Fraunhofer
IPMS

Laser Deflection Cube
User Instruction Manual

Rev 1.2 WiM
Hardware Rev 1.2 / Firmware Rev 2.03

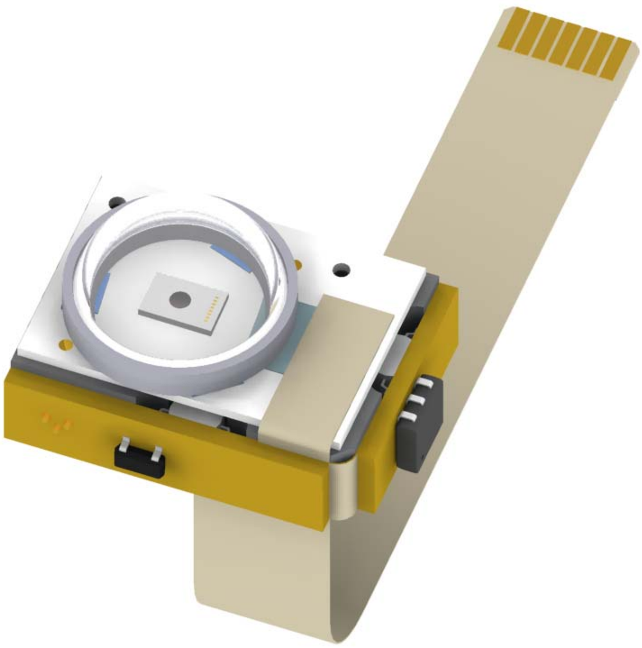

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Table of Contents

1 Safety Instructions

Laser Safety

Laser class II implemented
λ = 650 nm
P < 1 mW

Laser emits towards the back-side of scanner mirror.

- Do not disassemble scan head.
- Do not use with missing scanner mirror.
- No consumer product
- Operation by trained personnel only.

High Voltage

200 V / 2.5 mA

Do not touch electronic board, if powered.
The maximum amount of energy stored in the converter is less than 50 mJ below any hazardous levels.

ESD

The LDC scan head as well as the driver electronics, uses semiconductors that can be damaged by electrostatic discharge (ESD). When handling, care must be taken so that the devices are not damaged.

The following precautions must be taken:

- Do not open the protective conductive packaging until being at an approved anti-static work station.
- Use a conductive wrist strap attached to a good earth ground.
- Always discharge yourself by touching a grounded bare metal surface or approved anti-static mat before picking up an ESD - sensitive electronic component.
- Use an approved anti-static mat to cover your work surface.

2 Preparation for use

2.1 Delivery Contents

- Scan head
- Driving electronics
- Power adaptor
- PICKit™ Serial Analyzer SPI-USB interface
- USB cable
- CD with API and application software

2.2 Unpacking

The scan head has to be handled carefully.
The scan head as well as the electronic board has to be handled solely in an ESD qualified environment.

2.3 Connecting scan head with driver electronics

To realize a very small form factor of the scan head, the connection to the driver electronic board is implemented as a plug-less FPC (Flexible Printed Circuit) connection with 1 mm pitch.
The connecting needs caution especially while inserting the flex tail into the jack.
To avoid damaging of the flex tail and the pins, pull the lever approx. 1 mm out of the jack until a mechanical stop is noticeable. After, insert the flex tail with pins downwards into the jack and carefully close the lever.
Never bend the flex tail with a radius smaller than 5 mm!

2.4 Start-up procedure

The LDC module driving electronics is factory configured to start the scanner at the specified frequency and amplitude after powering-up by connecting the power supply.
The wire of electronic board is unmistakably reverse polarity protected matching to the delivered power supply.
To change the scan amplitude the PC interface (see chapter 5) can be used.

3 Scan Head

3.1 Layout

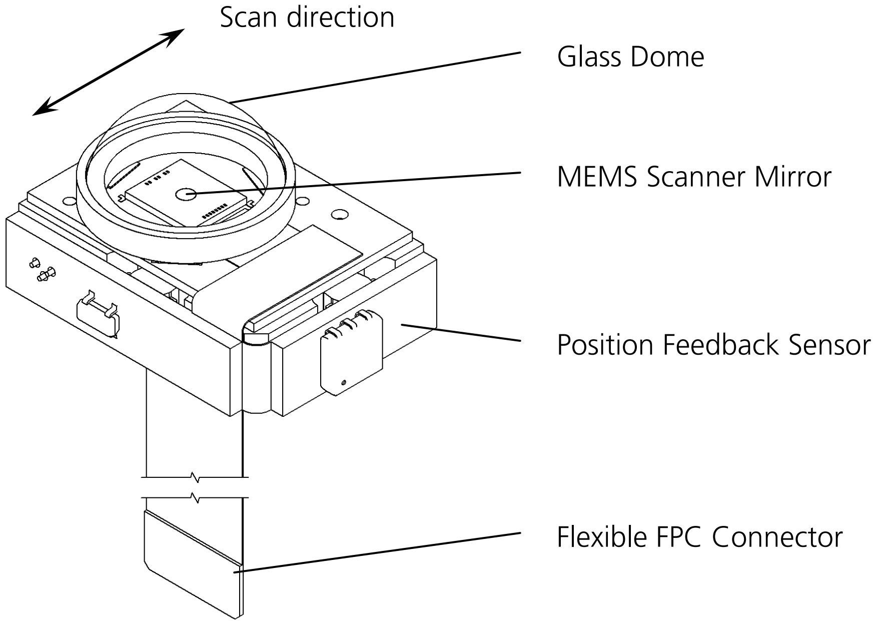


Figure 1: Scan head layout

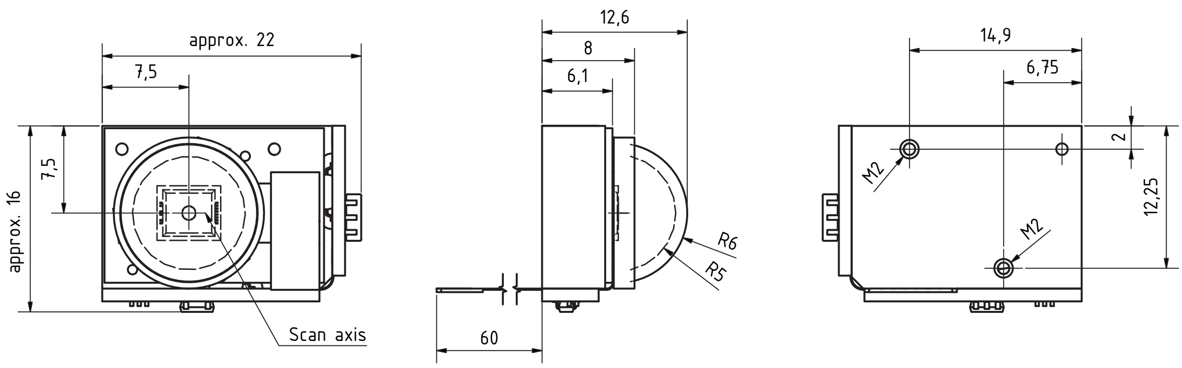


Figure 2: Drawing LDC scan head

3.2 Resonant Micro Scanning Mirror Theory

The scan head contains as the key component a MEMS micro scanning mirror, designed for periodical deflection of light. The scanner chip (Figure 3) is fabricated at the Fraunhofer IPMS using CMOS compatible technology. It consists of a 30 to 75 µm thick plate, suspended by two torsional springs. The optical reflection coefficient is enhanced by a thin layer of aluminum. The edges between fixed frame and moving mirror plate are formed as comb-electrodes. The membrane with the mechanical active structures is carried by a patterned bulk silicone.

