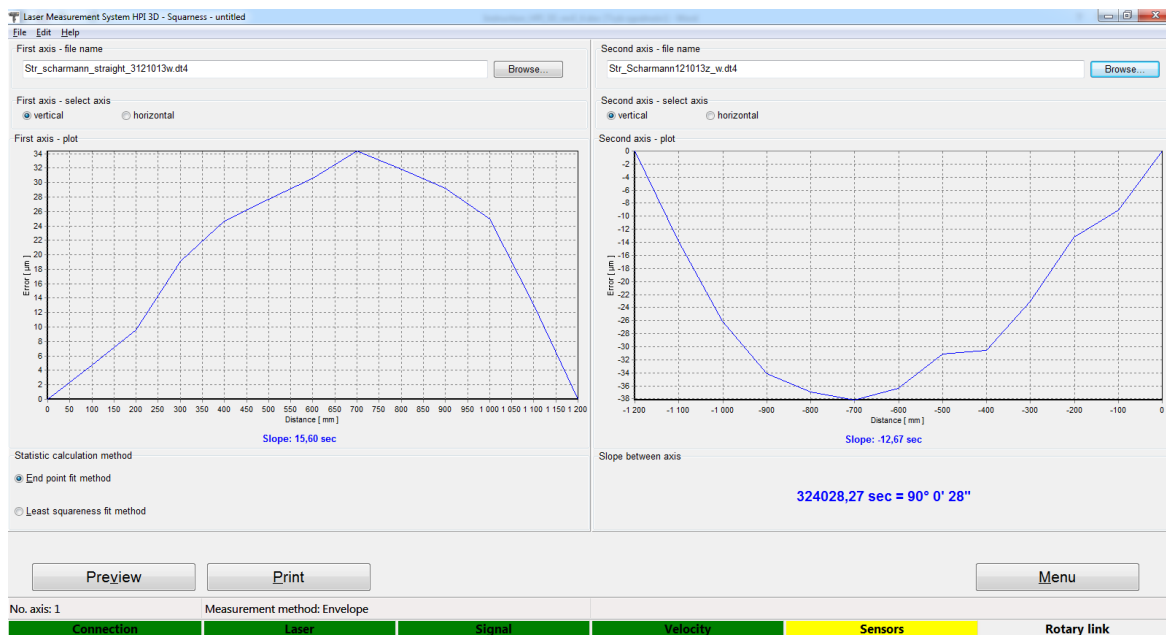
FIG.10.1. AN EXEMPLARY SQUARENESS RESULTS

In the case of the Wollaston type measurement the necessary components are:

- Laser Head

- Power Supply

- Wollaston prism **WP2**

- Wollaston retro-reflector **WRP2**

- Right angle etalon **REW**

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For both methods the optional elements are similar:

- USB cable

- Manual Strobe

- Magnetic holder **UM2**

- Tripod stand

- Air temperature sensor

- Base temperature sensor

Squareness measurements based on the 3D method require optical elements IL1 and RL1 to be first aligned along the laser beam as shown in the figure 10.2A. The element RL1 should be moved. Obtained results of the axis straightness should be saved for further processing.
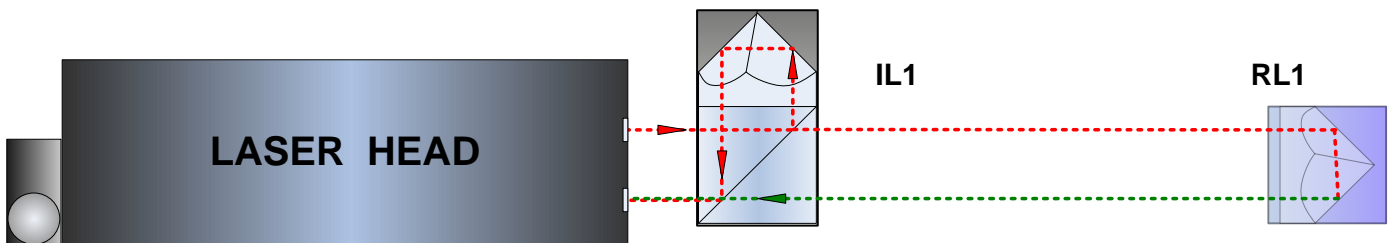
FIG.10.2A. OPTICAL PATH SET UP FOR 3D SQUARENESS MEASUREMENTS-FIRST AXIS

In the next phase of the measurements the beam should be directed to the perpendicular axis with the use of right angle etalon RE3D or REW. **Be careful** not change the position of the laser head during alignment of the laser path – the beam path has to be aligned only with the rotation of

either the RE3D or the REW element! The optical configuration is shown in the Figure 10.2B. The measurement of the axis straightness should be performed with the movement of the RL1 element.

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RE3D

LASER HEAD
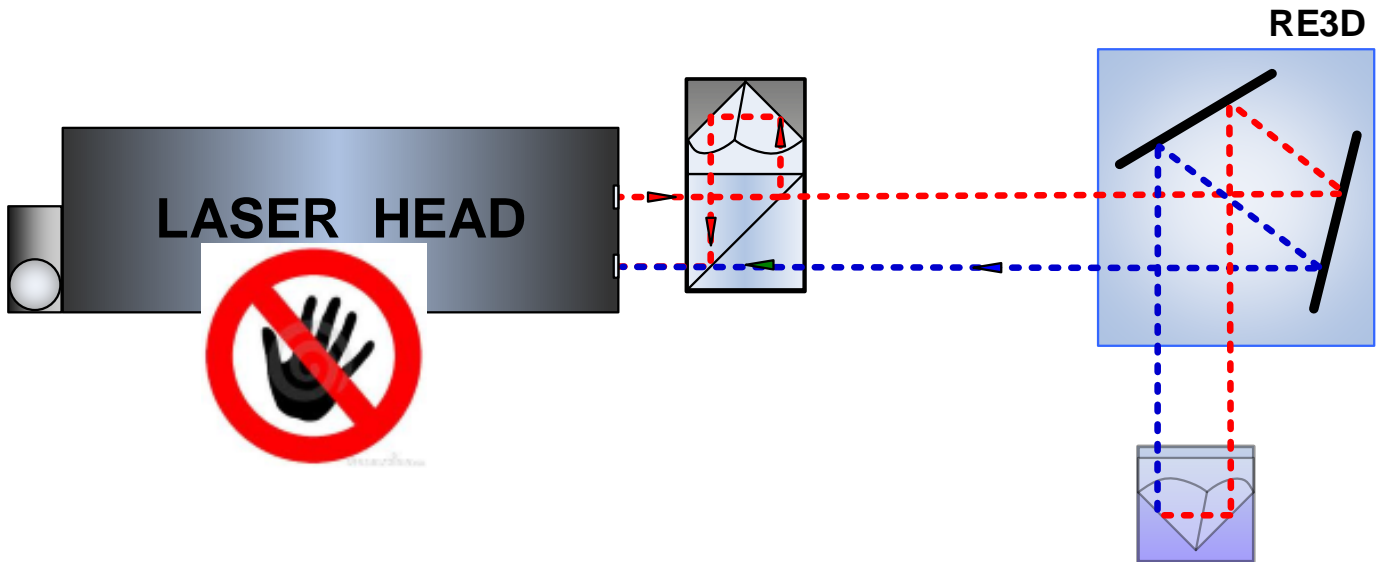
FIG.10.2B. OPTICAL PATH SET UP FOR 3D SQUARENESS MEASUREMENTS- SECOND AXIS

Wollaston squareness measurements require optical elements WP2 and WRP2 to be aligned along laser beam as shown in the figures 10.3A and 10.3B. The beam should be directed to the perpendicular axis with the use of right angle etalon REW.

The measurements consist of two parts. In the first part the WP2 is moved between the laser head and the REW prism (Fig. 10.3A). During the second part the WP2 should be placed between REW and WRP2 (Fig. 10.3B).

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REW

WRP2

WP2

LASER HEAD
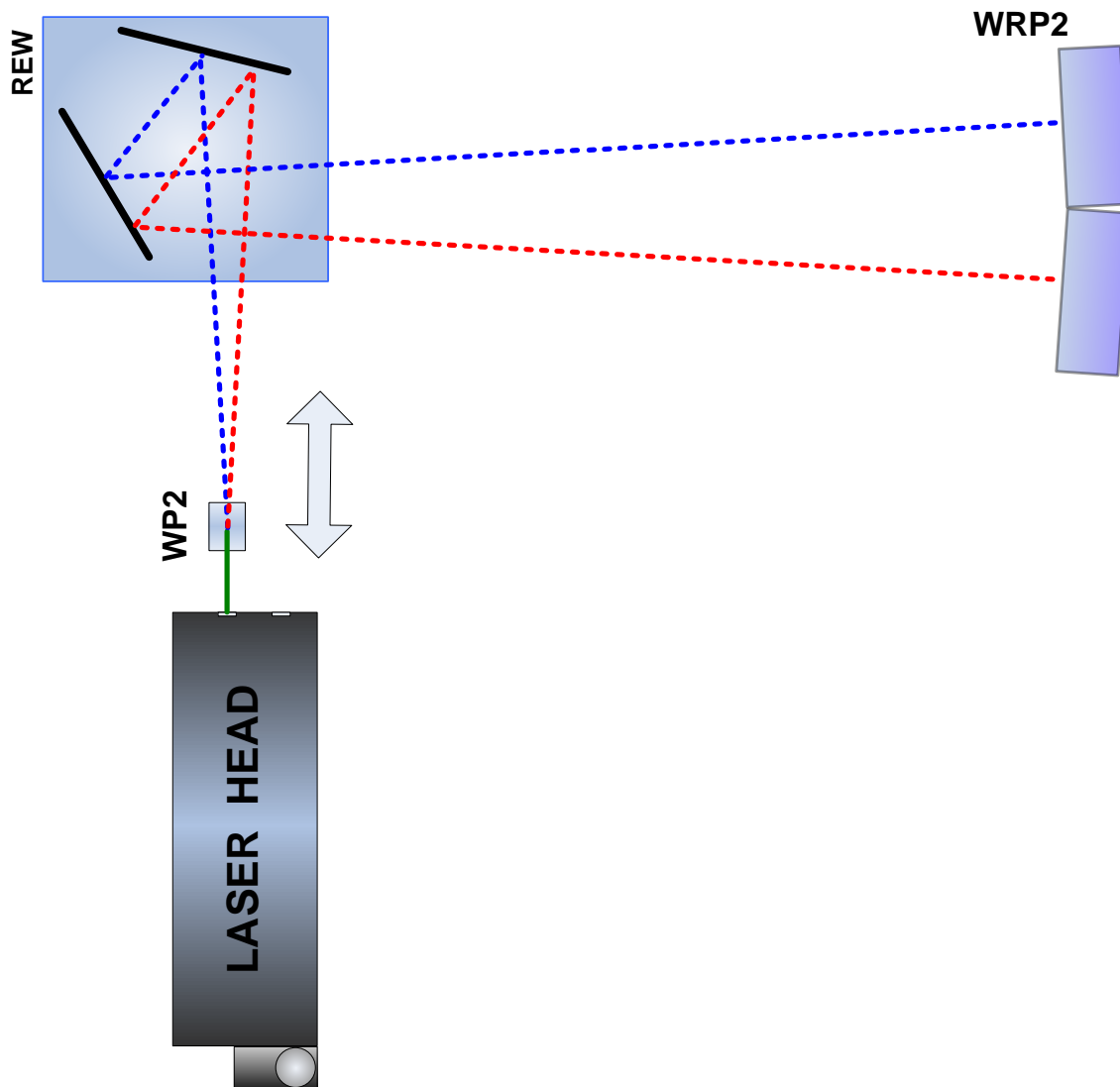
FIG.10.3A. OPTICAL PATH SET UP FOR WOLLASTONE SQUARENESS MEASUREMENTS - SCHEMATIC FOR FIRST AXIS. RETURN BEAMS NOT DRAWN FOR FIGURE CLARITY

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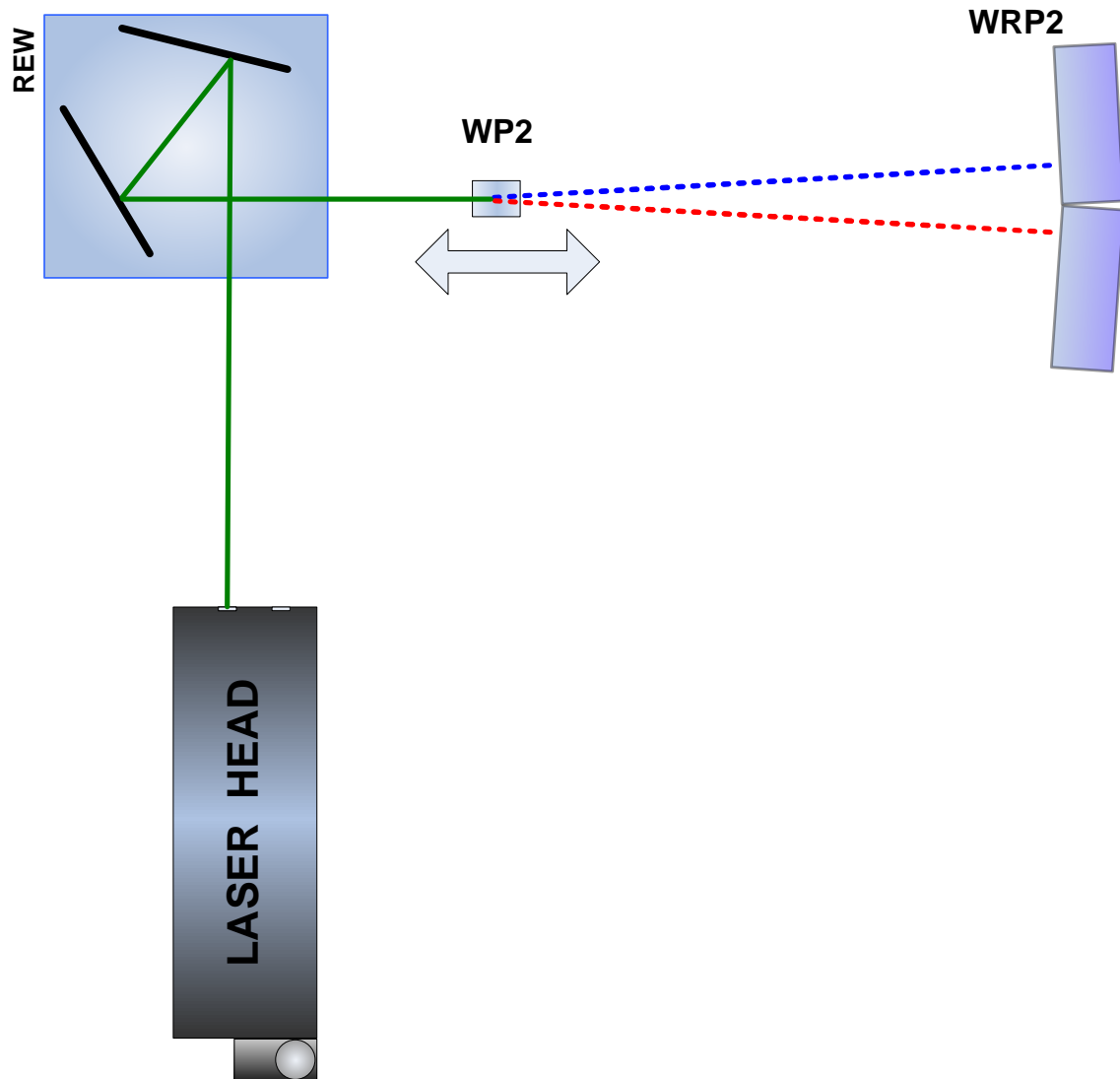
FIG.10.3B. OPTICAL PATH SET UP FOR WOLLASTONE SQUARENESS MEASUREMENTS - SCHEMATIC FOR SECOND AXIS. RETURN BEAMS NOT DRAWN FOR FIGURE CLARITY

The element WRP2 **MUST NOT** be moved during measurements. The laser head and the REW should also be not touched during both parts of the measurement.

During squareness measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

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c. Software description

Squareness is measured in the **Squareness** option, chosen from the **Main Menu**. The *HPI Software* program window looks like it is shown in the Fig. 10.4. The Squareness Measurement Summary window consists of three main parts:

- Display – presents measured straightness of axes and calculated squareness;

- Schematic chart – allows changing the currently edited axis;

- Panel with buttons
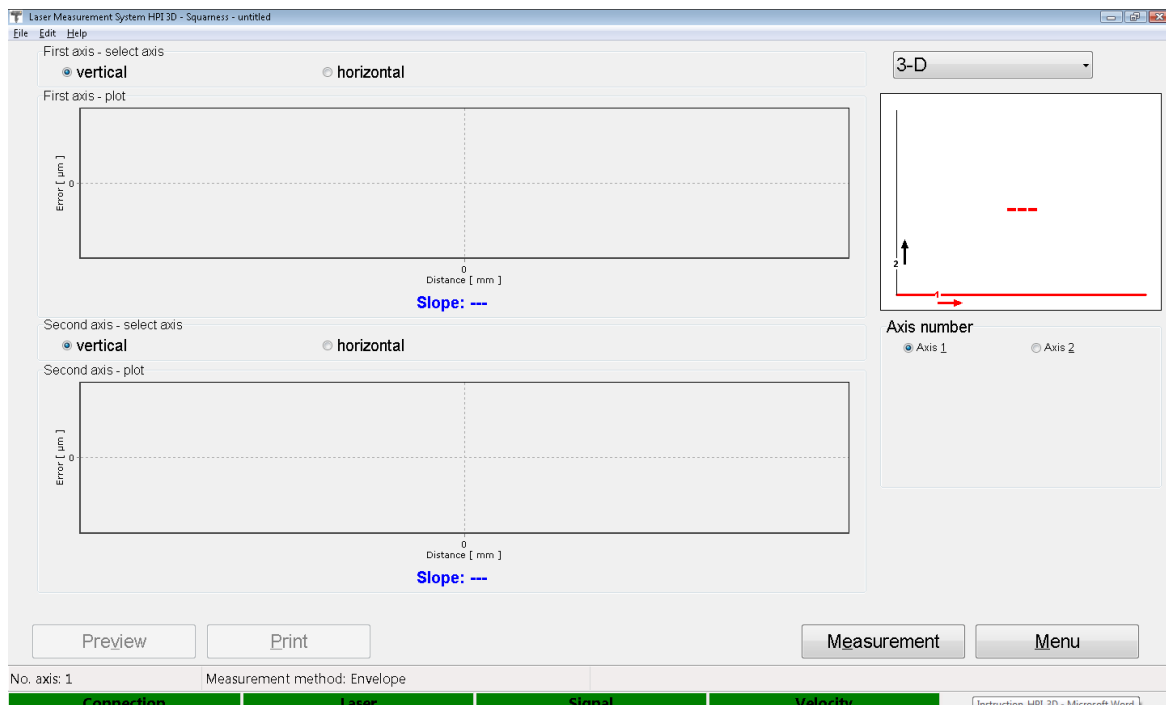
FIG.10.4. SQUARENESS MEASUREMENT SUMMARY WINDOW

Measurement is started by the **Measurement** button and window shown in the figure 10.5 appears. In this window it is possible to change the measured axis and analyze the straightness results of each individual axis. The axis can be changed by clicking the proper axis on the axes chart or by choosing it from the *No. axis* pull down list.

FIG.10.5. SQUARENESS MEASUREMENT WINDOW

The options available in the squareness measurement window also enable to repeat the single straightness measurement (**Repeat** button) or print the results (of a single measurement) in the form of the Report (**Preview** or **Print** button).

The graph can be printed or saved to a file. Those commands can be found in **File** menu (i.e. Save, Save as, Print – see figure 10.6).
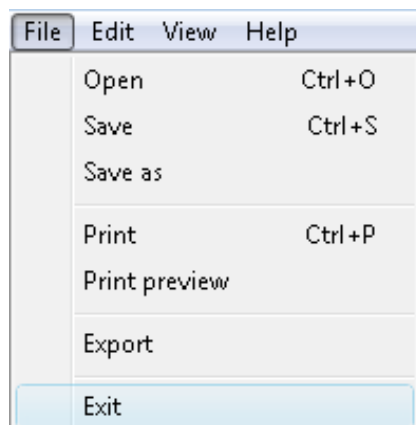
FIG.10.6. SQUARENESS PULL-DOWN MENU *FILE*

Before saving the file the program asks about changing machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator (see figure 10.7). Those values allow describing performed measurement for later analysis and they are also present on the printed report.

Measurement report can also be generated from obtained data, either by pressing *Print* or *Preview* on the measurement analysis window. The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.

It is also possible to copy the straightness graph to the clipboard and then paste it for example to a Word editor document. **Copy to clipboard** command is available from

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popup menu that appears after right-click on the area of the graph.

FIG.10.7. MACHINE DATA WINDOW

The squareness option can be configured in the **Configuration** window accessible both from the **Main Menu** or from pull down menu *Edit->Configuration* in the *Straightness* tab (figure 10.8).

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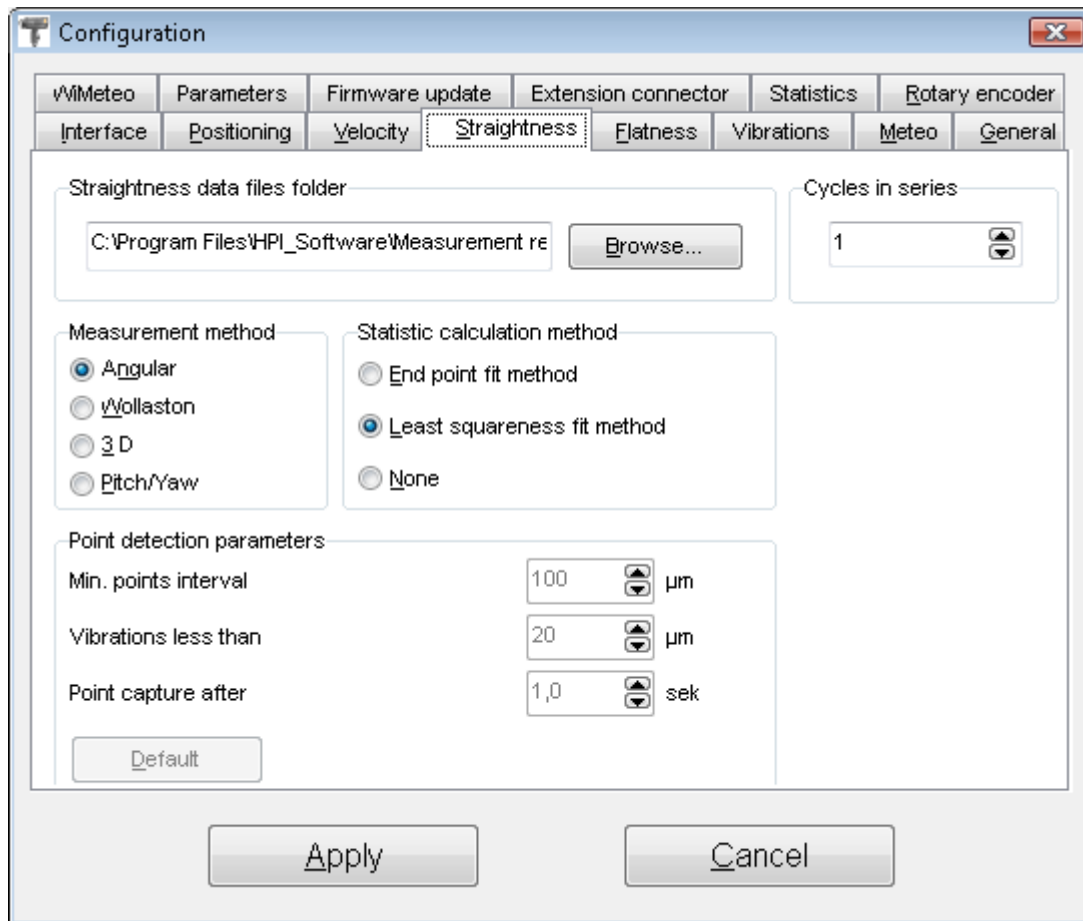
FIG.10.8. STRAIGHTNESS CONFIGURATION OPTIONS

The Straightness Configuration Tab allows configuration which is described in the *Measurement->Straightness* chapter with the difference that the Measurement methods used for squareness measurements are Wollaston or 3D.

d. Alignment of optics for the squareness measurements

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The squareness measurement consists of the straightness measurements for two axes. The measurement axis is selected on the measured surface as shown in the figure 10.9. In this figure there are also shown: directions of measurements and margins that have to be kept during measurements.
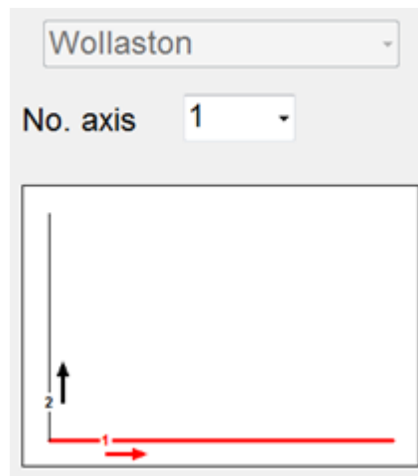
FIG.10.9. AXES CHOICE CHART

The measurements of deviations from straightness are performed with linear or Wollaston optics as described in the Chapter *Measurements - Straightness*. Depending on the measurement axis, a different set of optical components is used and the alignment of the optical path is performed in a slightly different way.

The measurements **have to** be performed without changing the position of the laser head.

In both cases the measurements have to be performed in the directions pointed by arrows on the schematic graph on the main screen of squareness measurement (fig. 10.9).
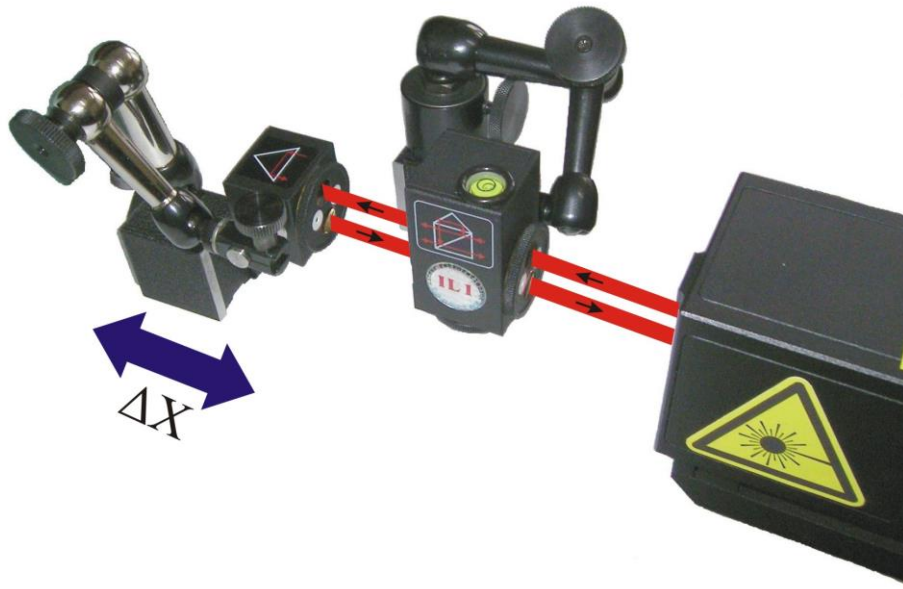
FIG.10.10 OPTICAL PATH SET UP FOR 3D STRAIGHTNESS MEASUREMENTS IN X AXIS

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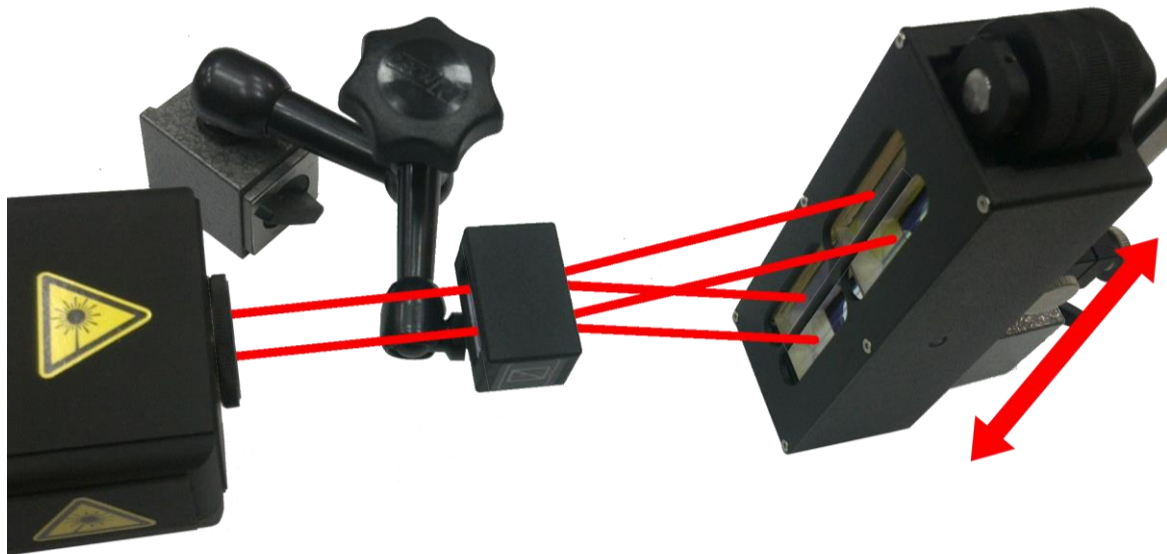
FIG.10.11 OPTICAL PATH SET UP FOR WOLLASTON STRAIGHTNESS MEASUREMENTS IN X AXIS

Configuration of optical components for 3D and Wollaston methods are shown in the figures 10.10 and 10.11. In the figures there is omitted an REW element (see figures 10.3A and 10.3B).

When the machine data is properly configured (*Edit-> Machine Data*), the *Measurement* button should be pressed. Next step is a measurement axis selection (fig. 10.9) and the optical path should be adjusted (see figures 10.10.and 10.11). If the straightness of the first axis is measured the optical path should be realigned and the next axis should be selected in the software. If both axes are measured, Back button should be pressed. Obtained squareness measurements summary (fig. 10.1) can be saved, printed or exported to a text file (*File->Save*, *File->Print* or *File->Export*).

e. Measurement procedure

1. Set up the laser on the measured machine and align the first optical path.
2. Start the HPI Software and select Squareness option.

3. Press Measurement button on the Squareness summary screen.

4. Choose the proper axis on the axis choice chart and press Start, New or Repeat button.

5. Move the **RL1** or **WP2** to the next measurement point.

6. Continue measurements until all points on the path are measured.

7. Stop the measurement.

8. Realign the optical path to the perpendicular axis and repeat steps 4-7

9. When straightness data of all axes are measured then the Back button should be pressed. The software returns to the Squareness Summary screen – see figure 10.1

10. For 3D measurement type the correct axes (Vertical or Horizontal) should be chosen for comparison.

In order to make the measurement in the manual capture mode, the *Measurement->Manual point capture* should be selected. The measurement begins by pressing **Start/New/Repeat**. Measurement points can be captured by the *Space* key from the computer keyboard, *Point capture* button on the panel, or by the remote Strobe button. If the last point is captured, the **Stop** button should be pressed.

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Measurement report can also be generated from obtained data, either by pressing Print or Preview on the measurement analysis window. The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.

11. MEASUREMENTS - PARALLELISM

11

a. General Description

The parallelism measurement is used to characterize the measured machine geometry, i.e. the parallelism of axes. The measurement is performed using 3D or Wollaston straightness technique. In order to obtain the proper results, two measurements with the use of a right angle etalon are necessary. From obtained axes straightness data the parallelism is calculated and drawn (fig.11.1.).

b. Measurement Setup

The choice of optical elements necessary for parallelism measurements depends on the selected measurement method: i.e. 3D or Wollaston. If 3D method is used then the linear optics plus right angle etalon should be used. In this case the necessary components are:

- Laser Head

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- Power Supply

- Linear Interferometer **IL1**

- Linear Retro-reflector **RL1**

- Right angle etalon **RE3D**
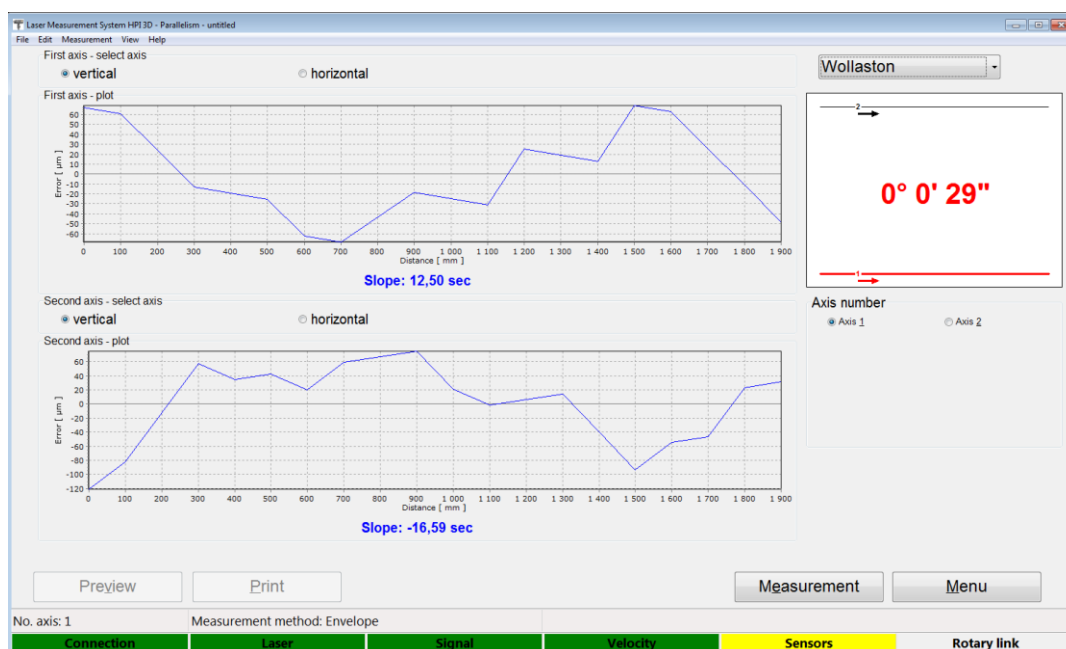
FIG.11.1. AN EXEMPLARY PARALLELISM RESULTS

In the case of the Wollaston type measurement the necessary components are:

- Laser Head

- Power Supply

- Wollaston prism **WP2**

- Wollaston retro-reflector **WRP2**

- Right angle etalon **REW**

For both methods the optional elements are similar:

- USB cable

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- Manual Strobe

- Magnetic holder **UM2**

- Tripod stand

- Air temperature sensor

- Base temperature sensor
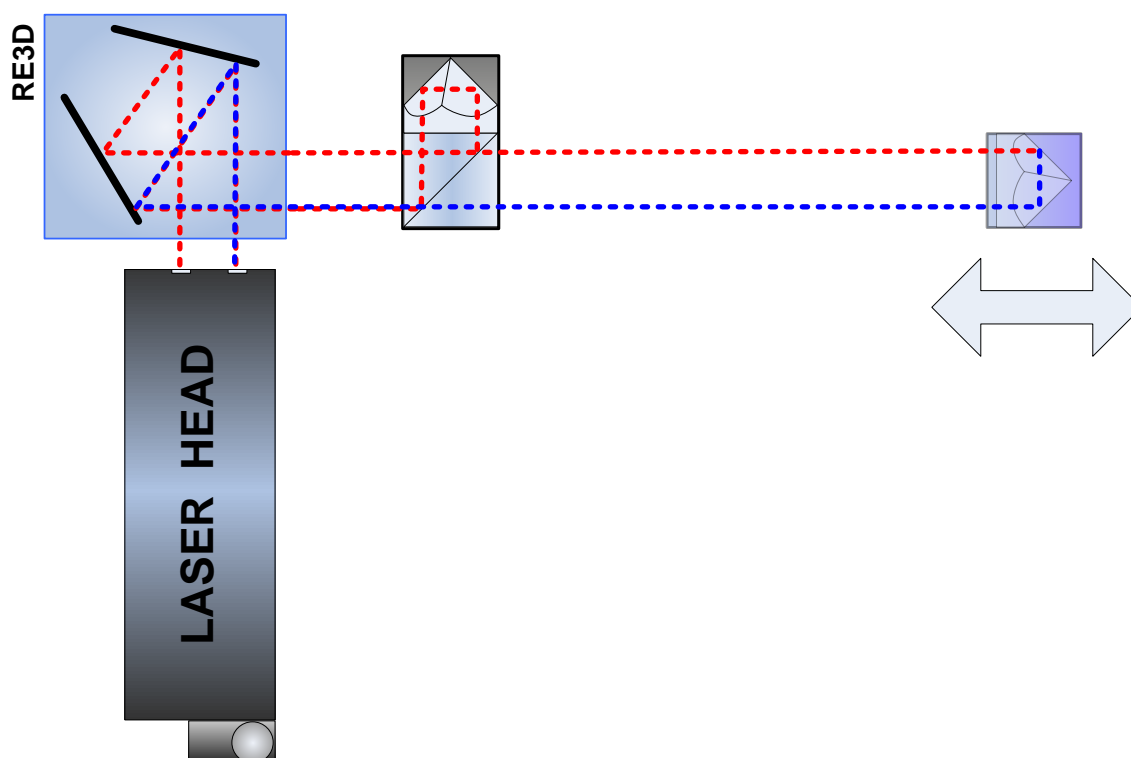
FIG.11.2A. OPTICAL PATH SET UP FOR 3D PARALLELISM MEASUREMENTS-
SCHEMATIC FOR AXIS 1.

Parallelism measurements based on the 3D method require optical elements IL1 and RL1 to be aligned along laser beam as shown in the figures 11.2A and 11.2B. The element RL1 should be moved. The beam should be directed to the perpendicular axis with the use of the right angle etalon RE3D.

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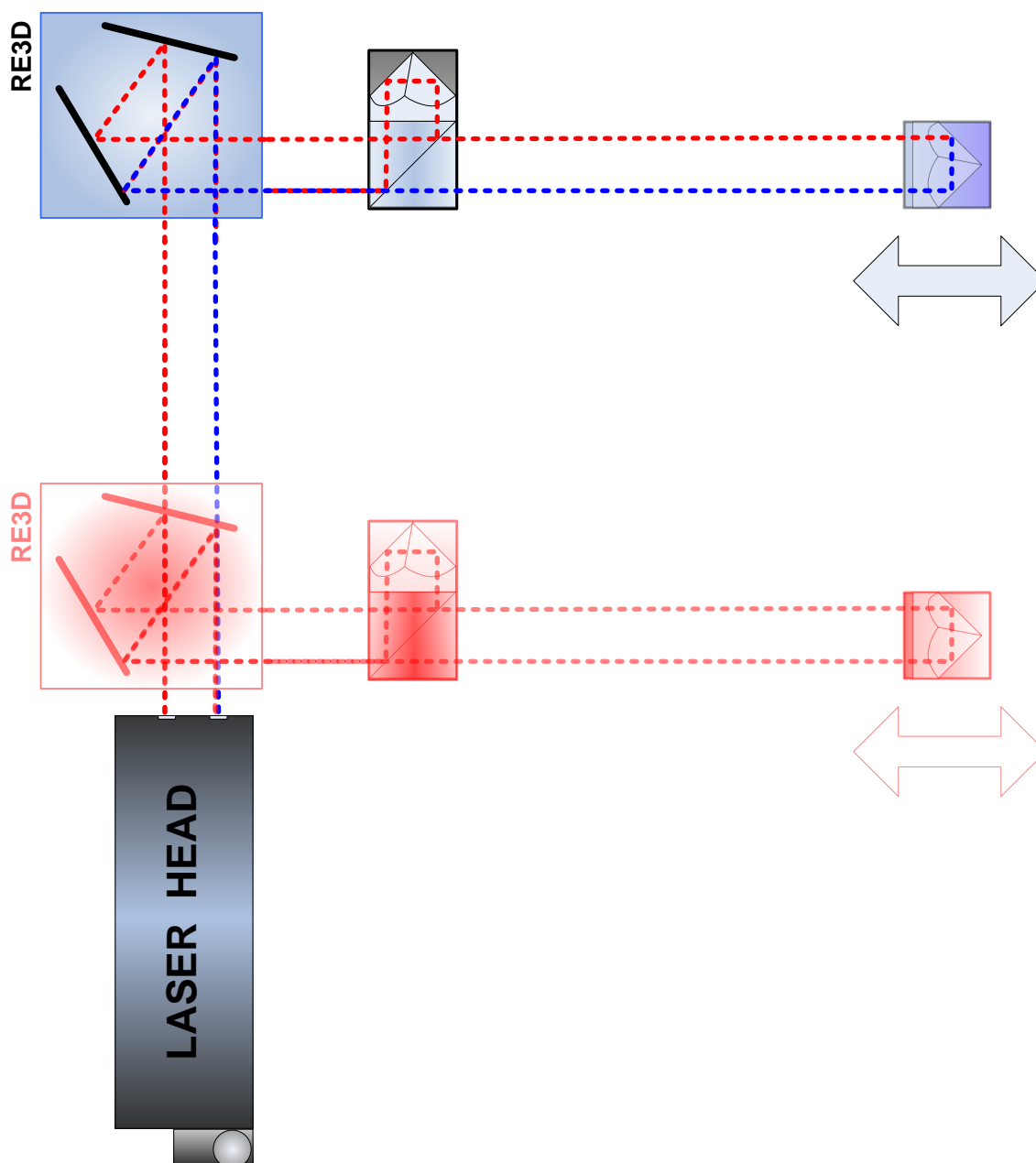
FIG.11.2B. OPTICAL PATH SET UP FOR 3D PARALLELISM MEASUREMENTS-
SCHEMATIC FOR AXIS 2.

