MANUAL

Shape Sensing Software

Version 1.3

Author	Jan Van Roosbroeck	**Issue date**	15/04/2020
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CONTENT

Content ... 2

1 *Introduction* ... 3

2 *Hardware Setup* ... 3

3 *ILLumiSense Settings* ... 5

4 *Shape Sensing Software* ... 5

4.1 **Shape Sensing Main panel** ... 5

4.2 **The Shape Sensing Settings panel** ... 6

4.3 **Calibration** ... 10

4.3.1 Reference wavelengths ... 10

4.3.2 Reference Twist ... 11

4.4 **TCP-streaming** ... 13

4.5 **Software Development Kit** ... 15

1 INTRODUCTION

This document contains a manual for proper usage of the FBGS **Shape Sensing software version 1.3.** This software (SW) calculates the curvature and 3D-shape of an array of Draw Tower Gratings (DTGs) written in a Multi Core Fiber (MCF). The SW runs in parallel with the standard ILLumiSense readout SW of the FBG-Scan measurement device and it receives the wavelength information of the DTGs from the different cores via TCP-streaming from the ILLumiSense.

The User Interface consists of 2 different windows: the 'Shape Sensing Main' screen and the 'Shape Sensing Settings' screen. The software has the following main features:

- Collect the wavelength data send out by the ILLumiSense software via the TCP-interface.
- Entering the sensor specific parameters for the MCF-sensor needed for curvature and shape calculation: sensor configuration, core-to-center spacing, strain gage factor, core to channel correspondence.
- Sensor configuration can contain multiple sections with different wavelength and position spacings.
- Performing the 2-step referencing process for calibration of the MCF: reference wavelengths and reference twist.
- Saving of new and retrieving of earlier recorded reference data files (calibration data) as determined with this software.
- Calculation, real time visualization, TCP-streaming and snapshot saving of curvature, curvature angle and 3D-shape data.
- Optional Software Development Kit (SDK) based on a DLL that allows integration of the software into customer specific applications.

2 HARDWARE SETUP

The components needed for Shape Sensing are:

- **Multi Core Fiber (MCF)** with an active sensing area. The DTGs all have different wavelengths in order to discriminate them (so-called 'Wavelength Division Multiplexing' or 'WDM').
- A **Fanout box**, needed to split the different cores from the MCF into a set of single core fibers so that they can be read out individually.
- An **FBG-Scan measurement device** with minimum 4 channels needed to read out the sensor wavelengths from the different cores.

The MCF has several **key parameters** that are required for proper setup of the Shape Sensing SW:

- **Core configuration:** 4 or 7 cores, see Figure 1. Notice the standard FBGS numbering convention of the cores: the central core is always number 1 from the fanout box. Core 2 is the one on the 12 o'clock position and the other cores are numbered in ascending order in clockwise direction. (The direction of looking is towards the fiber from the connector side. The lid of the E2000 connector determines the 12 o'clock position.) The central core is not required for curvature and shape sensing. Therefore, it does not need to be connected to the interrogator. The **outer cores** carry in principle all curvature information of the MCF.

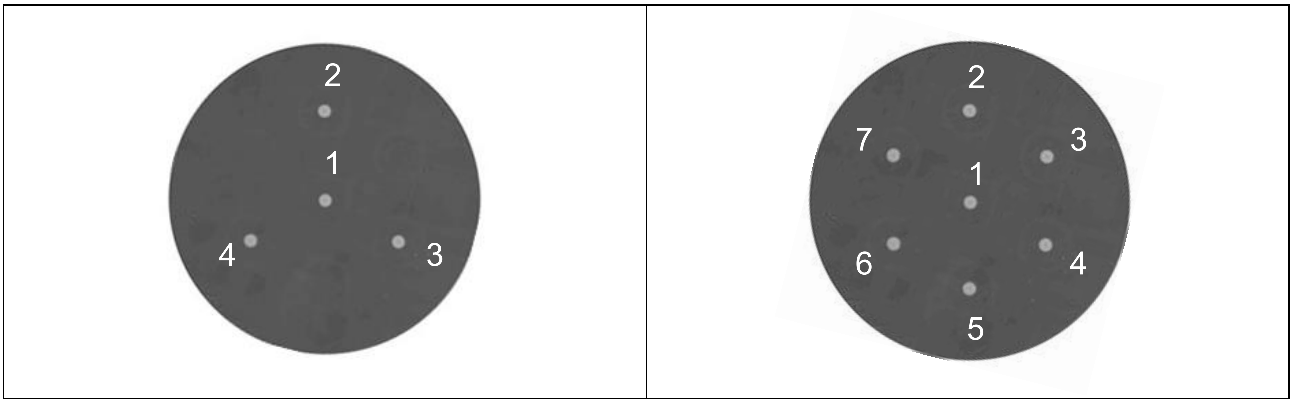


Figure 1: Cross section of the 4 and 7 core fibers.