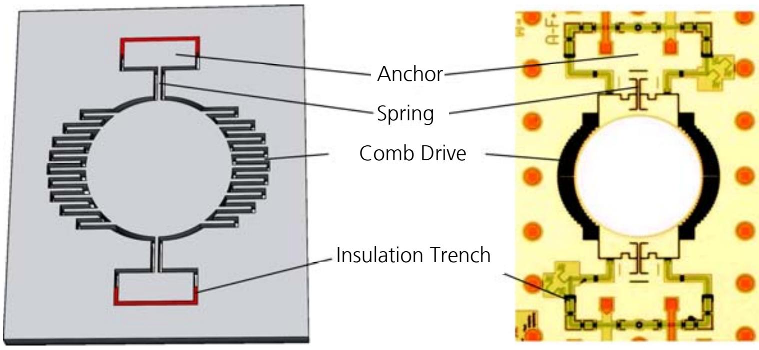


Figure 3: Exemplary design of a micro scanner mirror

The vertical sides of the comb like driving electrodes and of the mirror plate form a variable capacitance. The oscillation of the plate is excited resonantly with the double mechanical oscillation frequency. An applied voltage creates an electrostatic torque which accelerates the plate towards its rest position. To prevent a deceleration of the plate's movement after passing the rest position the voltage between the electrodes must be switched to zero at zero crossing. At the maximum deflection angle the voltage is switched on again. A typical resonance curve is shown in figure 3. The asymmetric behavior is explained by the deceleration and therewith the collapse of oscillation due to a remaining electrostatic torque after passing rest position. This always occurs for driving frequencies smaller than the double mechanical resonance frequency. The resonance curve shows a hysteresis. Therefore, different parts of the curve are obtained dependent from the direction of the frequency sweep. The largest deflection angle will be achieved, applying a frequency sweep starting with a frequency higher than a type-specific frequency f_2 down to a frequency slightly higher than the resonance frequency f_1. This start-up procedure is already implemented in the firmware of the driving electronics.
Due to the in-plane electrode configuration this scanner design is not suitable to achieve a static deflection.

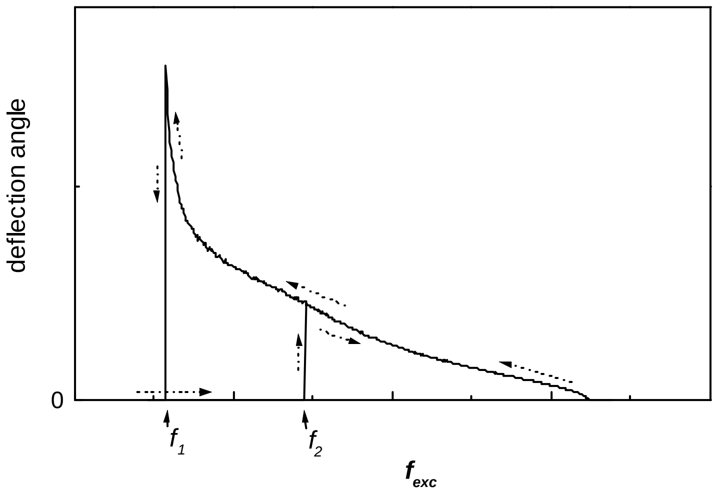


Figure 4: MEMS micro scanner resonance behavior

After the start-up procedure, the amplitude of the scanner can be controlled theoretically by both, the voltage and the frequency of the drive signal. Using the frequency as controlled parameter, one has to take care that the frequency always has to be larger than the resonance frequency, otherwise the oscillation aborts. To avoid this state, especially in view of the fact that

the resonance frequency can be slightly shifting under changing environmental conditions, normally the phase of the mirror oscillation is controlled instead. Utilizing a phase controlled operation; the coupling efficiency for the driving signal is maximal at a minimal phase (running near the mechanical resonance of the scanner). This causes the lowest possible driving voltage and thereby the lowest power consumption of the driving circuit. On the other hand, the oscillation frequency wills then slightly changing depending on the environmental conditions. Due to a steep rise of the frequency response curve near resonance, changing conditions effects also a drift of the deflection amplitude.
To obtain a certain deflection in practice, the amplitude is always controlled by the driving voltage. The phase control can be used additionally to reduce the necessary driving voltage.
All these driving theory aspects are implemented in the delivered driving electronics.

3.2.1 Position Feedback Sensor Theory

To control amplitude and/or phase of the MEMS scanner mirror device, an optical position feedback sensor sub-module is implemented in the scan head. The position sensor consists of a red laser diode as light source and two photo diodes as detectors. The laser emits a beam towards the back-side of the scanner mirror. This beam is reflected by the moving scanner mirror. The two photo diodes are arrange in a way, that the laser beam hits one photo diode at zero deflection crossing, the other at a certain angular deflection. Using the timing of the trigger signals, generated by the photo diodes and be pre-processed by a logic circuit, the phase and the amplitude of the scanner can be evaluated (Figure 5).
The amplitude is calculated from the AMPL signal according

$$A = \frac{\Theta_{sensor}}{\sin\left[\pi\left(\frac{1}{2} - \frac{t_A}{T}\right)\right]} \tag{1}$$

where Θ_{sensor} is the angular position of the photo diode and *T is* the cycle duration of the scanner oscillation.
The phase is calculated from the REF and the TRIG signal. The REF signal is the master clock reference for the scanner drive. Ideally, the length of high and low level of the TRIG signal should be equal. Due to fabrication inaccuracies regarding the position of the photo diode relative to the scanner die position, the two times are not completely matching. To compensate the offset, a mathematical correction has to be accomplished:

$$\varphi = \left[\frac{2\left(t_{phase1} + t_{phase2}\right) - T}{2\,T}\pi\right] \tag{2}$$

On-board, the sensor signals are analyzed by a time-to-digital converter and are also available at the I/O connector. The phase and the amplitude calculation are already implemented in the firmware of the controller and can be read out using the SPI interface.
Figure 5 shows the relations between the signals and the timing. Note, that due to the not determined direction of transient oscillation the mirror oscillation can also be 180° phase shifted.

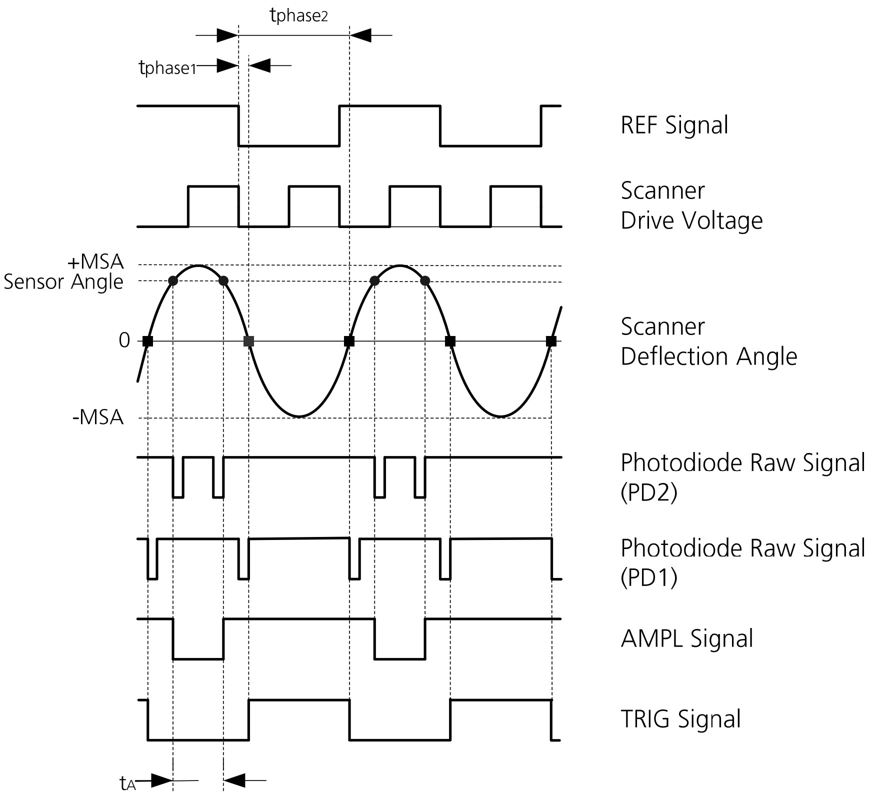


Figure 5: Sensor Signal Timing Characteristic Diagram

Table1: Position feedback sensor characteristic

Symbol	Characteristic	Min	Typ.	Max	Units	Conditions
λ	Laser Wavelength	645	655	660	nm	

4 Driving Electronics

The driving electronics is designed to run the LDC module either independently or under permanent data exchange with a controlling PC.