Wollaston parallelism measurements require optical elements WP2 and WRP2 to be aligned along laser beam as shown in the figure 11.3. The element WP2 should be moved

first along Axis 1 and then along Axis 2. No right angle prism is necessary for this measurement.
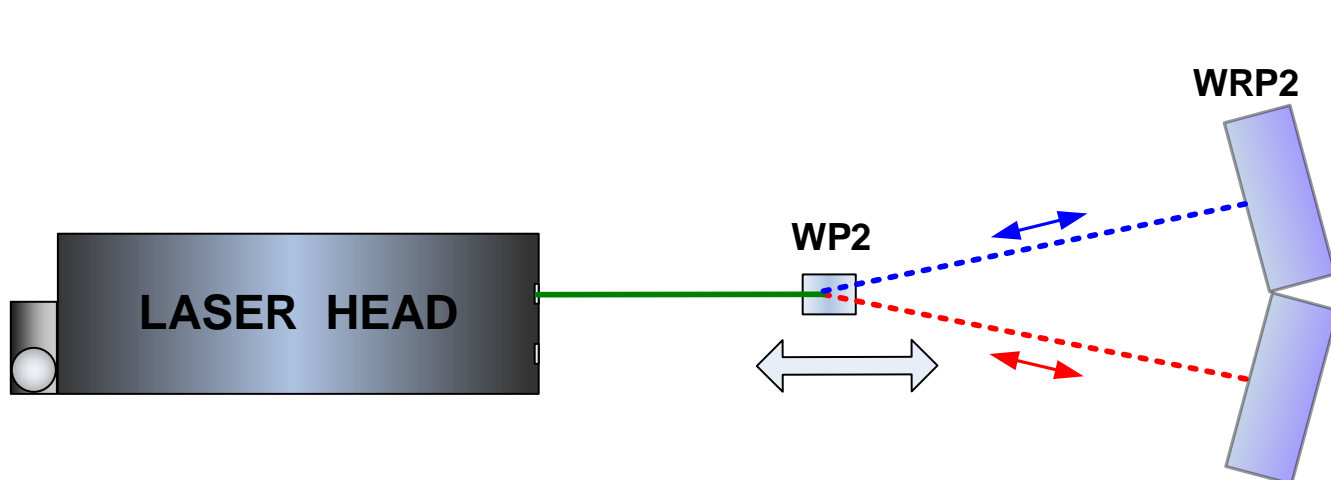
FIG.11.3. OPTICAL PATH SET UP FOR WOLLASTONE PARALLELISM MEASUREMENTS - SCHEMATICS

During parallelism measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

c. Software description

Parallelism is measured in the **Parallelism** option, chosen from the **Main Menu**. The *HPI Software* program window looks like it is shown in the Fig. 11.4. The Parallelism Measurement Summary window consists of three main parts:

- Display – presents measured straightness of axes and calculated parallelism;

- Schematic chart – allows changing the currently edited axis;

- Panel with buttons

FIG.11.4. PARALLELISM MEASUREMENT SUMMARY WINDOW

Measurement is started by the **Measurement** button and window shown in the figure 11.5 appears. In this window it is possible to change the measured axis and analyze the straightness results of each individual axis. The axis can be changed by clicking the proper axis on the axes chart or by choosing it from the *No. axis* pull down list.
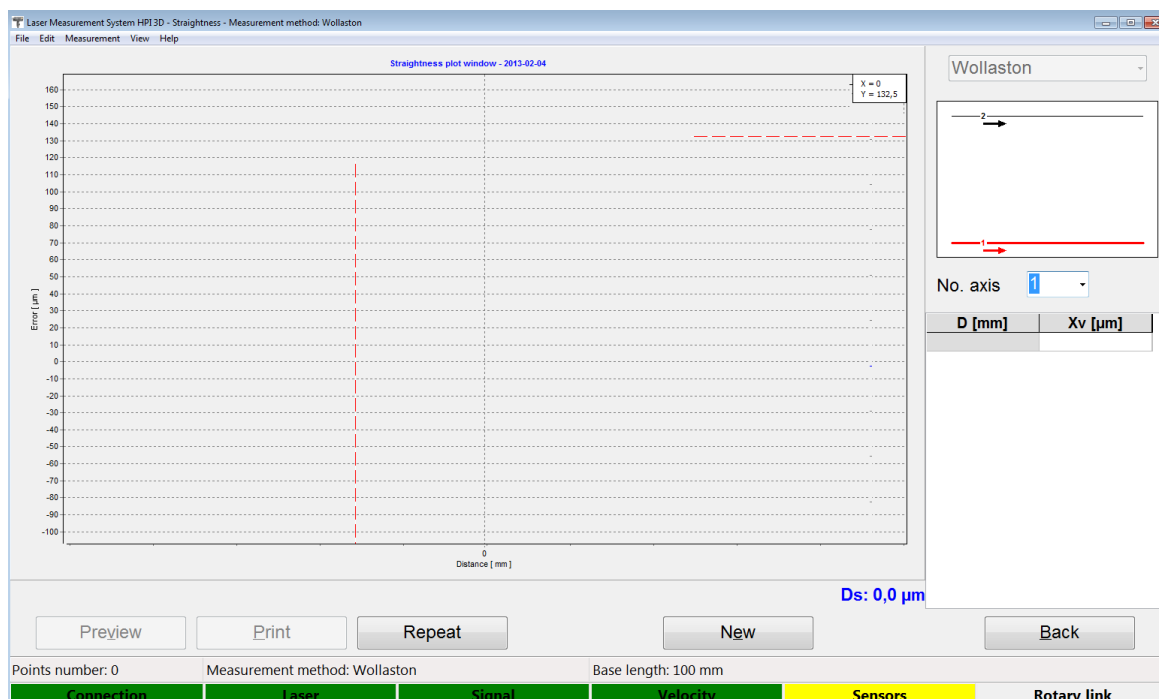
FIG.11.5. PARALLELISM MEASUREMENT WINDOW

The options available in the parallelism measurement window also enable to repeat the single straightness measurement (**Repeat** button) or print the results (of a single measurement) in the form of the Report (**Preview** or **Print** button).

The graph can be printed or saved to a file. Those commands can be found in **File** menu (i.e. Save, Save as, Print – see figure 11.6).
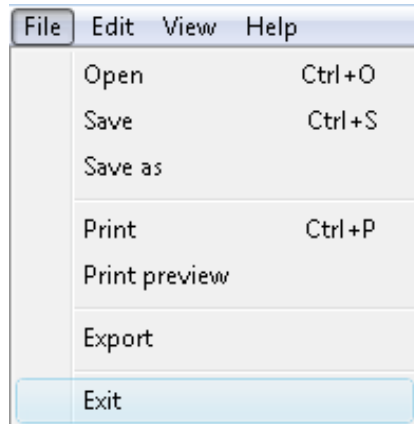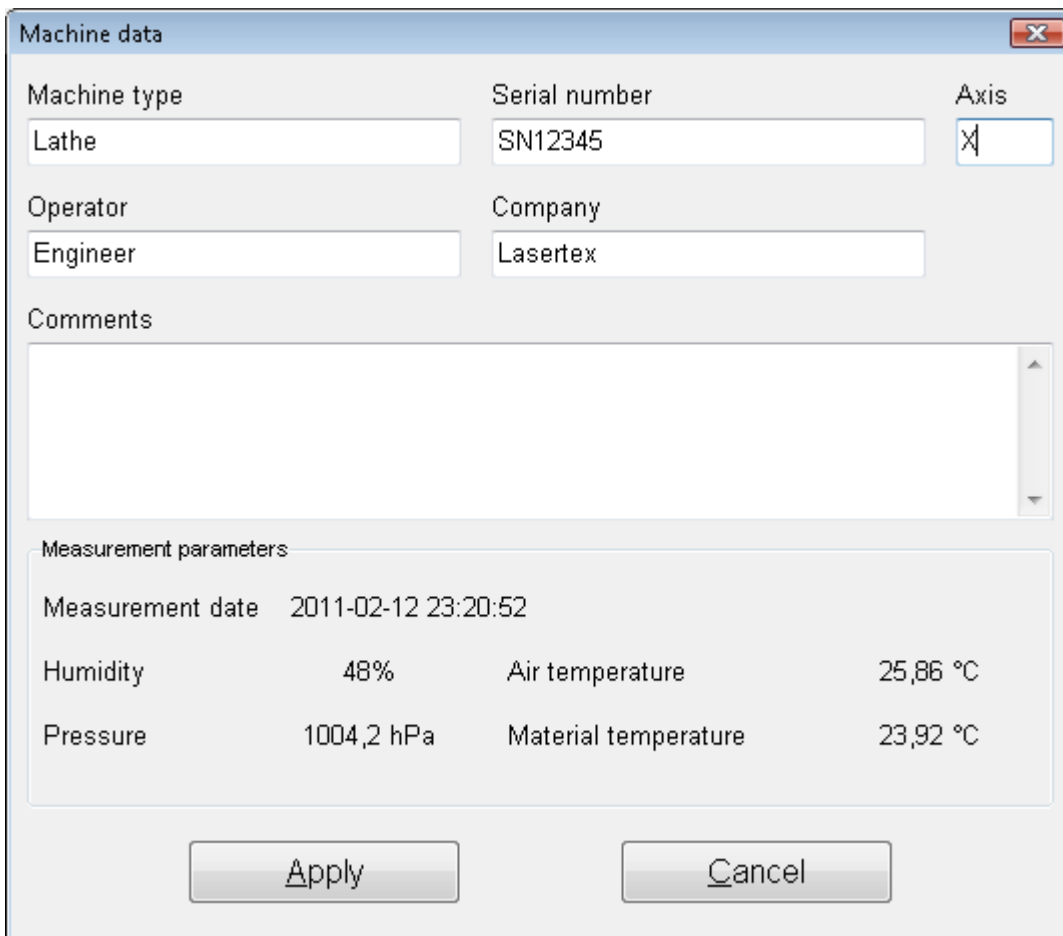
FIG.11.6. PARALLELISM PULL-DOWN MENU *FILE*

Before saving the file the program asks about changing machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator (see figure 11.7). Those values allow describing performed measurement for later analysis and they are also present on the printed report.

Measurement report can also be generated from obtained data, either by pressing *Print* or *Preview* on the measurement analysis window. The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.

It is also possible to copy the straightness graph to the clipboard and then paste it for example to a Word editor document. **Copy to clipboard** command is available from popup menu that appears after right-click on the area of the graph.

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FIG.11.7. MACHINE DATA WINDOW

The parallelism option can be configured in the **Configuration** window accessible both from the **Main Menu** or from pull down menu *Edit->Configuration* in the *Straightness* tab (figure 11.8).
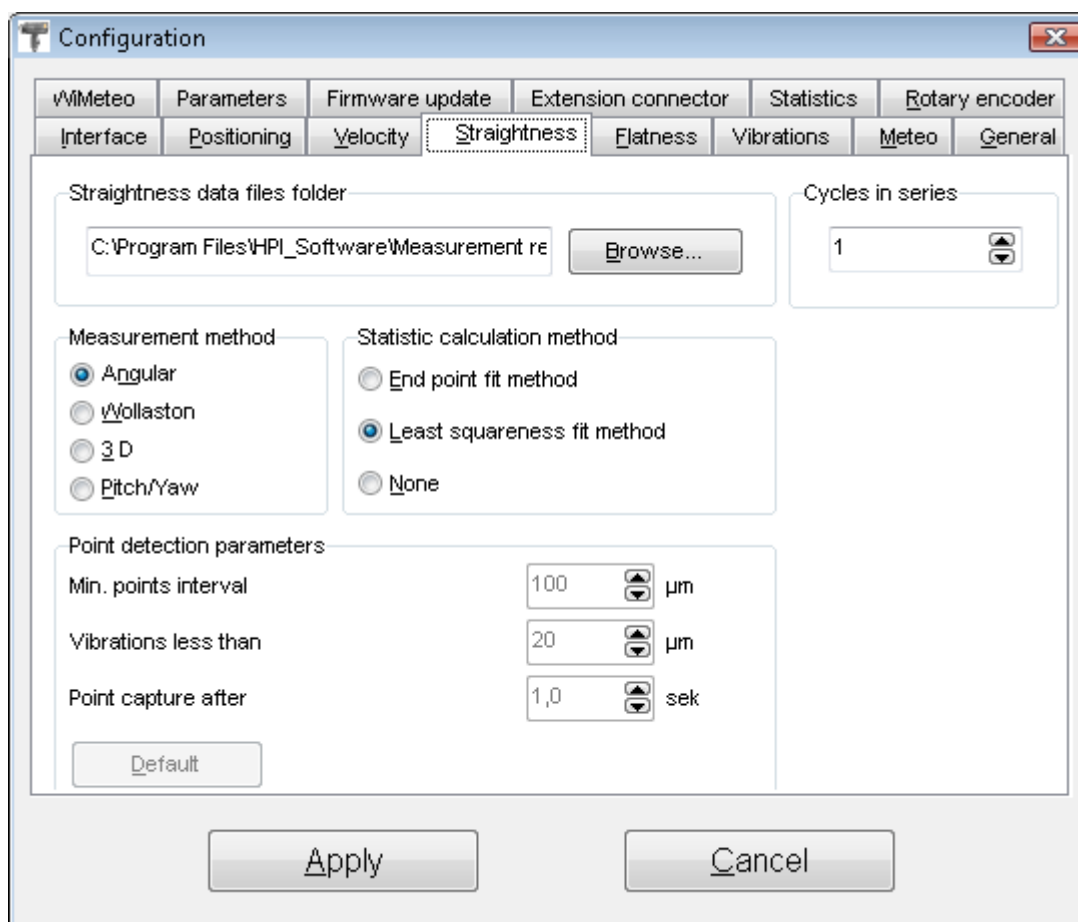
FIG.11.8. STRAIGHTNESS CONFIGURATION OPTIONS

The Straightness Configuration Tab allows configuration which is described in the *Measurement->Straightness* chapter with the difference that the Measurement methods used for parallelism measurements are Wollaston or 3D.

d. Alignment of optics for the parallelism measurements

The parallelism measurement consists of the straightness measurements for two axes. The measurement axis is selected on the measured surface as shown in the figure 10.9. In this figure there are also shown: directions of measurements and margins that have to be kept during measurements.
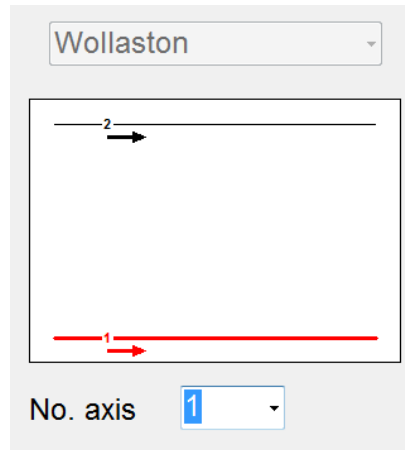
FIG.11.9. AXES CHOICE CHART

The measurements of deviations from straightness are made with linear or Wollaston optics as described in the Chapter *Measurements - Straightness*. Depending on the measurement axis, a different set of optical components is used and the alignment of the optical path is done in slightly different way.

The measurements **have to** be performed without changing the position of the laser head.

In both cases the measurements have to be performed in the directions pointed by arrows on the schematic graph on the main screen of parallelism measurement (fig. 11.9).

Configuration of optical components for 3D and Wollaston methods are shown in the figures 11.10 and 11.11.

11
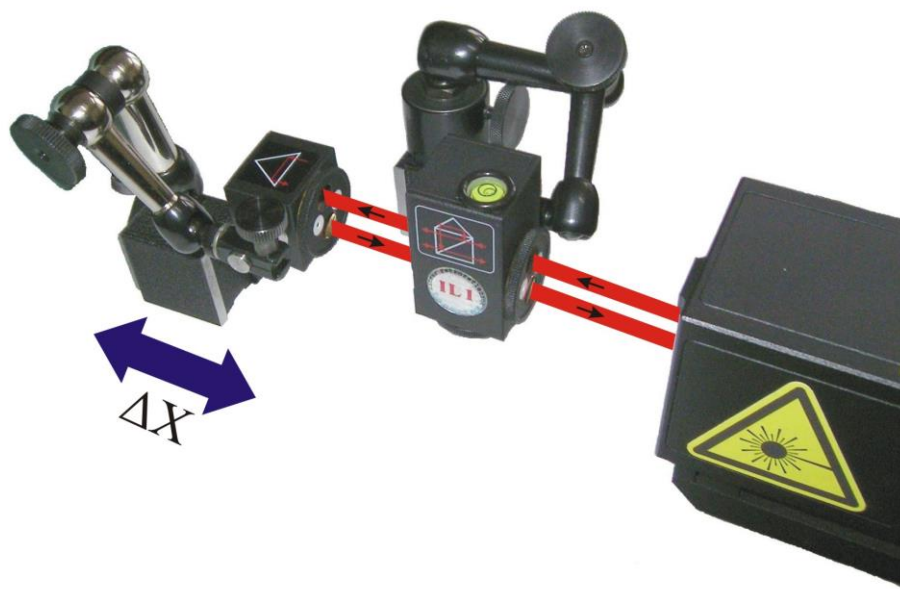
FIG.11.10 OPTICAL PATH SET UP FOR 3D STRAIGHTNESS MEASUREMENTS IN X AXIS

When the machine data is properly configured (*Edit-> Machine Data*), the *Measurement* button should be pressed. Next step is a measurement axis selection (fig. 11.9) and the optical path should be adjusted (see figures 11.10.and 11.11). If the straightness of the first axis is measured the optical path should be realigned and the next axis should be selected in the software. If both axes are measured, Back button should be pressed. Obtained parallelism measurements summary (fig. 10.1) can be saved, printed or exported to a text file (*File->Save*, *File->Print* or *File->Export*).
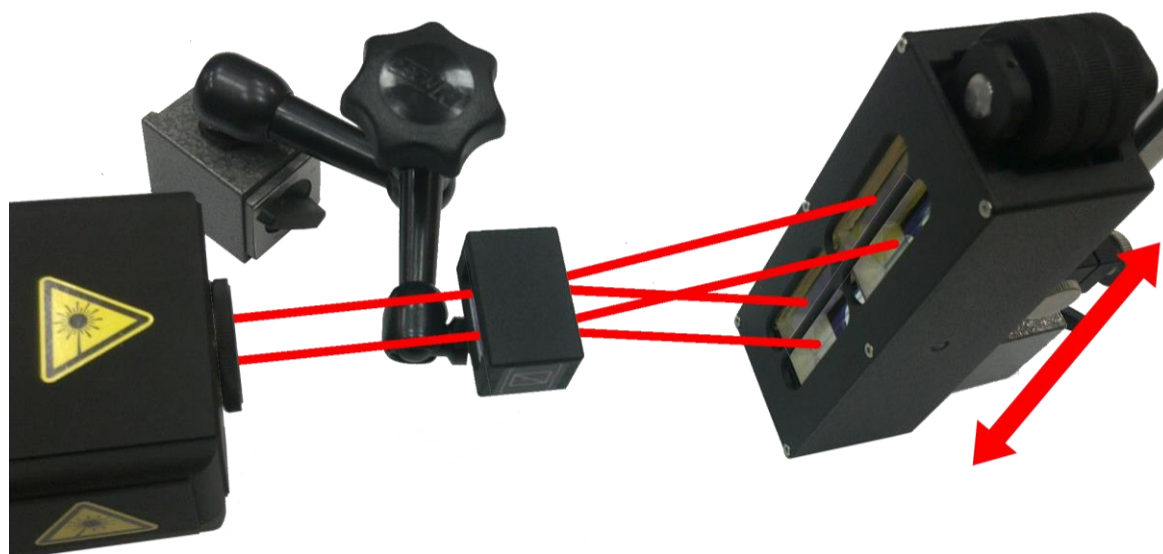
FIG.11.11 OPTICAL PATH SET UP FOR WOLLASTON STRAIGHTNESS MEASUREMENTS IN X AXIS

e. Measurement procedure

1. Set up the laser on the measured machine and align the first optical path.

2. Start the HPI Software and select Parallelism option.

3. Press Measurement button on the Parallelism summary screen.

4. Choose the proper axis on the axis choice chart and press Start, New or Repeat button.

5. Move the **RL1** or **WRP2** to the next measurement point.

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6. Continue measurements until all points on the path are measured

7. Stop the measurement.

8. Realign the optical path to the perpendicular axis and repeat steps 4-7

9. When straightness of all axes is measured then the Back button should be pressed. The software returns to the Parallelism Summary screen – see figure 11.1

10. For 3D measurement type the correct axes (Vertical or Horizontal) should be chosen for comparison.

In order to make the measurement in the manual capture mode, the *Measurement->Manual point capture* should be selected. The measurement begins by pressing **Start/New/Repeat**. Measurement points can be captured by the *Space* key from the computer keyboard, *Point capture* button on the panel, or by the remote Strobe button. If the last point is captured, the **Stop** button should be pressed.

Measurement report can also be generated from obtained data, either by pressing Print or Preview on the measurement analysis window. The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.

12. MEASUREMENTS - VIBRATION

12

a. General Description

Vibration measurements are performed with the use of linear optics. This measurement can be used, for example, for characterization of motor movement. The laser measurement system HPI-3D is capable of detecting machine vibrations in the frequency range from 0 to 500 Hz in Bluetooth mode and 0 to 50 kHz in USB mode. The sensitivity of measurements is 100pm.

The System allows measuring vibration in different units in single shot and continuous mode. The parameters of the measurement can be set in the *Configuration->Vibration* option.

b. Measurement Setup

For velocity measurements linear optics should be used. Necessary components are (see also figures 12.1 to 12.4):

- Laser head
- Power Supply
- Linear interferometer **IL1**
- Linear retro-reflector **RL1**

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Optional elements are:

- USB cable
- Magnetic holder **UM2**
- Tripod stand
- Base temperature sensor
- Air temperature sensor

Vibration measurements require optical elements IL1 and RL1 to be aligned along laser beam as shown in the figure 12.1. The laser measures the difference of vibrations of both optical elements (i.e. IL1 and RL1).

During vibration measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

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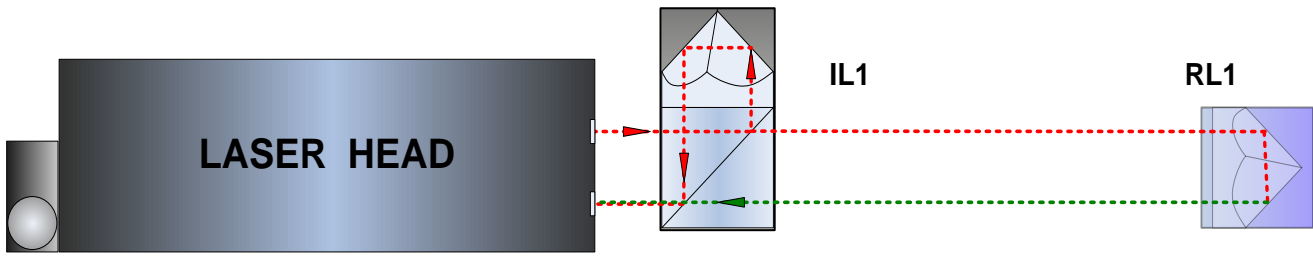
FIG.12.1 OPTICAL PATH SET UP FOR VIBRATION MEASUREMENTS-SCHEMATIC

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Vibration measurements can be performed not only along the laser beam (as shown in the figures 12.1 and 12.2) but also in directions perpendicular to the laser beam. These configurations are shown in the figures 12.3 and 12.4. In those two configurations only the retro-reflector RL1 can be moved.
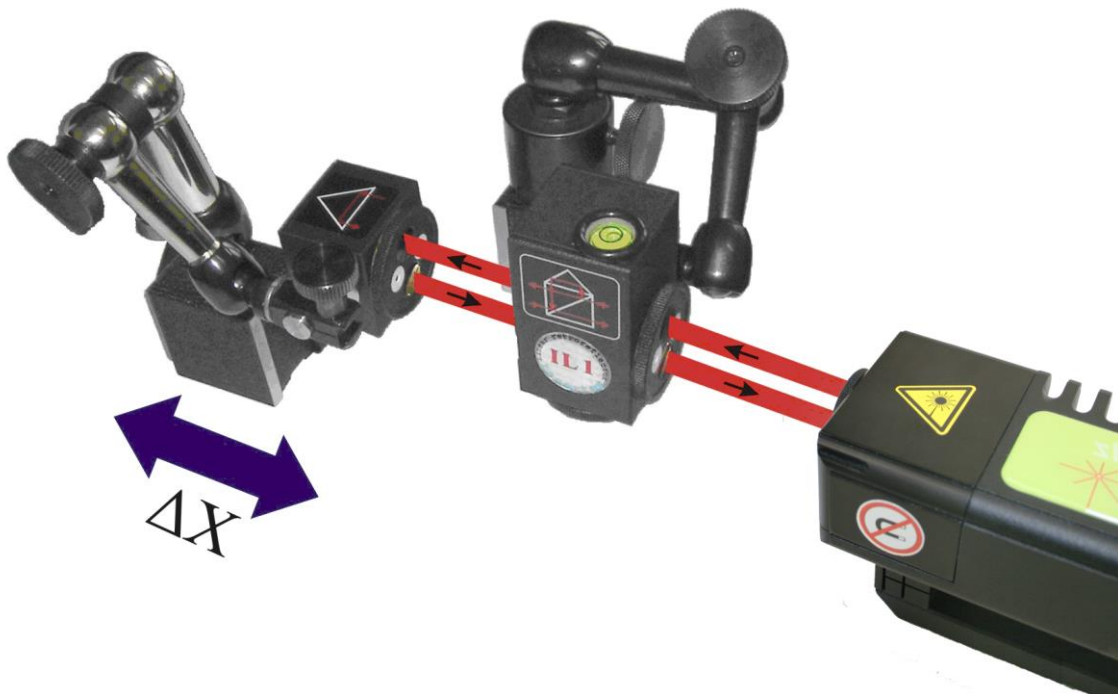
FIG.12.2 OPTICAL PATH SET UP FOR VIBRATION MEASUREMENTS IN X AXIS
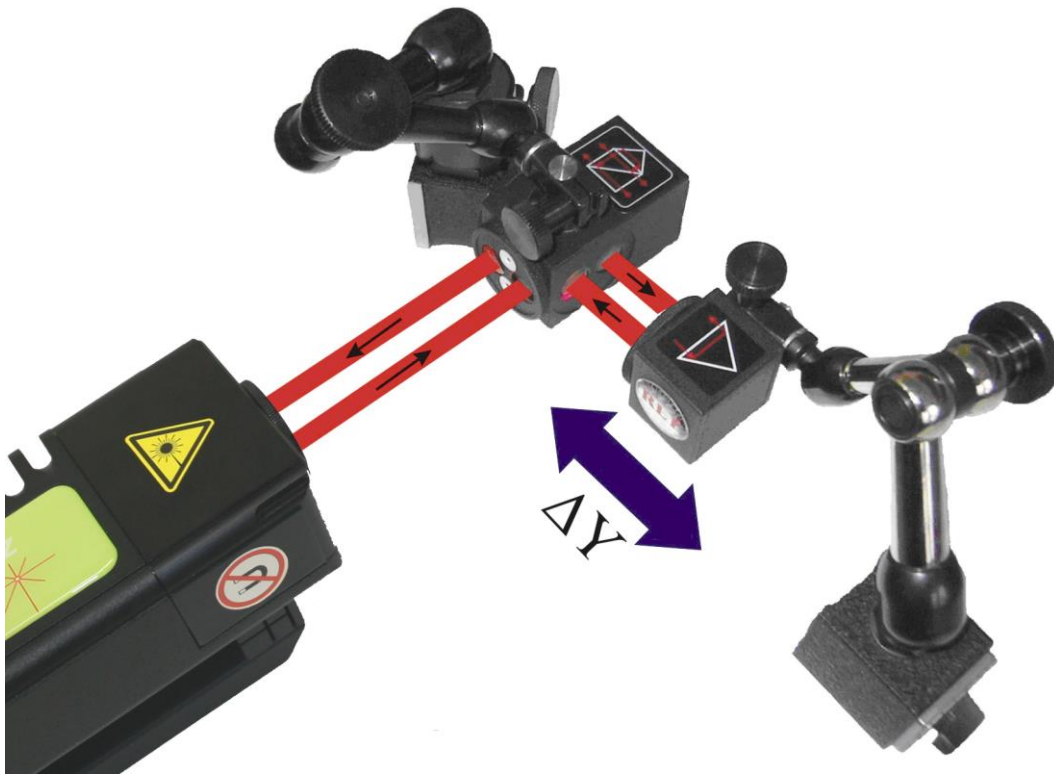
12

FIG.12.3. OPTICAL PATH SET UP FOR VIBRATION MEASUREMENTS IN Y
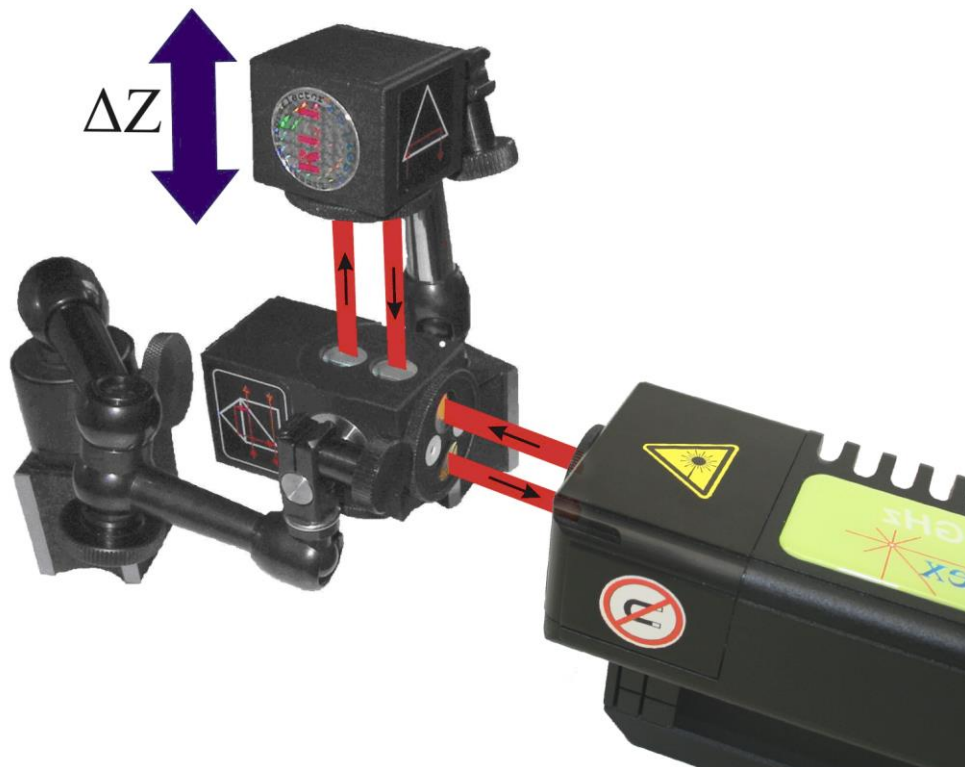
AXIS

FIG.12.4. OPTICAL PATH SET UP FOR VIBRATION MEASUREMENTS IN Z

AXIS

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c. Software description

Vibrations are measured in the **Vibration** option, chosen from the **Main Menu**. The HPI-3D program window looks like it is shown in the Fig. 12.5. The window consists of four main parts:

- Display – presents measurement signal level and percent of gathered samples;

- Two plots – upper presents gathered distance, velocity, or acceleration data, lower the Fourier Transformation (FFT) of the upper plot;

- Measurement options;

- Panel with buttons.

12
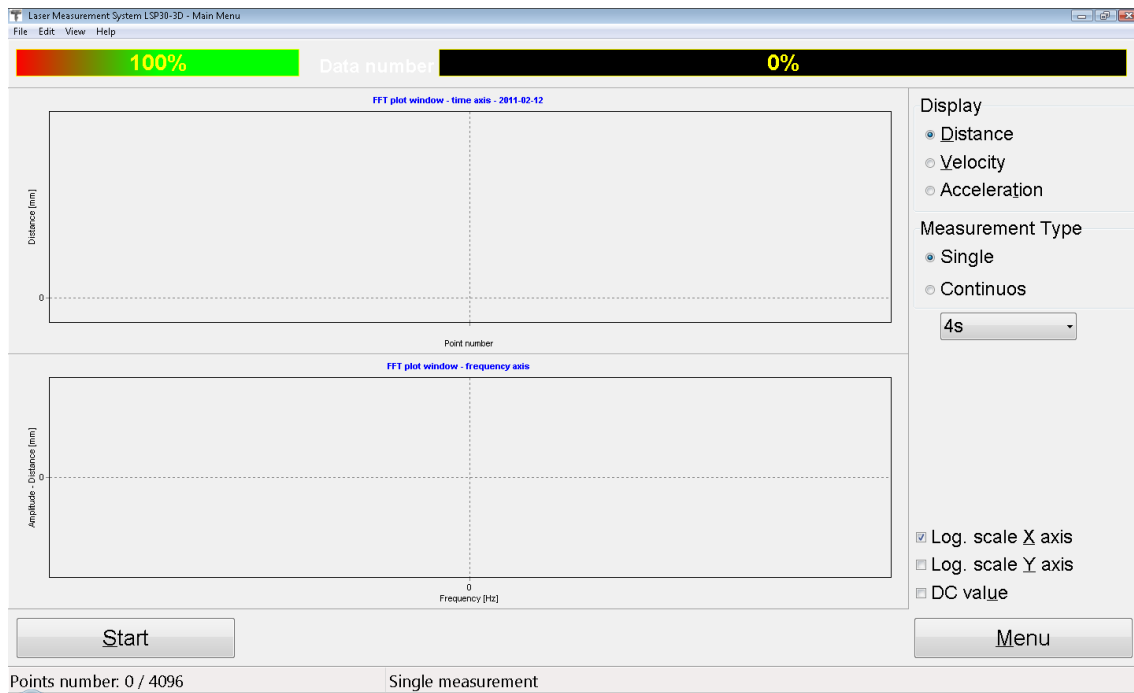
FIG.12.5. VIBRATION MEASUREMENT WINDOW

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Before starting the measurements the options located in the right panel should be set according to the current requirements. Radio buttons enable to select the type of input data, i.e. whether amplitude of Distance, Velocity or Acceleration is important. Pull-down lists are used to configure measurement duration for single cycle and to select averaging strength respectively. Measurement is started by the **Start** button. If *Continuous* option is selected, the measurement has to be finished by pressing the **Stop** button. During *Continuous* measurements the graph on the screen is constantly updated every measurement cycle.

Measurement result is presented on the time domain diagram and its FFT analysis on the frequency diagram (fig.12.8). The frequency diagram is configured (logarithmic scales for X and Y axes and DC offset elimination) by checkboxes located in the bottom right part of the window. The results can be saved, printed or exported (menu File).
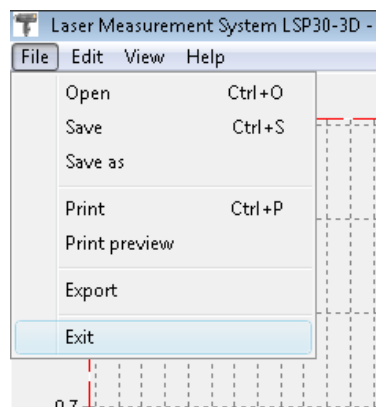
FIG.12.6. VIBRATION PULL-DOWN MENU *FILE*

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Before saving the file the program asks about changing machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator (see figure 12.7). Those values allow describing performed measurement for later analysis and they are also present on the printed report.