The Shape Sensing software requires 3 outer cores to be connected to the interrogator. For a 4 core fiber, the only possible option is to use cores 2, 3 and 4. The order in which the cores are selected has no impact on the measured curvature profile but determines the orientation of the reference frame for its shape.

For the 7 core fiber, there are multiple options of cores to select. Typically, the cores with the cleanest optical spectra are selected. These are usually indicated in the documentation that comes together with the MCF samples (the recommended cores are indicated).

In general, the selected set of cores can be classified in 2 main categories: the **'adjacent'** cores and the **'complementary'** cores, see Figure 2. Adjacent cores are cores that are adjacent to each other, like for example 4, 5 and 6, or 7, 2 and 3. Complementary cores are cores that are arranged in a triangle with angles of 120°, in similarity to the 4 core fiber arrangement.

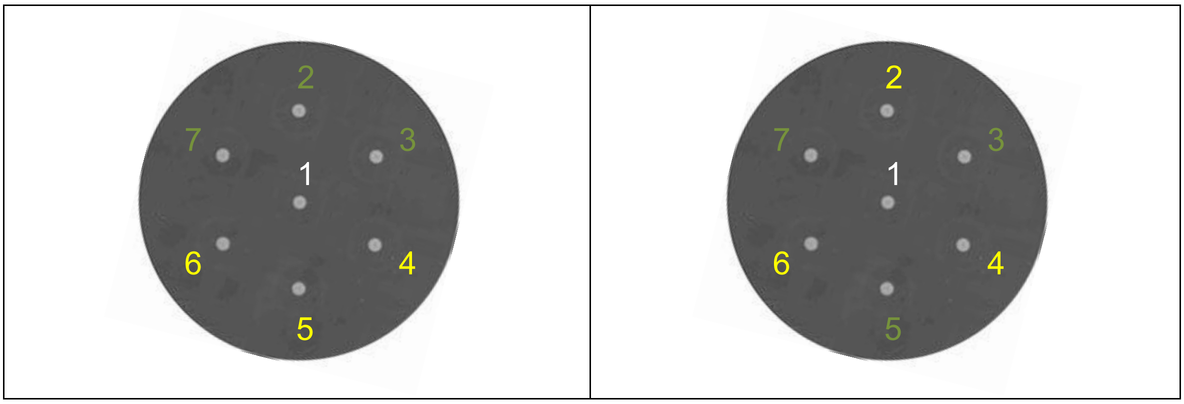


Figure 2: Example sets of adjacent cores (left) and the complementary cores of a 7-core fiber.

In similarity to the 4-core MCF, the order in which the complementary cores are selected is not important for the curvature calculation. It just fixes the orientation of the reference frame for the shape calculation. For the adjacent cores, the order is equally not important but the core in the middle should also be selected as the one in the middle. For example, if one selects cores 2, 3 and 4 then 2, 3 , 4 will give the same curvature profile as 4, 3, 2 but 3, 2, 4 will result into erroneous data. This may seem obvious but care should be taken for combinations containing cores 2 and 7. For example, the combination 2, 3, 7 is not allowed but 7, 2, 3 and 3, 2, 7 are allowed.

- **Core distance:** this parameter indicates the distance of the outer cores to the central core. Due to symmetry reasons of the core configurations, this parameter is identical for all outer cores. For the standard MCF from FBGS, this parameter is typically 37 µm. It will be provided in the documentation that comes together with the MCF. The parameter is important since it dictates the curvature sensitivity of the MCF.

- **Strain gauge factor:** this is the strain sensitivity of the fiber, often also indicated by ($1-P_e$) with P_e the strain optic coefficient of the glass. The value is typically 0.777 $\mu strain^{-1}$ but can vary slightly depending on the used fiber type. The gauge factor is also an input parameter for the shape software.

- **FBG-Spacing:** The number of DTGs and their wavelengths are obvious since these are measured by the interrogator and transferred to the Shape Sensing SW. But the physical distance between the DTGs is an input parameter that is required for the shape reconstruction. The spacing can be different for different sections within a DTG-array. The software can accept multiple DTG-spacings for a single array. The DTG-spacing information can also be found in the documentation that comes together with the MCF samples.

With the above information at hand, it is possible to compose the hardware setup. The MCF is plugged into the fanout box and the selected cores are connected to the FBG-Scan with patch cables.

3 ILLUMISENSE SETTINGS

The next step is to set up the ILLumiSense software. With the hardware connected, the quality of the different signals need to be checked. This goes as follows:

- Enable all active channels
- Check that the number of measured peaks corresponds to the number of expected peaks. If this does, confirm it. If it does not, go to the Initialization Settings and adjust Integration Time, Noise Threshold or Sensitivity Mode until all peaks are properly detected.
- If all channels are enabled and the error status is green, enable the TCP-streaming in the Initialization Settings window.