4.1 Layout

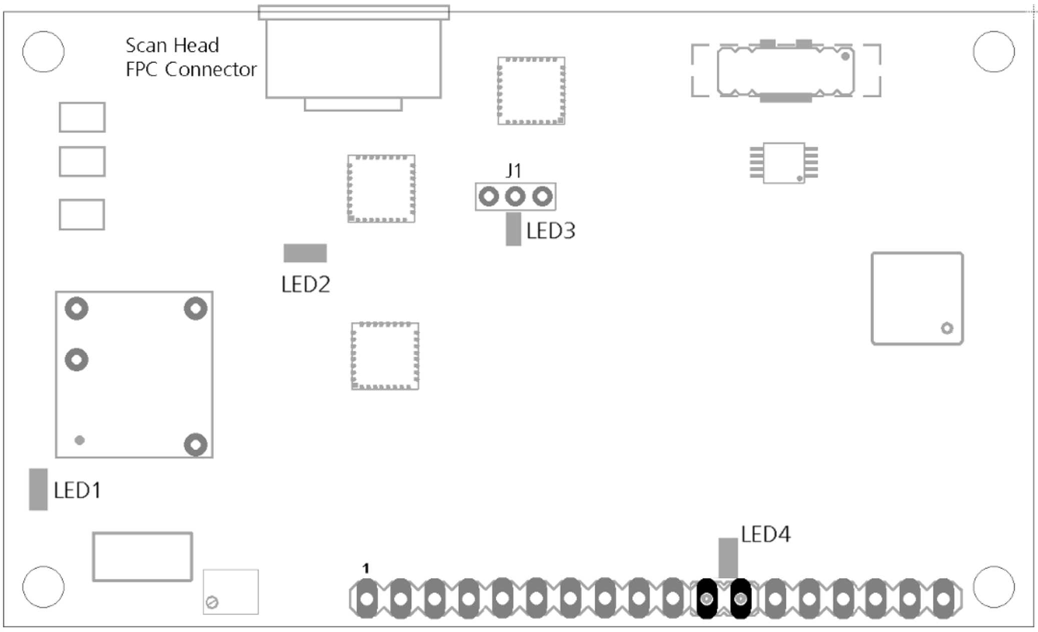


Figure 6: Electronic board layout (top view)

4.2 I/O Connector

The power supply input as well all provided I/O pins are connected to a 18-pin 2.54 mm pitch header (Figure 6). The I/O port includes a set of digital state signals, the raw and pre-processed position feedback sensor signals and a SPI interface.

Table 2: Pin out I/O Connector

Pin	Group	Symbol	In/Out	Signal	Description
1	SPI Interface	SS	IN	5V Logic	Slave Select
2		3V3	OUT	Power Supply	
3		SDO	OUT	5V Logic	Serial Data Out (Master In Slave Out, MISO)
4		GND	—	Power Supply	Ground pin
5		SCK	IN	5V Logic	Serial Clock
6		SDI	IN	5V Logic	Serial Data In (Master Out Slave In, MOSI)
7	Digital Sensor Signals	PD1	OUT	3.3V Logic	Raw output signal of zero-deflection switching photo diode
8		PD2	OUT	3.3V Logic	Raw output signal of amplitude measurement photo diode
9		REF	OUT	3.3V Logic	Reference clock of scanner drive signal Drive signal frequency doubled derived from the REF signal
10		Reserved	—	—	Keep disconnected!
11	Power Supply	GND	—	Power Supply	Ground pin
12		VDD	—	Power Supply	Main power supply (5V)
13	I/O	RDY	OUT	5V Logic	Ready signal of scanner module
14		ERR	OUT	5V Logic	Error signal of scanner module
15		EN	IN	5V Logic	Enable Signal of scanner module
16		MODE	IN	5V Logic	Switches between open and close loop scanner control
17	Digital Sensor Signals	AMPL	OUT	5V Logic	Preprocessed amplitude measurement signal
18		TRIG	OUT	5V Logic	Preprocessed zero deflection measurement signal, can be used as a synchronization signal for scanner oscillation

4.3 State Indicators Leeds

LED	Color	Description
LED1	yellow	Power supply
LED2	red	Start-up frequency sweep, control activity
LED3	orange	control activity
LED4	Red	Error (connected to the ERR state signal)

Figure 7: State indicator Leeds

4.4 Absolute Maximum Ratings

Stresses above those listed can cause permanent damage to the device. This is a stress rating only, and functional operation of the device at those or any other conditions above those indicated in the operation listings of this specification is not implied. Exposure to maximum rating conditions for extended periods can affect device reliability.

Power Supply

V_{DD} Supply Voltage vs. GND..6 V

5V Logic

Voltage at any SPI input pin with respect to GND, board power $V_{DD} \geq 4.85V$ .... -0.3V to +5.6V
Voltage at any SPI input pin with respect to GND, board power $V_{DD} < 4.85V$ ... -0.3V to V_{DD} -1.1V
Maximum output current sunk by any SPI I/O pin.. 4 mA
Maximum output current sourced by any SPI I/O pin.. 4 mA

3V Logic (Output only)

Maximum output current sunk by any 3.3V logic pin .... 8 mA
Maximum output current sourced by any 3.3V logic pin .... 8 mA

4.5 DC Voltage Specifications

Table 3: Thermal conditions

Symbol	Characteristic	Min	Typ.	Max	Units	Conditions
ϑ_A	Operating Temperature	15		35	°C	
ϑ_S	Storage Temperature	0		70	°C	

Table 4: DC voltage characteristic

Symbol	Characteristic	Min	Typ.	Max	Units	Conditions
V_{DD}	Supply Voltage vs. GND	4.85		5.5	V	
V_{OH_3V3}	3.3V Logic high level output voltage	2.9	3.1	—	V	
V_{OL_3V3}	3.3V Logic low level output voltage	—	0.2	0.4	V	
V_{IH_5V}	5V Logic high level input voltage	2.3	—	5.5	V	
V_{IL_5V}	5V Logic low level input voltage	0	—	0.6	V	
V_{OH_5V}	5V Logic high level output voltage	2.4	—	—	V	
V_{OL_5V}	5V Logic low level output voltage	—	—	0.4	V	