12

FIG.12.7. MACHINE DATA WINDOW

Measurement report can also be generated from obtained data, either by pressing *Print* or *Preview* on the measurement analysis window (fig. 12.8). The report can be

generated in the basic form where only the plots of the measured values and calculated frequency transformation are shown (fig. 12.9) or in the extended version, which contains also tables with measured data.
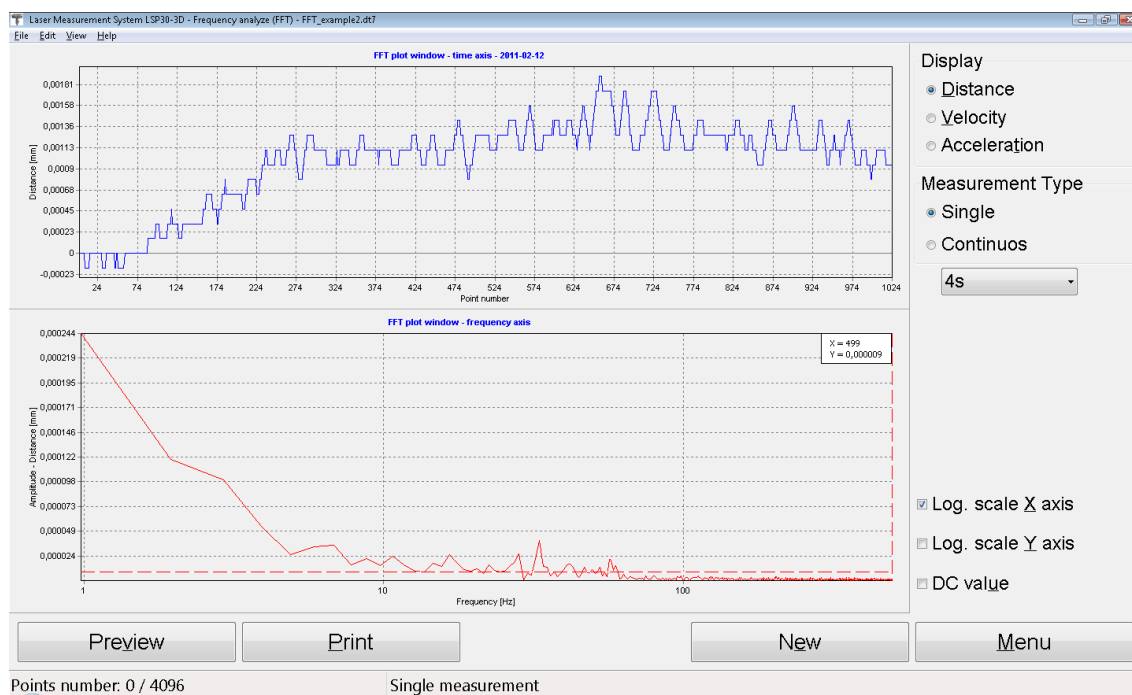
FIG.12.8. VIBRATION MEASURED DATA ANALYSIS WINDOW
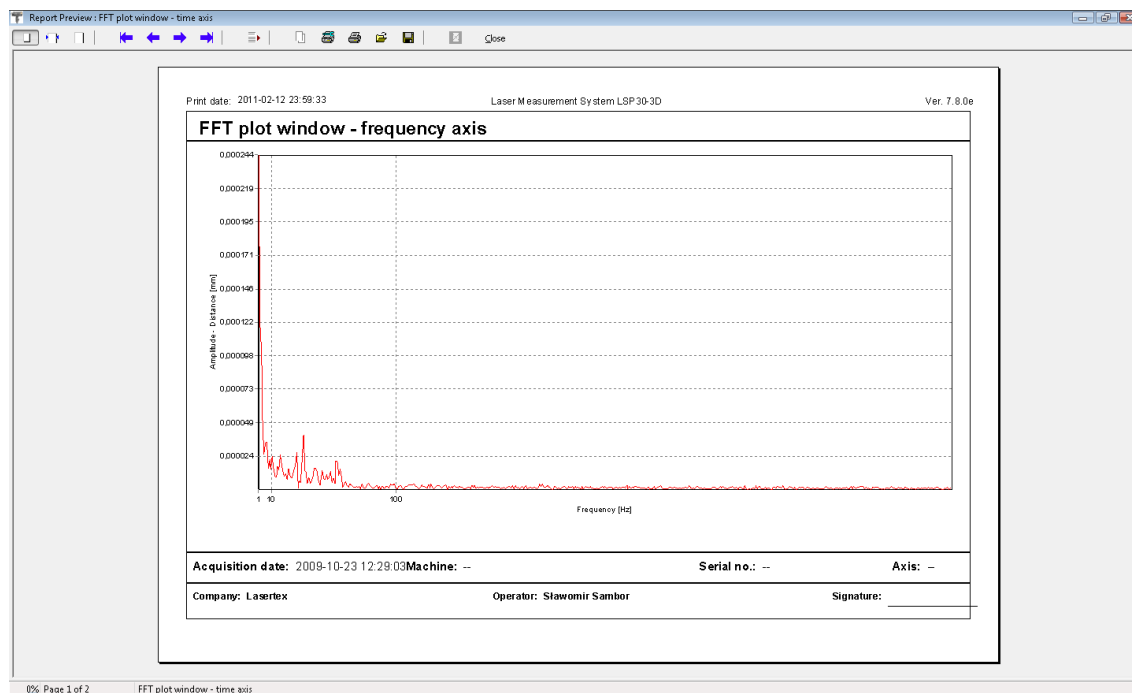
FIG.12.9. VIBRATION REPORT PREVIEW WINDOW (PAGE 1)

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It is also possible to copy the straightness graph to the clipboard and then paste it for example to a Word editor document. **Copy to clipboard** command is available from popup menu that appears after right-click on the area of the graph.

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d. Measurement procedure

1. Set up the laser on the measured machine and align optical path.
2. Start the HPI-3D software and select Vibration option.
3. Configure Vibration measurement.
4. Press Start button and run the machine.
5. In the continuous mode press Stop button; in the single-shot mode wait for the end of measurements
6. Save the results and/or print the measurement report.

To obtain correct results, a point where the retro-reflector is attached to the machine, has to be carefully chosen. If the point is chosen improperly, instead of a sought frequency *f,* a multiple frequencies *n*f* appear (where n=1,2,...) on the FFT chart. For that reason the retro-reflector

must not be used with the magnetic holder **UM2**. *Magnetic Base*, *Stainless Rod* (**SR1**), and *Holding Block* (**HB1**) should be used instead. It is worth to mention that the system measures the vibration only in the axis of the optical path. Any vibrations in perpendicular axes do not influence the measurement (see fig.12.11).

12
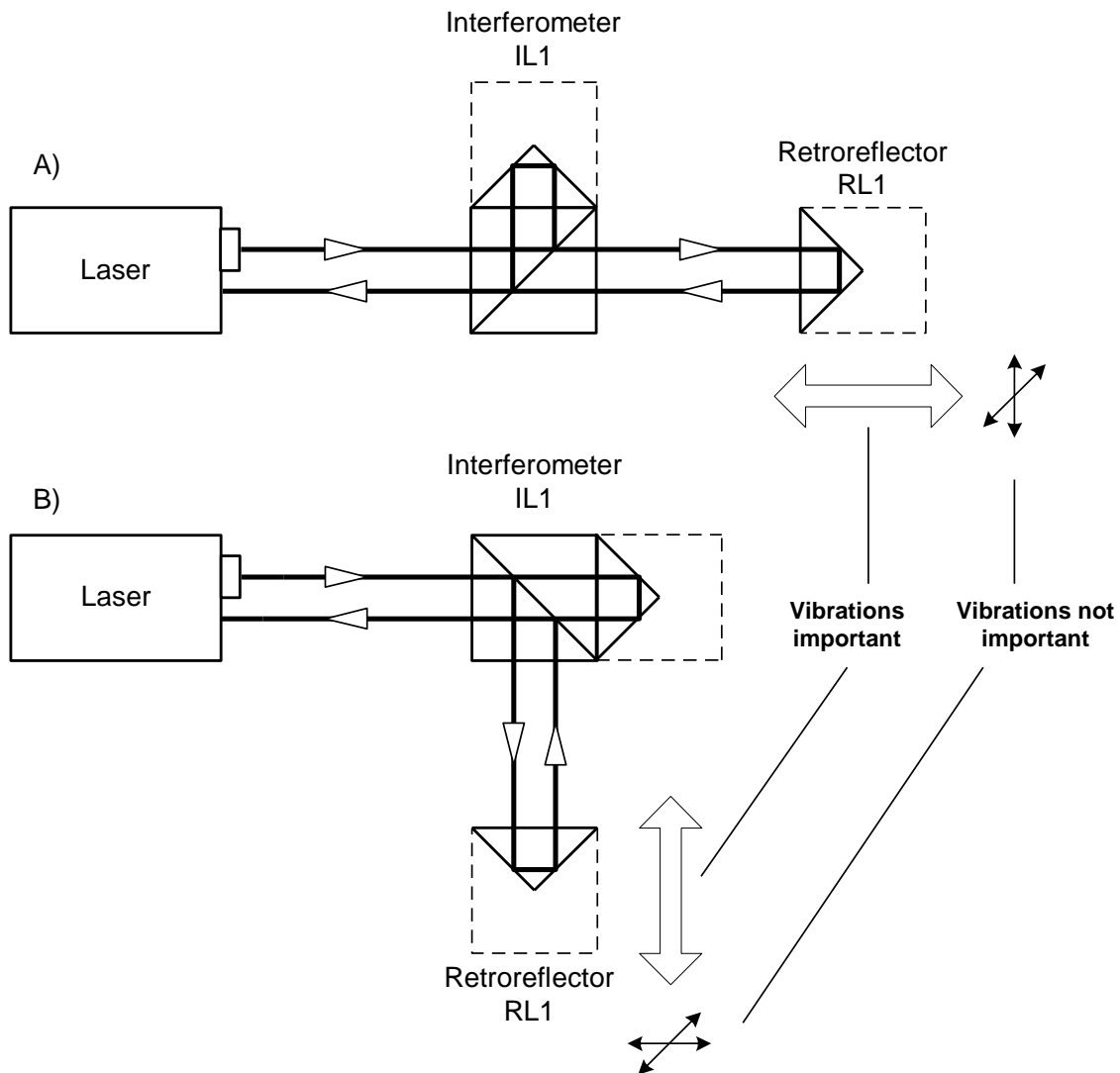
FIG.12.11. VIBRATION MEASUREMENT IN DIFFERENT AXES

13. MEASUREMENTS - DYNAMIC

13

a. General Description

Dynamic measurements are usually used for characterization of subtle machine movement. The laser measurement system HPI-3D is capable of characterizing the tested machine with up to 1000 samples per second in the Bluetooth mode and up to 100000 samples per second in the USB mode. In both modes the measurement resolution is 100pm. Dynamic measurements are performed with the use of linear optics, angular, or Wollaston optics.

The System enables to perform dynamic measurement of distance, velocity, acceleration, angle or straightness in different units..

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b. Measurement Setup

i. Dynamic measurements of distance, velocity or acceleration

For dynamic measurements of distance, velocity and acceleration the linear optics should be used. Necessary components are (see also figures 13.1 to 13.4):

- Laser head
- Power Supply
- Linear interferometer **IL1**
- Linear retro-reflector **RL1**

Optional elements are:

- USB cable
- Manual Strobe
- Magnetic holder **UM2**
- Tripod stand
- Base temperature sensor
- Air temperature sensor

Dynamic measurements of distance, velocity and acceleration require optical elements IL1 and RL1 to be aligned along laser beam as shown in the figure 13.1. The laser measures the difference of distance between optical elements (i.e. IL1 and RL1).

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During dynamic measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

FIG.13.1 OPTICAL PATH SET UP FOR DYNAMIC MEASUREMENTS OF DISTANCE, VELOCITY OR ACCELERATION – SCHEMATIC

13
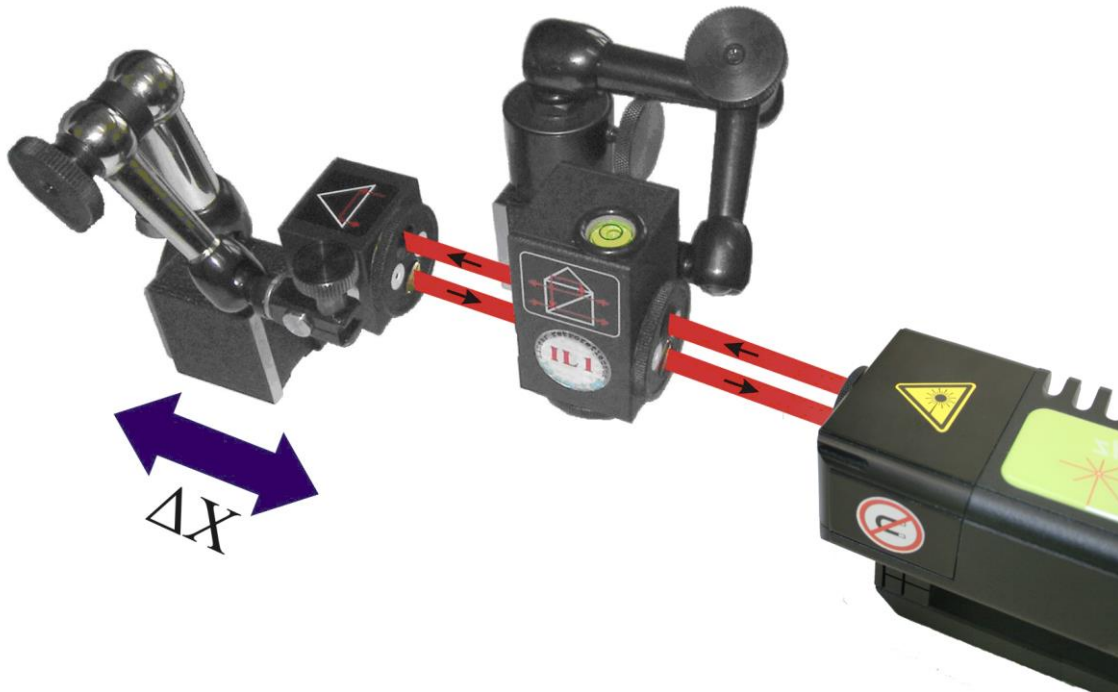
FIG.13.2 OPTICAL PATH SET UP FOR LINEAR DYNAMIC MEASUREMENTS IN X AXIS

Dynamic measurements can be performed not only along the laser beam (as shown in the figures 13.1 and 13.2)

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but also in directions perpendicular to the laser beam. These configurations are shown in the figures 13.3 and 13.4. In those two configurations only the retro-reflector RL1 can be moved.

FIG.13.3. OPTICAL PATH SET UP FOR LINEAR DYNAMIC MEASUREMENTS IN Y AXIS

FIG.13.4. OPTICAL PATH SET UP FOR LINEAR DYNAMIC MEASUREMENTS IN Z AXIS

ii. Dynamic measurements of angle

For dynamic measurements of angle the angular optics should be used. Necessary components are:

- Laser Head
- Power Supply
- Angular Interferometer **IK1**
- Angular Retro-reflector **RK1**

Optional elements are:

- USB cable
- Manual Strobe

- Magnetic holder **UM2**

- Tripod stand

- Air temperature sensor

- Base temperature sensor

Dynamic measurements of angle require optical elements IK1 and RK1 to be aligned along laser beam as shown in the figure 13.5. Each of the elements can be moved.

During Angular straightness measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.
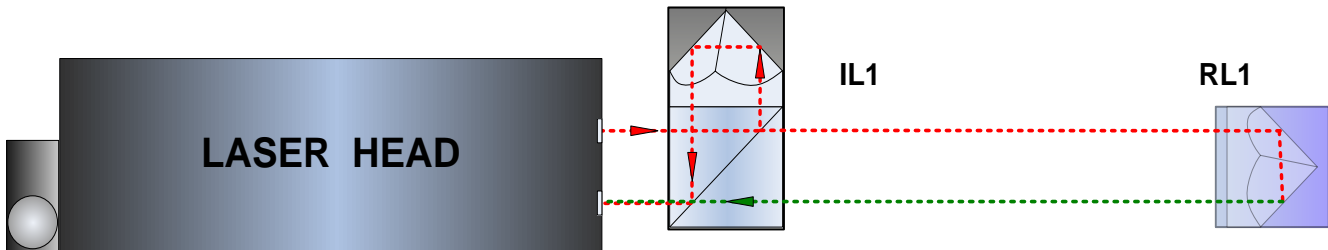
13
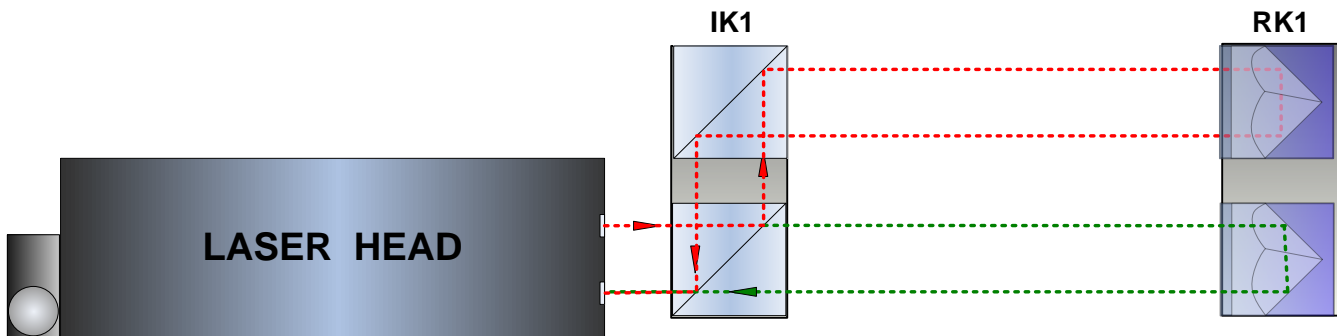
FIG.13.5 OPTICAL PATH SET UP FOR ANGULAR DYNAMIC MEASUREMENTS - SCHEMATIC

Angular straightness measurements can be performed not only along the laser beam (as shown in the figures 13.5 and 13.6) but also in directions perpendicular to the laser beam. These configurations are shown in the figures 13.7 and 13.8. In those two configurations only the retro-reflector RK1 can be moved.
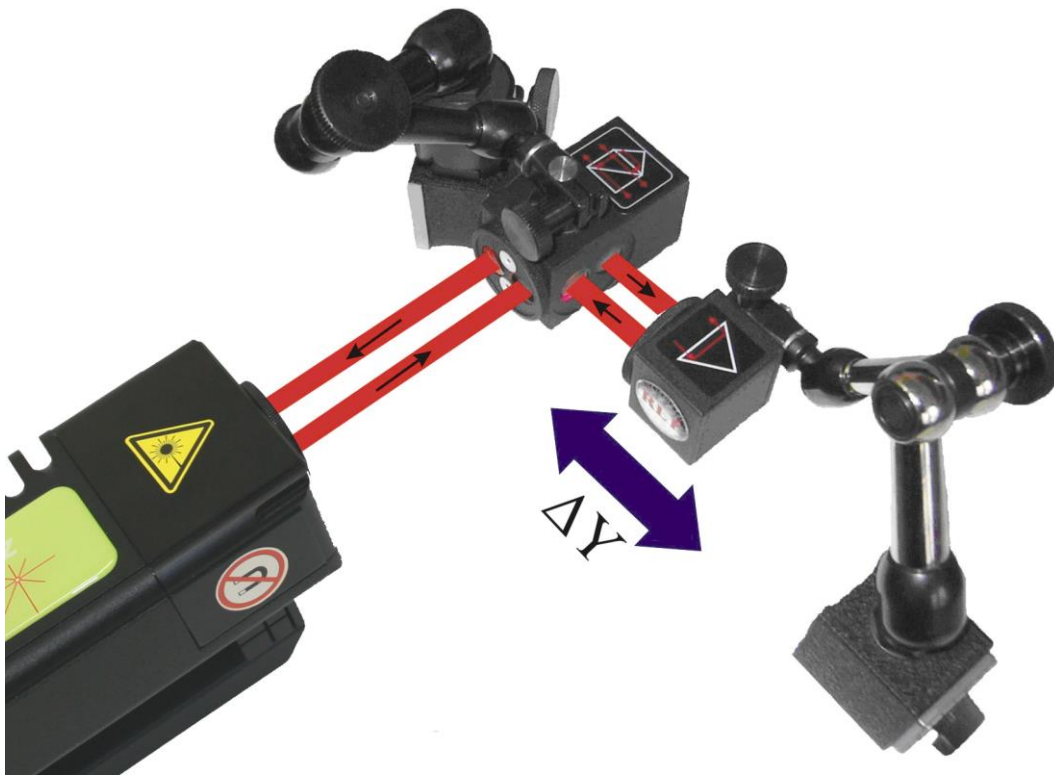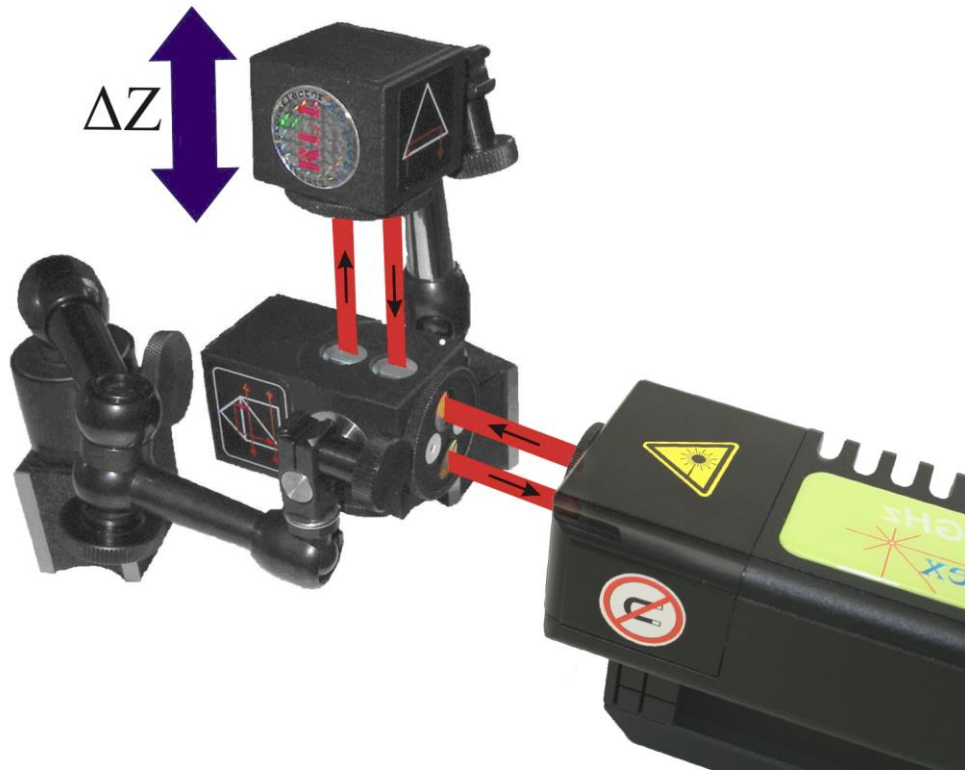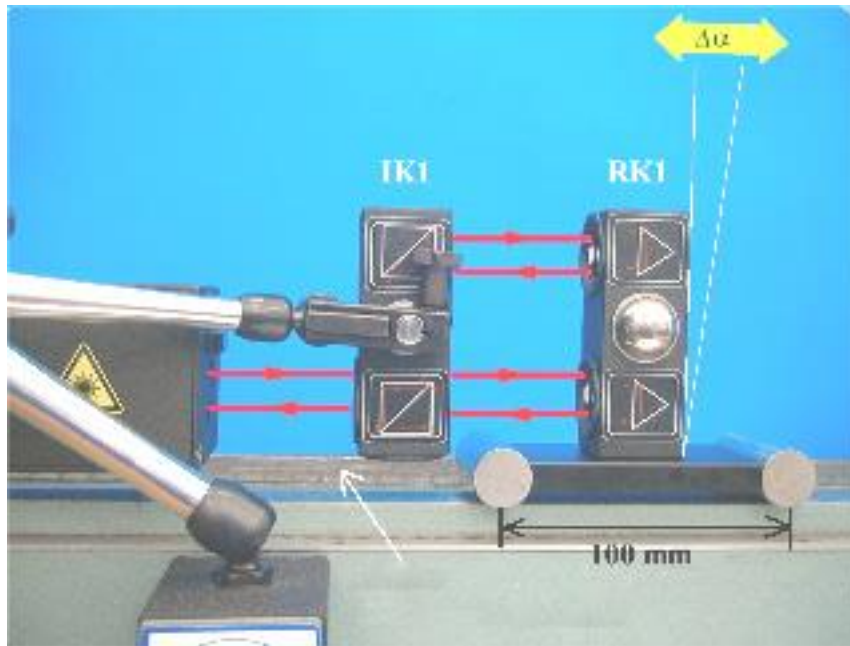
FIG.13.6. OPTICAL PATH SET UP FOR ANGULAR DYNAMIC MEASUREMENTS IN X AXIS
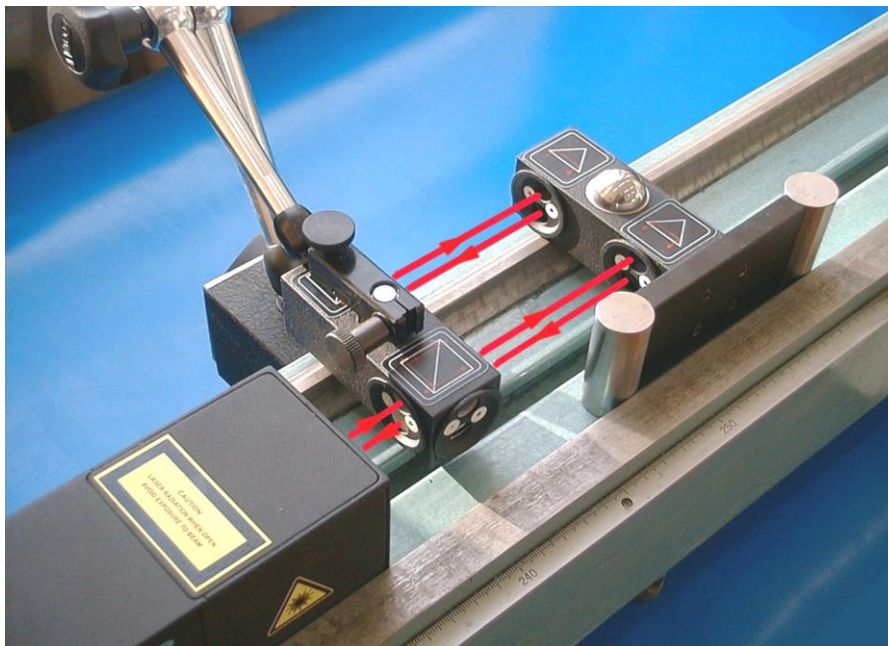
FIG.13.7. OPTICAL PATH SET UP FOR ANGULAR DYNAMIC MEASUREMENTS IN Y AXIS
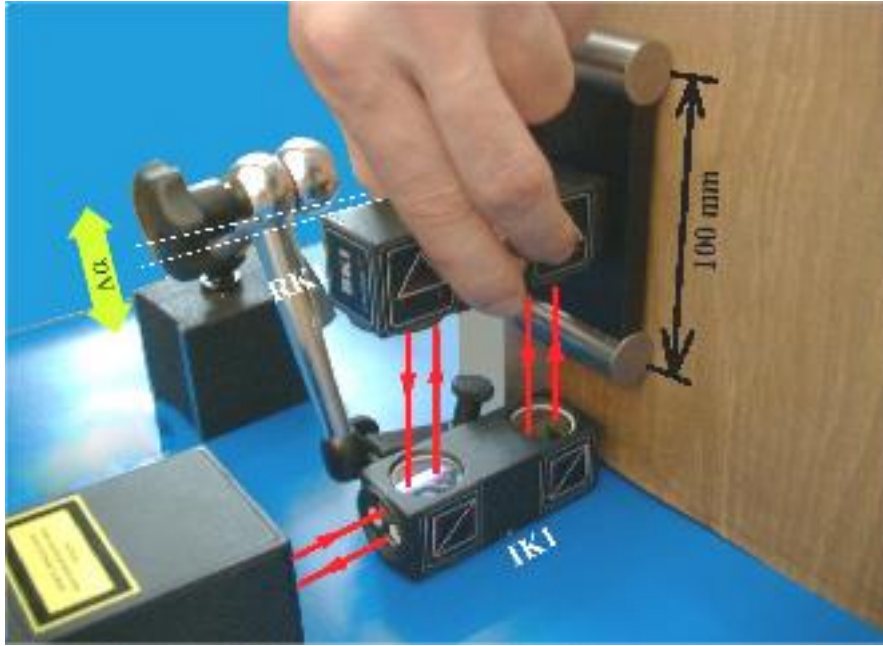
FIG.13.8. OPTICAL PATH SET UP FOR ANGULAR DYNAMIC
MEASUREMENTS IN Z AXIS

iii. Dynamic measurements of straightness (Wollaston)

For dynamic measurements of straightness the Wollaston optics should be used. Necessary components are:

- Laser Head
- Power Supply
- Wollaston prism **WP2**
- Wollaston retro-reflector **WRP2**

Optional elements are:

- USB cable
- Manual Strobe
- Magnetic holder **UM2**
- Tripod stand

- Air temperature sensor

- Base temperature sensor

Dynamic straightness measurements require optical elements WP2 and WRP2 to be aligned along laser beam as shown in the figure 13.9. Each of the elements can be moved.

During dynamic straightness measurements the usage of the air temperature sensor is recommended. Base temperature sensors do not have to be used.

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WRP2

WP2

LASER HEAD

FIG.13.9. OPTICAL PATH SET UP FOR DYNAMIC STRAIGHTNESS MEASUREMENTS- SCHEMATIC

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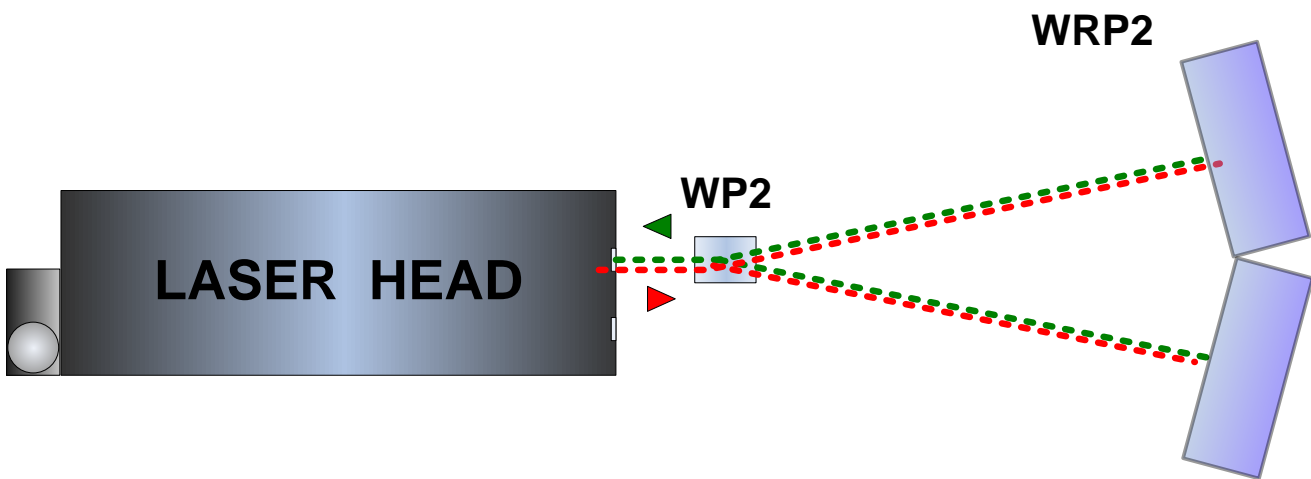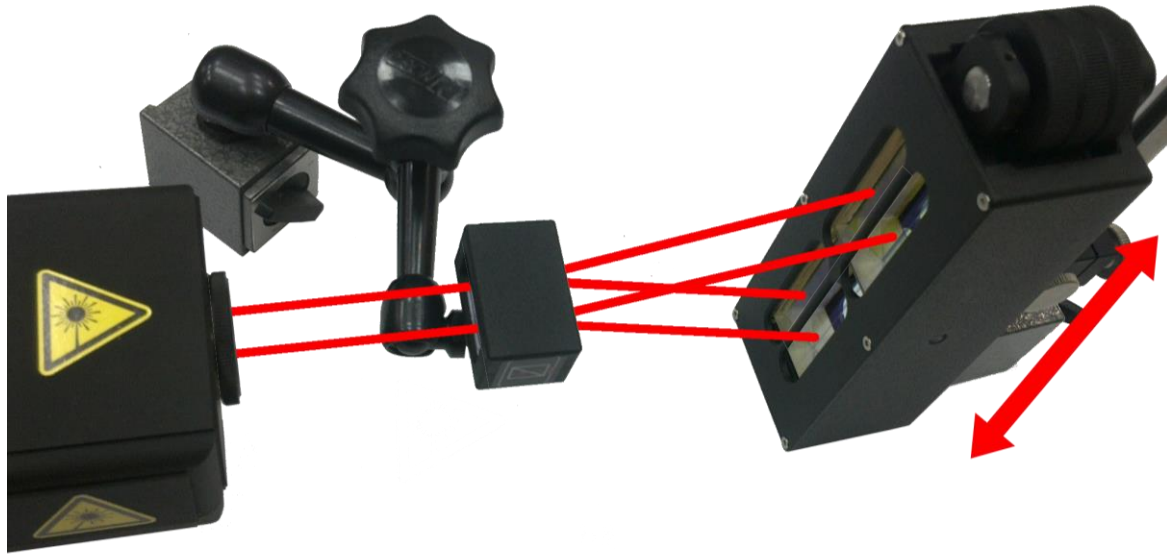
FIG.13.10. OPTICAL PATH SET UP FOR DYNAMIC STRAIGHTNESS
MEASUREMENTS IN X AXIS

Dynamic straightness measurements can be performed in two configurations – horizontal X (figure 13.10) or vertical Z (figure 13.11). In the configuration X only the straightness of path in the X axis is measured. The same situation is with the Z setup.

FIG.13.11. OPTICAL PATH SET UP FOR DYNAMIC STRAIGHTNESS MEASUREMENTS IN Z AXIS

c. Software description

All types of dynamic measurements are performed in the **Dynamic** option, chosen from the **Main Menu**. The HPI-3D program window looks like it is shown in the Fig. 13.12. The window consists of four main parts:

- Display – presents measurement signal level and percent of gathered samples;
- The main plots – presents gathered distance, velocity, acceleration, angle, or straightness (Wollaston) data;
- Configuration panel (right panel);

- Panel with buttons (bottom panel).

FIG.13.12. DYNAMIC MEASUREMENT WINDOW

Before the measurement is started, the options in the right panel should be set according to current requirements. The **Averaging** has four available options that limit the maximum frequency of the measured movement to: 50 kHz in *0s*, 50Hz in *0.1s*, and 5Hz in *1s* and 0.5Hz in *10s* mode. The **Sample Rate** button is used to set the sampling frequency. The maximum value over USB connection is 100 kHz and 1 kHz over Bluetooth connection. For both connection types the minimum sample rate value is 50 Hz. If, for some reasons, slower sample rate is necessary, then the measurements should be performed in the *Velocity* option.

The **Measurement time** is used for setting the total measurement time in seconds. The **Delay time** option defines the time that will elapse between pressing the **Start** button and the actual start of the measurements. The **Threshold** box allows setting the minimum value of movement in nm units that will trigger the measurements. Both **Threshold** and **Delay time** can be used simultaneously: if the registered movement value exceeds the value set as threshold, the delay time counter starts counting down to 0. Only when the counter finishes decrementing, the acquisition is started.

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Choosing the **DC Block** option causes switching on the high pass digital filter in the path. This option can be used for example to eliminate thermal expansion effects from the measurement.

Measurement is started by the **Start** button. During measurements the data are registered to the buffer. They are displayed after the measurement is finished (i.e. after **Measurement time** elapses) or after the user breaks the measurements (by the **Stop** button).

When both the measurement and the transmission are completed, the measurement results are presented on the time diagram (fig.13.15). The results can be saved, printed or exported (menu File). With the use of radio buttons the type of input data may be chosen: Distance, Velocity or Acceleration, Angle or Straightness (Wollaston).

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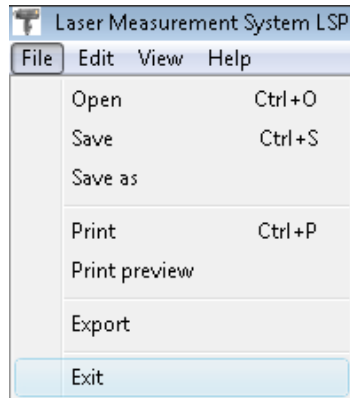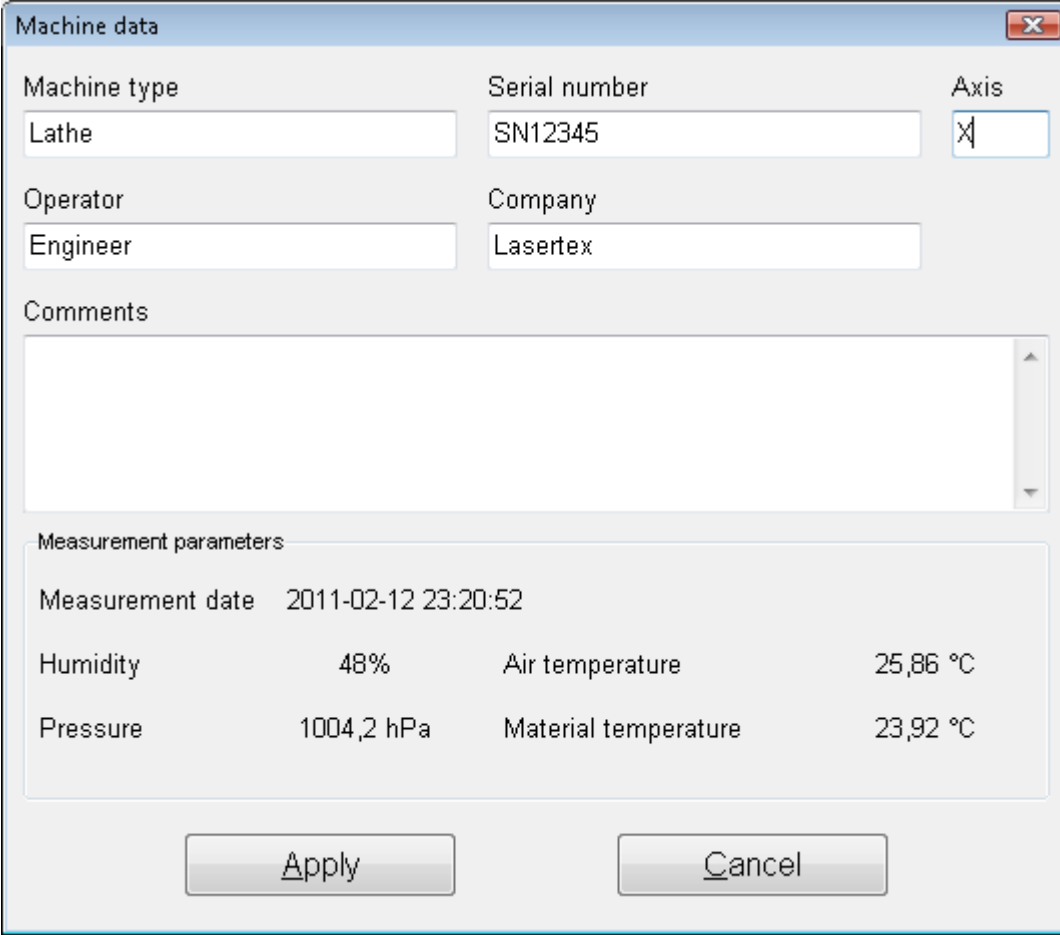
FIG.13.13. DYNAMIC PULL-DOWN MENU *FILE*

Before saving the file the program asks about changing machine data (option available from pull-down menu *Edit->Machine data*), like machine type, machine serial number, measured axis or machine operator (see figure 13.14). Those values allow describing performed measurement for later analysis and they are also present on the printed report.

Measurement report can also be generated from obtained data, either by pressing *Print* or *Preview* on the measurement analysis window (fig. 13.15). The report can be generated in the basic form where only the plot of the measured values is shown or in the extended version, which contains tables with measured data.

FIG.13.14. MACHINE DATA WINDOW

It is also possible to copy the straightness graph to the clipboard and then paste it for example to a Word editor document. **Copy to clipboard** command is available from popup menu that appears after right-click on the area of the graph.

FIG.13.15. DYNAMIC DATA ANALYSIS WINDOW

d. Measurement procedure

1. Set up the laser on the measured machine and align optical path.
2. Start the HPI-3D software and select Dynamic option.
3. Configure Dynamic measurement.
4. Press Start button and run the machine.
5. Wait for the end of the measurements or press Stop button.
6. Save the results and/or print the measurement report.

14. MEASUREMENTS – ANGULAR POSITIONING

a. General Description

The angular positioning measurements are performed with the use of a Rotary Encoder (**Wally**). This measurement is used, for example, to characterize a movement quality of rotary axes or for very precise measurements of a rotation angle. The System measures angular positioning accuracy, repeatability and backlash by comparing the position to which the machine moves (i.e. the position displayed on the machine's readout) with the true position measured by the laser interferometer.

The laser measurement system HPI-3D together with the rotary encoder is capable of measuring any rotation angle with precision down to 1 arcsec. The System allows measuring angle in different units. The parameters of the

measurement can be set in the *Configuration->Rotary Encoder* option.