4 SHAPE SENSING SOFTWARE

4.1 Shape Sensing Main panel

With the ILLumiSense running and the TCP-streaming enabled, the next step is to start up the Shape Sensing software. The main User Interface (UI) will be displayed, see Figure 3.

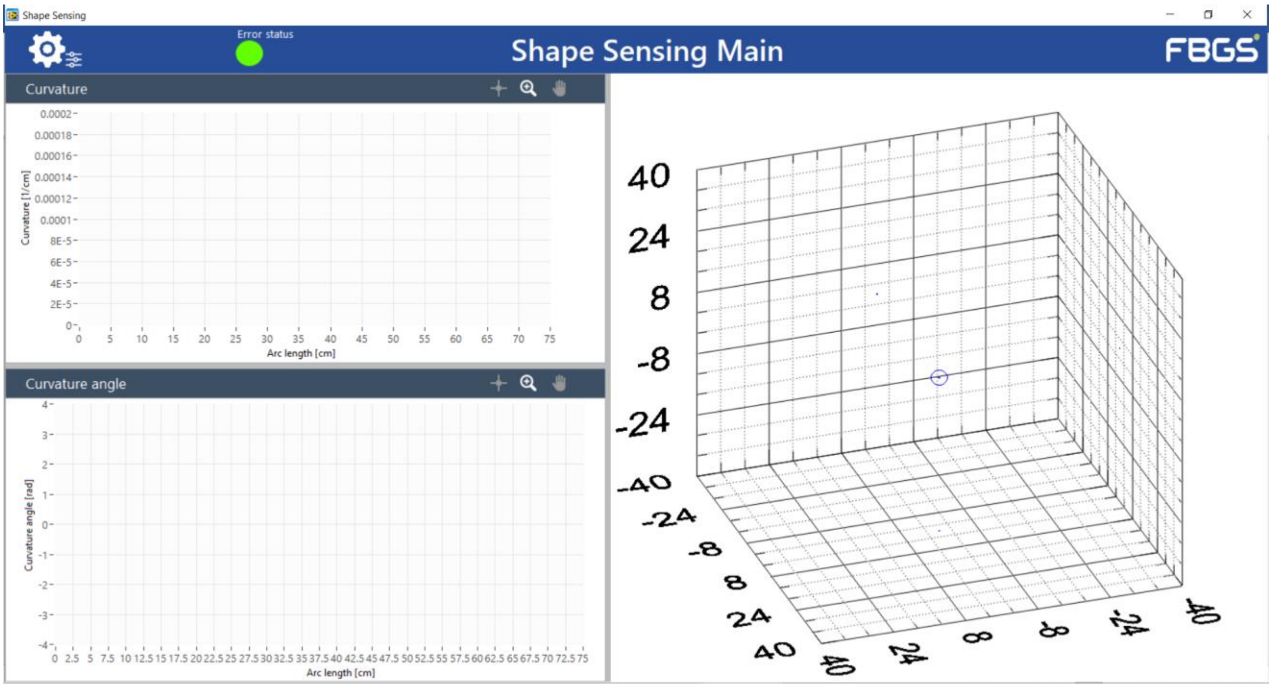


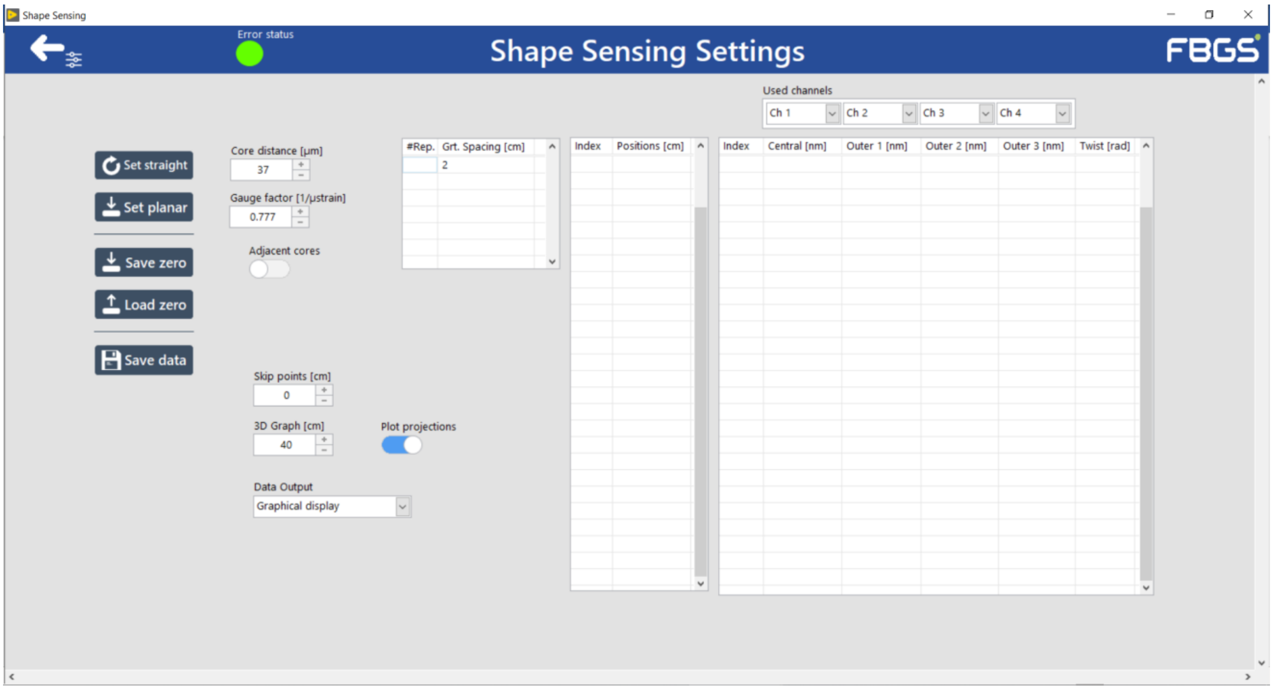
Figure 3: Screenshot of the UI of the Shape Sensing software after startup.

It shows 3 graphs:

- The **curvature** as function of fiber arc length (top left): the x-axis represents the arc length of the fiber (in cm). The y-axis represents the curvature (in cm^{-1}) for each position.
- The **curvature angle** as function of the fiber arc length (bottom left): the x-axis represents the arc length of the fiber (in cm). The y-axis represents the direction of curvature i.e. the angle of the bending axis (in radians) with respect to the first plugged outer core.
- The **3D-shape** (right): this is the 3-dimensional shape reconstructed from both the curvature as well as curvature direction information derived from the DTGs. The curve always starts at the origin and the straight fiber is lying in the direction of the x-axis. It also shows the projections of the 3D-curve on the principal planes (xy-, xz- and