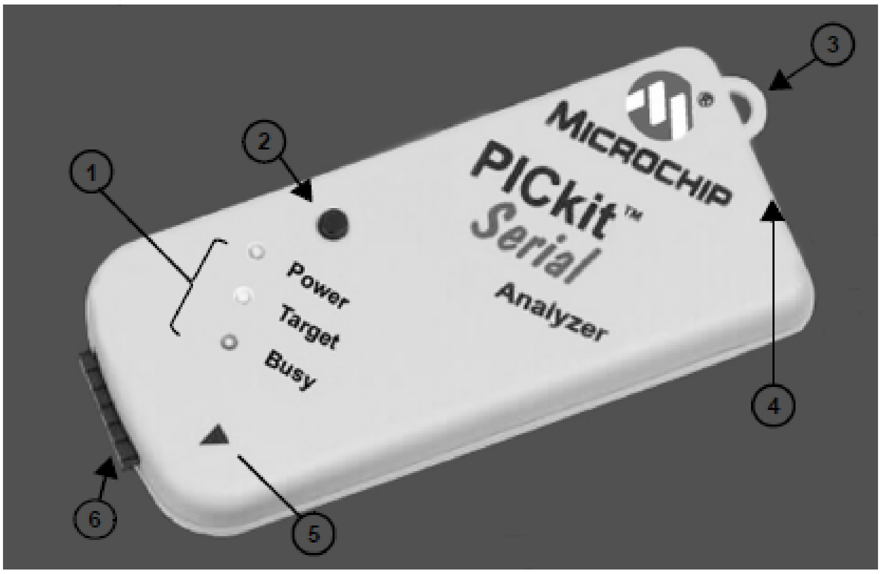
5 PC Interface

The LDC module driving electronics can be controlled optionally from a PC running on Windows XP or later.
In delivery there is included a SPI – USB adapter, which is directly connectable to LDC module driving electronics, an USB cable, an interface API and a simple application which can control the LDC module easily.

5.1 System requirements

- Windows XP, Vista, 7
- .NET framework 2.0 (2.0.50727) or later
- USB 2.0
- For LDC interface API: Software development environment supporting .NET like Visual Studio 2005 (Express) or later, LabView 8 or later)

5.2 SPI-USB adapter PICkit™ Serial analyzer



Legend:

1 – Status LEDs 3 – Lanyard Connection 5 – Pin 1 Marker
2 – Push Button 4 – USB Port Connection 6 – Communications Connector

Figure 8: PICkit™ Serial Analyzer – Layout and description

The PICkit™ serial analyzer provides access to the onboard SPI interface of the LDC module driving electronics. It can be directly connected to the header of electronic board. The marked pin 1 (⑤) has to be match to pin 1 of the multi-purpose header of the LDC module driving electronics. (Figure 9)

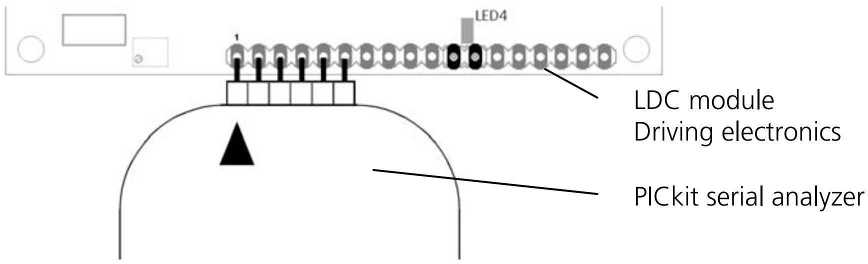


Figure 9: Wiring of PICkit™ serial anlyzer

5.3 Graphical User Interface

The control panel allows controlling the scanner with a minimum of functionality getting started with PC interfacing.
The GUI is stored on the CD as IPMS_LDC_Control_Panel.exe.
The Software allows to set the scanning amplitude (mechanical scan amplitude, half angle), to start and stop the scanner and provides some status information.

After starting the software directly from CD or a copy from a PC drive, the window opens in its start-up appearance (Figure 10).

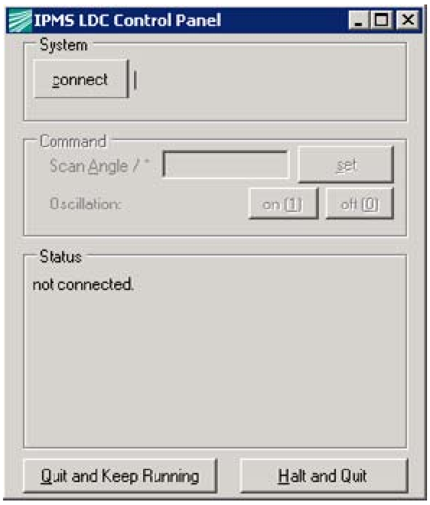


Figure 10: Graphical user interface in start-up appearance

The connect button establishes a permanent communication with the LDC module. In case, the LDC module driving electronics is not connected or powered an error message is generated. Further, the connection is checked for errors always it was started once. If the connection breaks, the control panel generates an error message and falls back to start-up behavior.

In command frame (Figure 11) now the scan angle (mechanical scan half angle) can be set in the predefined scan angle range displayed is status frame. *On* starts a sweep to the set scan angle and keeps that angle constant. *Off* stops the scanner oscillation.

In the status window further following parameters are displayed:

- Serial number of electronics and scan head
- Current scan angle
- Current mechanical oscillation frequency
- Current scanner drive voltage
- Current scanner oscillation phase

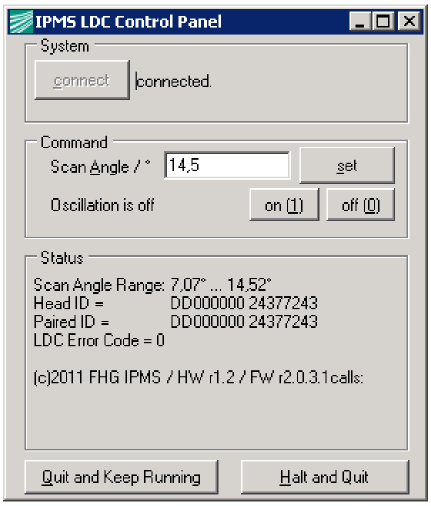


Figure 11: Graphical user interface

The control panel can be closed with keeping the LDC module in the last state, this means the scanner oscillation continues (*Quit and Keep Running*) or with stopping the mirror oscillation before quitting (*Halt and Quit*).

Controls and settings much more than these can be programmed using the LDC Interface API and a common programming language.

5.4 LDC Interface API

The API does not require any driver or software installation.
To use the API it is only necessary to refer the .NET class library *LDCInterfaceAPI.dll* from CD within the software project of the target application.
The class library *LDCInterfaceAPI.dll* contains two classes *LDCInterfaceAPI* and *PICkitS*. The *PICkitS* class provides all functionality of the PICkit™ Serial analyzer. Low level access to the SPI layer of the *PICkitS* is completely encapsulated by *LDCInterfaceAPI* class.
Direct calling of *PICkitS* functions may damage the LDC module.

5.4.1 Command reference

The commands are a one by one translation of the SPI commands described in chapter SPI Interface (Table 9). Additional the command list contains functions to initialize and clean up the USB-SPI interface hardware.

5.4.1.1 SPI initialization / Clean up

```
static int Init(double dBitate)
```

This function initializes the PICkit serial analyzer and configures the interface as SPI master
Init must be performed prior any other communication.

Parameters:
dBitrate: data transmission bandwidth in kHz (0.61...1250 kHz)

Returns:
error code, see Table 5

```
static int CleanUp()
```

Shuts down communication threads and closes file handles.
CleanUp must be performed prior to closing host application.

Returns:
error code, see Table 5

5.4.1.2 Module Activation

```
static int EnableModule(byte chParameter)
```

Enables or disables the resonant scanner. Enable starts the scanner with a frequency sweep and the predefined start-up parameters. After start-up the scanner control is switched to the configured operation state.