The Rotary System **Wally** is connected to the PC wirelessly. The measurements can be performed either when the Encoder is mounted exactly in the in the center of rotation of the measured axis (*in-axis* configuration) or outside the center of rotation (*off-axis* configuration).

b. Measurement Setup

For angular positioning measurements an angular optics together with rotary encoder should be used. Necessary components are (see also figure 14.1):

- Laser Head
- Power Supply
- Angular Interferometer **IK1**
- Air Temperature Sensor (TH sensor)
- Rotary System **RE1** with integrated RK1

Optional elements are:

- USB cable
- Manual Strobe
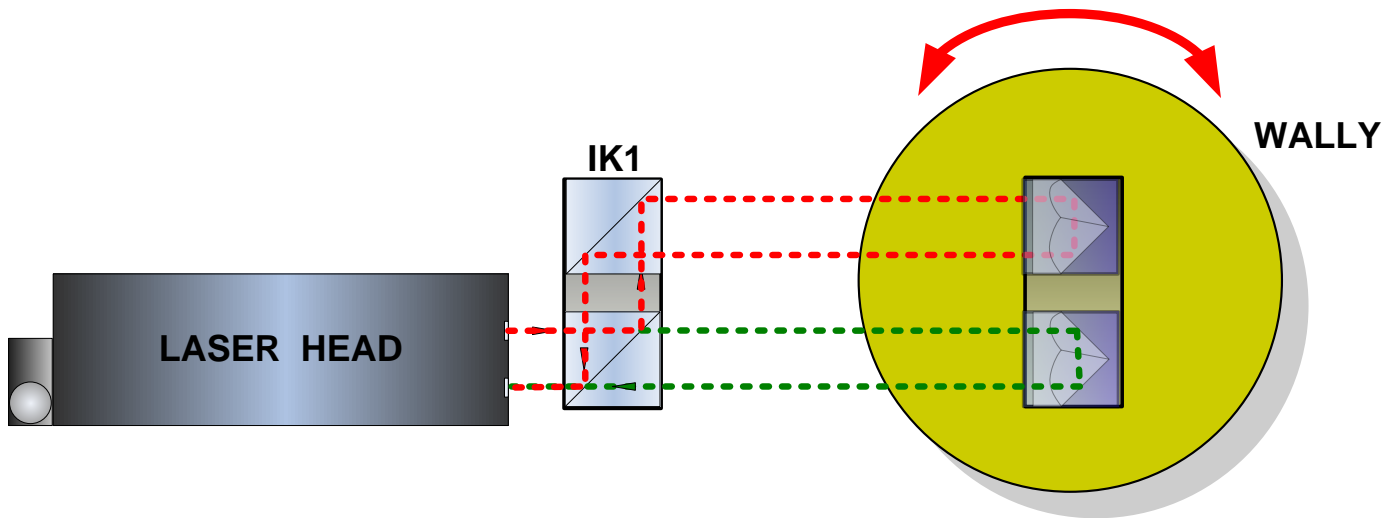- Magnetic holder **UM2**
- Tripod stand
- Base temperature sensor

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FIG.14.1. OPTICAL PATH SET UP FOR ROTARY MEASUREMENTS IN-AXIS - SCHEMATIC

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FIG.14.2. OPTICAL PATH SET UP FOR ANGULAR POSITIONING MEASUREMENTS- PHOTO

Angular positioning measurements require usage of the rotary encoder RE1 together with optical elements IK1 and RK1. The Rotary Encoder is to be mounted precisely in the center of rotation of the measured axis. With the Rotary Encoder there is integrated the Angular Retro-reflector RK1. Outside the Rotary Encoder there are placed the Laser Head and the Angular Interferometer IK1 as shown in the figures 14.1 and 14.2.

i. Characteristics of **Wally** – *Rotary Measurement System*

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The Rotary Measurement System **Wally** is a standalone device destined for accurate measurement of rotation. Any angle rotation can be measured with precision reaching below 1 arcsecond. The device is battery operated and connects to a PC computer over wireless Bluetooth interface. High capacity Li-on battery allows 24 hour operation with fast charging lasting less than 2 hours. Battery is not replaceable. The power supply of the *Wally* is identical and exchangeable with the power supply of the *HPI-3D* laser head.

Although it is possible to use the *Wally* in a standalone configuration, it is recommended to operate it together with

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the *HPI-3D*. The main advantages of the combined laser/encoder operation are:

- independence of the measurement accuracy on an imperfect mounting on the machine,
- measurement of the angle against the laser beam, i.e. much greater flexibility of the setup,
- fully automatic operation with machine compensation files and measurement reports generation.

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The Rotary Measurement System is delivered in a separate case consisting of:

- o Rotary unit,
- o Mounting ring,
- o Mounting kit for milling machines,
- o Mounting kit for turning machines,
- o Power supply unit,
- o Necessary screws.

In a separate set there is delivered a special mounting for off-axis measurement – as shown in the Figure 14.5, element 3.

Before measurements it is necessary to mount the whole kit depending on the mechanical configuration. In the figures 14.3 and 14.4 there are shown necessary elements for milling machines (turning tables) and for turning machines.

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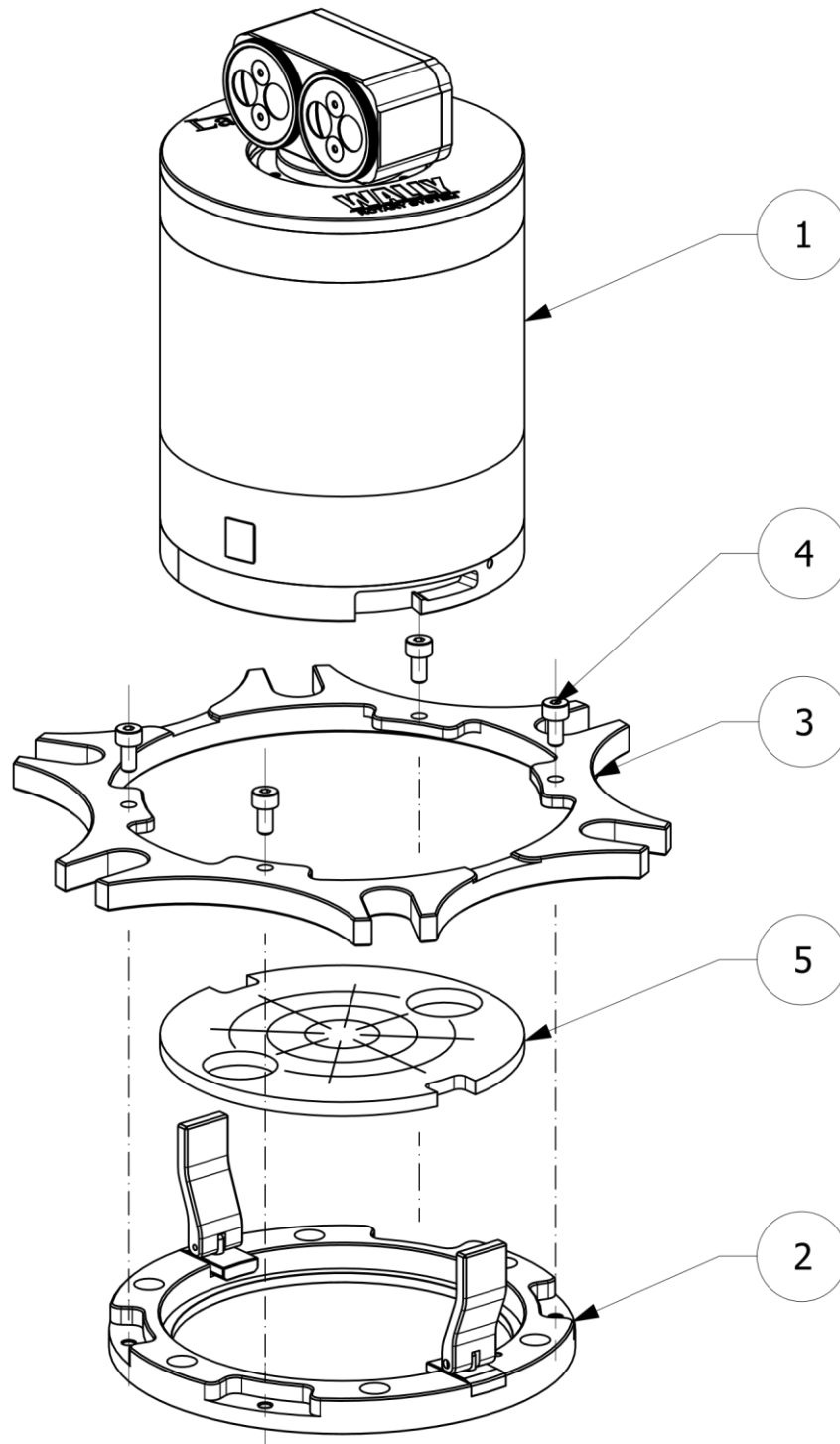Assembled rings do not have to be disassembled if not necessary.

FIG.14.3. CONFIGURATION OF WALLY FOR MILLING MACHINES MEASUREMENTS.

1 – CENTRAL UNIT, 2 – MOUNTING RING, 3 – RING FOR TURNING TABLES,

4 – SCREWS M4X8, 5 – TEMPORARY TOOL FOR FINDING TABLE CENTER

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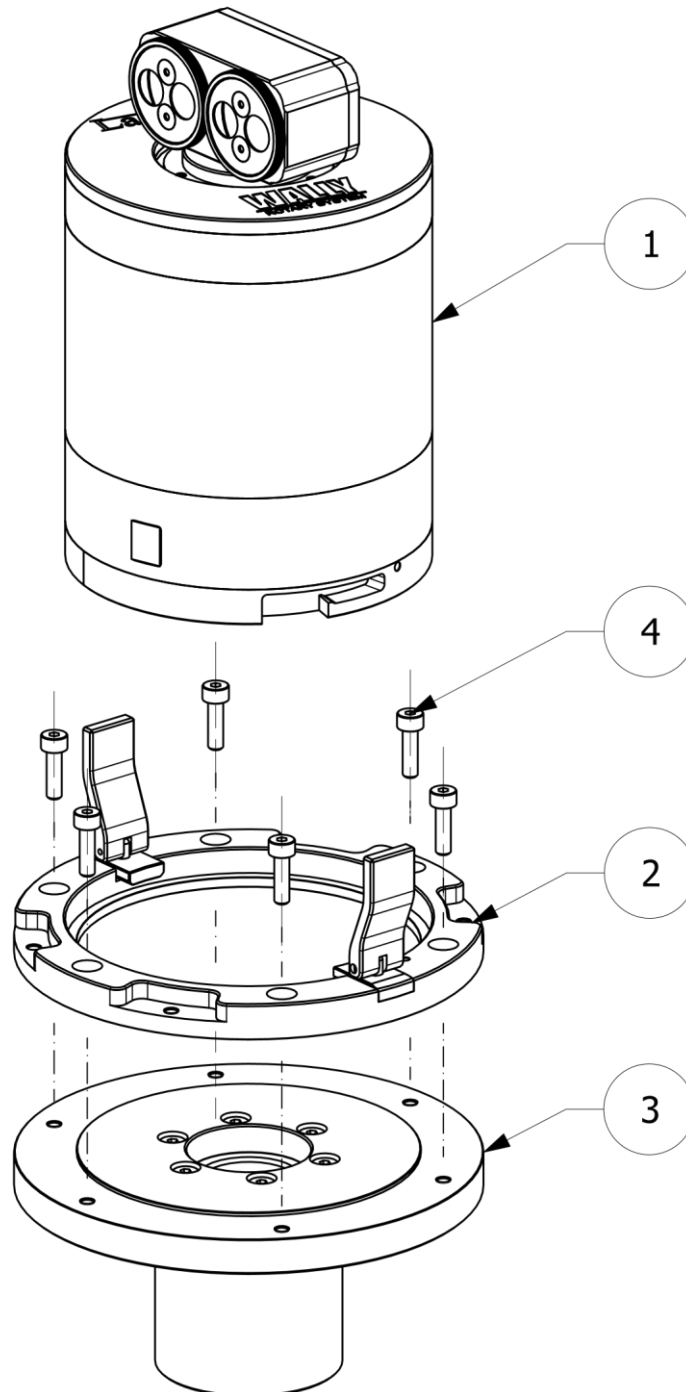
FIG.14.4. CONFIGURATION OF WALLY FOR TURNING MACHINES MEASUREMENTS. 1 – CENTRAL UNIT, 2 – MOUNTING RING, 3 – RING FOR TURNING MACHINES, 4 – SCREWS M4X12.
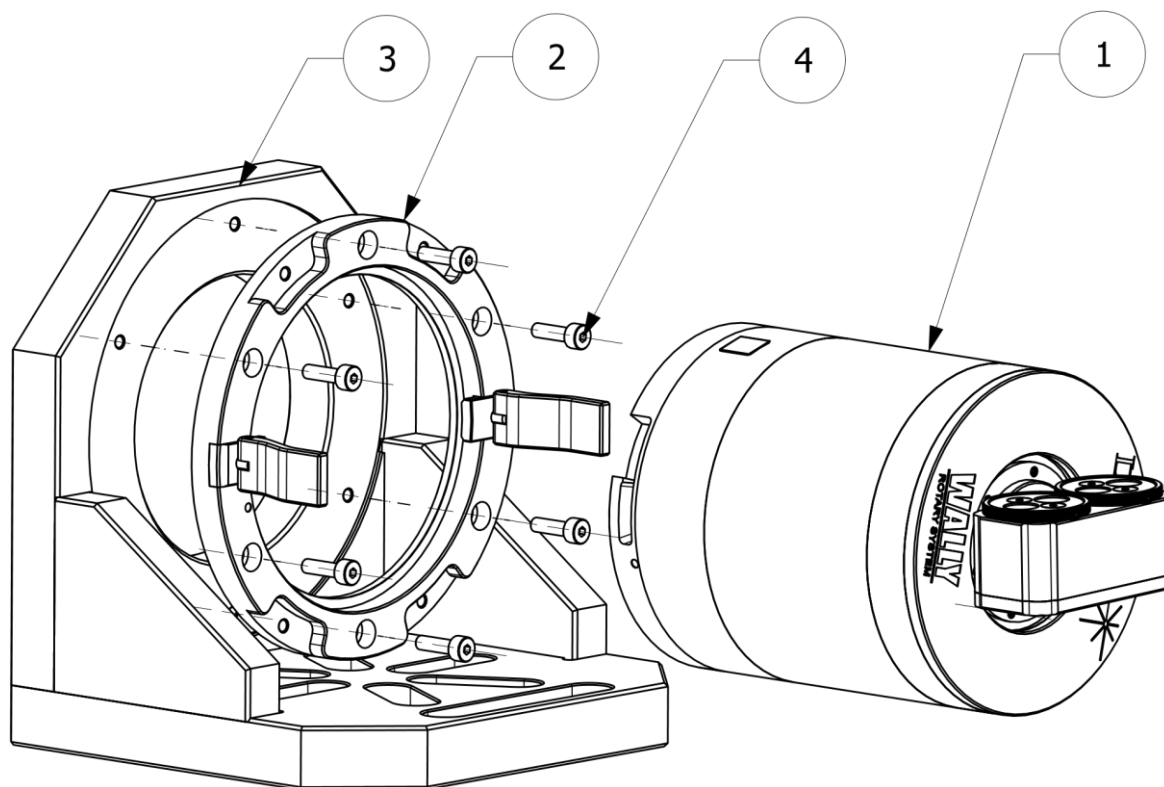
FIG.14.5. CONFIGURATION OF WALLY FOR OFF-AXIS MEASUREMENTS. 1 – CENTRAL UNIT, 2 – MOUNTING RING, 3 – MECHANICHAL SET FOR OFF-AXIS MEASUREMENT, 4 – SCREWS M4X12.

ii. Theory of operation

The Angular Positioning measurements are performed with the use of two measurement instruments working together: the Rotary Measurement System – *Wally* and the Laser Head.

The coarse value of the angle is given by the rotary encoder RE1.

The laser head has two functions during the measurements: it controls and drives the whole process and at the same time measures the fine value of the angle in the range of +/-10 degrees with the resolution of 0.01''. The measurements are performed with the use of angular optics – IK1 and RK1 and mechanical mounts.

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The Laser Head and the Rotary Encoder communicate with the PC computer over Bluetooth interface. The laser can be also connected over USB port. The presence of the powered on the encoder is detected after connection and signalized by the yellow color on the *Rotary link* field in the Status bar.

Proper rotary measurements are possible only if the laser sets up measurement link with the encoder. During the link set up procedure the wireless link quality and the optical signal strength are tested. The laser tries to drive the table to rotate -5 degrees, then +10 degrees and then -5 degrees. If all the tests are succeed, then the link with the encoder is set (*Rotary link* field in the Status bar changes to green) and the measurements are possible.

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> The procedure of setting the **Rotary link** requires optical path to be aligned.
>
> The **Rotary link** can be set by pressing *Rotary link* field in the Status bar.
>
> The **Rotary link** is automatically broken when the optical path is broken.

During measurements the laser monitors the current rotation of the RK1 element. If the measured angle is outside internally set range then the HPI Software issues wireless command the encoder to counter rotate.

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Preferably the measurements should be performed with mount of the central unit in the center of axis rotation, i.e. in so called *in-axis* configuration. If such mechanical configuration is not possible, then the *off-axis* setup has to be used with or without the additional off-axis mounting (depending on the mechanical configuration of the measured axis).

iii. Rotary measurements – hardware preparations

Depending on the requirements the Wally has to be properly assembled and mounted on the machines. In the case of turning tables or milling machines, the configuration shown in figure 14.6 has to be mounted.

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First the assembled ring has to be installed in the center of the rotation of the machine's measured axis. For this purpose special tool can be used – see element 5 in the figure 14.3. Then the central unit has to be placed inside the ring, rotated clockwise and fastened with both wings.

> For highest accuracy red dots on the ring and the central unit have to be close to each other.
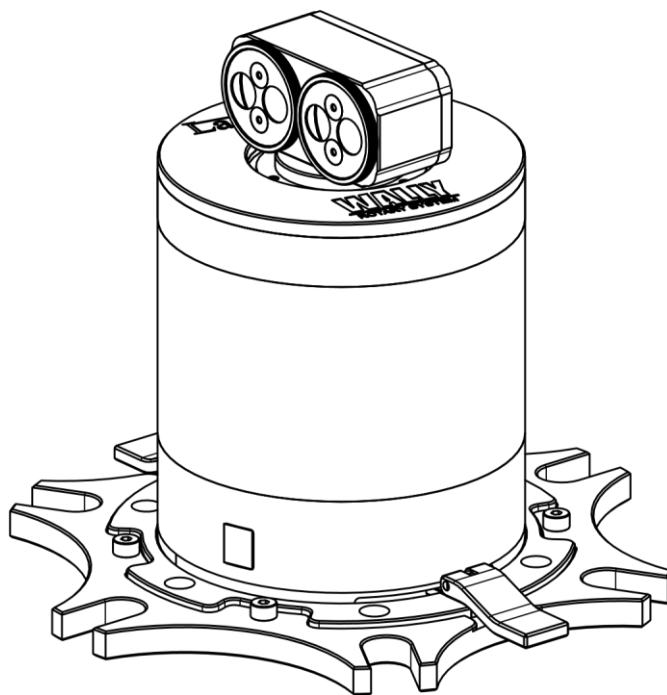
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FIG.14.6. ROTARY SYSTEM ASSEMBLED FOR MILLING MACHINES MEASUREMENTS

In the case of turning machine the assembled ring has to be installed in the machine's spindle. Then the central unit has to be placed inside the ring, rotated clockwise and fastened with both wings – see figure 14.7.

For measurements off the rotation axis there is necessary precision right angle set (delivered separately). The elements of the off-axis setup are shown in the Figure 14.5 and the assembled system in the Figure 14.8.
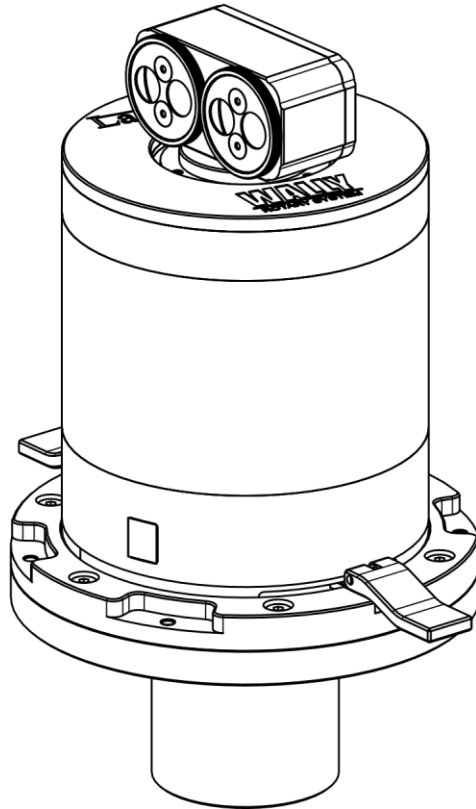

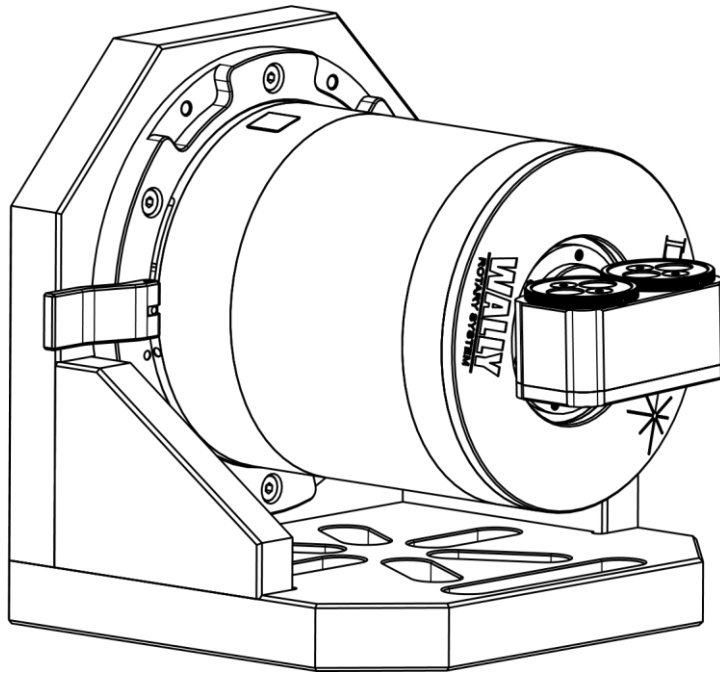**FIG.14.7.** ROTARY SYSTEM ASSEMBLED FOR TURING MACHINES MEASUREMENTS

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FIG.14.8. ROTARY SYSTEM ASSEMBLED FOR OFF-AXIS MEASUREMENTS

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iv. *Rotary measurements – battery charging*

The central unit of the Wally is operated from an internal, high quality, lithium-ion battery. The battery is rechargeable and non-replaceable. It can be charged either with the attached power supply unit or with the power supply unit of the HPI-3D laser head. The charging process takes around two hours to complete, yet 20 minutes charge is usually enough for 8 hours of measurements.

v. *Rotary measurements – elimination of error sources*

One of the main advantages of the laser based angle measurement systems is their low sensitivity to imperfect mounting of the measurement components. Still an attention is required for proper mounting on the machine in order to reduce the errors to unmeasurable values.

The two main possible error sources are:

- mounting the rotary encoder outside the rotation axis,
- mounting the rotary encoder at an angle to the rotation axis.

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Mounting the encoder precisely inside or outside the rotation center does not influence the measurement accuracy as long as the eccentricity is lower than 1mm.
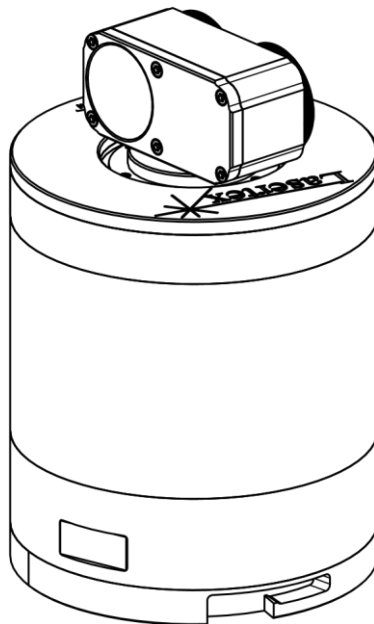

FIG.14.9. ROTARY SYSTEM TURNED INTO THE ALIGNMENT POSITION

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A non-negligible influence on the accuracy has the mounting the laser and the central unit at an angle to the rotation axis. In order to minimize this problem certain precautions should be taken:

1) When inserting the central unit into the ring, the red dots should be close to each other;

2) In the beginning of the alignment procedure, before the IK1 element is used, the rotary unit should be rotated to the alignment position (see Fig. 14.9), i.e. with the mirror facing the laser. The laser head should be aligned (mostly with angular mountings) in such a way that the beam reflected from the mirror returns back to the front of the laser head. This operation forces the laser beam to be perpendicular to the rotation axis.

3) In the next step the laser beam should be directed to the input of laser head and the software should be started with *Display -> Adjustment* shown. The position of the laser beam should be within the middle of the chart. Then the axis under measurement should be rotated by 90 degrees with Wally counter rotated by the same angle. The change of beam position on the chart should be marked. The operation should be repeated for 180 and 270 degrees. The lower are variations of the beam

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position, the better accuracy of the angle measurement. For radiuses of the measured tables of 0.5-3m good accuracy is obtained if the beam position variations are within +/- 0.5mm. If the variations are higher, then the mounting of the Wally has to be checked.

4) Only then the Wally can be rotated to the measurement position and IK1 can be inserted into the optical path. Laser head position should be changed only in horizontal or vertical plane (no angular adjustments).

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c. Software description

The described device option can be used either for measurement of any rotation angle or for angular positioning measurement.

i. *Connecting with Wally*

The Wally is to be wirelessly connected to the PC computer over Bluetooth 4.0 or higher interface. The connection is carried on in the *Configuration->Interface* option (see figure 14.10). In the *Communication interface* pane the *Wally* button has to be pressed and then the *Search…* After a

while the compatible rotary units will be listed in the *Devices list*. Now the device with proper serial number (it can be read on the bottom steel ring of the central unit) has to be chosen and *Reconnect* button should be presses. After a short while the devices should be connected and a value in the **Battery level** should appear.
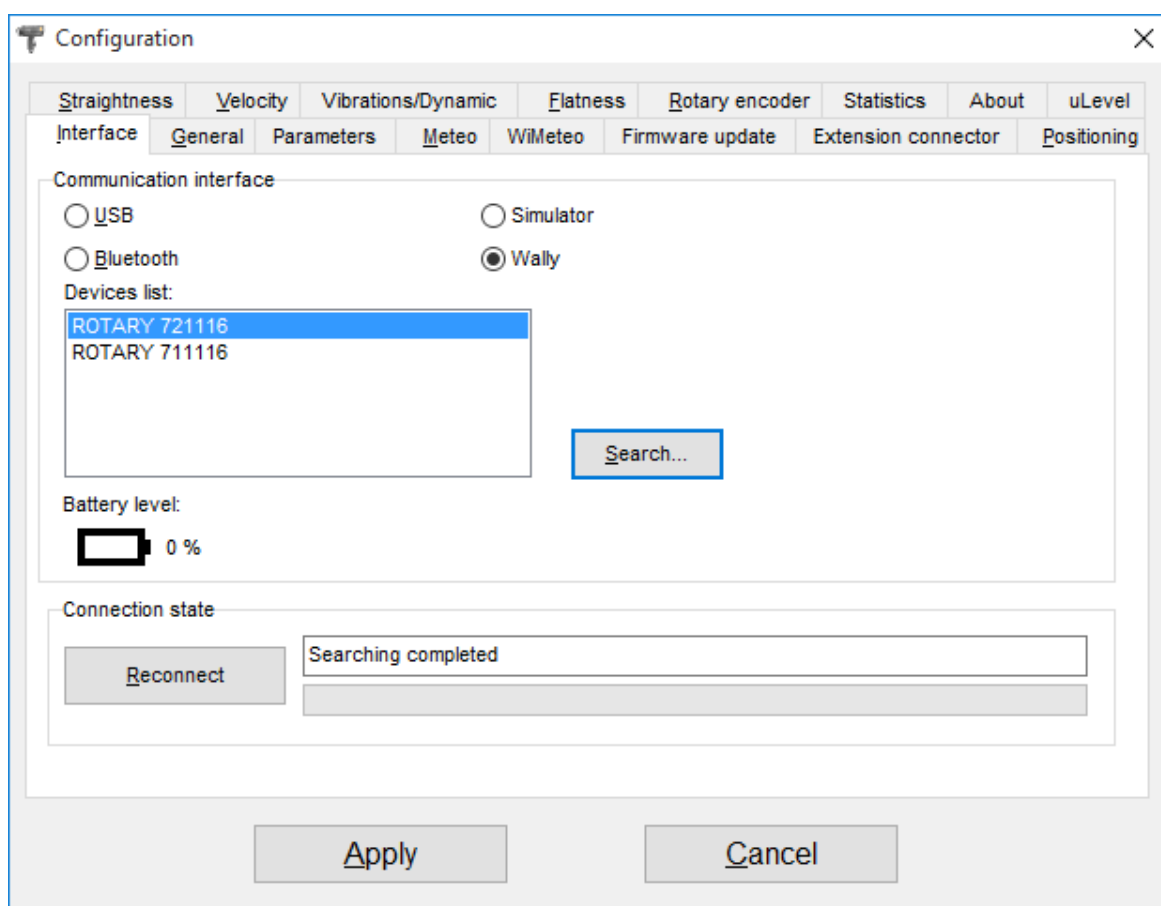

FIG.14.10. CONNECTION TO THE ROTARY SYSTEM

ii. *Measurements of the rotation angle*

In order to start *Rotation* measurements in the **Main Menu** the **Display** button should be pressed. On the screen there should appear a window **Display** as shown in the fig. 14.11. The functionality of the window is very similar to the one described in the chapter 3 with the difference that options necessary for rotary measurements are visible (see figure 14.12). In the top left corner of the window there is give Wally battery level indicator.

The additional options become visible in the bottom right corner of the window only after the **Measurement** type is set to **Wally**.
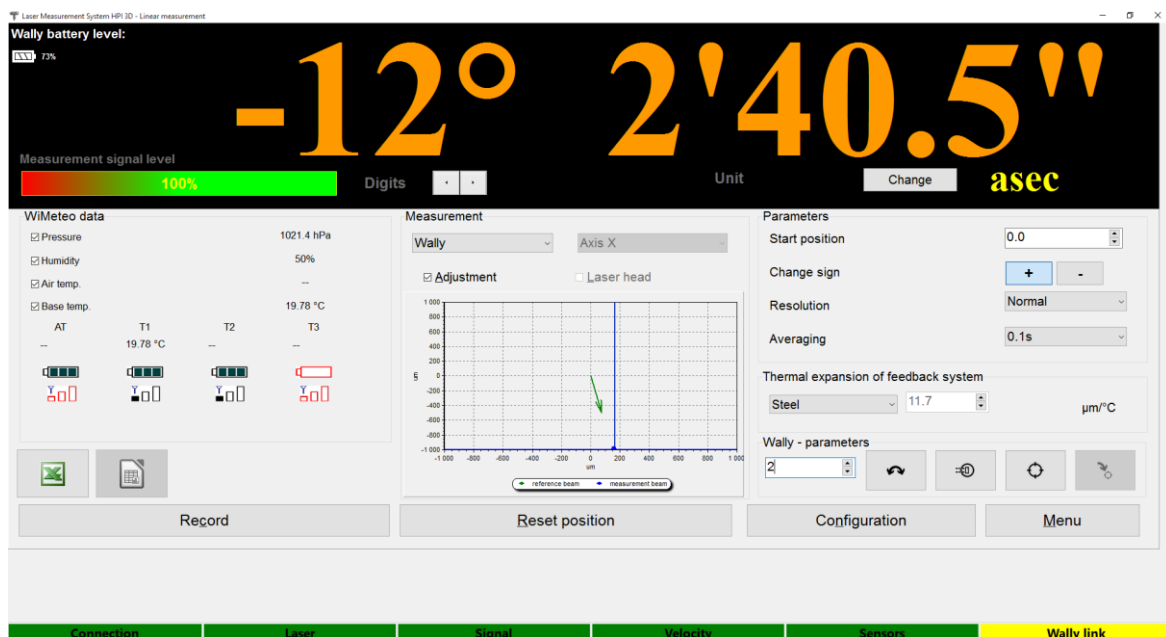

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FIG.14.11. DISPLAY WINDOW WHEN ROTARY ENCODER IS PRESENT

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On the Status bar on the very bottom of the screen there is present a *Wally link* segment. As described in the chapter 3 this segment has three states:

- gray – rotary encoder RE1 not present or not detected;

- yellow – rotary encoder RE1 detected but no link to the laser or the link was broken;

- green – rotary encoder RE1 properly connected and linked.

The measurements are possible only when the link with encoder is set – i.e. when the *Wally link* segment is green. Setting the link requires proper alignment of IK1 and RK1 first. Only when the elements are aligned the *Wally link* segment should be double clicked. The procedure of setting the link, as described in *Theory of operation* section, should be started. When the procedure is finished successfully the *Wally link* segment turns green and the measurements are possible.
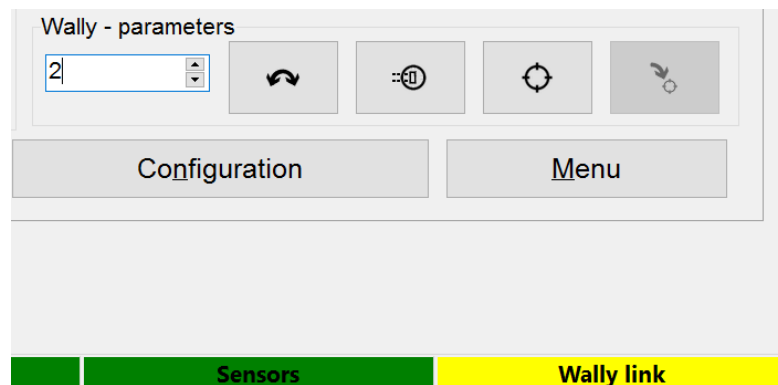
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**FIG.14.12.** DISPLAY WINDOW OPTIONS FOR ROTARY ENCODER

Setting link to the rotary unit is possible by left mouse button press on the *Wally link* segment of the status bar. Breaking the link with the rotary table is done automatically when the laser beam path is broken.

> ⚠️ Only when there is set link between Wally and HPI Software the laser automatically traces the position of the Wally.
>
> Breaking the beam path breaks the Wally link.

Buttons in the *Wally – parameters* pane are used as additional tools during operation with Wally. The buttons are described below. The buttons are useful only when there is no *Wally link*!

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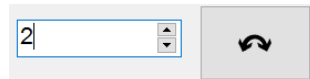
- after pressing the button Wally rotates by the value set in the box. The value is in degrees, e.g. 20.2 means rotation by 20.2 degrees or 20 degrees and 12 minutes.

- after pressing the button Wally searches automatically for the best position of the RK1 element by rotating the element and monitoring input beam strength.

- after pressing the button the curent position of Wally is remebered. The, after for example

machine movement, the position can be retained by pressing the button [ ] .

iii. Measurements of angular positioning

In order to start *Angular Positioning* measurements in the **Main Menu** the **Angular Positioning** button should be pressed. On the screen there should appear a window **Angular Positioning** as shown in the fig. 14.13
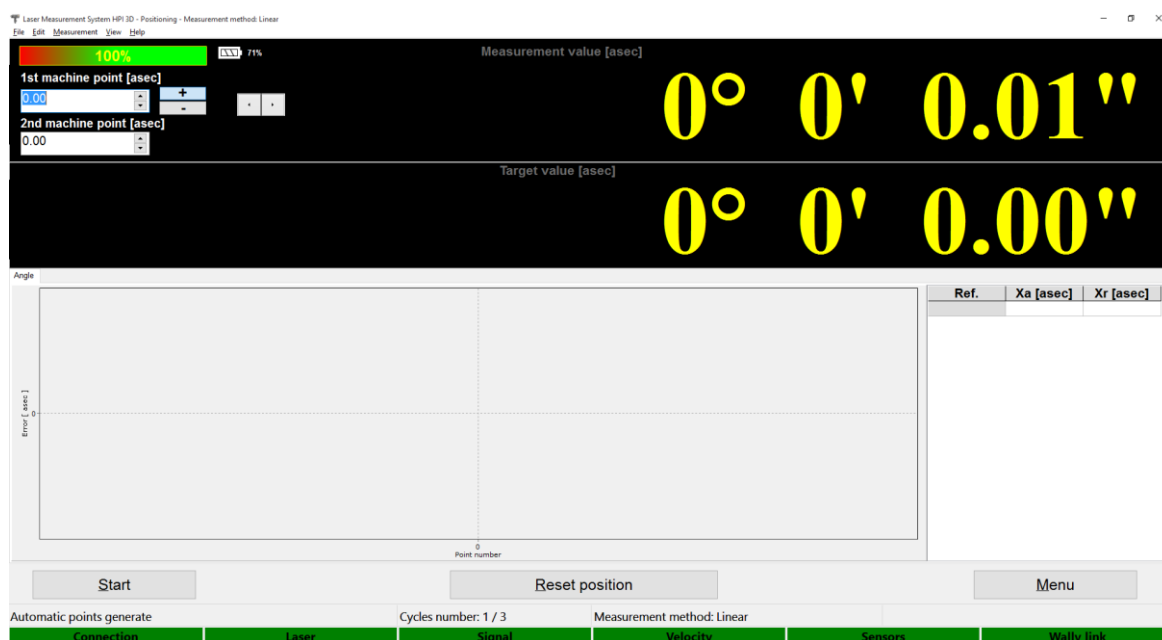

FIG.14.13. ANGULAR POSITIONING WINDOW

iv. Pull down menu - File

The menu bar of this window contains following options: File, Edit, Measurement, View, and Help. In the File

option (figure 14.14) there can be found commands for reading measured data from a file, saving the data to a file, printing measurements results or exporting them to a file.
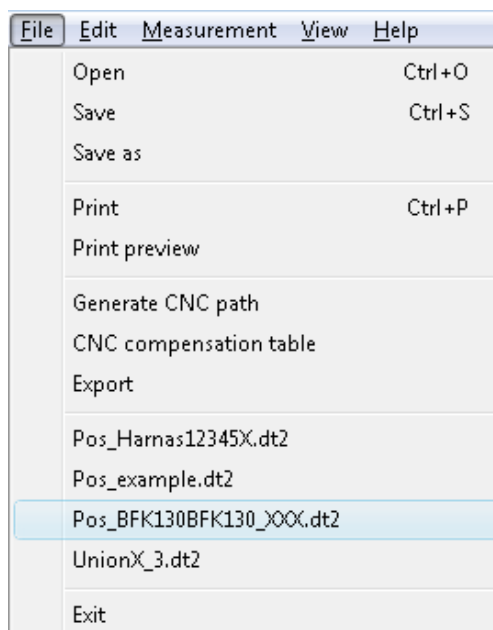

FIG.14.14. POSITIONING PULL-DOWN MENU *FILE*

Other important options available in the *File* menu are options for generating CNC path and preparing compensation table.

v. CNC path generation for in-axis measurements

CNC path generation options allows automatic preparation, by the HPI-3D software, the G-code program compatible with most CNC control systems. The options of the path generation are set in the separate window as shown

in the Figure 14.15 for *in-axis* measurement and in the Figure 14.16 for *off-axis* measurements.

In the upper part of the window the machine movement parameters are set. In the lower part the generated program can be viewed end edited. The results can be saved to a text file or previewed and printed.

FIG.14.15. CNC PATH GENERATION WINDOW FOR IN-AXIS MEASUREMENTS

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Following parameters in *Software parameters* panel should be configured in order to generate the proper code:

- **Measurement method** - should be set accordingly with the chosen measurement method (see below). Choice must be made between linear, pendulum, pilgrim effective and pilgrim standard;

- **Axis** – the measured machine movement axis should be chosen (X, Y, Z, U, V, W, A, B, C).

- **Feed Rate** – the maximum machine feed rate in the chosen axis during measurements can be modified. The chosen value cannot be greater than machine limitations (see manual of the tested machine).

- **Stop Time** – the time the machine stops at every measurement point. This time is necessary for the HPI Software to capture measurement point. The proper value of this parameter depends on the tested machine and on *Point Capture* parameters of the laser (described later in this chapter).