yz-planes). The 3D graphical representation can be rotated by dragging it with the mouse. Zooming in and out can be done by scrolling with the mouse wheel. Changing the overall scale of the graph can be done in the settings window with the parameter '3D graph [cm]', which fixes the maximum size of the x, y and z-axes.

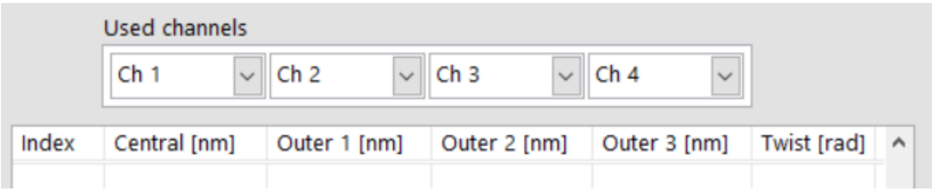
4.2 The Shape Sensing Settings panel

Pressing on the Settings button (top left) shows the settings window, which looks as follows:

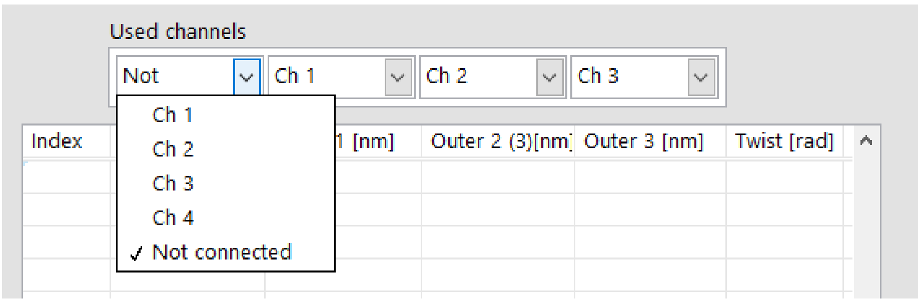


It contains the following tables, buttons and controls:

- **Used channels:** indicates the channels used for the center and outer cores 1, 2 and 3, see page 4.



If the center core is not connected, select 'not connected' from the drop down box. For the outer cores, this option is disabled because at least 3 outer cores are needed to do shape sensing.



- **Compressed array spacing table (left):** this table summarizes the sensor spacings. Each row can be used for an array section with equal spacings. The '# Rep.' column stands for the 'number of repetitions' of a certain spacing. For example, if the array contains 38 DTGs with equal spacing, the number of repetitions is 37.