Parameters:
chParameter: 0: disable / stop
1: enable / start

Returns:
error code, see Table 5

```
static int EnableExtern(byte chParameter)
```

EnableExtern switches the activation behavior between software and hardware control.

Parameters:
chParameter: 0: hardware pin is ignored – software control
1: Scanner module is enabled with hardware pin at low

Returns:
error code, see Table 5

5.4.1.3 Resonance scanner parameters

```
static int SetAmplitude(float fValue)
static int GetAmplitude(byte chParameter, out float fValue)
```

Mechanical scan amplitude (MSA) in degree. The SetAmplitude function sets the target for the amplitude control. The GetAmplitude function returns the target or the current value depending on the parameter.
Note: Feedback sensor must be switched on and amplitude control must be enabled. Otherwise the amplitude will not be controlled.

Parameters:

fValue: target value for the amplitude control

chParameter: 0: current mechanical scan amplitude (MSA) in degree
1: mean mechanical scan amplitude (MSA) in degree
2: current raw value in ns
3: mean raw value in ns
4: target mechanical scan amplitude (MSA) in degree
5: target value in ns

Returns:

error code, see Table 5
fValue (out): value cornsponding to the transmitted parameter

```
static int GetAmplitudeLimits(out float fMinValue, out float fMaxValue)
```

Returns the factory-defined range for amplitude values, the minimum and the maximum. The limits represents the parameter input range and the range of a internal watchdog. Electronics switches to an error state if the limit is achieved.

Returns:

error code, see Table 5
fMinValue: minimum
fMaxValue: maximum

```
static int SetPhase(float fValue)
static int GetPhase(byte chParameter, out float fValue)
```

Phase of the scanner oscillation respective to the drive signal. The SetPhase function sets the target for the phase control. The GetPhase function returns the target or the current value depending on the parameter.
Note: Feedback sensor must be switched on and amplitude control must be enabled. Otherwise the amplitude will not be controlled.

Parameters:

fValue: target value for the phase control

chParameter: 0: current value in degree
1: mean value in degree
2: current raw value in ns
3: mean raw value in ns
4: target value in degree
5: target value in ns

Returns:

error code, see Table 5
fValue (out): value cornsponding to the transmitted parameter

```
static int GetPhaseLimits(out float fMinValue, out float fMaxValue)
```

Returns the factory-defined range for phase values, the minimum and the maximum. The limits represents the parameter input range and the range of a internal watchdog. Electronics switches to an error state if the limit is achieved.

Returns:
error code, see Table 5
fMinValue: minimum
fMaxValue: maximum

```
static int SetVoltage(float fValue)
static int GetVoltage(out float fValue)
```

Peak to peak voltage of the resonance scanner drive signal.
Note: The Voltage is not stored in EEPROM. On Power-up the scanner starts with the pre-configured start-up voltage.
A voltage, set in idle mode (module disabled), is overwritten by pre-defined start-up parameters if the scanner is enabled.
Setting voltage during scanner start-up is denied and returns illegal command.
Setting voltage directly in amplitude and phase control mode is not interlocked but strictly not recommended.
SetVoltage can be inactivated in the some customized module configuration.

Parameters:
fValue: voltage in V

Returns:
error code, see Table 5
fValue (out): current voltage in V

```
static int GetVoltageLimits(out float fMinValue, out float fMaxValue)
```

Returns the factory-defined range for voltage values, the minimum and the maximum [V]. The limits define the parameter input range. Furthermore the internal amplitude control (control variable: voltage) is limited to this range.

Returns:
error code, see Table 5
fMinValue: minimum
fMaxValue: maximum

```
static int SetFrequency(float fValue)
static int GetFrequency(out float fValue)
```

Sets and returns the frequency of scanner drive signal in Hz. The drive frequency is double the mechanical oscillation frequency. This frequency setting is only possible if phase control is disabled and amplitude control is in voltage mode or disabled.
Note: The frequency is not stored in EEPROM. On power-up the scanner starts with the pre-configured start-up frequency.
A frequency, set in idle mode (module disabled), is overwritten by pre-defined start-up parameters if the scanner is enabled.
Setting frequency during scanner start-up is denied and returns illegal command.
Setting frequency directly in amplitude and phase control mode is not interlocked but strictly not recommended.

SetFrequency can be inactivated in the some customized module configuration.
Parameters:

Value: frequency

Returns:

error code, see Table 5
fValue (out): current frequency of resonance scanner drive

```
static int GetFrequencyLimits(out float fMinValue, out float fMaxValue)
```

Returns the defined range for frequency values, the minimum and the maximum in Hz.

Returns:

error code, see Table 5
fMinValue: minimum
fMaxValue: maximum

```
static int GetResonanceFrequency(out float fValue)
```

Returns the resonance frequency of the MEMS scanner, stored in EEPROM [Hz]. The limits define the parameter input range.

Returns:

error code, see Table 5
fValue: eesonance frequency

5.4.1.4 Optical feedback sensor and control

```
static int EnableSensor(byte chParameter)
```

Switches the scan head internal optical feedback sensor. With activated sensor amplitude and phase of scanner oscillation can be set and measured. Further sensor activation is necessary for amplitude and phase control.
Function EnableSensor can be inactivated in the some customized module configuration.
Parameters:

chParameter: 0: Sensor disabled and laser off
1: Sensor

Returns:

error code, see Table 5

```
static int EnableAmplitudeControl(byte chParameter)
```

Enables / disables the scanner amplitude control using the feedback sensor signal.
Disabling amplitude control can be prohibited in the some customized module configuration.

Parameters:

chParameter: 0: amplitude control disabled, amplitude regulation via voltage or frequency
1: amplitude control is enabled

Returns:

error code, see Table 5

```
static int SetAmplitudeControlMode(byte chParameter)
static int GetAmplitudeControlMode(out byte chValue)
```

AmplitudeControlMode mode selects the parameter, the amplitude is controlled with.
This function can be inactivated in the some customized module configuration.

Parameters:

chParameter: 0: … use voltage as control variable
1: … use frequency as control variable

Returns:

error code, see Table 5

chValue: 0: … use voltage as control variable
1: … use frequency as control variable

```
static int EnablePhaseControl(byte chParameter)
```

Enables / disables the scanner phase control using the feedback sensor signal. Disabling phase control can be prohibited in the customized module configuration.

Parameters:

chParameter: 0: phase control disabled
1: phase control is enabled

Returns:

error code, see Table 5

```
static int EnableAutoRestart(byte chParameter)
```

Defines the behavior, if the feedback sensor detects an error state, mainly if after start-up or while operation the sensor detects no more oscillation. Independent from setting of EnableAutoRestart, the auto-restart functionality is only possible if the feedback sensor is activated.

Parameters:

chParameter: 0: The current operation of the scanner is continued and an error is signaled
1: The module is re-set and re-started

Returns:

error code, see Table 5

```
static int GetModuleConfiguration(out UInt16 nValue)
```

Returns the settings of the module configuration registers for module enabling, sensor enabling and control modes as 2-byte value. The bit mapping is shown in

Table 10.

Returns:

error code, see Table 5

nValue*: see*

Table 10

```
static int GetControlState(out byte chValue)
```

Returns in the state of the scanner oscillation, amplitude control and phase control. If a value (phase or amplitude) is changed, the assigned bit is set to 0. If the scanner oscillation is on target the bit is set to 1.

Returns:
error code, see Table 5
chValue: see Table 11

5.4.1.5 Diagnostics

```
static int GetSerial(out UInt32 nValue)
```

Returns a unique serial number of the LDC-Module.

Returns:
error code, see Table 5
nValue: serial number

```
static int GetVersion(out string szValue)
```

Returns the firmware version of the LDC module driving electronics.