- **Step** – the distance between measurement points.

- **Start point** – the initial position of the machine in its own coordinate system.

- **Clearance** – additional machine movement used to compensate backlash. The chosen value should be large enough for the proper backlash compensation of the machine.

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- **Cycles number** – sets the number of generated movement cycles. For proper calculation of statistical parameters in Report the number of measurement cycles should be not lower than three. The more measurement cycles is chosen the better characterization of the machine is done but the longer the measurement process lasts. The number of cycles should be the same with the value in *Configuration->Positioning->Cycles in series*.

- **Points number** – sets the number of measurement points.

- **g code/Heidenhain** – it is possible either to generate the standard G-code program or a version compatible with Heidenhain machine controls.

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- **Off axis measurement** – opens elements used for machine path generation for off-axis measurements – see Figure 14.16. Option is active only after software unlocking – please contact local distributor for more details. Path generation for off-axis measurement is described in more details in the next chapter.

FIG.14.16. CNC PATH GENERATION WINDOW FOR OFF-AXIS MEASUREMENTS

vi. CNC path generation for off-axis measurements

Proper off-axis measurements are not possible without proper movement of the measured machine. During machine movement the distance between optical elements IK1 nad RK1 (mounted on the Wally) should be constant. This requires during table rotation instantaneous movement in two linear axes: main and auxiliary one. Manual generation

of such a path is very difficult thus in the *HPI Software* there is included step-by-step tutorial, explained below.

0) ***Phase 0*** – Wally and laser are to be mounted on the machine as described in previous paragraphs.
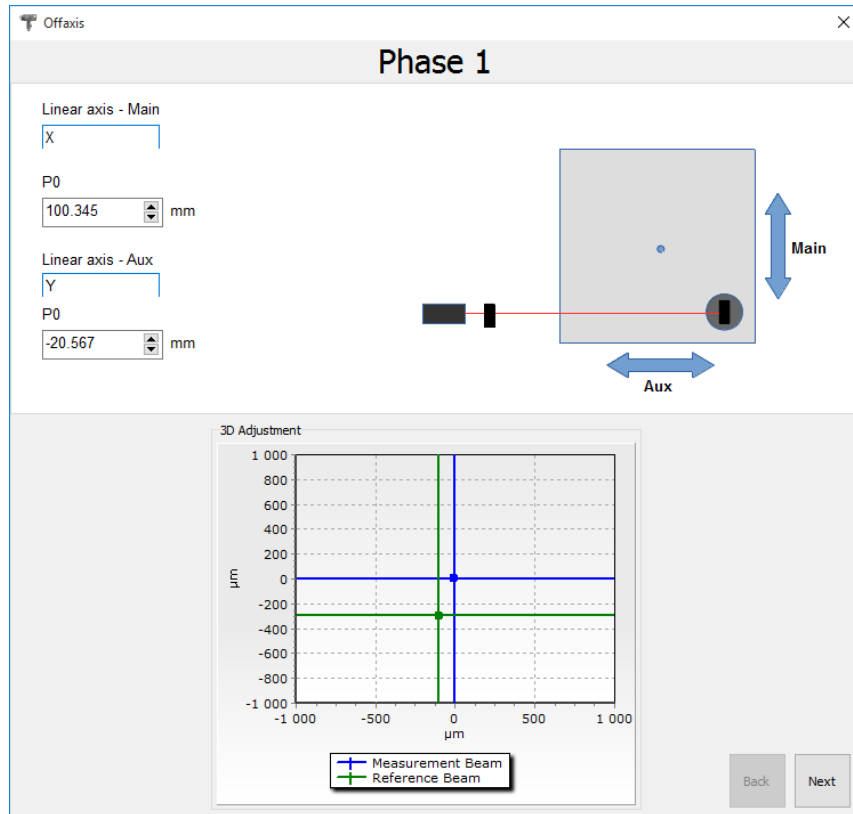
FIG.14.17. PHASE 1 OF THE OFF-AXIS PATH GENERATION

1) ***Phase 1*** – Main axis of the machine (see Figure 14.17) is to be moved to make the laser beam alignment crosses close to the center of the adjustment chart (fig. 14.17). With the movement of the auxiliary axis there is to be set a distance between IK1 element and

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the central unit. The accuracy of this distance should be better than 10cm and does not have to kept very precisely. After the machine is set, the markings of the Main and Aux axes are to be put in the software window – in *Linear axis – Main* and *Linear axis – Aux* fields respectively. In the example in the figure 14.17 Main is axis X, Aux is axis Y. The values from the machine absolute coordinate system are the written in the software as well in the *P0* fields.

2) **Phase 2** - machine is to be rotated in the measured axis by +45 degrees (figure 14.18)

FIG.14.18. PHASE 2 OF THE OFF-AXIS PATH GENERATION

3) *Phase 3* – Wally is to be rotated in the same direction like the machine. As shown in the figure 14.19, in the Phase 3 there available two buttons with arrows. Pressing the buttons rotates Wally by predefined +45 or -45 degrees.
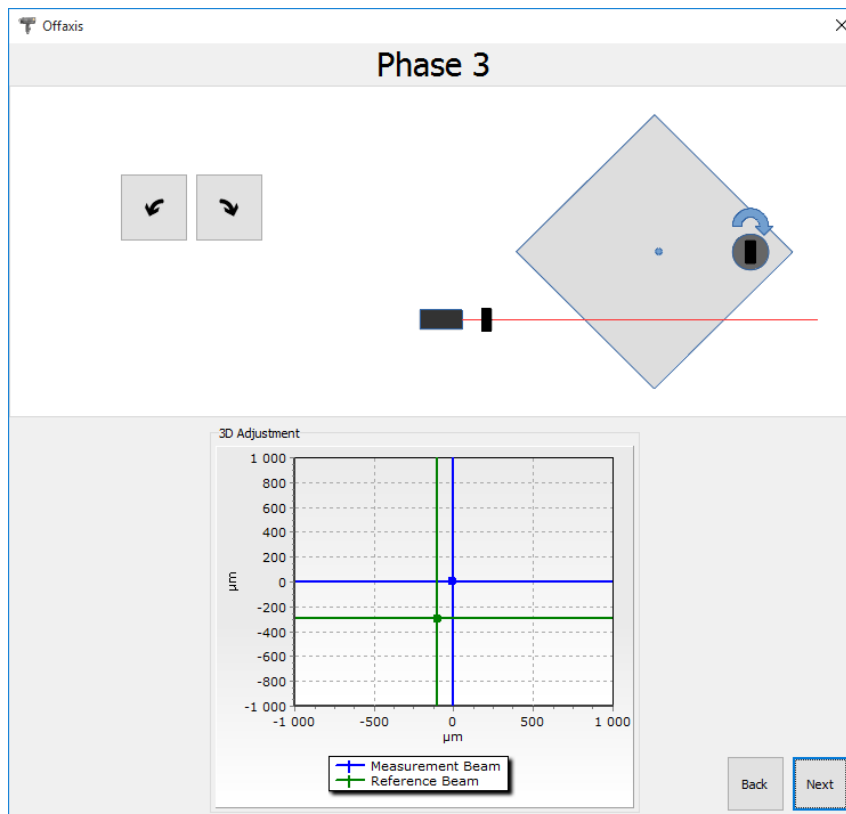
FIG.14.19. PHASE 3 OF THE OFF-AXIS PATH GENERATION

4) *Phase 4* – Machine is to be moved in the linear Main axis until the crosses return to the position they were during Phase 1 (see Figure 14.20).
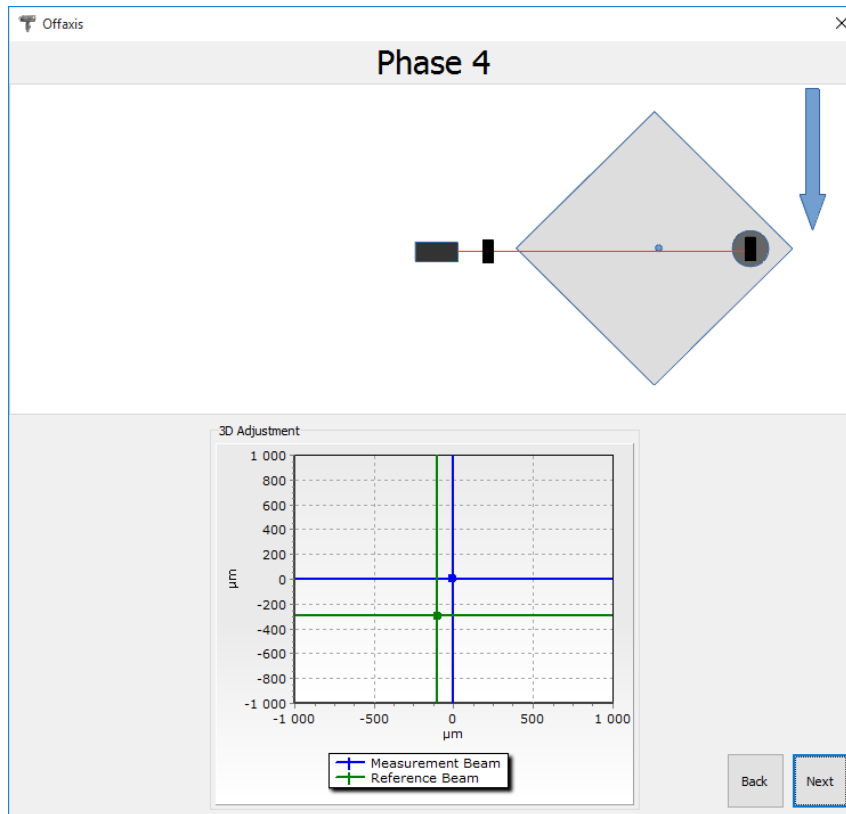
FIG.14.20. PHASE 4 OF THE OFF-AXIS PATH GENERATION

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5) *Phase 5* – Machine is to be moved in the linear Aux axis until the distance between IK1 and RK1 becomes similar to the value during Phase 1. The required accuracy is <10 cm. The absolute positions of the machine in the Main and Aux axes are to be written into the *P0+45ᵒ* fields in the software – see figure 14.21.

6) *Phase 6* - machine is to be rotated in the measured axis by -90 degrees (figure 14.22)
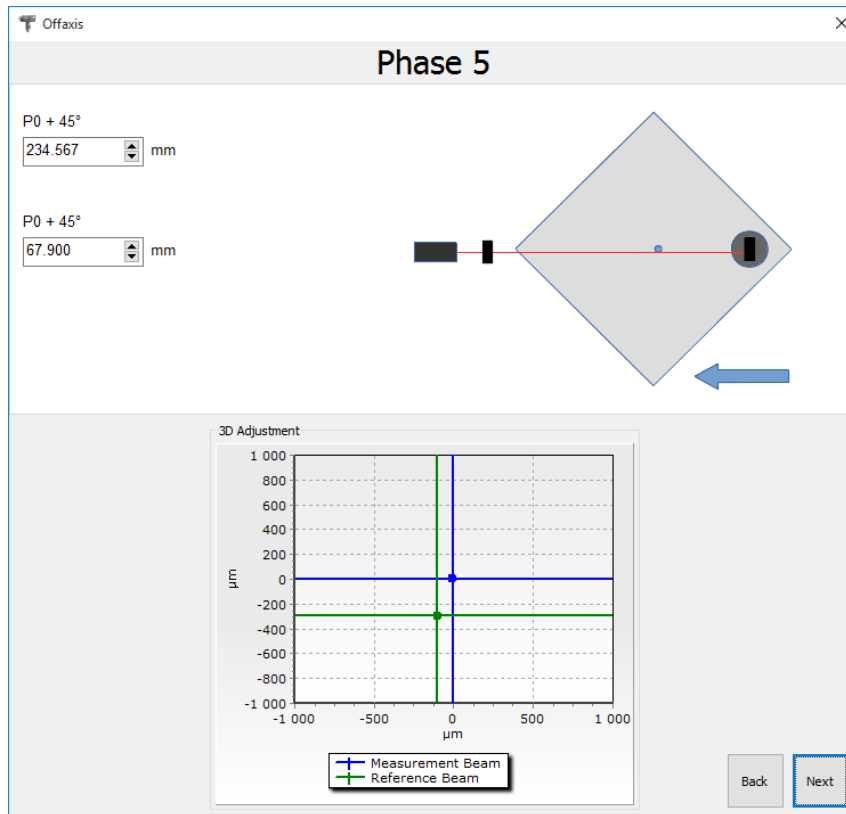
FIG.14.21. PHASE 5 OF THE OFF-AXIS PATH GENERATION

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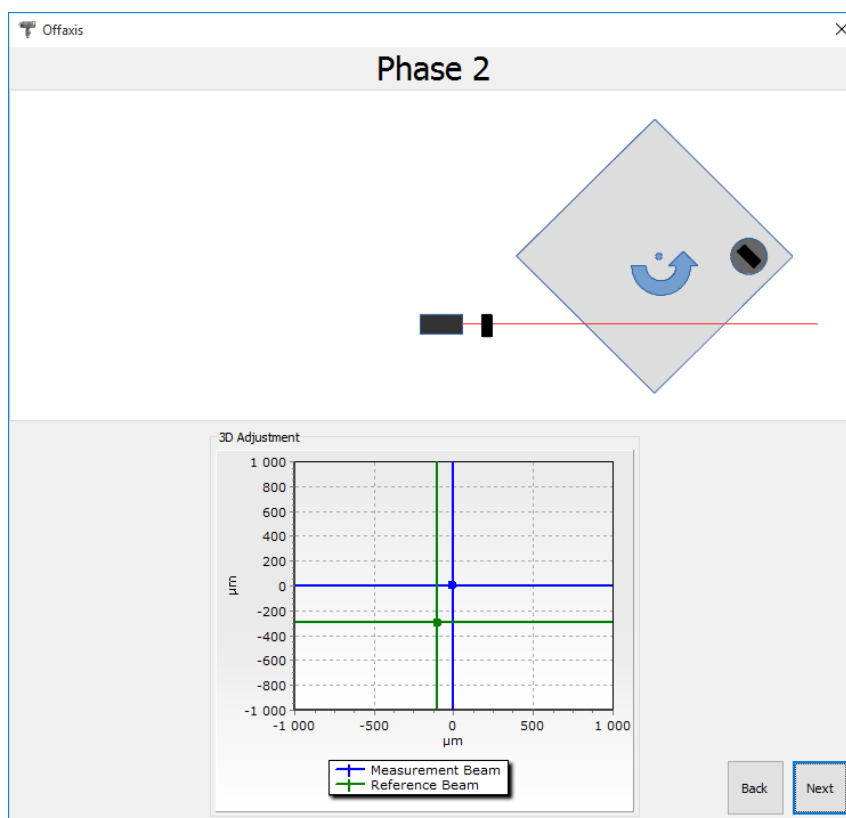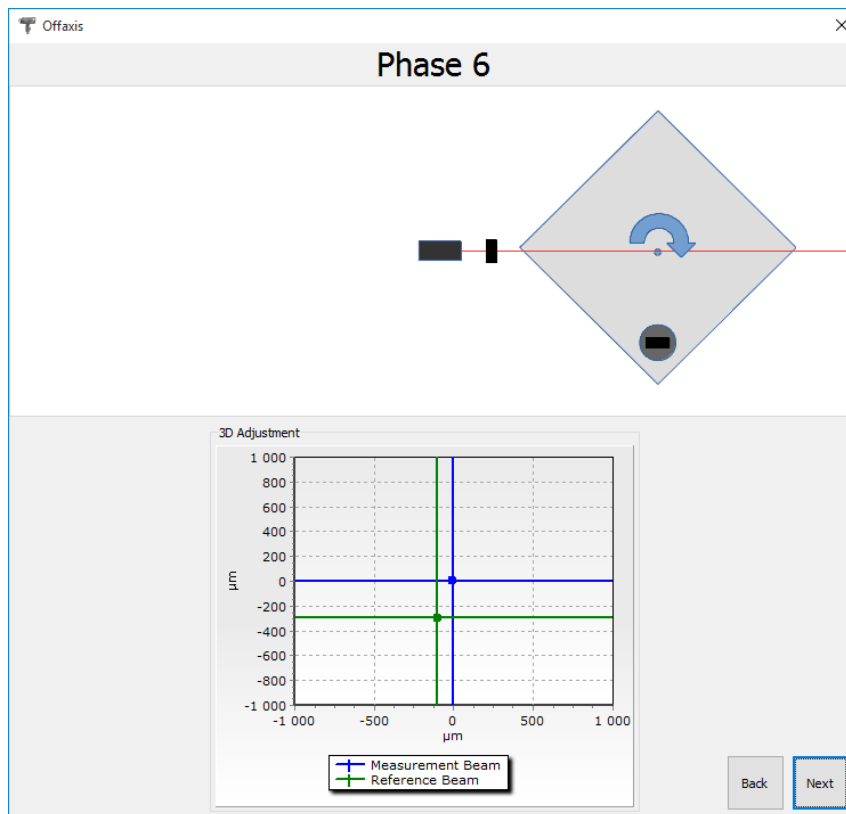**FIG.14.22.** PHASE 6 OF THE OFF-AXIS PATH GENERATION

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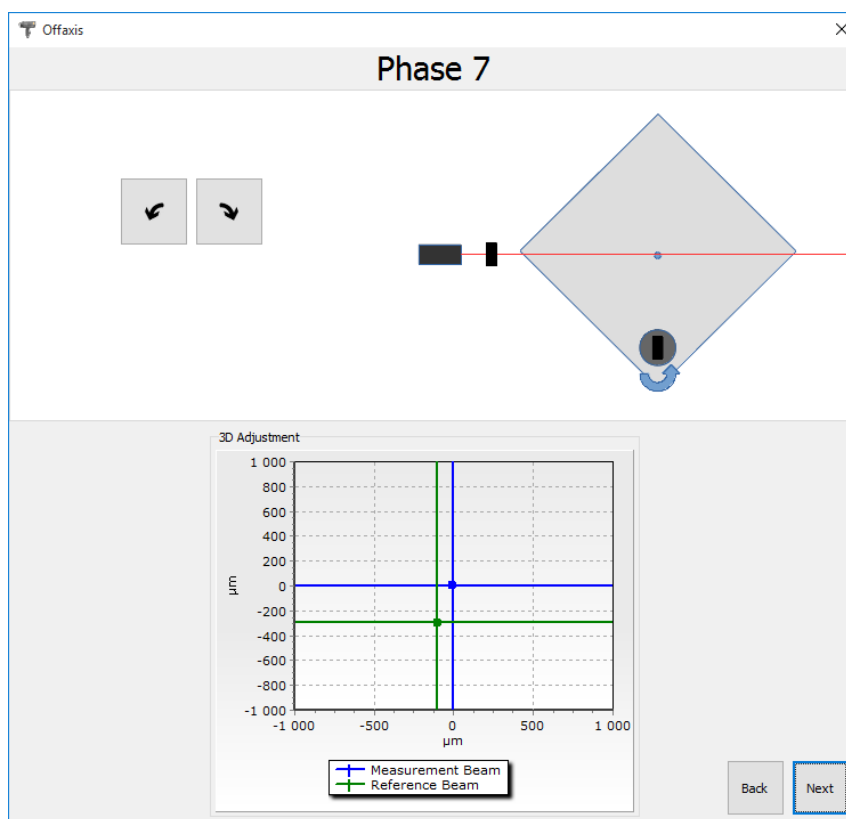
FIG.14.23. PHASE 7 OF THE OFF-AXIS PATH GENERATION

7) *Phase 7* – Wally is to be rotated in the same direction like the machine, i.e. by -90 degrees – see figure 14.23.

8) *Phase 8* - Machine is to be moved in the linear Main axis until the crosses return to the position they were during Phase 1.

9) *Phase 9* - Machine is to be moved in the linear Aux axis until the distance between IK1 and RK1 becomes similar to the value during Phase 1. The required accuracy is <10 cm. The absolute positions of the machine in the Main and Aux axes are to be written into the *P0-45º* fields in the software – see figure 14.24.
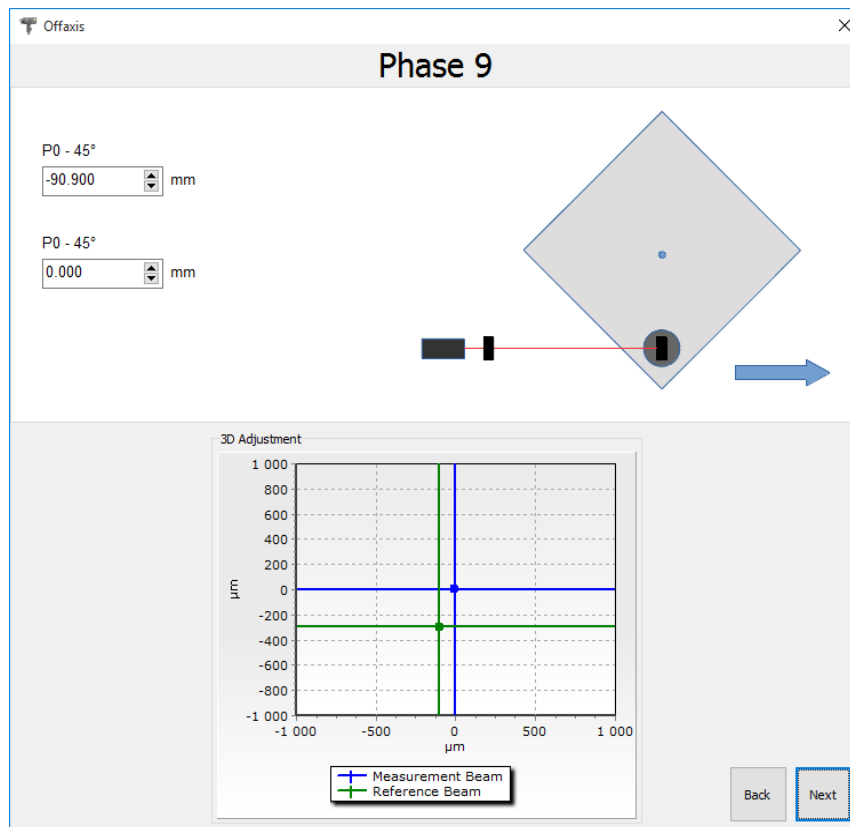
FIG.14.24. PHASE 9 OF THE OFF-AXIS PATH GENERATION

10) *Phase 10* – Machine is to be rotated back to the start position.

11) *Phase 11* – Wally is to be rotated back to the start position.

12) *Phase 12* – Machine is to be moved back in the linear Main axis to the start position.

13) *Phase 13* – Machine is to be moved back in the linear Aux axis to the start position.

14) *Summary* – after the movement phases the machine and the Wally should be in the start position and the software should show the summary screen as

presented in the Figure 14.25 with collected data. From the generated data the CNC path is generated.
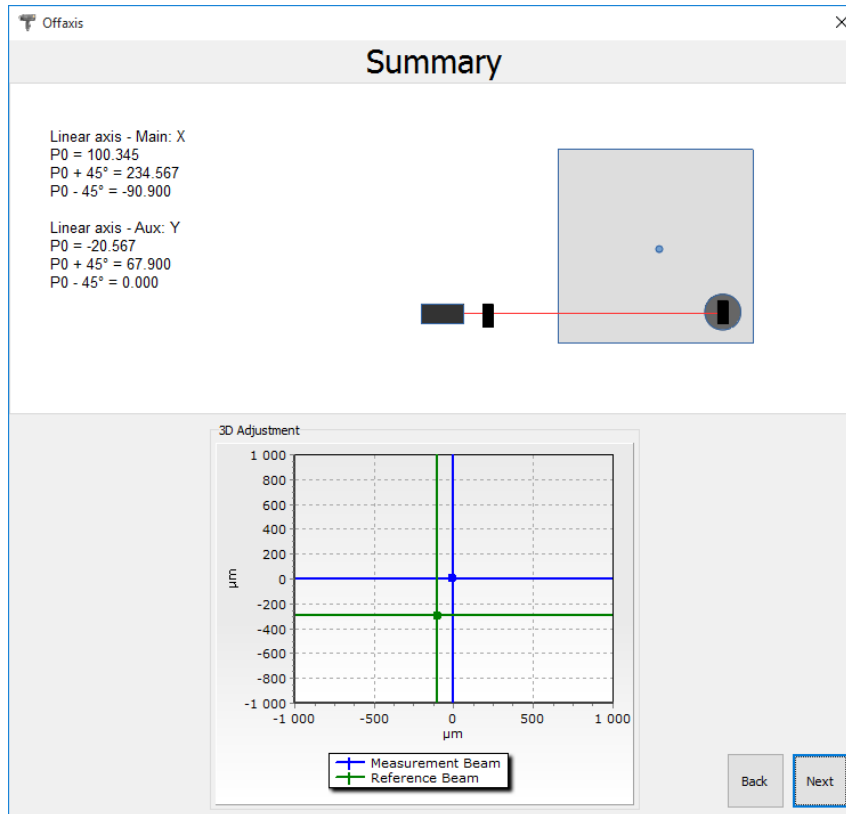
FIG.14.25. SUMMARY OF THE OFF-AXIS PATH GENERATION

vii. Pull down menu - Edit

In the pull-down menu **Edit** option (fig. 14.26) there are commands for setting measured machine data (Fig 14.27), defining machine error limits (fig. 14.28), previewing obtained positioning results, editing positioning points (when option **Target Points from List** from menu

Measurement is active) and changing overall positioning configuration.
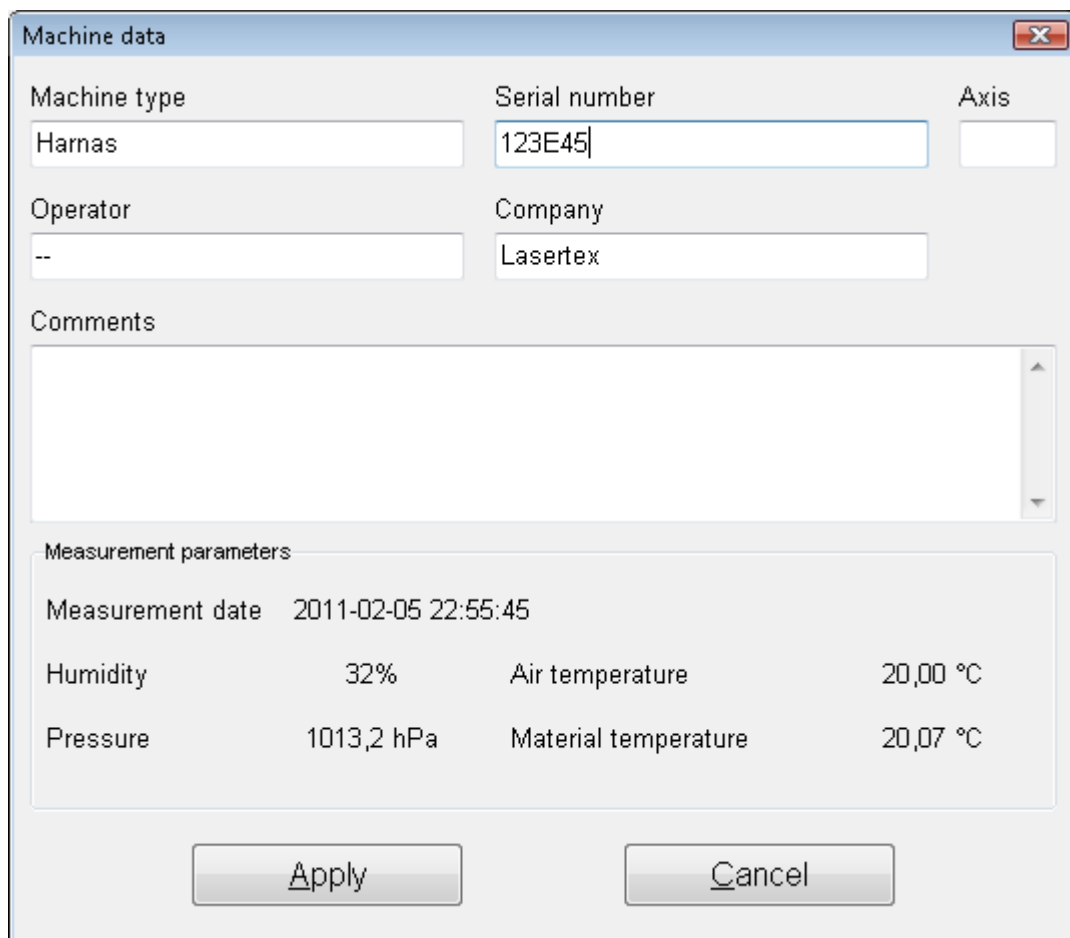
FIG.14.26. POSITIONING PULL-DOWN MENU *EDIT*

FIG.14.27. MACHINE DATAWINDOW

viii. Machine error limits
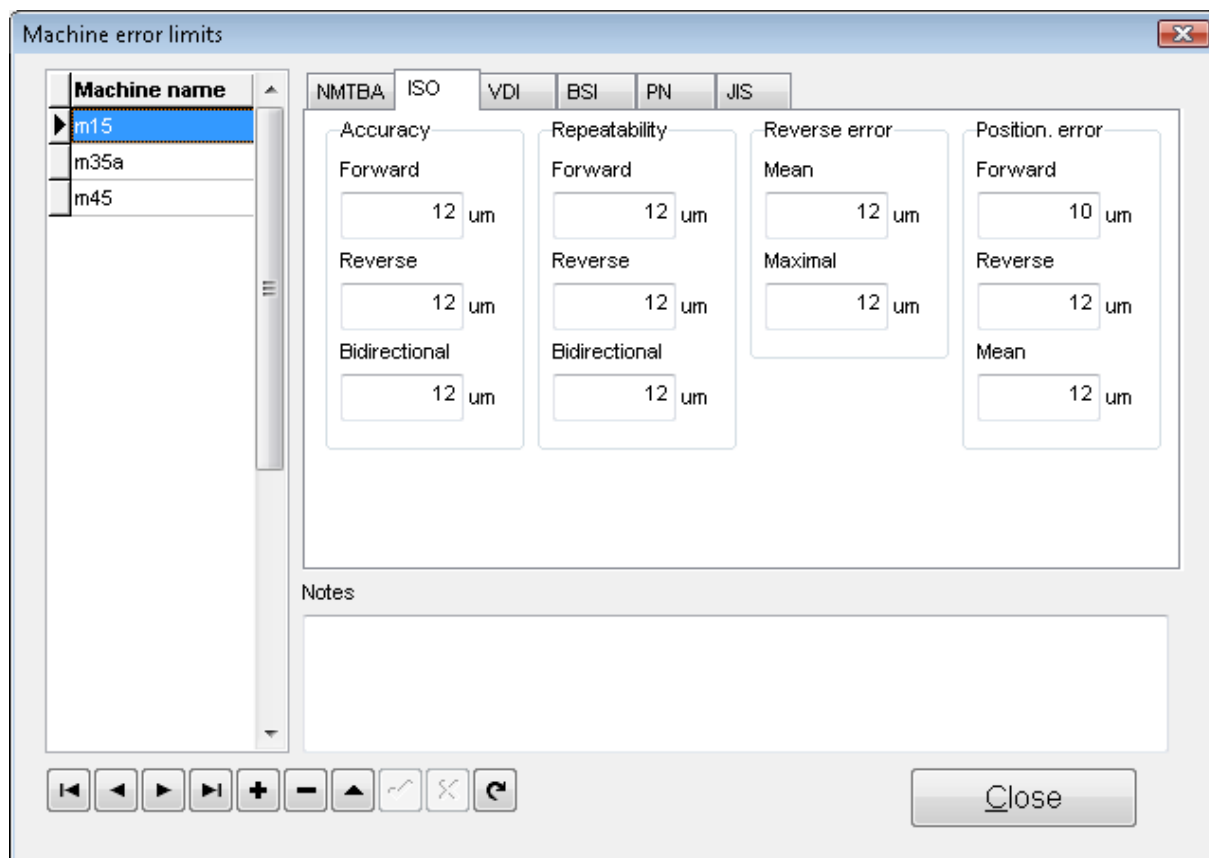
FIG.14.28. MACHINE ERROR LIMITS WINDOW

In the **Edit** option allowable error limits of the machine for different norms (option **Machine error** limits - Fig. 14.28) are configured. The results of the angular positioning measurements are compared with these limits (see Fig. 14.29). This option is especially useful when there are checked many machines of the same type and the same requirements on their accuracy are expected.

FIG.14.29. MACHINE ERROR LIMITS COMPARATION PANEL

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ix. *Positioning points generation*

If option **Target Points from List** from **Measurement** menu is active, then the program expects the measured machine to stop in points defined in the Positioning points window as shown in the figure 14.30. Points can be entered manually or can be generated from the input parameters: start position, distance and interval or number of points. The points are calculated when *Calculate* button is pressed. Obtained points can be saved to a file.
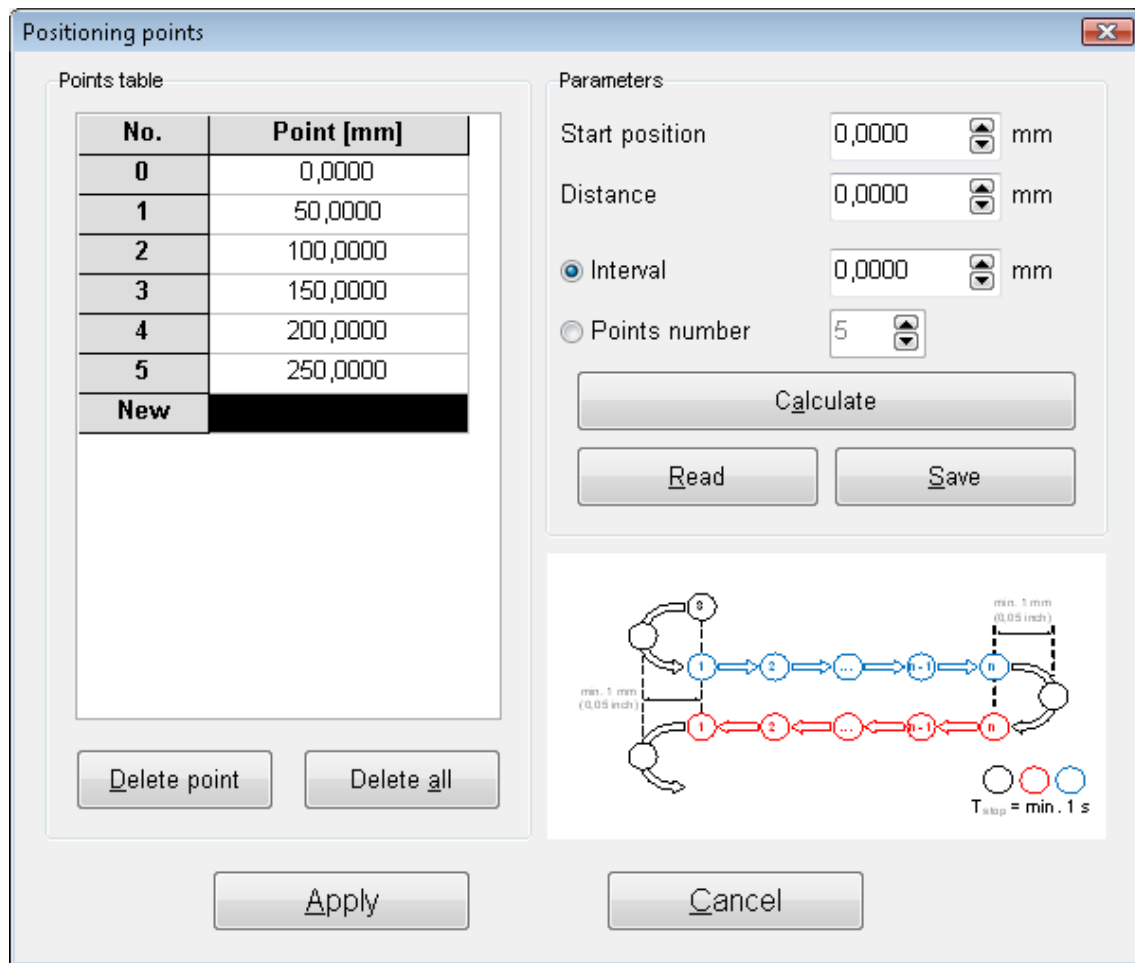
FIG.14.30. POSITIONING POINTS GENERATION WINDOW

x. *Configuration of Positioning measurement*

In the **Rotary encoder** tab in the **Configuration** window the important parameters of the angular positioning measurements can be set (Fig. 14.31). There are four available methods for checking machine's positioning: Linear, Pendulum, Pilgrim standard and Pilgrim effective (buttons in *Measurement method* panel).
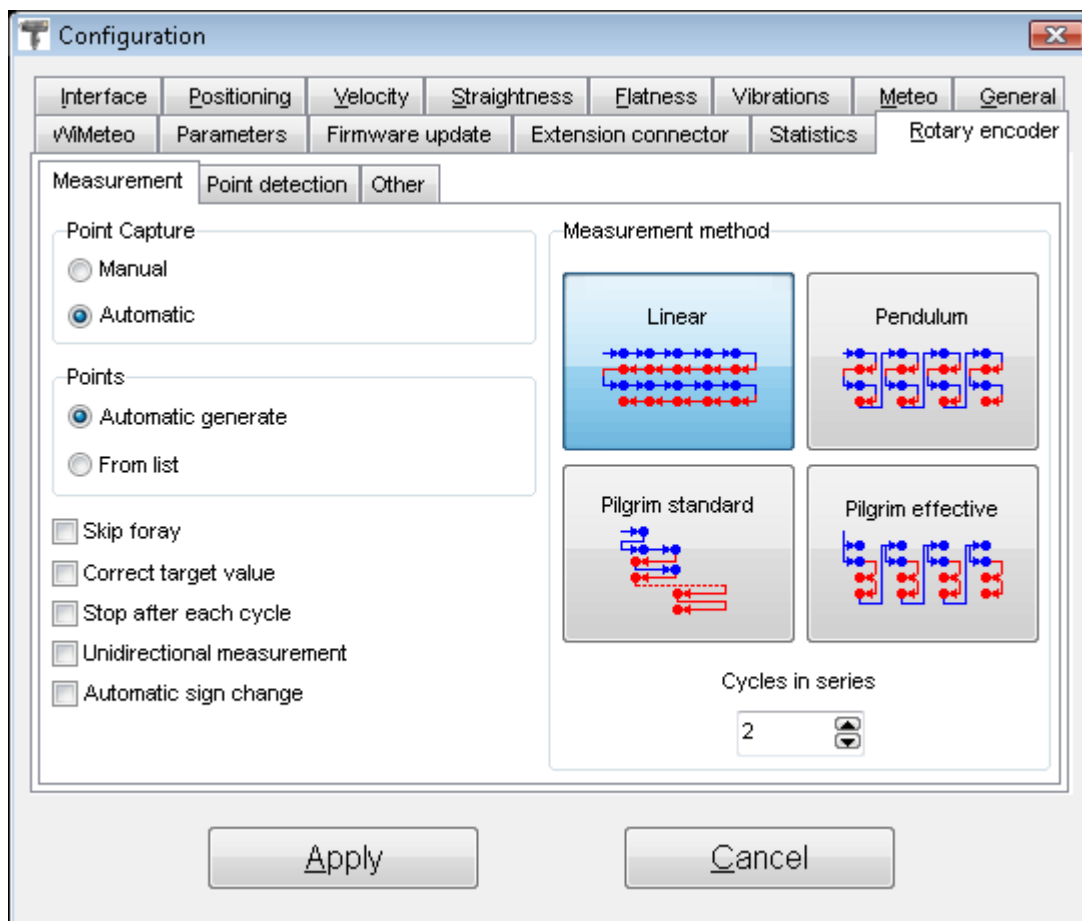
FIG.14.31. LINEAR POSITIONING COFIG WINDOW

In the *Cycles in series* field the number of complete measurements cycles is set. The greater number of cycles is used the better result is achieved.

Max Acceptable Error is an option where the maximal acceptable error level is set. Above this limit, the software generates a warning.