  The default setting is for an array with constant spacing of 2 cm. The number of repetitions is derived from the number of detected wavelengths from the first plugged outer core.

#Rep.	Grt. Spacing [cm]
37	2

The spacing needs to be modified if the spacings are different. If the array contains multiple sections with different spacings, multiple rows will need to be filled in. An example for an array with 3 different sections is shown below:

#Rep.	Grt. Spacing [cm]
15	4.8
3	3.2
5	1.6

This table is used to calculate the indexed array spacing table (middle). The results are immediately updated when the compressed array spacing table is modified.

- **Indexed array spacing table (middle):** is calculated from the compressed array spacing table but can overrule it by making extra modifications within this table. From the example above, the following indexed array spacing table is calculated:

Index	Positions [cm]
1	0.000
2	4.800
3	9.600
4	14.400
5	19.200
6	24.000
7	28.800
8	33.600
9	38.400
10	43.200
11	48.000
12	52.800
13	57.600
14	62.400
15	67.200
16	72.000
17	75.200
18	78.400
19	81.600
20	83.200
21	84.800
22	86.400
23	88.000
24	89.600

- **Reference data table (right):** this table contains the reference wavelengths for the different cores and the reference curvature angles (‘twist’) as measured during the 2-step calibration procedure, see section 4.3.

Index	Central [nm]	Outer 1 [nm]	Outer 2 [nm]	Outer 3 [nm]	Twist [rad]
1	1513.065	1512.933	1512.912	1513.108	1.361
2	1515.098	1514.979	1514.934	1515.128	1.266
3	1517.122	1517.015	1516.953	1517.143	1.160
4	1519.147	1519.049	1518.974	1519.161	1.088
5	1521.141	1521.041	1520.971	1521.159	1.027
6	1523.096	1522.992	1522.924	1523.116	0.945
7	1525.095	1524.992	1524.927	1525.122	0.859
8	1527.104	1526.979	1526.936	1527.128	0.761
9	1529.103	1528.991	1528.936	1529.125	0.666
10	1531.070	1530.965	1530.894	1531.095	0.551
11	1533.027	1532.927	1532.860	1533.055	0.473
12	1534.998	1534.890	1534.827	1535.023	0.397
13	1536.987	1536.882	1536.811	1537.010	0.308
14	1539.076	1538.976	1538.907	1539.103	0.216
15	1541.085	1540.978	1540.911	1541.106	0.126
16	1543.079	1542.970	1542.902	1543.102	0.031
17	1545.067	1544.966	1544.896	1545.092	-0.072
18	1547.060	1546.949	1546.885	1547.080	-0.166
19	1549.039	1548.932	1548.867	1549.060	-0.265
20	1550.979	1550.879	1550.817	1551.003	-0.382
21	1552.974	1552.854	1552.805	1552.996	-0.510
22	1555.002	1554.883	1554.828	1555.025	-0.608
23	1557.022	1556.903	1556.842	1557.048	-0.684
24	1559.061	1558.954	1558.877	1559.082	-0.766
25	1561.122	1561.018	1560.940	1561.147	-0.838
26	1563.163	1563.065	1562.982	1563.191	-0.893
27	1565.133	1565.033	1564.947	1565.163	-0.949

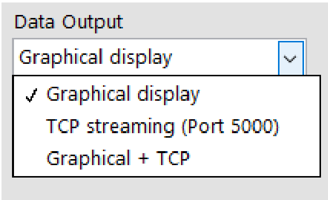
By default, the reference table is empty and in this case, the graphs from the main window will remain empty. The table can be loaded from an earlier calibration measurement or can be completed after a new calibration measurement.

- **'Set straight' button:** used for straight calibration measurement, see section 4.3.
- **'Set planar' button:** used for planar calibration measurement, see section 4.3.
- **'Save zero' button:** to save the reference data table to file for later uploading.
- **'Load zero' button:** to load the reference data from an earlier calibration recording.
- **'Save data' button:** to write a snapshot of the curvature and shape data to file. The data is saved in a table and the various parameters are stored in columns (1 for curvature, 1 for bending angle and 3 for x, y, and z coordinates of the 3D-shape). The rows represent the measurement values along the arc length in 1mm steps, starting from the first FBG. (Note that the arc length steps can be slightly different from 1 mm in case the entered sensor spacing has higher precision than one millimeter. In such cases, the arc length is slightly adapted so that the cumulated distance between 2 sensors corresponds to the entered distance. For example: if the spacing between adjacent sensors is entered as 2.25 cm = 22.5 mm (i.e. precision of 0.5 mm < 1 mm), the step size is 22.5 / 22 = 1.0227 mm so that after 22 steps the accumulated distance is 22.5 mm.)
- **Core distance [µm]**: the distance from the outer cores to the central core. This parameter determines the curvature sensitivity and is typically in the range of 37 µm. The actual value can be found in the MCF-documentation.
- **Gauge factor [1/µstrain]**: the strain sensitivity factor. This is typically in the range of 0.777 $\mu strain^{-1}$ but will be supplied by FBGS in case it is different.
- **'Adjacent cores' selector**: needs to be switched on if the selected cores are adjacent and off when the cores are complementary, see section 2.