Returns:
error code, see see Table 5
szValue: string with the firmware version

```
static int GetState(out byte chValue)
```

Returns the current state of the internal state machine.

Returns:
error code, see Table 5

chValue: state, see

Table 10.

```
static int GetErrorCode(out byte chValue)
```

Returns the error code of the last error detected by the LDC driving electronics

Returns:
error code of the function, see Table 5
chValue: see Table 12

5.4.1.6 Storing of settings

```
static int EEPROM(byte chParameter)
```

Stores and loads the configuration to or from the electronic internal EEPROM.

Parameters:
chParameter: 0: Store
1: Load

Returns:
error code of the function, see Table 5

5.4.1.7 Low-level functions

Low level fuctions are not needed to call directly for a communication with the LDC module.

```
static int TransmitFrame(byte chOpCode, byte[] chTXData, out byte[] chRXData)
```

Low level function to transmit data frames to the LDC module. The function is not necessary for the user to communicate with the LDC module. It is called from the SetCommand/GetCommand function and can be used for own low-level access to the SPI protocol.

Parameters:
chOpCode: SPI command code, see table 6, Manual Laser Deflection Cube Returns:
chTXData: Data to transmit to LDC module
chRXData: Data to receive from LDC module
Returns:
error code of the function, see Table 5

Note: Data length of the arrays must be match with the transmitted data type (table 6, Manual Laser Deflection Cube)

```
static int GetCommand(byte chOpCode,out…)
static int SetCommand(byte bOpCode,…)
```

The functions GetCommand / Set Command can be used to call a function via its OpCode. Types of parameter are identical to upper description.

Parameters:
chOpCode: SPI command code, see Table 9
Returns:
error code of the function, see Table 5

5.4.2 LDC Interface API Error Codes

Table 5: LDC Interface API Error Codes

Wert	Name	Beschreibung
0		No error
1	SPI_ERROR_PICKIT	PICKit inizialization error, e.g. not connected
2	SPI_ERROR_BUSY	LDC module driving electronics busy *Try again*
3	SPI_ERROR_OUT_OF_RANGE	Values are out of range in a Set Command *Check the limits*
4	SPI_ERROR_ILLEGAL_COMMAND	Command not allowed in this context
5	SPI_ERROR_ACCESS_DENIED	Command is not accessible in this customized configuration. *The LDC module driving electronics covers a wide range of scanners and applications. To avoid damaging certain not usefull commands are denied.*
6	SPI_ERROR_CRC	Via SPI transmited data frames are corrupted. *Reduction of data transmission bitrate (see 5.4.1.1)* *Reduction of cable length*
7	SPI_ERROR_TIMEOUT	Command reply timout *Reduction of data transmission bitrate (see 5.4.1.1)* *Reduction of cable length*
8	ERROR_DATA_LENGTH	An other data length was expected *Error can only occur with low level commands*
9	ERROR_INIT_PKSA	Hardware error of PICKit serial analyzer while initialization
10	ERROR_INIT_SPI	Hardware error of PICKit serial analyzer while initialization of the SPI interface application
11	ERROR_INIT	Error while initalization of SPI communication
13	ERROR_WRONG_PKSA_FW	Firmware version of PICKit serial is to low for this application
14	ERROR_BITRATE	Bitrate tranmitted with command Init is not valid
15	SPI_ERROR_ENDTOKEN	No transmission frame end token received *Reduction of data transmission bitrate (see 5.4.1.1)* *Reduction of cable length*

5.4.3 Code sample

The following code (C#, Microsoft Visual Studio 2005) initializes the PICkit and the SPI Interface, activates the scanner and reads out the actual voltage. Last, the PICkit interface is removed from memory.

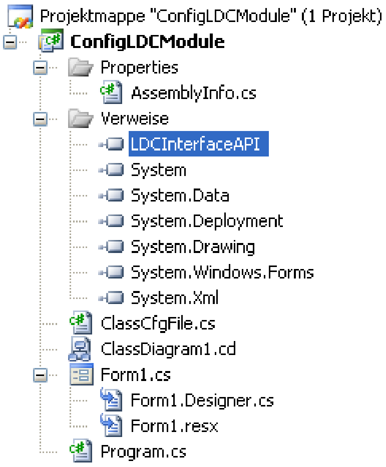


Figure 12: Implementation of LDC Interface API as class library in Microsoft Visual Studio 2005

```
using LDCInterfaceAPI;

private void LDCFunction()
{
  int ret;
  ret = LDCInterface.Init(1000);
  if (ret!=0)
     MessageBox.Show("Error initializing PICKit Serial. Error "+ret);
  ret = LDCInterface.EnableModule(1);
  if (ret!=0)
     MessageBox.Show("Error enabling scanner. Error "+ret);
  float Voltage;
  ret = LDCInterface.GetVoltage(out Voltage);
  if (ret!=0)
     MessageBox.Show("Error reading voltage. Error "+ret);
  MessageBox.Show("Current Voltage: "+Voltage);
  LDCInterface.CleanUp;
}
```

6 SPI Interface

6.1 Interface Hardware Description

The LDC electronic board provides a Serial Peripheral Interface (SPI) interface to configure the control of the micro scanner device and to receive operational status information of the scanner and the position feedback sensor by a superordinated system controller.
The SPI interface of the on-board digital signal controller is electrically connected directly to the edge connector of the board.
The SPI interface is configured to run in slave mode. This means, that both, the Serial Clock (SCK) and the transmission request, controlled by Slave Select (SS) have to be provided by the SPI master device.
To initiate a data transmission or reception, the SS signal must be driven low. The interface is further configured that the data transmission occurs at the rising edge of the high-active Serial Clock input signal (SCK). The word length of data is determined to one byte. A command frame embodies multiple bytes, so the SS command must be hold on low until the complete sequence is transmitted.
To transmit data to the LDC board, the data must be provided at Serial Data In (SDI). Data can be read from the LDC board using the Serial Data Out Signal (SDO). Both data transmission lines are served simultaneously with the serial clock.
Figure 13 shows the timing diagram of the serial communication.