Options **Point capture after** and **Vibrations** are valid only when the automatic point capture is chosen. These options are used to configure a time delay required by the machine to settle the position successfully and the acceptable

level of vibration (level of vibration depends mainly on the measured machine).

Min Points Interval configures minimal distance between positioning points.

xi. Pull down menu – Measurement
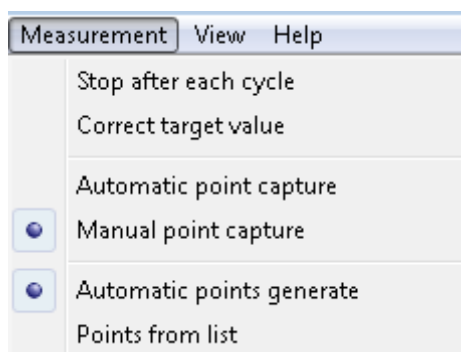
FIG.14.32. POSITIONING PULL-DOWN MENU *MEASUREMENT*

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Measurement menu includes the options related to the measurement process:

Stop after each cycle – if this option is active program breaks the measurement when a measuring cycle is completed; if it is not active the configured number of cycles is executed.

Correct target value – setting this option enables to change an earlier defined distance value of a measuring point during the measurement process. Before the point is captured, appears a window in which a new distance value can be written. In the edit field there are only marked places

after comma what causes that it is not necessary to write the whole distance.

Automatic point capture – program captures measurement points automatically using settings from *Configuration*. In this mode the system itself recognizes the moment of stop, the value of target point, the direction of movement and the series number. Option exclusive with "Manual point capture".

Manual point capture – measured points are captured by the program when a **Manual Capture** button, *Space* key or a remote *Strobe* button is pressed. Option exclusive with "Automatic point capture".

Automatic points generate – positioning points are calculated automatically by the program. Points calculation is performed in first measuring cycle. Option exclusive with "Points from list".

Points from list – when this option is selected on the screen appears a window for positioning points edition. This window enables to write or calculate distance values for positioning points which are compared to measured points during positioning measurement. Option exclusive with "Automatic points generate".
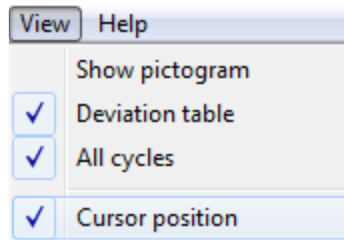
FIG.14.3. POSITIONING PULL-DOWN MENU *VIEW*

View menu is used to switch on or off a **Deviation table** and to switch on schematic diagram of selected measurement method.

d. Measurement procedure

If the system is ready to work, then two digital displays and the gauge of measuring signal level appear on the screen. On the upper display the measured value is shown. On the bottom display the value of the target position (read from data points table or appointed automatically) is shown. Under the displays on the left side there is shown a graph on which the results of measurements are shown. On the right side an **Error Table** can be found. Under the graph three buttons can be found: **Start** - begins the measurement, **Reset Position** – resets the measured value and the button **Main Menu** - re-enters to the Main menu.

In the bottom part of the window a status bar can be found which presents a configuration of the positioning measurements. In the first field the information about the

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points capture method is placed (manual or automatic). The next field informs about number of cycles in series (number of cycles executed one after one, if not active is the option **Stop After Cycle**). In the third field there is shown the information about measurement method selected in the **Configuration**.

The angular positioning measurement requires target positions which define the points where positioning errors are calculated. The target points can be automatically defined during the first cycle in the measurement, or manually written to the list or calculated (**Target Points From List**). Points are detected with 1 degree tolerance in automatic mode. In case of manual mode accuracy is also defined.

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During the measurement points can be captured automatically or manually as described earlier in this chapter.

i. *Rules of automatic positioning measurement*

For correct operation of the automatic positioning measurement option below rules should be followed:

1) The time of machine stand still duration in the positioning point must be no less than 1 second – default value (this can be changed in the *Configuration->Positioning->Point detection->Point capture after*),

2) Vibrations of the target should be less than 10 arcsec - default value (this can be changed in the *Configuration->Positioning->Point detection->Vibrations less than*),

3) Backlash compensation move of the machine should exceed 1 arcmin.

If vibrations are too large and system does not capture points, the option Manual Capture should be switched on in the Measurement menu.

ii. Remarks on measurements and data analysis
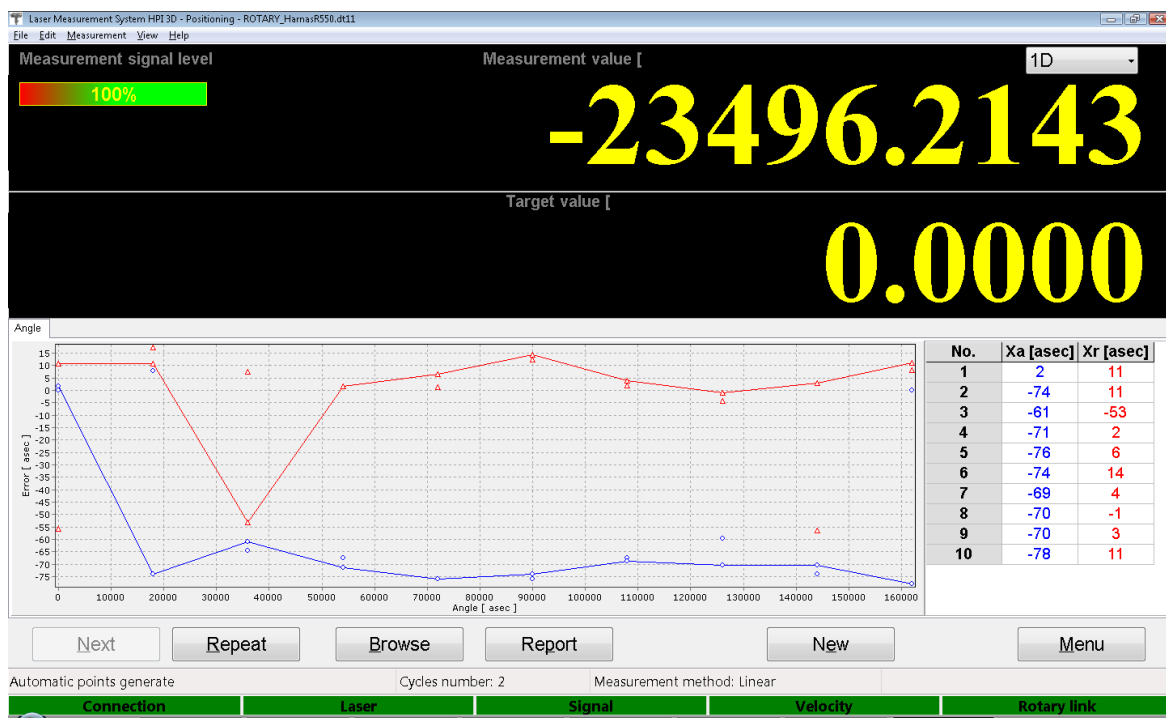
FIG.14.34. POSITIONING WINDOW AFTER FINISHING A FULL MEASUREMENT CYCLE

Examination of angular positioning of machine consists of at least 2 measuring cycles.

In every cycle the measured machine rotates the retro-reflector for programmed distance clockwise and counterclockwise.

After each rotation the machine should stop for a short time (at least one second).

The measured angle by the laser system is saved in the table of results.

After one cycle, if **Stop after each cycle** is set or after the whole measurement process, the window with results appears (figure 14.34).

Buttons **Remove** and **Add** can be used to remove or add the measurement cycle. It is possible to change the measuring cycle in which accidental error is possible. **Browse** button opens data browsing window (figure 14.33) where each data cycle can be viewed and analyzed.

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FIG.14.35. DATA BROWSING WINDOW

Both from main positioning window and from data browsing window the measurement report can be generated. If at least two series of measuring cycles are completed, statistical calculations can be performed and the report can be generated. In order to get the final report the **Report** button has to be pressed. The screen of the computer after pressing the **Report** button is presented in fig. 14.35.

FIG.14.36. ANGULAR POSITIONING REPORT WINDOW

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The positioning results are presented on the graph and in the **Results** panel. This panel is also used to set measurement data processing parameters. The norm defines a statistical method used in calculations and can be chosen from a pull-down list. Norm selection causes recalculation of the results. Limit values for measured machine parameters are presented in this panel. They are assigned to the machine that is chosen from **Machine** pull-down list. If the error value exceeds limits for the machine, this error is displayed in red.

Under the graph there are: buttons used for report **Preview**, **Print** the report, change of the graph **Parameters**, and return to the previous window.

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The axis scale can be changed using **Axis Scale** (automatic scaling or assignment, minimum and maximum values) option available by right mouse click on the graph.

The report can be generated in a simplified or an extended form. The selection window is shown each time the **Preview** or **Print** buttons is pressed. The simplified version consists of three pages: the title page, the results page and the chart page. The logo on the title page can be changed in the **Configuration**. In the Extended Report additional pages with measurement results are added. The number of additional pages depends on the number of measurement points.

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15. CONNECTING LASER HEAD TO MACHINE

a. General Description

The main functionality of the HPI-3D are measurements of machine geometry with the use of a PC computer connected over BT or USB interface. The functionality can be significantly enhanced by the **Extension Connector** available at back of the laser as shown in the figure 15.1.

With the use of signals available on this connector it is possible to use the laser as a standalone device. The main applications are:

- Monitoring the measured shift with an external counter;
- Using the laser as a feedback part of a machine control loop;
- Driving with the laser a motor through an external motor driver;

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- Changing behavior of the laser by connecting different sensors (like end sensor or zero-crossing sensor).
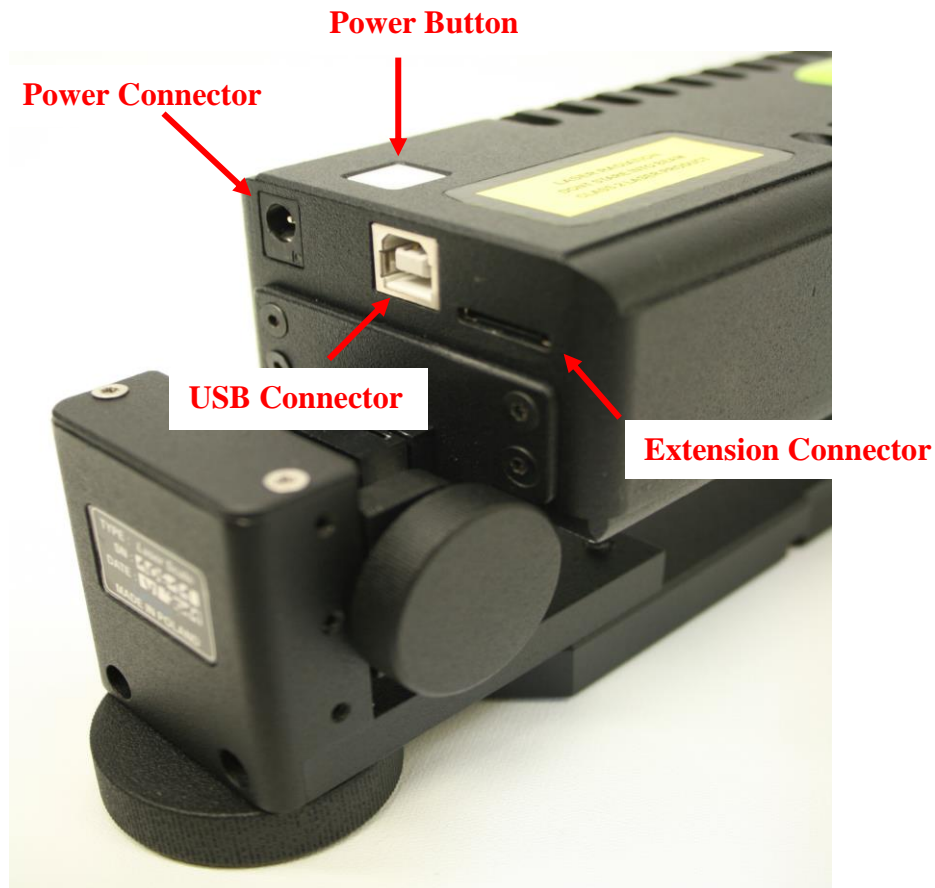
FIG.15.1. CONNECTIONS OF THE HPI-3D.

b. Extension Connector

i. Extension Connector pinout

The **Extension Connector** available at the back of the laser head is a miniature Hirose Connector LX40-20P CL No. CL245-0017-0. The pinout of this connector is shown in the table 15.1.

Pin number		Function
1		24V / 100mA Supply
2-7	Digital IO	Software configurable Input/Output
8	Digital Output	• Negative output of Differential B signal pair (Digital AquadB Output) • Negative output of Differential Sign signal pair (Shift/Sign Output)
9	Digital Output	• Negative output of Differential A signal pair (Digital AquadB Output) • Negative output of Differential Module signal pair (Shift/Sign Output)
10	Digital Output	• Positive output of Differential B signal pair (Digital AquadB Output) • Positive output of Differential Sign signal pair (Shift/Sign Output)
11	Digital Output	• Positive output of Differential A signal pair (Digital AquadB Output) • Positive output of Differential Module signal pair (Shift/Sign Output)
12		5V /150 mA Power Supply
13	Analog Output	Negative output of Differential Cosine signal pair (Sine/Cosine Output)
14	Analog Output	Negative output of Differential Sine signal pair (Sine/Cosine Output)
15	Analog Output	Positive output of Differential Cosine signal pair (Sine/Cosine Output)
16	Analog Output	Positive output of Differential Sine signal pair (Sine/Cosine Output)
17-20		Ground

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TAB.15.1. EXTENSION CONNECTOR PINOUT.

There are four groups of signals available on the Extension Connector:

- Power supply pins - +24VDC, +5VDC and GND pins are available for user application;

- Digital IO pins – functionality configurable through HPI Software – see later in this Chapter;

- Encoder type Digital Output pins – functionality partially configurable through HPI Software; Used for digital output of A-Quad-B or Shift/Sign output;

- Encoder type Analog Output pins – analog output in SinA/CosB format (see later in this Chapter).

ii. Extension Cable EX1

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FIG.15.2. EXTENSION CABLE EX1.

Because the Extension Connection is of high integration scale it is recommended to use the Extension Cable EX1 – figure 15.2.

The Cable has on one end the appropriate miniature Hirose connector that should be inserted into the Extension Connector while on the other end there is a standard female three-row DSUB15 connector. The signals available on the DSUB connector are described and can be configured in the HPI Software in *Configuration->Extension Connector* panel.
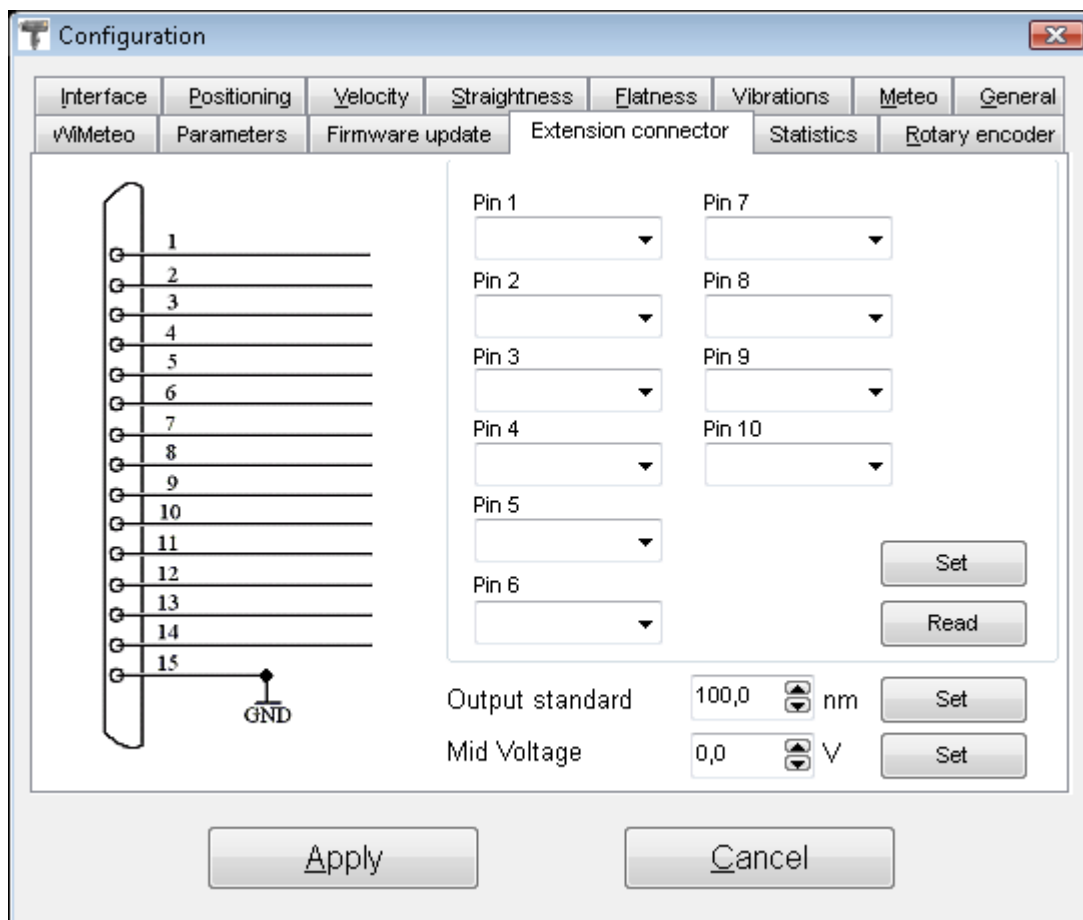

FIG. 15.3. CONFIGURATION WINDOW – EXTENSION CONNECTOR PANEL

Pin number		Function
1-6	Digital IO	Software configurable Input/Output
7	Digital Output	• Negative output of Differential B signal pair (Digital AquadB Output) • Negative output of Differential Sign signal pair (Shift/Sign Output)
8	Digital Output	• Negative output of Differential A signal pair (Digital AquadB Output) • Negative output of Differential Module signal pair (Shift/Sign Output)
9	Digital Output	• Positive output of Differential B signal pair (Digital AquadB Output) • Positive output of Differential Sign signal pair (Shift/Sign Output)
10	Digital Output	• Positive output of Differential A signal pair (Digital AquadB Output) • Positive output of Differential Module signal pair (Shift/Sign Output)
11	Analog Output	Negative output of Differential Cosine signal pair (Sine/Cosine Output)
12	Analog Output	Negative output of Differential Sine signal pair (Sine/Cosine Output)
13	Analog Output	Positive output of Differential Cosine signal pair (Sine/Cosine Output)
14	Analog Output	Positive output of Differential Sine signal pair (Sine/Cosine Output)
15		Ground

TAB.15.2. EXTENSION CABLE EX1 PINOUT.

In the Table 15.2 there shown the default pinout of the Extension Cable EX1. Comparing this table with Table 15.1 it

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can be seen that the only thing lacking on the EX1 are the power pins. All signal pins visible on the Extension Connector are as well accessible on the Extension Cable.

iii. Encoder type outputs

On the output of the HPI-3D there are available two types of encoder outputs: digital (A-Quad-B format, TTL) and analog (SinA/cosB format, 1Vpp). Both types are available at the same time on the Extension Connector and the EX1 cable – see figure 15.4.

The edges of the digital signals and the sinusoidal wave of the analog output appear on the connector in real time after the movement of an optical element is detected by the laser head. The delay between measured movement and output signals is not greater than 10 μs.
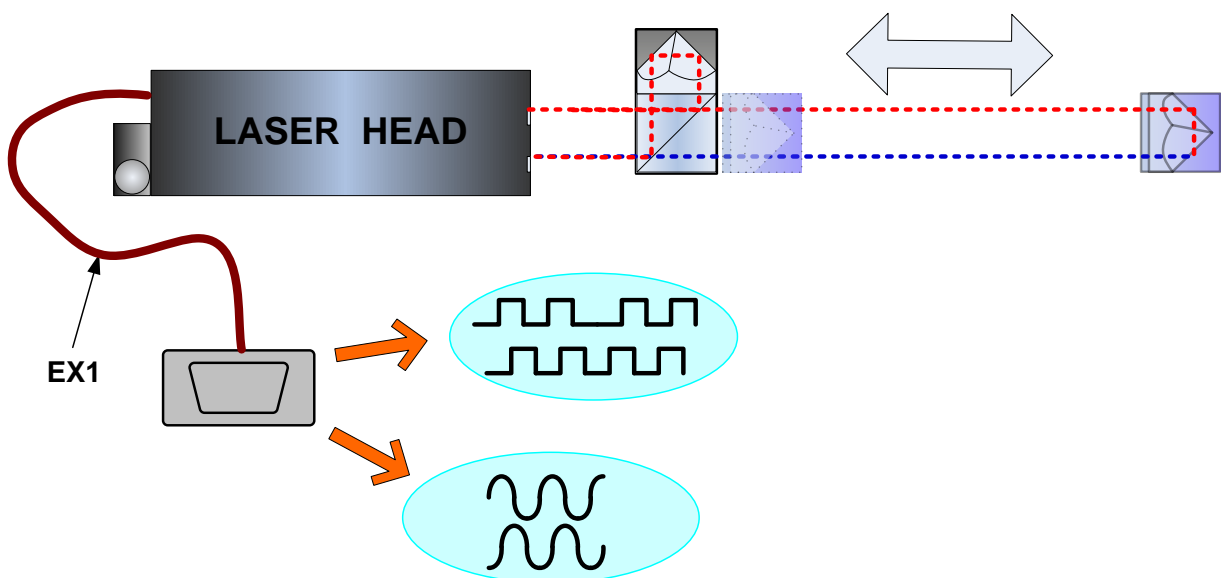
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FIG. 15.4. ENCODER SIGNAL GENERATION

The output signals are in real time compensated versus environmental parameters change. The process is shown schematically in the figure 15.5.
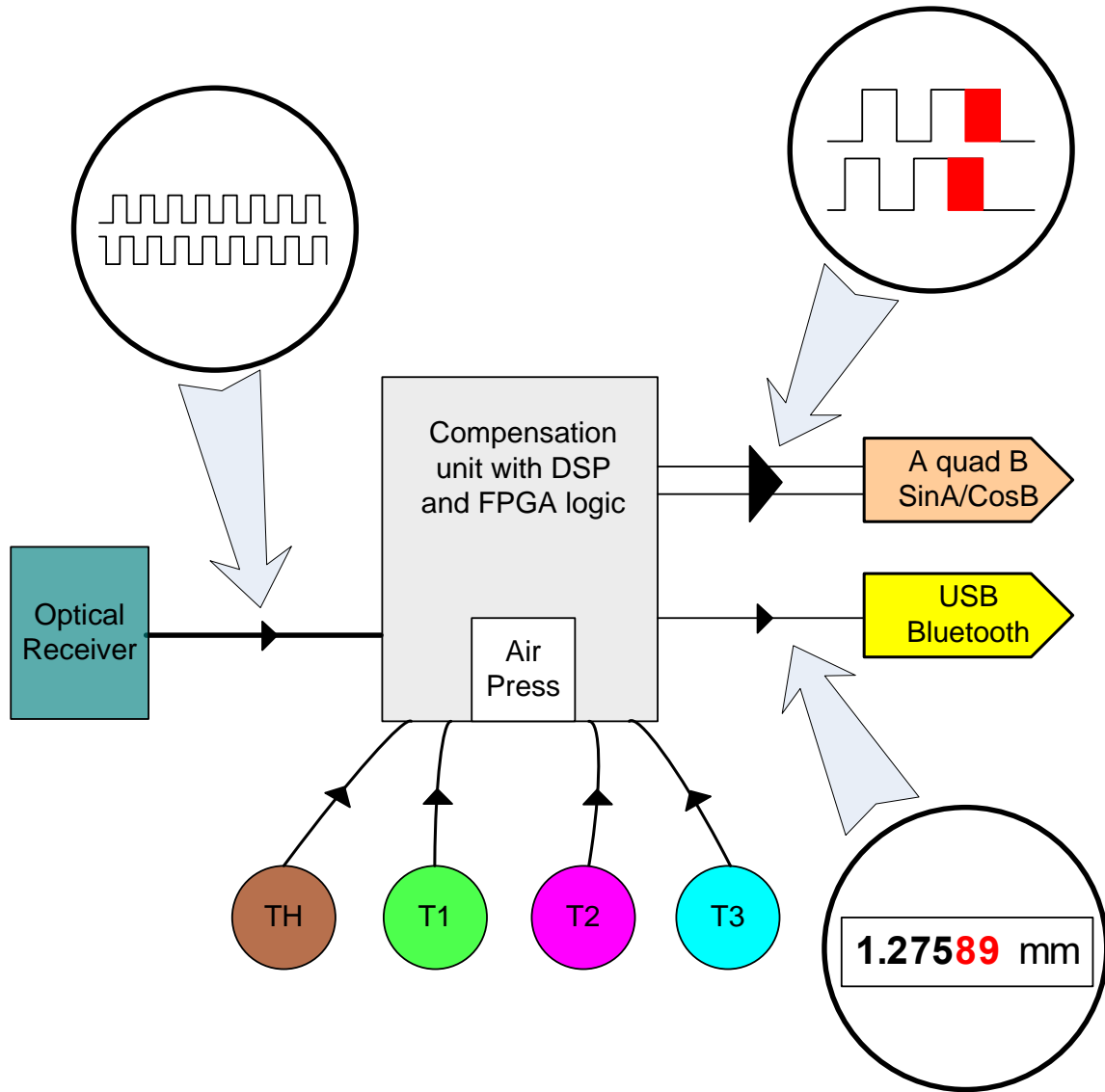

FIG. 15.5. REAL TIME COMPENSATION MECHANISM

The detected optical signal is read by the main processor inside the laser head. The processor receives also data from environmental sensors (TH, T1, T2 and T3) and uses advanced algorithms to calculate the corrections of the input

signal. The calculations are performed each 10 μs. The data from each sensor are received each one second.

The corrected distance value is then sent over USB or Bluetooth interfaces to the PC computer. At the same time the main processor communicates with a special coprocessor for generating encoder type signals. The coprocessor is responsible for adding corrections to the original optical signal and for generating the output signal in a desired standard.

> The standard of the output encoder type signals can be changed by the user in *Configuration->Extension Connector->Output Standard* box.
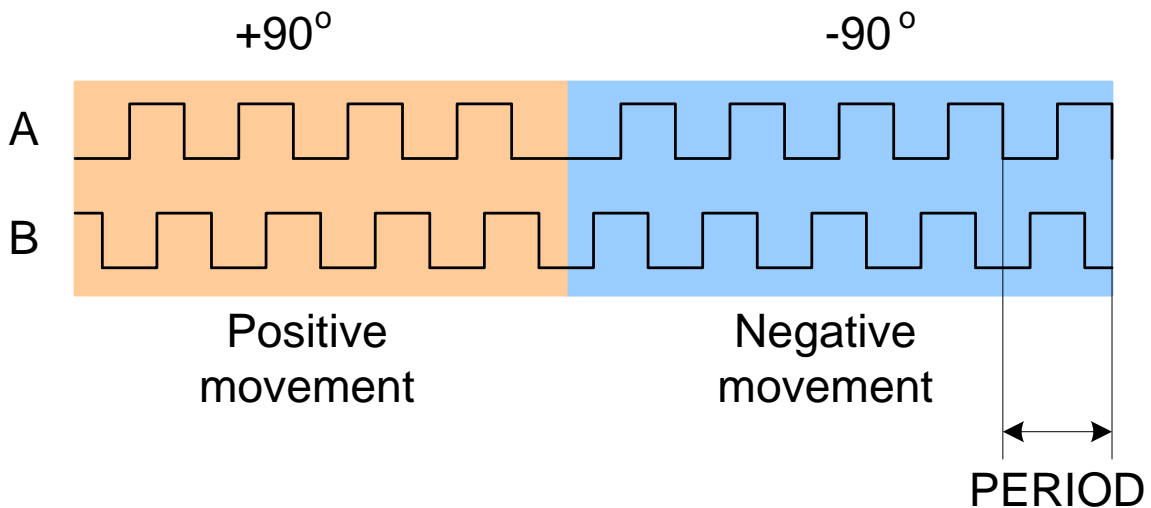
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FIG. 15.6. OUTPUT SIGNAL – A-QUAD-B FORMAT

The digital A-Quad-B signal consists of two digital signals A and B shifted in phase by +90° or -90° depending on the direction of movement (figure 15.6). The signals are in

5V CMOS standard and on the connector there are also available negated A and negated B signals – so a differential cable can be used. The PERIOD of the signal as shown in the figure 15.6 is four times greater than the *Output Standard* set in the *Configuration*.

For example if the *Output Standard* is set to 100 nm then the full cycle on A and B outputs will be generated after the measured object shift of 400 nm is detected.
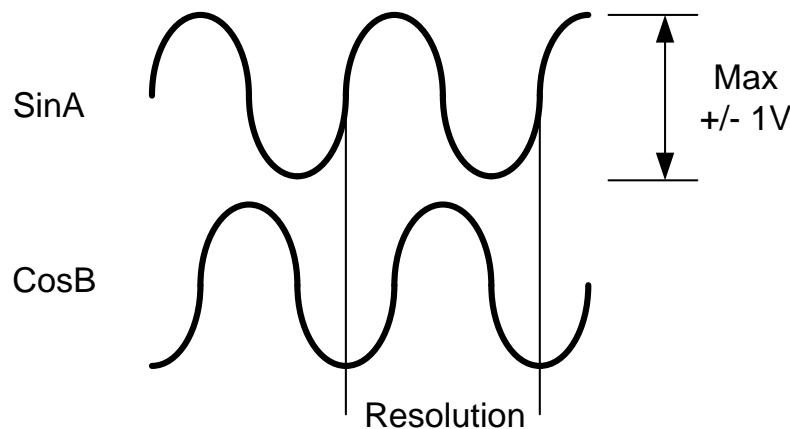

FIG. 15.7. OUTPUT SIGNAL – SINA/COSB FORMAT

The analog sinA/cosB signal consists of two analog signals sinA and cosB shifted in phase by +90° or -90° depending on the direction of movement (figure 15.7). The amplitude of the signals is 1Vpp single ended and 2Vpp differentially. The differential signals are available as a combination of sinA - /sinA and cosB - /cosB signals. The RESOLUTION of the signal as shown in the figure 15.7 is

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forty times greater than the *Output Standard* set in the *Configuration*.

For example if the *Output Standard* is set to 100 nm then the full cycle on sinA and cosB outputs will be generated after the measured object shift of 4 µm is detected.
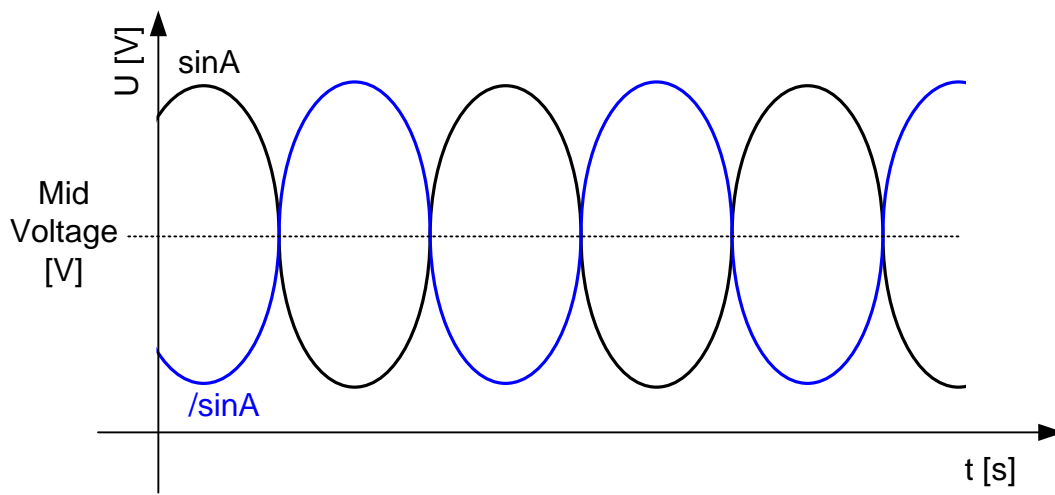

FIG. 15.8. OUTPUT ANALOG SIGNAL

The output drivers deliver only positive voltages thus the *Mid Voltage* value of both output signals is important. This voltage can be set in *Configuration->Extension Connector->Mid Voltage* as shown in the fig. 15.3 and should exceed 1V.

The maximum frequency of analog output signals (sinA, cosB) is limited to 2.4 MHz.

The maximum frequency of digital output signals (A, B) is limited to 24 MHz.

c. HPI-3D in a machine control loop

Because of the encoder type signals available at the *Extension Connector* it is possible to use the HPI-3D in a machine control loop. The laser configured with the linear optics can be used as a very high-precision position encoder.
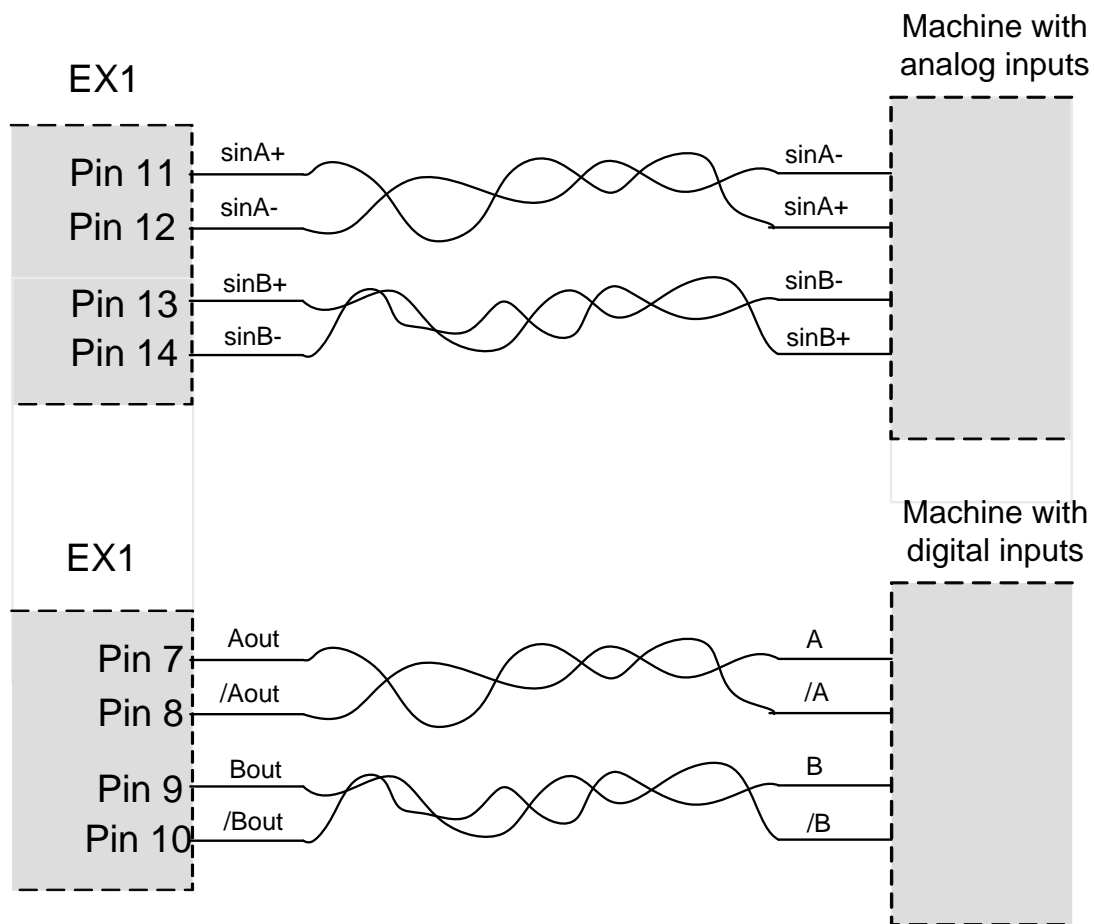
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FIG. 15.9. CONNECTING LASER HEAD TO A MACHINE

Method of connection depends on the type of inputs of the machine as it is shown in the figure 15.9.

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16. CONFIGURATION

General Description

All configuration options of the interferometer are available in the **Configuration** located in the **Main Menu** or in each measurement option in pull down menu *Edit->Configuration*.

In the **Configuration** (Fig. 15.1) the user can configure the behavior of the HPI-3D during measurements and the appearance of the *HPI Software*. For example the language of the program can be changed - after installation the program opens in the language of the installed Windows system. Other panels are used to configure parameters of all types of measurements available with the system.

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Panel *Interface*

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In the *Interface* panel (fig. 16.1) the user can force the software to connect or reconnect with the laser over chosen interface. In order to do this the user should choose the right communication interface (USB, Bluetooth or Simulator) and press Reconnect. After a while an appropriate message will be displayed (with communication success or failure).
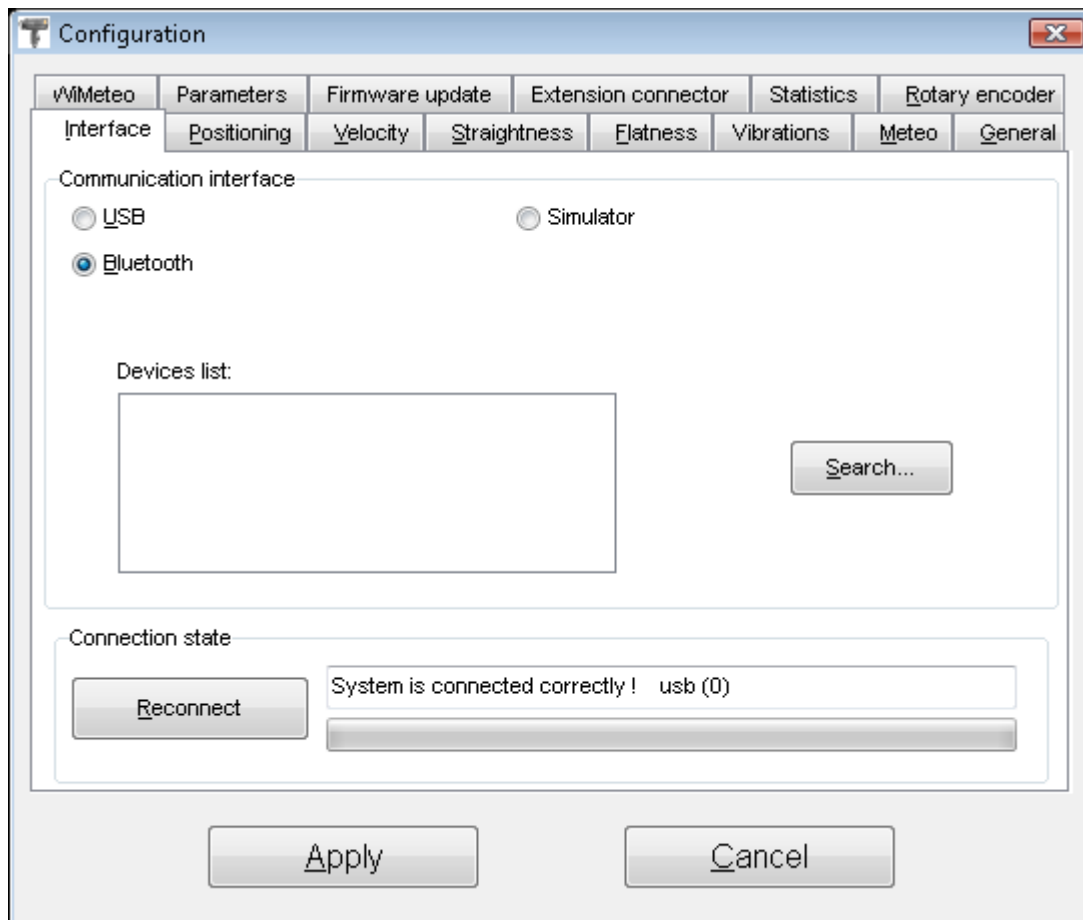

FIG. 16.1. CONFIGURATION WINDOW – INTERFACE PANEL

Panel *WiMeteo*

The options available in the *WiMeteo* panel (fig. 16.2) are used to control the operation of the wireless module. It is

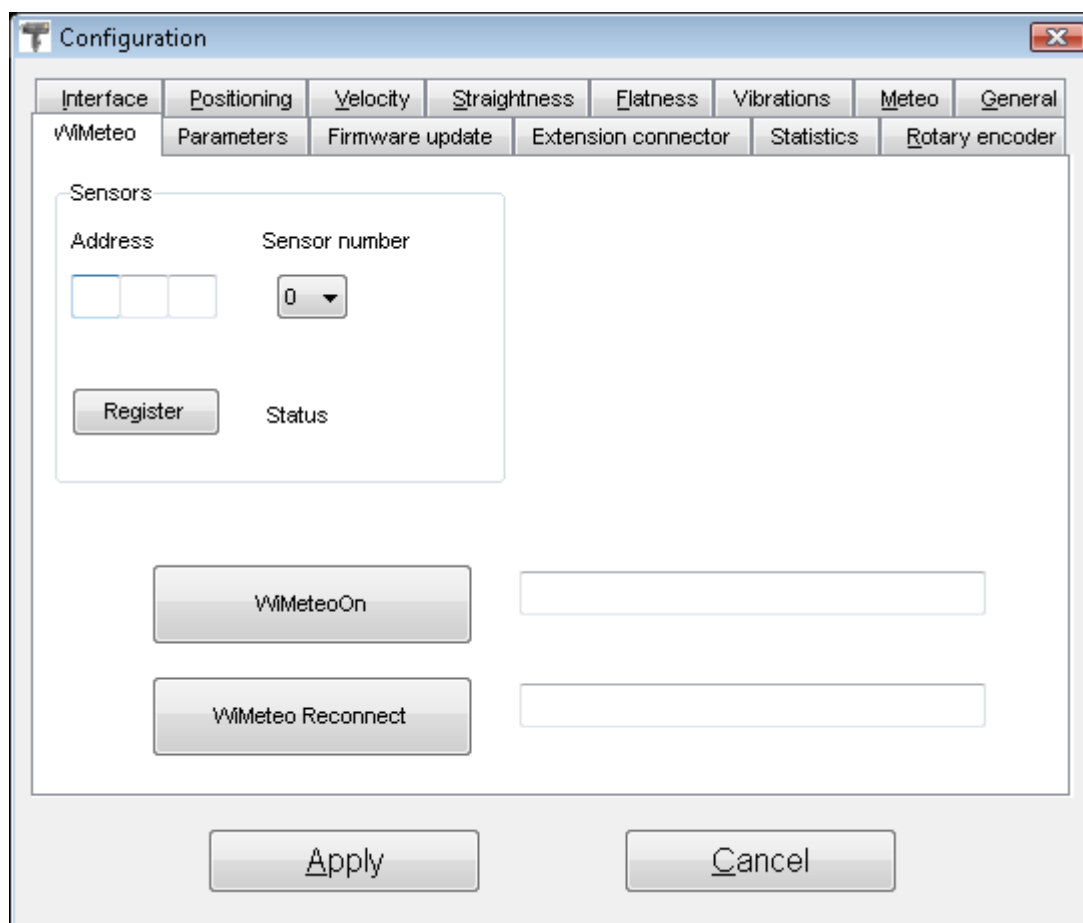responsible for communication with environmental sensors and rotary encoder.