- **Skip points [cm]:** can be used to remove the first part from the calculated shape in case this cannot be bend during the planar calibration step.
- **3D graph [cm]**: the length of the axes in the 3D-graph from the main panel. Can in principle be set to the length of the fiber when it is straight. This way, it will always be displayed completely on the graph. The default value is 40 cm.

- **Plot projections:** can be used to disable / enable plotting the projections of the 3D-shape onto the principal planes (XY, XZ and YZ) in the 3D-graph.

- **'Data output' selector**: can be used to switch on or off the TCP-data streaming. The different options are shown below. By default, the TCP-streaming is off and the graphical display is on.



It should be noted that the graphical display of the Shape Sensing software reduces the calculation speed of the software and hence reduces the maximum sampling rate that the software can deal with. Typical scan rates with the graphical display enabled are in the range of 10 – 20 Hz (depending on the number of DTGs). By disabling the graphical display, the scan rate can be increased significantly (to 100 Hz range, again depending on the number of interrogated DTGs).

More info on the TCP-streaming can be found in section 4.4

4.3 Calibration

After having adjusted the main sensor parameters, a calibration procedure needs to be done at least once for each MCF sample. The calibration parameters are sample specific and can be saved and uploaded at a later stage. The calibration consists of a 2-step process:

- Determination of the reference wavelengths
- Determination of the reference twist

The steps will be described in more detail below.

4.3.1 Reference wavelengths

The **reference wavelengths** are the wavelengths of the DTGs **in the absence of bending strain** and so for the fiber in straight position. Longitudinal strain (tension) can be present since it will have no impact on the measured curvature nor shape (common mode for all cores). Also the temperature at which the reference measurement is done is not important, as long as it is uniform over the entire active sensor area.

The knowledge of the reference wavelengths is needed to calculate the bending induced strain. Strain is always determined from a wavelength difference i.e. the shift with respect to the reference value.

Scope	To determine the **reference wavelengths** for the active MCF section.
Procedure	• Tape the fiber under slight tension on a table before and after the active sensor area so that the active sensor area is lying perfectly straight. • Ensure that there is uniform temperature in the room (no draught) • Press the 'Set Straight' button
Result	The reference wavelengths are stored in the memory and are displayed in the table.

Figure 4 shows a picture of the active sensing area kept straight during the first calibration step. The fiber was placed in a tube for better visualization. The entire active area needs to be put straight. Figure 5 shows the UI after having pressed the 'Set Straight' button. As can be seen, the curvature is close to zero, the bending angle is undetermined (random fluctuations between -π and π), the 3D-shape is straight and the shape overlaps with the x-axis.

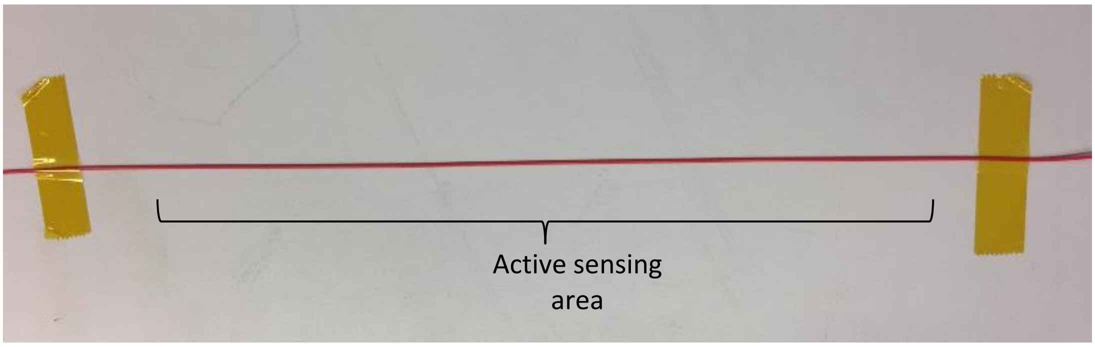


Figure 4: The MCF during the reference wavelength calibration. The fiber was placed in a tube for better visualization.