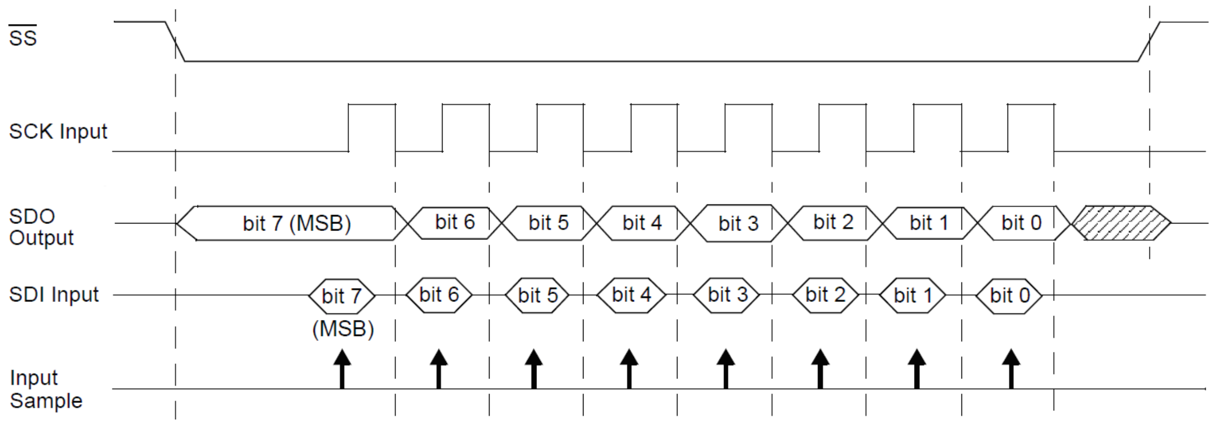


Figure 13: SPI Timing Diagram

6.2 Timing Characteristic

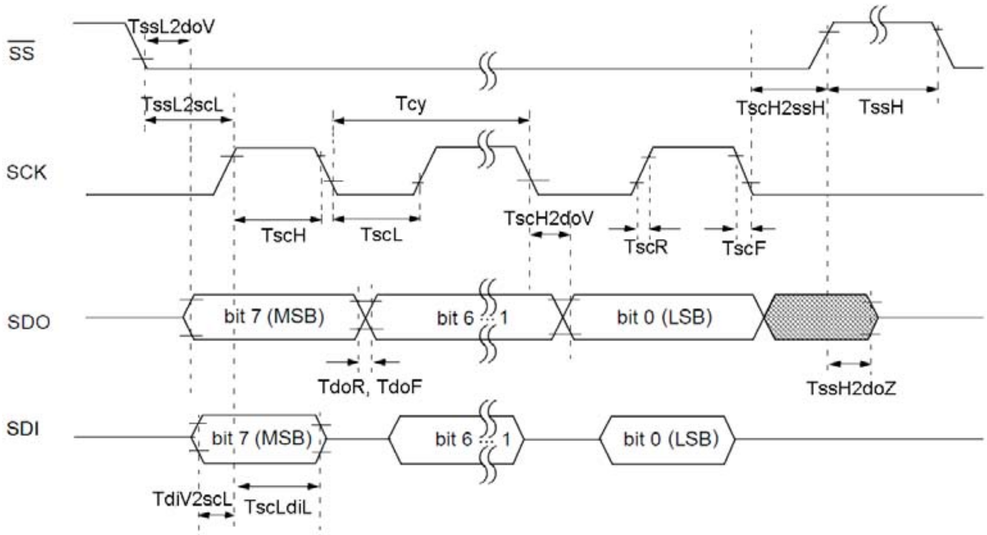


Figure 14: SPI Timing Characteristic Diagram

Table 6: Timing Requirements

Symbol	Characteristic	Min	Typ	Max	Units	Conditions
TscL	SCK Input Low Time	30	—	—	ns	The minimum clock period Tcy must not be violated
TscH	SCK Input Low Time	30	—	—	ns	The minimum clock period Tcy must not be violated
Tcy	SCK Cycle Time	32	—	—	µs	—
TssL2doV	SDO Data Output Valid after SS Edge	—	—	50	ns	—
TssL2scL	SS ↓ to SCK ↓ Input	120	—	—	ns	—
TscH2ssH	SS ↑ after SCK Edge	65	—	—	—	Assumes 50 pF load on all SPI pins (see Figure 15)
TscH2doV	SDO Data Output Valid after SCK Edge	—	—	30	ns	—
TscF	SCK Input Fall Time	—	10	25	ns	—
TscR	SCK Input Rise Time	—	10	25	ns	—
TssH2doZ	SS ↑ to SDO Output High-Impendance	10	—	50	ns	Assumes 50 pF load on all SPI pins (see Figure 15)
TdiV2scL	Setup Time of SDI Data Input to SCK Edge	20	—	—	ns	—
TscL2diL	Hold Time of SDI Data Input to SCK Edge	20	—	—	ns	—
TdoF	SDO Data Output Fall Time	—	10	25	ns	—
TdoR	SDO Data Output Rise Time	—	10	25	ns	—
TssH	Minimum SS Inactive Time	100	—	—	µs	

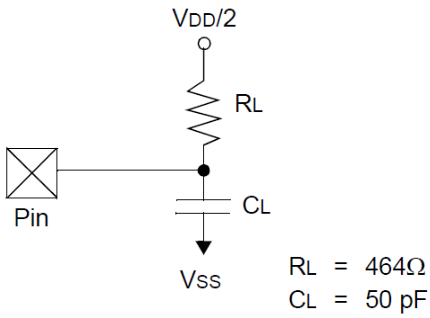


Figure 15: Load Conditions for Device Timing Requirements

6.3 Transmission Protocol

The communication protocol of the SPI interface is based on a fixed data frame architecture (Table 7). Each data frame, initialized by the master device, contains a command sequence followed by a data block with data to be transmitted to the LDC board as well a command response followed by a data block for receiving data from LDC board. Each data block is secured by a length byte and a checksum byte.

Considering the SPI physical layer definition, with each byte transmitted in one direction a byte is received vice versa. To ensure a failure-free data transmission, an empty byte token (*0xFF*) has to be transmitted to the slave while receiving data from slave. Likewise, the slave transmits the empty byte token (*0xFF*) during receiving data from master. Further, each transmission has to be finalized with an end token (*0xFF*).

After a data request by the master, the slave usually needs some calculations until the response is ready for transmission. If the master continues querying the slave by serving the serial clock (SCK) signal before the data are available, the slave transmits an empty byte token until calculation is finished. The protocol ensures that each response after the pause is different to the empty byte token (*0xFF*). So a byte different to the empty byte token (*0xFF*) can be interpreted as the continuation of the frame after the pause.

Table 7: SPI Data Transmission Frame

SDI	Command	Data Length	Data	CRC	End Token	Pause					
SDO							Response	Data Length	Data	CRC	End Token

Command

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0	0 (Axis)	Command ID					

Data Length

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
Data length without CRC (unsigned integer), can be null, in this case no data bytes follow							

Data
Depends on command

CRC

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
char sum of commando byte, length byte and data bytes							

End Token

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
1	1	1	1	1	1	1	1

Empty Byte Token

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
1	1	1	1	1	1	1	1

Response

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0	—	—	Access Denied	Illegal Command	Out of Range	CRC Error	Busy

Table 8: SPI Protocol characteristic

Characteristic	Min	Typ	Max	Units	Conditions
Time-Out[1]	—	—	10	ms	with or without serial clock (SS)
	—	—	1	s	Ditto, only for the EEPROM write command
Data Length	0	—	128	bytes	
Pause time	60	140	5000	µs	Commands without data conversion
	180	500	5000	µs	Commands with data conversion
	2	5	10	ms	EEPROM read command
	—	800	1000	ms	EEPROM write command

6.4 Error Handling

At each time, the transmission is initiated by enabling the Slave Select (SS) signal, the interface expects a sequence with the command code, regardless in which state the previous transmission was interrupted. This precaution obtains a determined data stream also in the case, a transmission fails or is not completed by the master.
Transmission errors can be identified by the data length, and the evaluation of the CRC. Commands responded by the slave with at least one error flag in the response byte are not executed and can be repeated immediately.
After an elapsed timeout (see Table 8) a reset of the SPI interface of the LDC board is performed. The timeout event arises regardless a serial clock (SCK) is provided by the master or not.

[1] If the specified time is elapsed, data from LDC board can be expected not anymore.

6.5 Data Formats

In present data transmission protocol multi-byte parameters are always sent least significant byte first (little endian). This is compliant e.g. to Intel x86- or x64- based machines.
Note the inverse *bit* endiness in data transmission with the most significant bit first (see Figure 17).