FIG. 16.2. CONFIGURATION WINDOW – WIMETEO PANEL

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It is possible to switch the whole module on (if it went accidentally off) by pressing the **WiMeteoOn** button or to force the sensors to search for the new connection channel with **WiMeteo Reconnect** button.

The reconnection takes usually between 2 and 3 minutes.

In the *Sensors* part of the WiMeteo panel the user can register a new sensor. The address of the registered sensor should be placed in the Address field, the sensor number should be chosen and then the Register button should be pressed. Sensor number 0 is TH sensor, while sensors numbered 1-3 are respectively sensors T1-T3.

This operation should be done carefully. Putting wrong address in the Address field results in loosing proper reading of the changed sensor.

Panel *Parameters*

In Parameters Panel (fig. 16.3) it is possible to set parameters of used optical components. **Base length** is the size of the carriage of the Angular Retroreflector RK1 element. The standard size is 10cm.

Wollaston Coefficient is a parameter of the Wollaston Prism WP2 element. The coefficient is delivered with every WP2 element. This field is password protected to avoid inadvertent modification of the parameter. The password is: "54321".

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Right angle prism Error is the parameter of the Right Angle Etalon REW element. The coefficient is delivered with every REW element. This field is password protected to avoid inadvertent modification of the parameter. The password is: "54321".
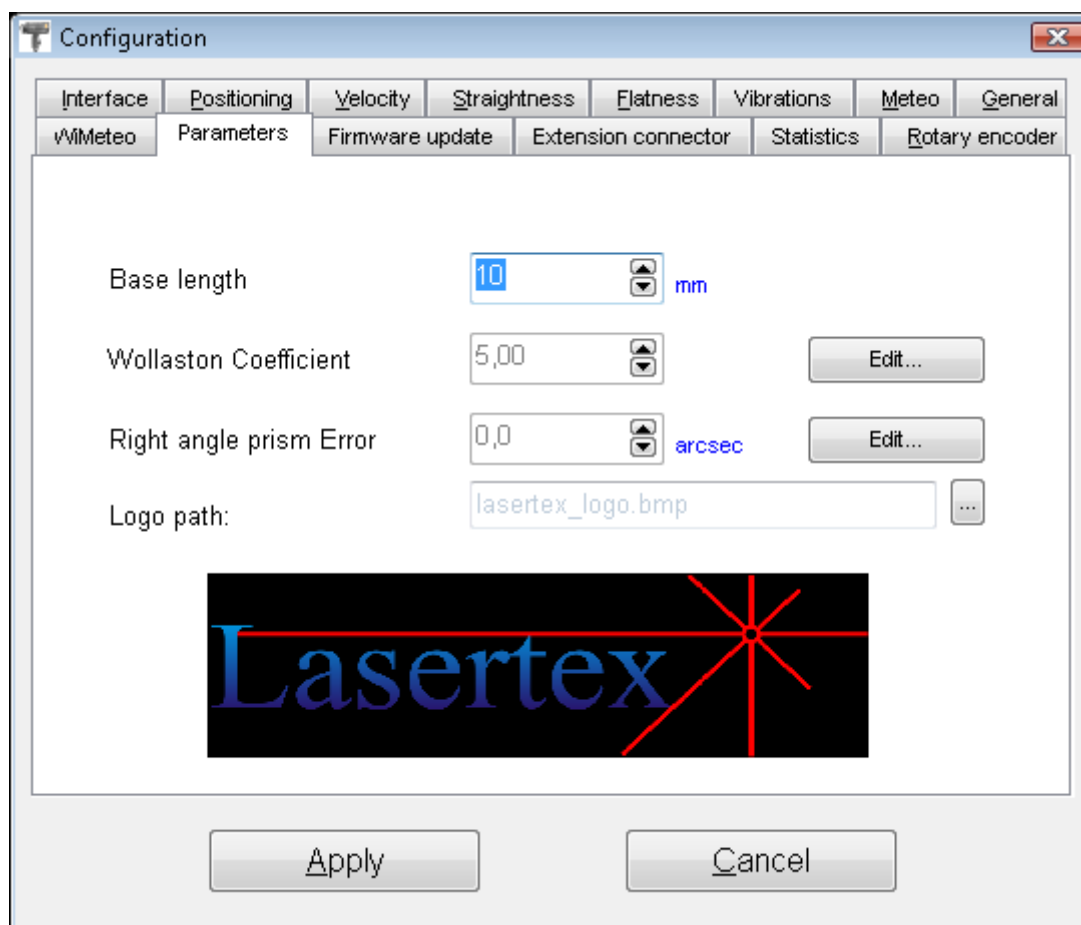

FIG. 16.3. CONFIGURATION WINDOW – PARAMETERS PANEL

On the front page of every report generated by the HPI Software there is placed the logo. Its path is set in the **Logo path** field. The file should have bmp file format.

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Parameters: **Base length, Wollaston Coefficient** and **Right angle prism Error** should be set to proper values after EVERY installation of the *HPI Software* on the new computer or in the new folder.

Panel *General*

The HPI Software can be easily tailored to different languages. This can be done by changing the language in the **Language** box in the General Panel (fig. 16.4). All language files are stored in the HPI_Software/Languages catalog on the hard drive and can be modified with the use of lngeditor.exe application which is present in the same catalog.

The resolution of the measurements can be modified in the **Precision** box. For laboratory use the *Extended* precision should be chosen. In this case all results are displayed with the highest possible precision. For normal use the *Normal* option should be chosen.
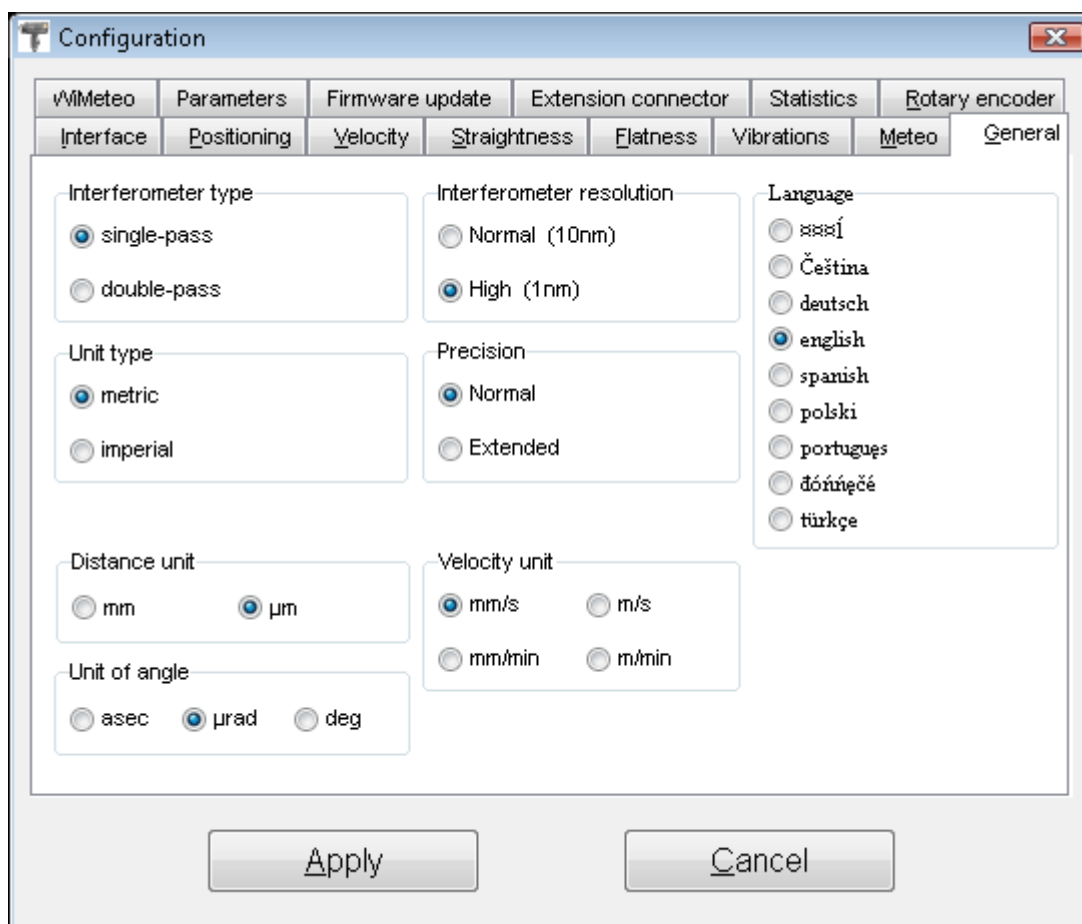
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FIG. 16.4. CONFIGURATION WINDOW – GENERAL PANEL

The double-pass option in the **Interferometer type** box should be chosen when the flat mirror type (so called double pass) interferometer is used in the optical path. In all other cases, i.e. for all other types of optical components the single-pass option has to be selected.

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Improper choice of the **Interferometer type** option results in large measurement error!

Other options present in the *General Panel* are used to change units for different measurements types.

Panel *Meteo*

The options available in the *Meteo* panel (fig. 16.5) are used for further configuration of environmental parameters. It is possible to change units of temperature and pressure (**Temperature unit** and **Pressure unit** boxes).
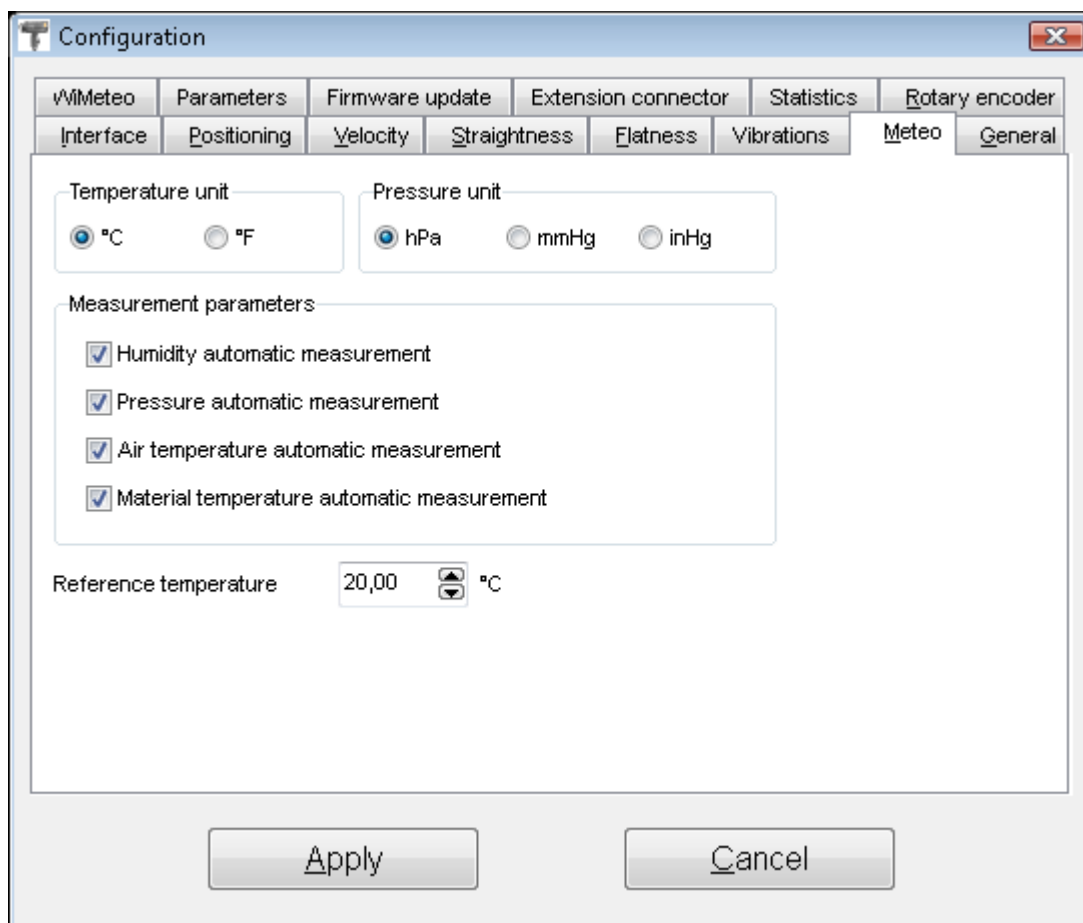
FIG. 16.5. CONFIGURATION WINDOW – METEO PANEL

Automatic measurements of selected parameters can be switched on or off in the **Measurement parameters** box.

It is also possible to change the **Reference temperature** which is the temperature the measured machine is corrected to. Usually 20.00°C is set.

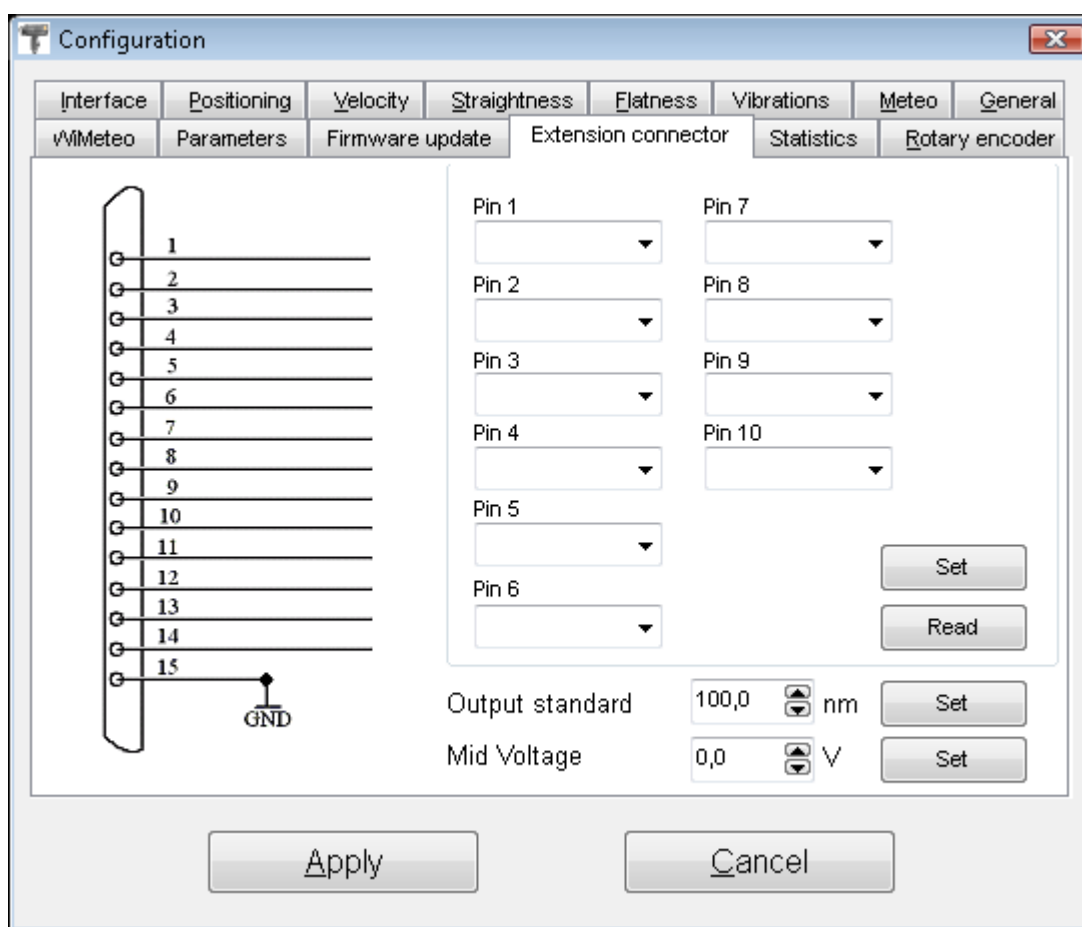## Panel *Extension Connector*

FIG. 16.5. CONFIGURATION WINDOW – EXTENSION CONNECTOR PANEL

The options grouped in the *Extension Connector* panel (fig. 16.6) are used to control the operation of the extension connector available on the back panel of the laser.

The signals described in the *Extension Connector* panel are available on the DB15 connector of the extension cable (not present in the standard delivery). The extension connector pinout is described in the *Technical Data* chapter.

On the left side of the panel there is visible the schematic drawing of the connector with the description of the functionality of the pins. The functionality can be modified with the list buttons in the right part of the panel. Each modification has to be approved by pressing **Set** button.

In the bottom part of the panel there are two parameters modifying the output analog and digital signals (i.e. **A, B, sinA** and **sinB**). The **Output standard** option defines the resolution of digital signals (A, B) – each edge of the digital signal means the measured movement of **Output standard** value.

The resolution of the analog outputs is 40 x **Output standard**, i.e. one full period of the sinA or sinB signal means the measured movement of 40 x **Output standard**.
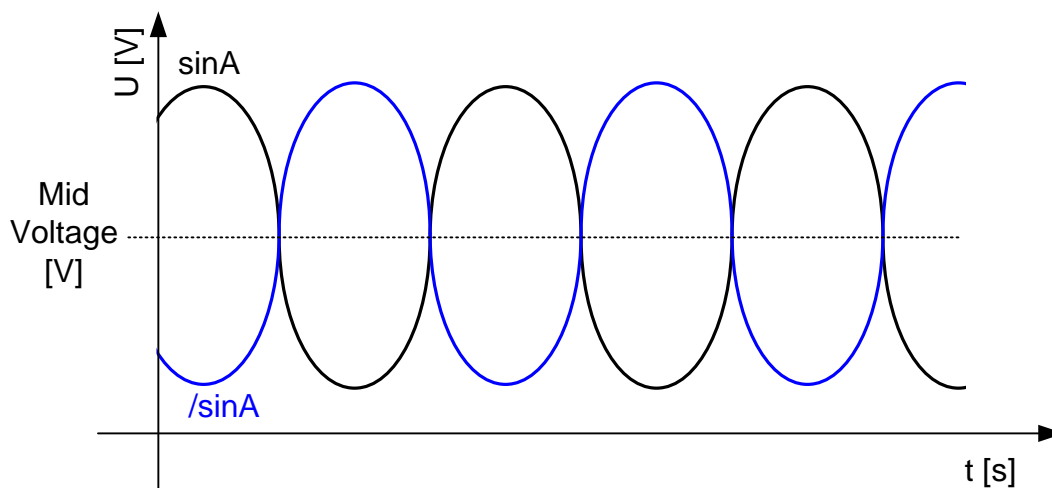
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FIG. 16.6. OUTPUT ANALOG SIGNAL

The **Mid voltage** option defines the medium value of the analog outputs as shown in the figure 16.6.

The value set as **Mid voltage** should be higher then 1V and lower than 4V.

Panel *Statistics*

The data visible in the *Statistics* panel (fig. 16.7) are for information only. **Laser work time** shows how long the laser tube was switched on during its lifetime. After 20000 hours the laser should be shipped to factory for testing and calibration unless recommended calibration times are used.
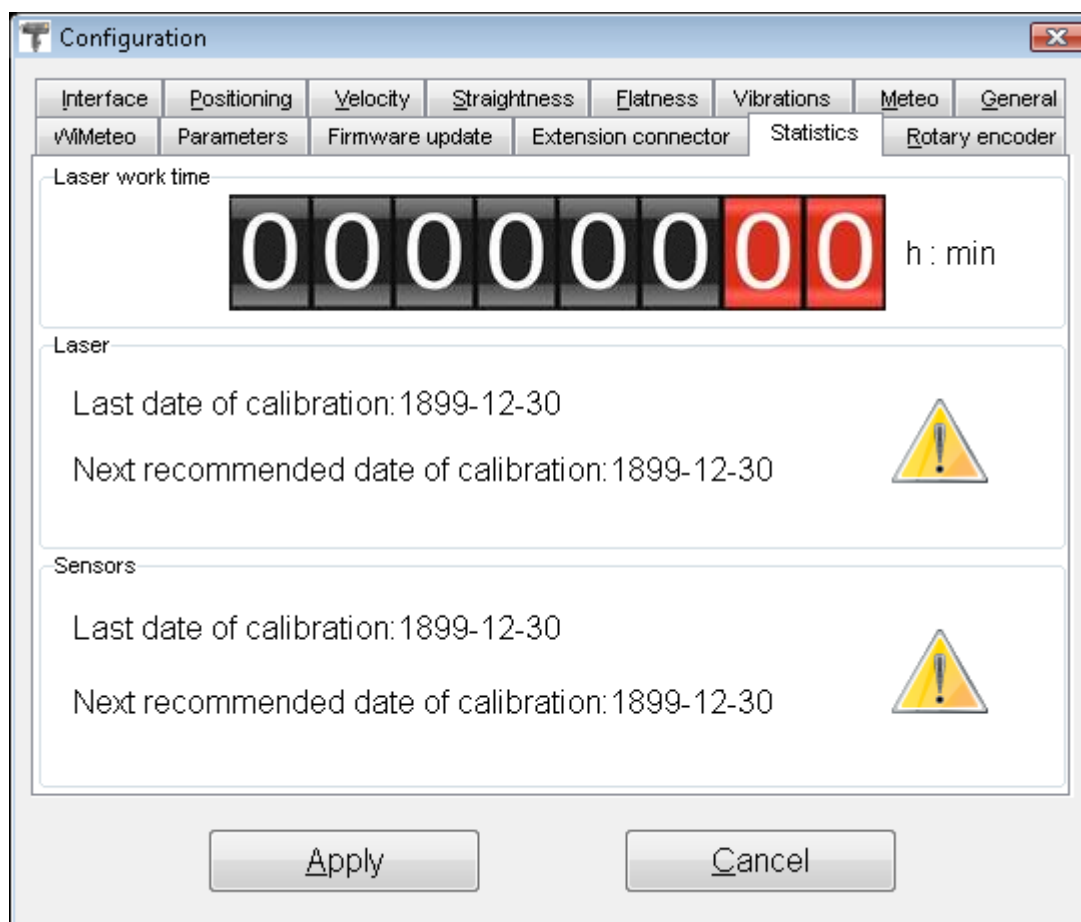
FIG. 16.7. CONFIGURATION WINDOW – STATISTICS PANEL

Panel *Firmware update*

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The HPI-3D device is fully software defined, which means that the digital processing of the signals is a very important part of the device. All internal digital modules are available through the USB interface and their firmware can be easily modified in the **Firmware update** panel.
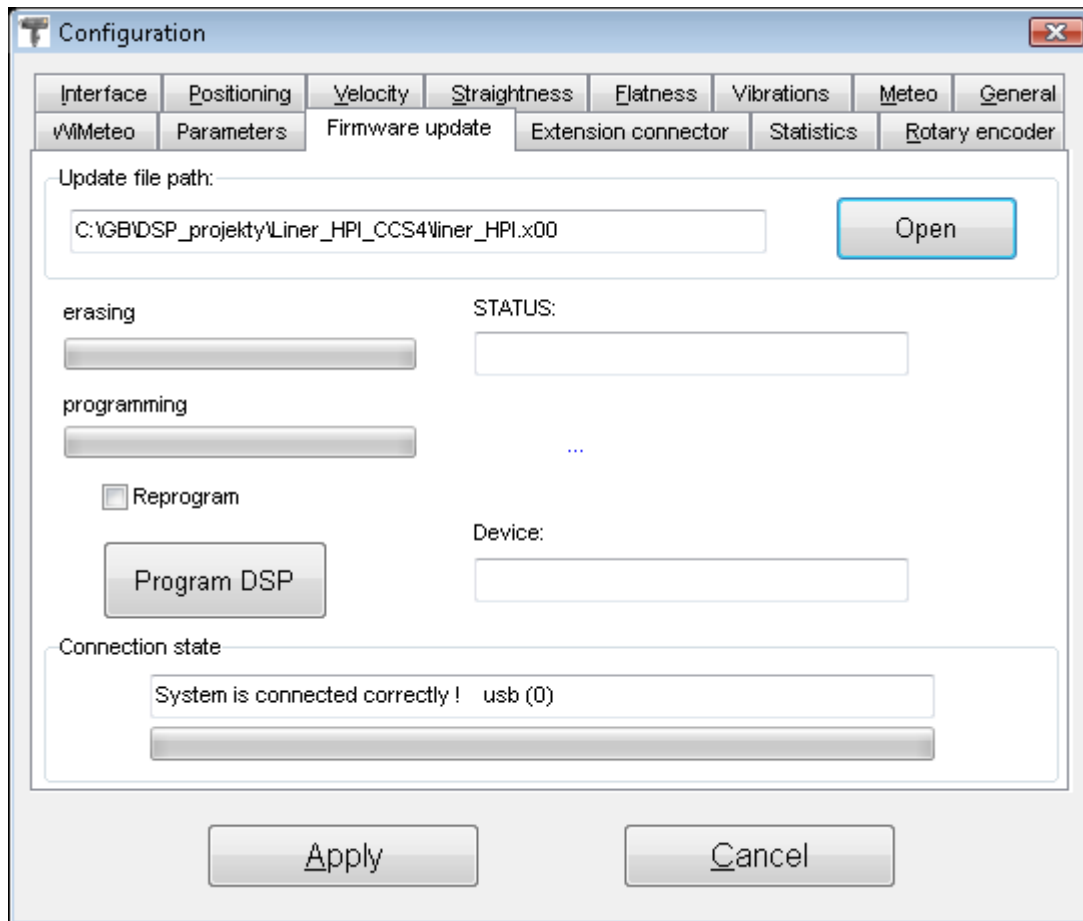
FIG. 16.8. CONFIGURATION WINDOW – FIRMWARE UPDATE PANEL

If firmware becomes available then below procedure should be followed:

1. Connect laser head by USB interface
2. Start HPI Software
3. Enter Configuration->Firmware update
4. Press **Open** button and choose the firmware file (with .x00, .mcs, .zig, or .hex extension)
5. Press **Program** button
6. Wait for the device to be programmed – up to 10 minutes

Other panels

Other panels available in the Configuration are described in the respective chapters:

- panel *Positioning* in Chapter 5;
- panel *Velocity* in Chapter 6;
- panel *Straightness* in Chapter 7;
- panel *Flatness* in Chapter 8;
- panel *Vibrations* in Chapter 12;
- panel *Rotary Encoder* in Chapter 14.

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17. PRINCIPLES OF OPERATION

a. The rules of laser displacement measurements

Displacement measurements with the use of a laser interferometer allow obtaining the accuracy of a displacement measurement of 0.4 ppm in air and 0.02 ppm in vacuum. The interferometer was first built by A.A. Michelson in 1881. The simplified schematic of the interferometer is shown in the fig. 17.1.

Coherent light beam falls on a semi-transparent mirror. This mirror splits the light into two beams. The first goes to the reference arm and reflects from the reflector Z_1; the second goes to the measurement arm and reflects form the reflector Z_2. The reflected beams meet again on the detector. Because these beams come from the same, coherent, source, they will interfere. When the moving reflector is being displaced, the frequency of the reflected beam in the measurement arm changes. The detector counts the

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frequency difference between reflected beams - f_D (see fig. 17.1). The measured value of the displacement is calculated according to

$$L = f_D * \frac{\lambda}{2} = N * \frac{\lambda}{2}$$
(1)

Where: N – number of pulses,

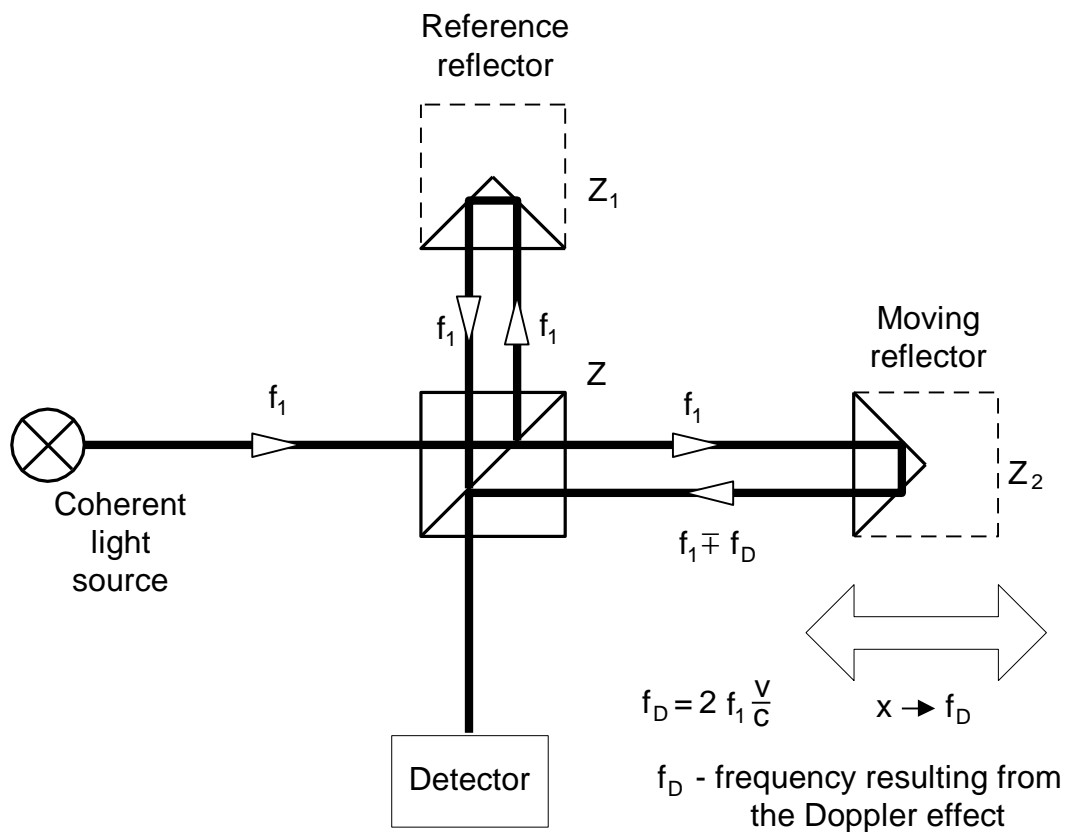λ - light wavelength.

FIG.17.1. THE MICHELSON INTERFEROMETER.

b. The construction of real interferometers

The main disadvantage of Michelson interferometer results from the fact that the detector cannot determine, whether f_D is negative or positive thus, from the measurements the displacement of the moving reflector without the sign is obtained. Currently there are widely used two methods that allow getting also the direction of the movement. Depending on the number of light frequencies (wavelengths) used in the interferometer, the first is called *homodyne* (one frequency) and the second *heterodyne* (two frequencies) method.

In the homodyne method, shown on figure 17.2, as a coherent source of light a linearly polarized laser is used. If it is two-mode laser (i.e. it generates two wavelengths) than one mode must be cut off with the use of a properly set polarizer. The polarizing splitter splits the light beam from the laser into two beams polarized vertically (90°) and horizontally (0°). The former is directed to the measurement arm and the latter to the reference one. The frequency of the beam in the measurement arm changes with the movement of the moving reflector. The polarization of the reflected beams is changed to circular with the use of a λ/4 waveplate. After 0° and 45° polarizers, two signals shifted in phase are obtained. The phase shift is +90° when the measurement arm moves to and -90° when it moves from the laser.

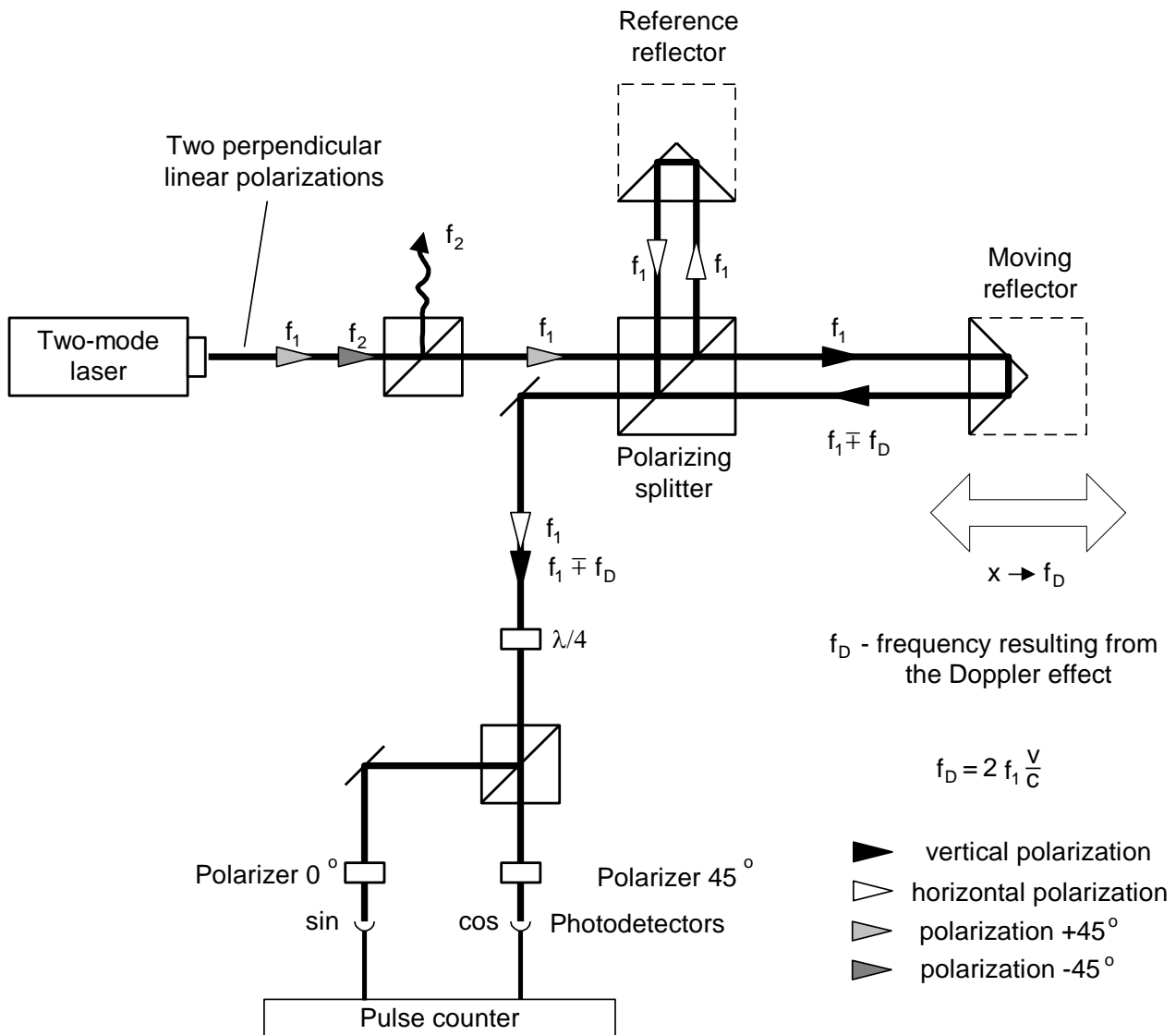**17**

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FIG.17.2. THE BLOCK DIAGRAM OF AN INTERFEROMETER WORKING ACCORDING TO THE HOMODYNE METHOD

In the heterodyne method, shown on figure 17.3, two laser frequencies are used. Therefore a two-frequency laser is needed, e.g. a Zeeman laser. A two-mode laser is not suitable for the heterodyne method interferometer, because the difference between f_1 and f_2 is usually too high for an electronic counter. The output beam of a Zeeman laser consists of two circularly polarized beams, one polarized

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leftward and the second rightward. A λ/4 waveplate changes circular polarization to linear. The main difference between two described methods is that in the heterodyne one the beam frequency in reference arm differs from the beam frequency in the measuring arm. A detection path is also different – subtracting differential frequencies of reference and measuring arms does the measurement.

The heterodyne method gives correct results only when f_D does not exceed the difference between the laser frequencies, i.e.: $f_2 - f_1$. In reality, that difference, resulting from the Zeeman effect, is about 1MHz. This limits the maximum available velocity of measuring arm, in one direction, to 0.3 m/s. The next disadvantage of the heterodyne method is, that two frequencies must be used for measurements, while in the homodyne method the second may be used for measuring e.g. a second axis.