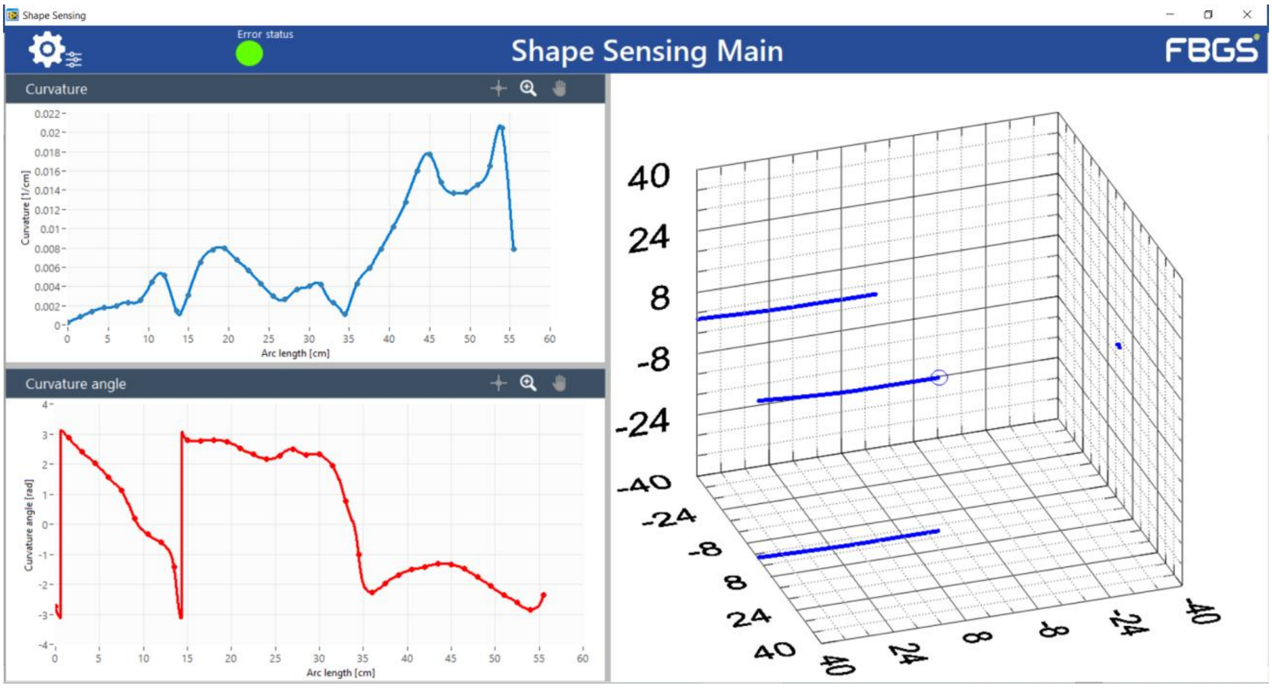


Figure 5: The Shape Sensing software after pressing the 'Set Straight' calibration button.

4.3.2 Reference Twist

The second calibration step is needed to determine the **reference twist** of the fiber. The MCF detects the combined effect of twist (or torsion) from the path that it follows and the twist of the fiber around its own axis. For shape sensing, only the torsion from the path is relevant. Measurement of the reference twist is needed to remove the initial twist from the fiber around its axis.

The reference twist can be measured by giving the fiber a planar bending. By remaining in one plane, we ensure that the torsion of the curve is zero (the bending angle is constant when we move in a 2D plane). Furthermore, when there is bending (= non-zero curvature), the bending angle can be measured and the changes in this angle come purely from the reference twist. The calibration procedure therefore goes as follows:

Scope	To determine the **reference twist** for the active MCF section.
Procedure	• Loop the active sensing area in the plane of a table (planar bending) without inducing twist. Avoid crossings of the fiber with itself. Also avoid changes in the bending direction of 180° i.e. avoid S-like shapes but rather make a circular or spiral shape. The actual size of the curvature is not important, as long as it is non-zero. • Tape the fiber ends so that the whole active length remains bended. • Press the ‘Set Planar’ button.
Result	The reference twist is stored in the memory and are shown in the reference table.

Figure 6 shows a picture of the MCF during the second calibration step. Figure 7 shows the UI after pressing the ‘Set planar’ button. The curvature is everywhere non-zero and the bending angle is constant, which ensures that the 3D-shape becomes truly planar. The shape is lying completely in the xy-plane and the xz- and yz-projections are flat.

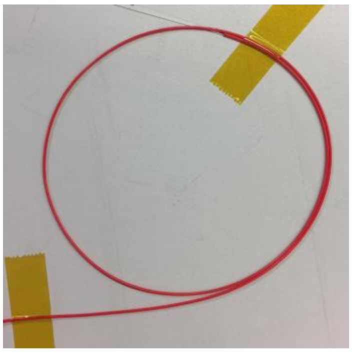


Figure 6: Picture of the MCF during the reference twist calibration step. The fiber is placed in a tube for better visualization.