The floating point data format (single precision), used for several parameters is compliant to the IEEE-754 standard. The format and an example are shown in Figure 16. The 4-byte word is transmitted also in little endiness byte order, least significant byte first and the most significant *bit* first, see Figure 17.

	s	exponent (8 bits)								fraction (23 bits)																							
Bit	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
	0	0	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	= 0.15625

Figure 16: IEEE-754 compilant float data format (single precision); s=sign

Memory data format (little endian)

Bit	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	
	0	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0	**0**	0	0	0	1	0	0	1	**1**	0	0	0	0	1	1	0	= 2438 (uint32)
	0	0	1	1	1	1	1	0	**0**	0	1	0	0	0	0	0	**0**	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0	= 0.15625 (float)

SPI transmission bit order

Clock	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	28	30	31	
	1	0	0	0	0	1	1	0	**0**	0	0	0	1	0	0	1	**0**	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0	= 2438 (uint32)
	0	0	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0	**0**	0	1	0	0	0	0	0	**0**	0	1	1	1	1	1	0	= 0.15625 (float)

Figure 17: Examples for bit/ byte order of values (little endian) and during data transmission via SPI

6.6 SPI Command List

Table 9: SPI Command List

Op Code	Command	Datatype	Description
01	EnableModule	byte	Enables / Disables module and scanner 0: Disable 1: Enable
02	EnableExtern	byte	Usage of external hardware pin for module enabling 0: hardware pin is ignored 1: module is enabled with hardware pin at low
03	EnableAmplitudeControl	byte	Enables / disables the scanner amplitude control using the sensor signal 0: Disabled 1: Enabled
04	SetAmplitudeControlMode	byte	Selection of the parameter used to control the amplitude 0 … use voltage as control variable 1 … use frequency as control variable For amplitude control
05	GetAmplitudeControlMode	byte	Returns the control variable for amplitude control 0 … Voltage 1 … Frequency
06	EnablePhaseControl	byte	Enables / disables the scanner phase control using the sensor signal. The control variable is the frequency. 0: Phase control disabled, laser off, amplitude limit watchdog off 1: Phase control enable
07	EnableSensor	byte	Switches the scan head internal optical feedback sensor. With activated sensor amplitude and phase of scanner oscillation can be set and measured. Further sensor activation is necessary for amplitude and phase control. 0: Sensor disabled and laser off 1: Sensor enabled
08	EnableAutoRestart	byte	Defines the behavior, if the feedback sensor detects an error state, mainly if after start-up or while operation the sensor detects no more oscillation. Independent from setting of EnableAutoRestart, the auto-restart functionality is only possible if the feedback sensor is activated. 0: The operation is continued (error signaled) 1: The module is re-set and re-started
09	GetModuleConfiguration	16 bit	Returns the settings of the module configuration registers for module enabling, sensor enabling and control modes as 2-byte value. The bit mapping is shown in Table 10.
0A	GetSerial	uint32	Returns the serial number

Op Code	Command	Datatype	Description
0B	GetVersion	string	Returns the hardware and firmware version
0C	GetState	byte	Returns the state of the internal state machine. See Table 11.
0D	GetControlState	byte	Returns the state of the scanner oscillation, amplitude control and phase control. If a value (phase or amplitude) is changed, the assigned bit is set to 0. If the scanner oscillation is on target the bit is set to 1. See Table 12.
0E	GetErrorCode	bytes	Returns the last error code occurred. See Table 13.
0F	EEPROM (0=Write / 1=Read)	byte	Stores and loads the configuration to or from internal EEPROM 0: Store 1: Load
10	SetAmplitude	float	Sets the target amplitude for amplitude control defined as mechanical scan amplitude (MSA) in degree Note: To get amplitude control working, amplitude control must be enabled (OpCode 03) and feedback sensor must be switch on (OpCode 07).
11	GetAmplitude	IN: byte OUT: float	Returns the current amplitude for amplitude IN: 0: current mechanical scan amplitude in degree 1: mean mechanical scan amplitude in degree 2: current raw value in ns 3: mean raw value ins 4: target mechanical scan amplitude in degree 5: target value in ns
12	GetAmplitudeLimits	float, float	Returns the factory-defined range for amplitude values, the minimum and the maximum. The limits represents the parameter input range and the range of a internal watchdog. Electronics switches to an error state if the limit is achieved.
13	SetPhase	float	Sets the target phase for phase control [ns] defined phase of the scanner oscillation respective to the drive signal. Note: To get phase control working, amplitude control must be enabled (OpCode 06) and feedback sensor must be switch on (OpCode 07).
14	GetPhase	IN: byte OUT: float	Returns the target value for phase control (pase between driving signal an scanner oscillation) IN: 0: current phase in degree phase (0…360°) 1: mean phase value degree phase (0…360°) 2: current raw value in ns phase shift 3: mean raw value in ns phase shift 4: target phase in degree phase (0…360°) 5: target value in ns phase shift

Op Code	Command	Datatype	Description
15	GetPhaseLimits	float, float	Returns the defined range for phase values, the minimum and the maximum [ns]. The limits define the parameter input range and the range of a watchdog. If the limit is achieved an error is generated.
16	SetVoltage	float	Sets the peak to peak voltage of the resonance scanner drive signal. **Note**: The Voltage is not stored in EEPROM. On Power-up the scanner starts with the pre-configured start-up voltage. A voltage, set in idle mode (module disabled), is overwritten by pre-defined start-up parameters if the scanner is enabled. Setting voltage during scanner start-up is denied and returns *illegal command*. Setting voltage directly in amplitude control mode is not interlocked but strictly not recommended.
17	GetVoltage	float	Returns the current peak to peak amplitude of scanner high voltage drive signal. [V]
18	GetVoltageLimits	float, float	Returns the defined range for voltage values, the minimum and the maximum [V]. The limits define the parameter input range. Furthermore the internal amplitude control (control variable: voltage) is limited to this range.
19	SetFrequency	float	Sets the frequency [Hz] of scanner drive signal. The drive frequency is double the mechanical oscillation frequency. This frequency setting is only possible if phase control is disabled and amplitude control is in voltage mode or disabled. **Note**: The frequency is not stored in EEPROM. On Power-up the scanner starts with the pre-configured start-up frequency. A frequency, set in idle mode (module disabled), is overwritten by pre-defined start-up parameters if the scanner is enabled. Setting frequency during scanner start-up is denied and returns *illegal command*. Setting frequency directly in amplitude and phase control mode is not interlocked but strictly not recommended.
1A	GetFrequency	float	Returns the current scanner oscillation frequency [Hz].
1B	GetFrequencyLimits	float, float	Returns the defined range for frequency values, the minimum and the maximum [Hz].
1C	GetResonanceFreqency	float	Returns the resonance frequency of the MEMS scanner, stored in EEPROM [Hz]. The limits define the parameter input range.

Table 10: Bit allocation of module configuration

Bit 15	Bit 14	Bit 13	Bit 12	Bit 11	Bit 10	Bit 9	Bit 8
—	—	—	—	—	—	—	—
Bit 7	**Bit 6**	**Bit 5**	**Bit 4**	**Bit 3**	**Bit 2**	**Bit 1**	**Bit 0**
—	Enable Auto Restart	Enable Sensor	Phase Control	Amplitude control mode	Amplitude Control	Enable Extern	Module Enable

Table 11: Return codes of internal state machine

State	Description
0	Booting hardware
1	Module disabled
2	Initializing hardware
3	Starting scanner (frequency sweep)
4	Waiting for sensor signals
5	Scanner oscillation with enabled control
6	Error
7	Hardware calibration mode (can not occur in normal operation)

Table 12: Bit allocation of the control state

Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
—	—	—	—	—	phase on target	amplitude on target	oscillation detected

Table 13: Error Codes

Error	Description
0	No error
1	Hardware error: EEPROM read error
2	No Data in EEPROM
3	Hardware error: Error initializing TDC1
4	Hardware error: Error initializing TDC2
5	Scanner startup error (no oscillation detection
6	No scanner oscillation detection
7	Upper phase limit exceed
8	Lower phase limit exceed
9	Upper amplitude limit exceed
10	Lower amplitude limit exceed

NOTES