17
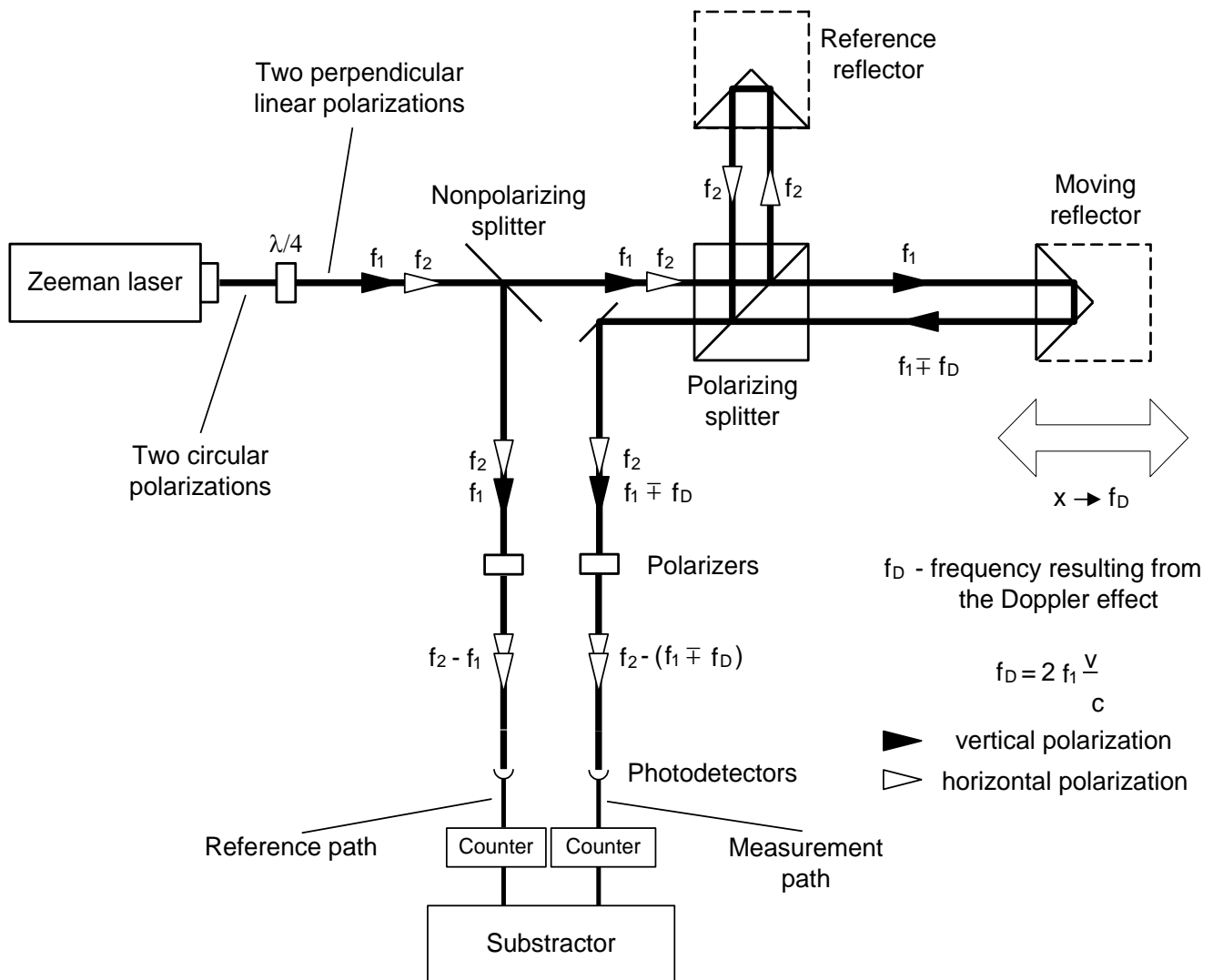
FIG.17.3. THE BLOCK DIAGRAM OF AN INTERFEROMETER, WORKING ACCORDING TO THE HETERODYNE METHOD

c. The influence of the outside conditions on the measurement accuracy

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According to equation (1) an interferometer's unit of measure in length measurement is laser's wavelength. From definition

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$$\lambda = \frac{v}{f} \qquad (2)$$

a wavelength depends on laser's frequency f and the speed of light v in the measuring path. If the measurement is done in vacuum, than $v = c = 3*10^8$ m/s. The speed of light in a medium other than vacuum (e.g. air, water) is lower and is described as

$$v = \frac{c}{n} \qquad (3)$$

Where: n – a refraction coefficient.

Normally the refraction coefficient n is a complex variable or even a tensor, but for less accurate calculations it is simplified to a constant. The air coefficient depends mostly on the pressure P, temperature T and humidity H. The dependence $n_{T,P,H}$, for the air was empirically determined by Edlen and is described as

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$$n_{T,P,H} - 1 = 2,8775*10^{-7}*P\frac{1+10^{-6}*P*(0,613-0,00997*T)}{1+0,003661*T} + \Delta n \qquad (4)$$

$$\Delta n = -3,033*10^{-9}*H*e^{0,057627*T} \qquad (5)$$

From the above equations one may obtain the refraction coefficient dependences on T, P and H in usual conditions (T=293K, P=1000hPa, H=50%):

$$\frac{\partial n}{\partial T} = -0,93*10^{-6}\left[\frac{1}{K}\right]$$

$$\frac{\partial n}{\partial P} = +0,27*10^{-6}\left[\frac{1}{hPa}\right]$$

$$\frac{\partial n}{\partial H} = -0,96*10^{-8}\left[\frac{1}{\%}\right]$$

It is worth to notice that the most critical parameter is the temperature, because its change influences the coefficient n more than changes in the pressure and much more than changes in the humidity.

d. The accuracy of laser interferometers

i. *Errors caused by the environment*

The most impotent source of errors in machine geometry measurements is the temperature (or more exactly, the change of the temperature) of the measured machine. For example, if the machine's base is made of steel, than the base's length increases 11.7μm when its temperature changes 1K. It shows how important it is for very precise measurements to measure the temperature of the controlled part of the machine and to use it in readout corrections. This

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is not a simple task for a few reasons, but the most important one is that, than when the machine operates, there are temperature gradients on it. That means that more than one temperature sensor is needed and that the more sensors are used the better accuracy can be achieved. Moreover the shape of the measured part of the machine may "absorb" a part of the expansion of the material or the part may be built of materials of different expandability.

As was mentioned in the previous chapter, the temperature influences the accuracy also as it changes the refraction coefficient of the medium the measurements are made in (usually it is air, but may be e.g. water). An Edlen equation was presented, showing how the refraction coefficient of the air changes with the change of the air temperature, pressure and humidity. The errors caused by the change of the wavelength are less important than the mentioned above, but they cannot be abandoned. Roughly, a 1ppm error (i.e. 1μm/m) is caused by: the air temperature change of o 1K, the air pressure change of 4hPa and the air humidity change of 30%.

ii. Dead path error

A dead path error is an error associated with the change in environmental parameters during a measurement. This error occurs when some part of the light path (a *dead path*) is

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not included in the temperature (both air and base), pressure and humidity compensation.

The *dead path* of the light path is a distance between the optical interferometer and the base (or the null point) of the measuring position (L_1 on figure 17.4). Let the position of the interferometer and the retro-reflector does not change. When there is a change in the air temperature, pressure or humidity, than the wavelength changes on the whole path length ($L_1 + L_2$). The path length changes also when the temperature of the base changes. But the correction system will use the correct wavelength only on the length L_2 and will correct only this length. The correction will not be made on a dead path L_1. In this way, the laser system will "move" the base point.

A dead path error is the more severe the greater is the distance between the interferometer and the base point. This error is especially important in laser interferometers where the interferometer is build-up in a common casing with a laser head, because it is than very difficult to reduce a dead path.

17
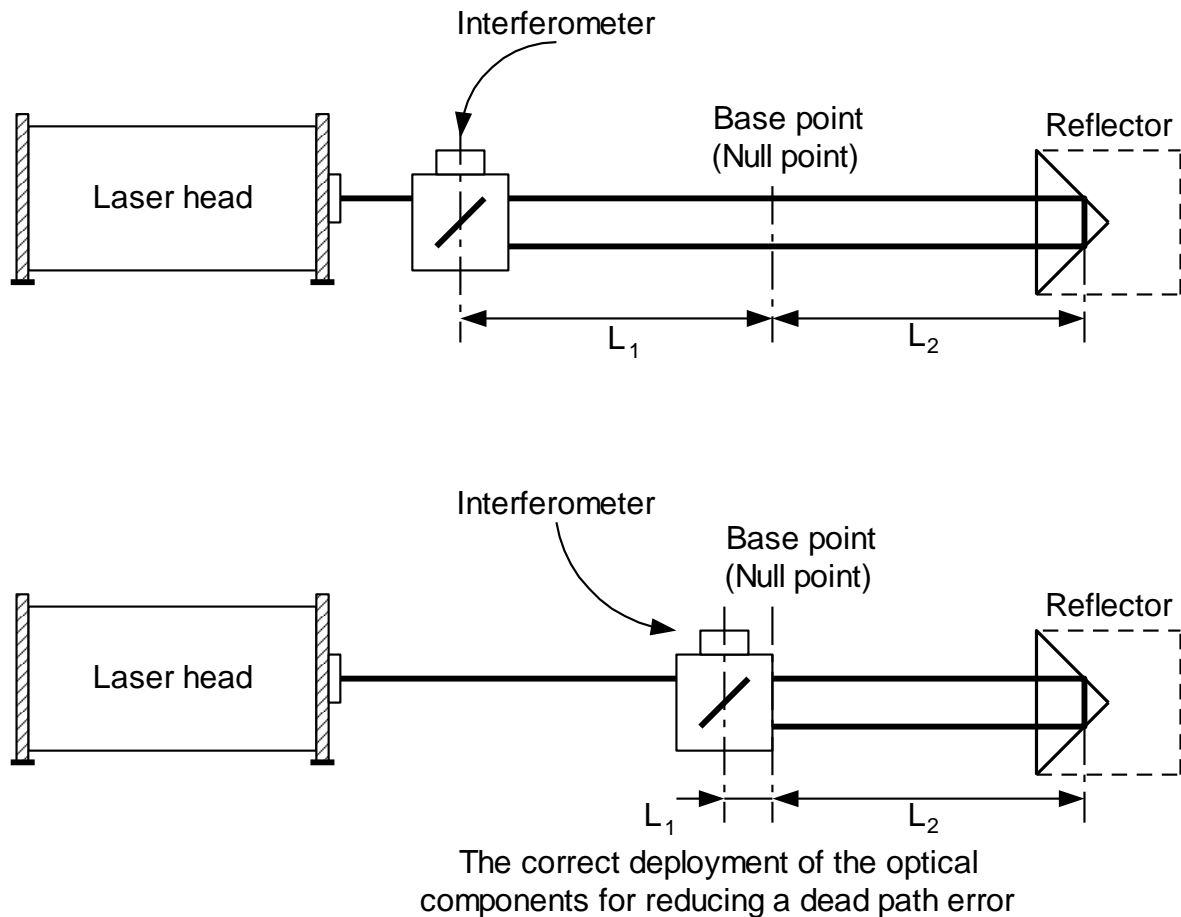
The correct deployment of the optical
components for reducing a dead path error
FIG.17.4. AN ILLUSTRATION OF A DEAD PATH ERROR

iii. Cosine error

If the laser beam is not parallel to a measured axis of a machine (i.e. the optical path is not properly adjusted) than a difference between the real distance and the measured distance occurs. This error of misalignment is known as a cosine error, because its magnitude depends on the angle between the laser beam and the axis of the machine (fig. 17.5).

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If, as a reflector a flat mirror is used, than the beam must be perpendicular to it. If the machine changes its position form point A to point B, than the beam stays perpendicular to the mirror, but moves on its surface. The distance measured by the laser interferometer L_{LMS}, will be smaller, than the real distance L_M, according to

$$L_{LMS} = L_M * \cos\Theta \qquad (6)$$

The above equation is valid also when as a reflector a corn cube is used.
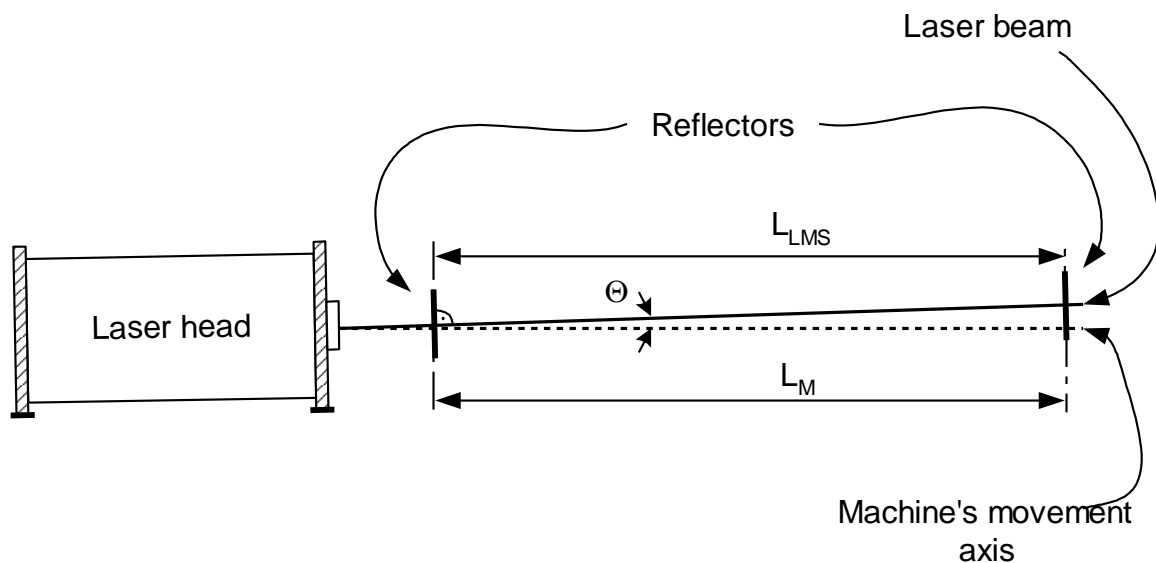
FIG.17.5. THE BEAM UNALIGNMENT AS A CAUSE OF A COSINE ERROR

The only method of eliminating the cosine error is a proper laser beam alignment done before a measurement.

iv. Abbe error

An Abbe error occurs when, during measurements, the measured part does not move perfectly straight and there appear angular movements, which cause sloping of the retro-reflector. The sloping of the reflector is the greater the longer is the distance between the axis of the measurement and the axis of movement. This distance is called *An Abbe offset*. Only the movements in the axis of the measurement are important (see fig. 17.6). An Abbe error may be avoided only when there are no angular movements of the retro-reflector in the axis of the measurements.
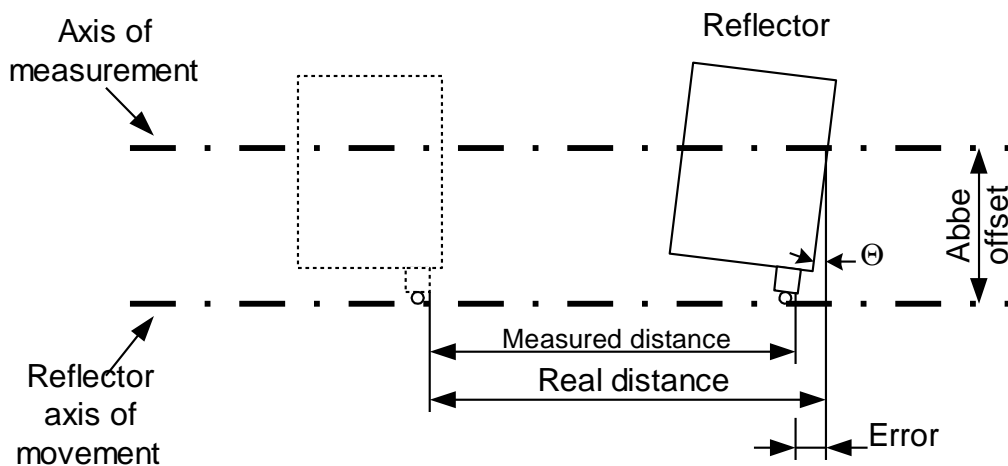
FIG.17.6. AN ILLUSTRATION OF AN ABBE ERROR

v. Laser stability error

As was already mentioned, in laser measurements the laser wavelength instability changes directly the readout from the interferometer, e.g. a relative instability of the laser in the range of 1ppm (10^{-6}), causes an error of 1μm on every 1m of a measured distance. Therefore the laser instability error is important mainly in measurements in vacuum (where a refraction coefficient is constant) and when a low stability laser is used (e.g. a semiconductor laser). The stability of usually used in laser measurement systems, HeNe gas lasers is 0.02 ppm, so the stability error may be neglected.

vi. Other errors

In some conditions, a noticeable error may be caused by the electronic part of the interferometer. As the electronics is used mainly for counting, the errors may be associated either with miscounting (some pulses are not counted) or with miscalculating (the calculations are made with finite precision).

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vii. A summary of laser measurement system errors

In order to show which of the errors influence the accuracy of a laser measurement system the most, an exemplary calculation of errors on a 1m long steel machine is shown on figures 17.7 and 17.8. Different scales of the charts should be taken into account.
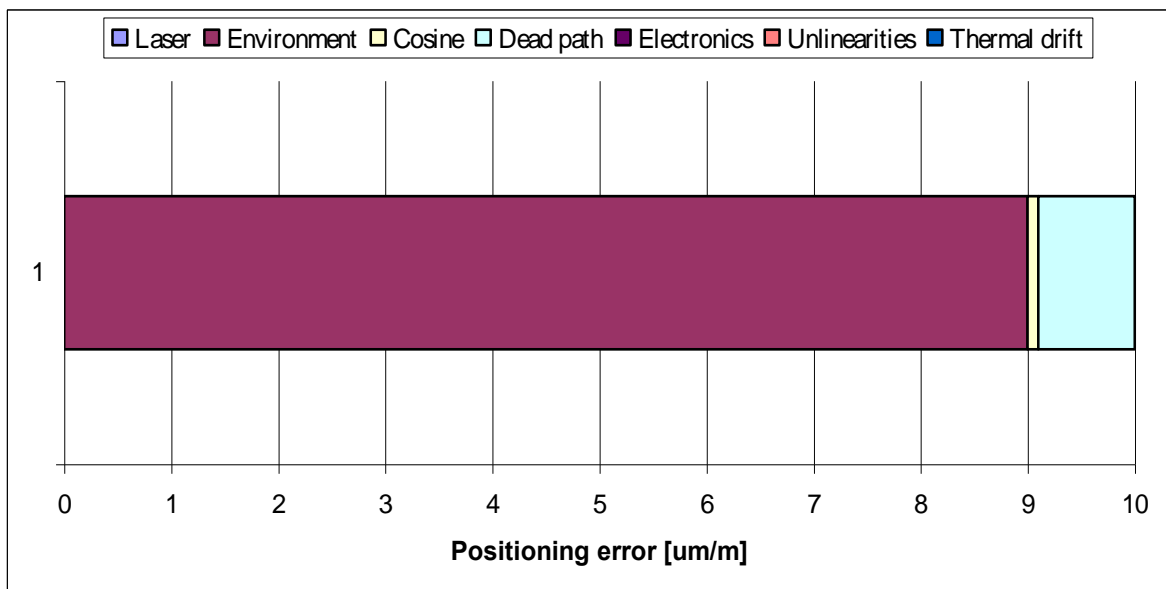
FIG.17.7. A CALCULATION OF ERRORS FOR A LASER MEASUREMENT SYSTEM **WITHOUT THE COMPENSATION** OF THE ENVIRONMENT

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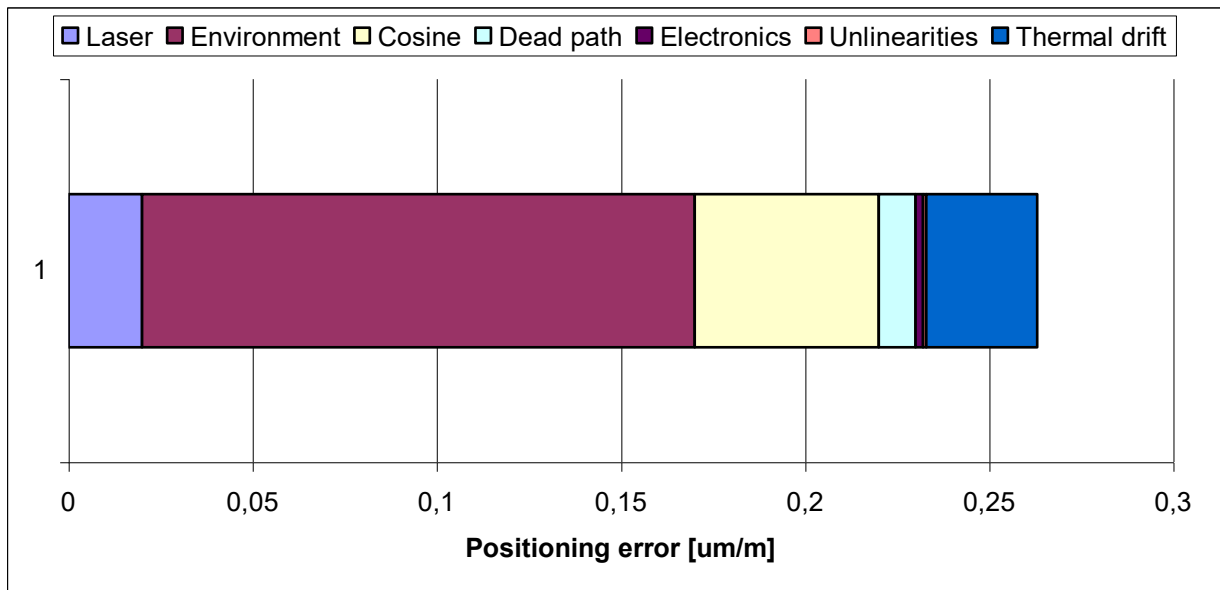
FIG.17.8. A CALCULATION OF ERRORS FOR A LASER MEASUREMENT SYSTEM **WITH THE COMPENSATION** OF THE ENVIRONMENT

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18. TROUBLESHOOTING

General Description

The troubleshooting of the possible problems with the HPI-3D is shown in this chapter on the basis of block diagrams. In each diagram the first block on the top names the problem that is dealt by the diagram.

Problems with connection over USB or Bluetooth

The diagram charts for solving problems with connection are shown in the figure 18.1 – connection failed problem and in the figure 18.2 – connection broken problem.

18
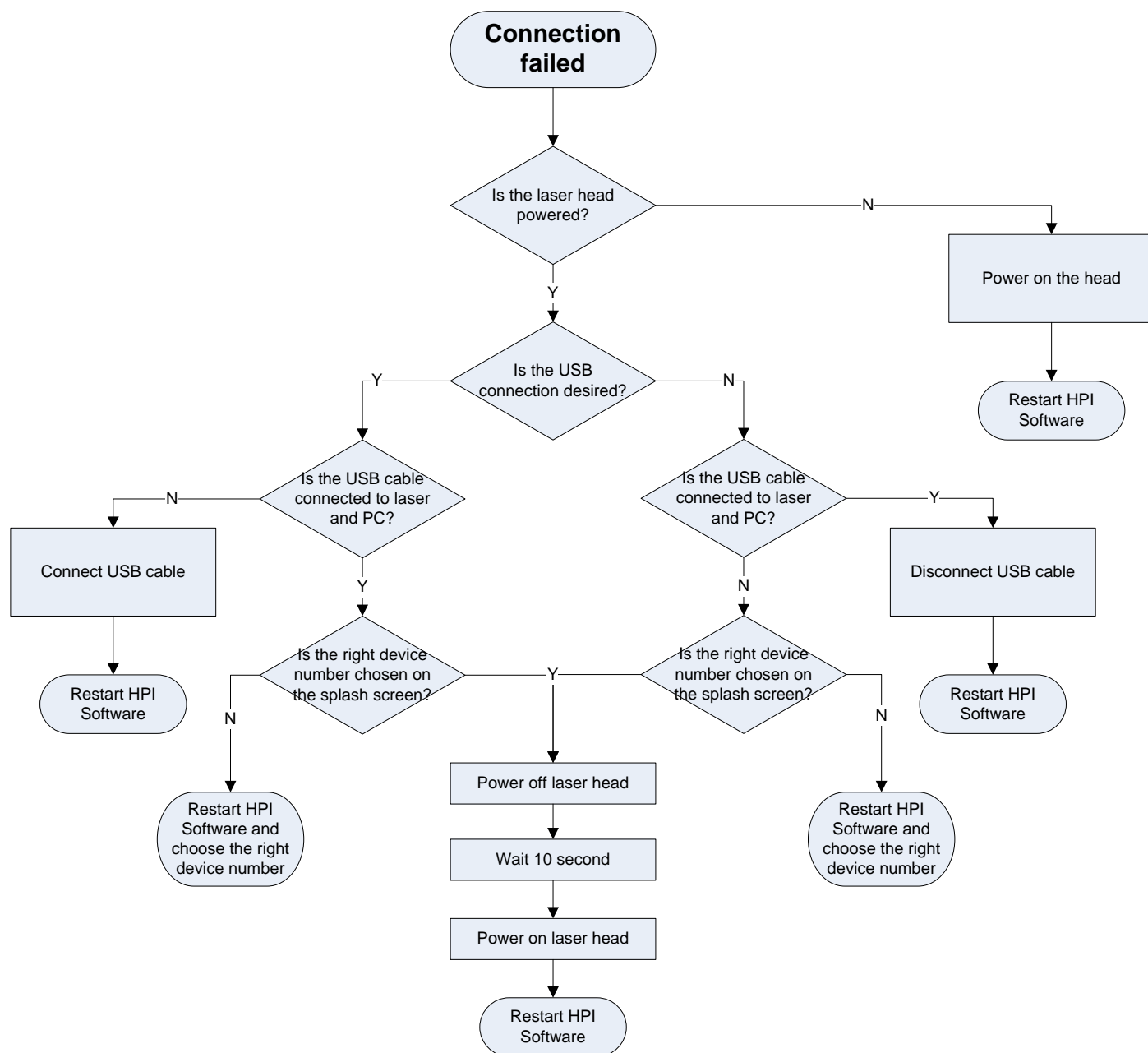
FIG.18.1. CONNECTION FAILED CHART

18
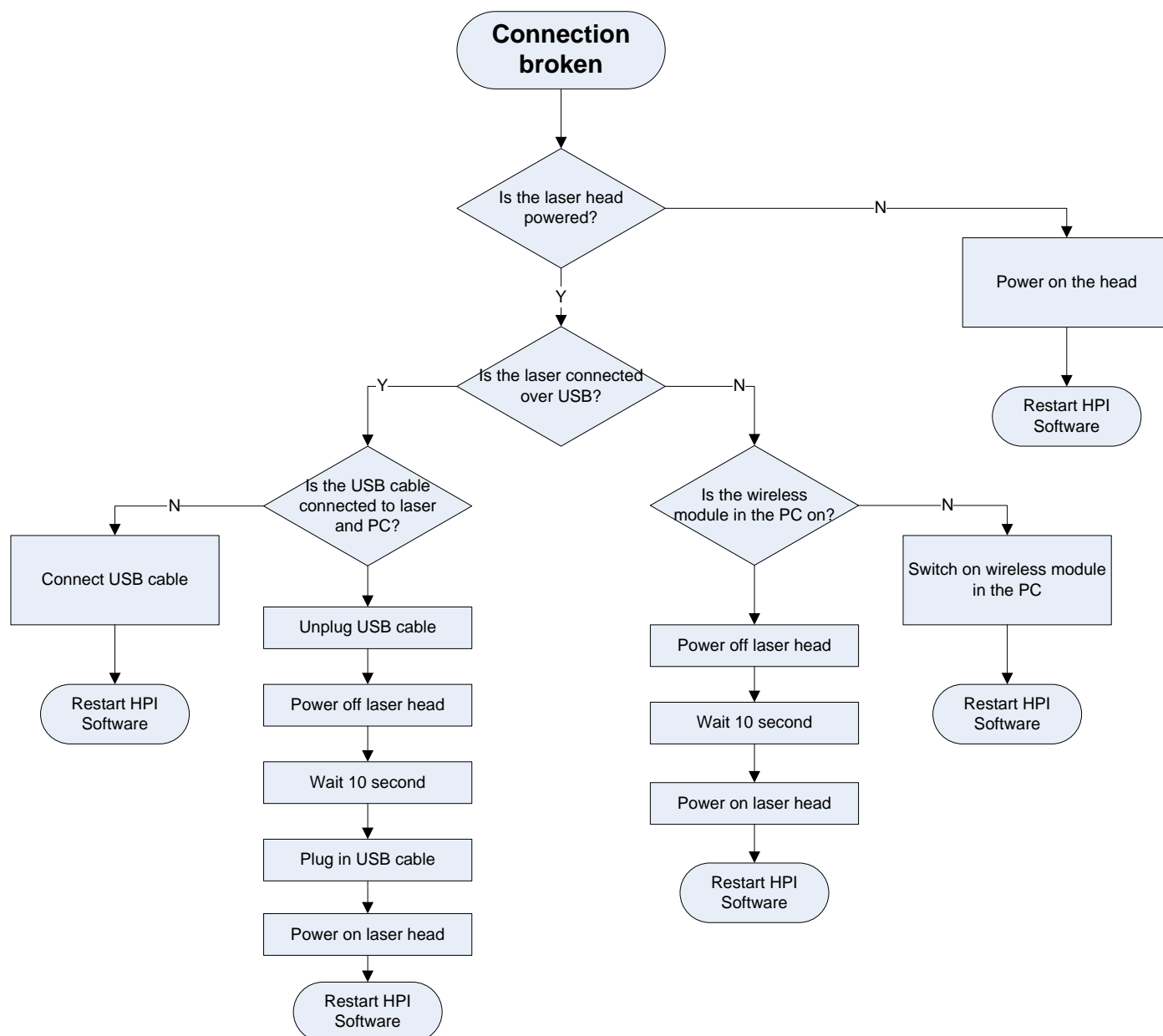
FIG.18.2. CONNECTION BROKEN CHART

Problems with connection with wireless sensors

The diagram charts for solving problems with connection with one or more sensors are shown in the figure 18.3.

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Sensor(s) not visible

Was the power plug of the laser inserted for more than 4 minutes?

N → Wait 4 minutes

Y

Are some sensors visible?

Y ←

N →

Y branch:

Unscrew the top cap of the non-working sensors and check/replace the battery

Did the sensor diode blinked on during closing the top cap?

Y →

Enter Configuration->WiMeteo option in HPI_Software

Press WiMeteo Reconnect button

Wait 4 minutes

N → Check the battery

N branch:

Unplug USB cable (if applicable)

Power off laser head

Wait 10 second

Plug in USB cable (if applicable)

Power on laser head

Restart HPI Software

FIG.18.3. SENSOR(S) CONNECTION PROBLEM CHART

Problems with linear measurements

The diagram charts for solving problems with measurements and laser stabilization are presented in the figures 18.4 and 18.5.

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Laser does not measure

Does the laser stabilise?

— N → Wait until laser stabilises

Y

Is the diode on the top of the laser green?

Y →

Y →

Is the diode on the top of the laser yellow?

Y → Align properly optical path

N

Is the diode on the top of the laser blinking?

N → Switch the laser on

Y → Wait until laser stabilises

In the HPI Software enter Main Menu and return to Display menu

Does the laser measure?

N →

Y → OK

Restart HPI Software

Does the laser measure?

N →

Y → OK

Close HPI Software

Power off laser head

Wait 10 second

Power on laser head

Start HPI Software

FIG.18.4. NOT MEASURING LASER PROBLEM CHART

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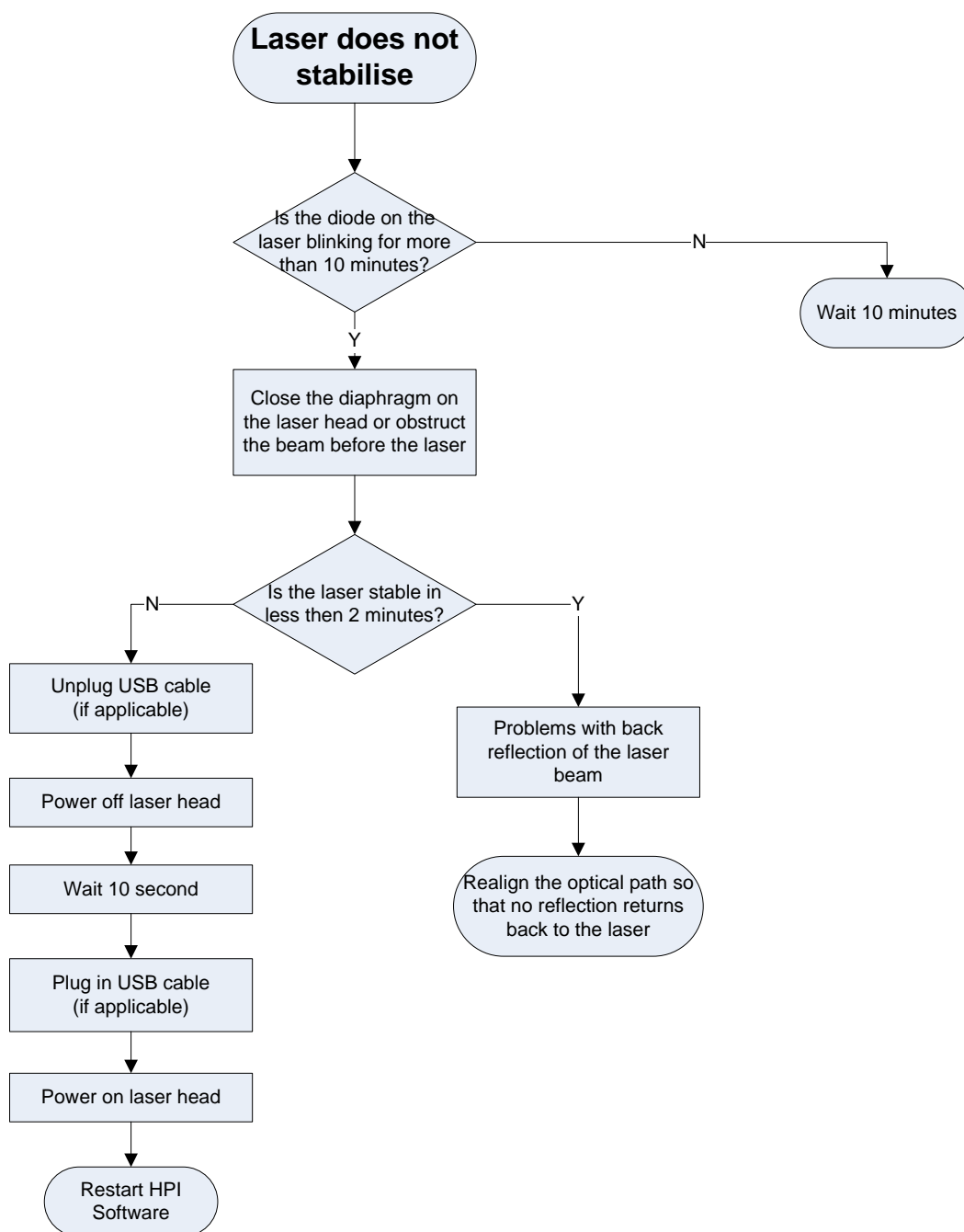
FIG.18.5. NOT STABILISING LASER PROBLEM CHART

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19. TECHNICAL DATA

a. System specifications

Measurement	Range	Resolution	Accuracy
Distance	0 – 30 m	100 pm	0,4 µm/m
Velocity	0 – 7 m/s	0.25 µm/s	0,1 %
Angular	0 – 3600 arcsec	0,001 arcsec	± 0,1 ppm
Straightness measurement (with angular optics)	0 – 15 m	0,01 µm (for 100 mm base)	± 0,2 %
Straightness measurement (with 3D optics)	0 – 6 m	0.1 µm	±(10+10*L)µm
Flatness	0 – 15 m Vertical range ±2 mm	0,01 µrad (for 100 mm base)	± 0,2 % x L
Straightness measurement (with Wollaston prism)	0.3 – 9 m Vertical range up to ±30mm	0.01 µm	±0.5% x L µm

Squareness	± 1000 arcsec	0.01 μm	± 0,5 arcsec
Rotary measurements	± 720 °	0,04 arcsec	± 0,2 %

L = axis length in meters

b. Laser head

Laser type	HeNe laser with frequency stabilization
Heating time	Approx. 5 min
Wavelength (vacuum)	632,990566 nm 632,992031 nm
Wavelength accuracy	± 0,005 ppm
Short time stability	± 0,001 ppm (1 hour)
Output power	900 – 1000 μW
Beam diameter	8 mm
Distance between outgoing and ingoing beam	12,7 mm
Laser Head dimensions	45x70x245 mm
Net weight	1500 g
Safety class	Class 2 Laser product according to PN-91/T-06700

c. Laser Head outputs - analog

Signal type	SinA / CosB
Voltage level	1 Vpp
Signal resolution	User defined: from 40nm/period to 200μm/period in 40nm/period step
Maximal signal frequency	2.5 MHz

d. Laser Head outputs – digital, type 1

Signal type	A quad B
Voltage level	5 V differential CMOS
Signal resolution	User defined: from 1nm/transition to 5µm/transition in 1nm/transition step
Maximal signal frequency	25 MHz

e. Laser Head outputs – digital, type 2

Signal type	Shift / Sign
Voltage level	5 V differential CMOS
Signal resolution	User defined: from 0.1nm/pulse to 5um/pulse in 0.1nm/pulse step
Pulse width	5 ns
Maximal signal frequency	100 MHz

f. Laser Head outputs – Extension connector pinout

Connector type	Hirose Connector LX40-20P CL No. CL245-0017-0

Pin number	Function
1.	24V Supply

2.	Digital IO	Reserved for future use
3.	Digital IO	Reserved for future use
4.	Digital IO	Reserved for future use
5.	Digital IO	Reserved for future use
6.	Digital IO	Reserved for future use
7.	Digital IO	Reserved for future use
8.	Digital IO	• Negative output of Differential B signal pair (Digital AquadB Output) • Negative output of Differential Sign signal pair (Shift/Sign Output)
9.	Digital IO	• Negative output of Differential A signal pair (Digital AquadB Output) • Negative output of Differential Module signal pair (Shift/Sign Output)
10.	Digital IO	• Positive output of Differential B signal pair (Digital AquadB Output) • Positive output of Differential Sign signal pair (Shift/Sign Output)
11.	Digital IO	• Positive output of Differential A signal pair (Digital AquadB Output) • Positive output of Differential Module signal pair (Shift/Sign Output)
12.		5V Supply
13.	Analog Output	Negative output of Differential Cosine signal pair (Sine/Cosine Output)
14.	Analog Output	Negative output of Differential Sine signal pair (Sine/Cosine Output)
15.	Analog Output	Positive output of Differential Cosine signal pair (Sine/Cosine Output)
16.	Analog Output	Positive output of Differential Sine signal pair (Sine/Cosine Output)
17.		Ground

18.	Ground
19.	Ground
20.	Ground

g. System work conditions

Temperature range	0 – 35 °C
Humidity range	10 – 90 % (non-condensing)

h. Power Supply

Voltage	90-230 VAC, 50-60 Hz
Power	100 W (during heating) 15 W (work)

i. PC interface

Type 1	USB 2.0
Data rate	3125000 bps (VCOM)

Type 2	Bluetooth 2.0 + EDR
Connection	Point-to-Point (pico net)
Frequency	2.400 to 2.4835 GHz
Tx Power	Max 18 dBm (Class 1)
Rx Sensitivity	-86 dBm typical
Coverage	Up to 25m

j. Environment compensation

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Wavelength compensation

Manual	Environments parameters entered from keyboard
Automatic	With the use of the Environmental Compensation Unit - (ECU) .

*Parameters of the **wireless** Environmental Compensation Unit - (ECU) compensation*

Air temperature	Range 0 – 50 °C, accuracy 0,15 °C
Base temperature	Range 0 – 50 °C, accuracy 0,1 °C
Pressure	Range 940 – 1060 hPa, accuracy 1 hPa
Humidity	Range 10 – 90 %, accuracy 10 %
Time constants	Temperature 8 s, pressure 2s, humidity 20 s
Dimension	ϕ50x55 mm
Net weight	150 g

***Wireless** material temperature compensation*

Manual	Temperature of material entered from keyboard
Automatic	With the use of 1 to 3 wireless temperature sensors .
Temperature sensor	Pt-1000
Time constant	10 s
Net weight	150 g

Our products are subject to continuous further development and improvement. Subject to technical changes without prior notice.

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