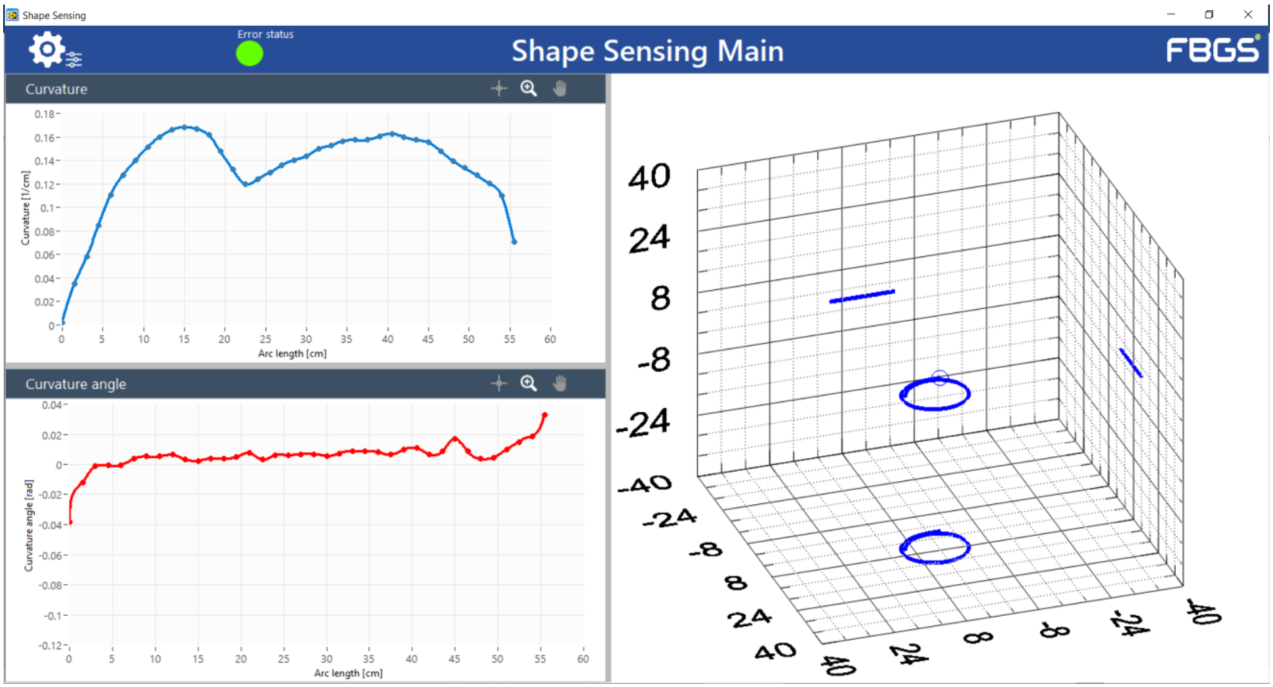


Figure 7: Screenshots of the Shape Sensing software after pressing the 'Set planar' calibration button.

After having performed both calibration steps, the Shape Software is ready to measure. The calibration data in the memory can be saved to file for later use with the 'Save Zero' button. It can be loaded later on with the 'Load Zero' button if one uses the same sample again.

It should be noted that the reference frame fixed to the fiber during the calibration step depends on the orientation of the cores with respect to the plane of the table. A rotation of the fiber with respect to the table will induce a rotation of the reference frame. Therefore, uploading an earlier calibration into the software does not guarantee the same orientation of the reference frame if the orientation of the fiber is not kept under control.

4.4 TCP-streaming

The Shape software allows to stream out the calculated curvature and shape data over TCP. Also the raw wavelengths and peak powers are contained in the data string. It is similar like the TCP-streaming from ILLumiSense and allows users to manipulate the curvature and shape data depending on their needs.

To enable TCP-streaming, the data output selector from the settings panel needs to be set to 'TCP streaming' or 'Graphical + TCP'. The used port is 5000. Note that graphical display in the shape software will reduce the scan rate of the TCP output and so if it is not needed, it is recommended to select the 'TCP-streaming' option and so without graphical display.

The format of the data is similar like that of the ILLumiSense. The data is transmitted in blocks and each block contains the data from a single sample i.e. the measurement of all sensors from the active channels. The rate of sending the data blocks thus corresponds to the sampling rate, but might be limited by the calculation speed and graphical display needs for curvature and shape. Each data block starts with a 4 byte (or 32 bit) signed integer that represents the length in bytes of the string to follow. The rest of the block is ASCII string data of which the different items are TAB delimited. Each data block has the following format:

1. **Length:** The total length of the string to follow in bytes. This value is a 4 byte (or 32 bit) integer.
2. **Date** DD/MM/YYYY where
    a. DD = day of month
    b. MM = month of year
    c. YYYY = year (with century)
3. **Time:** hh:mm:ss where
    a. hh = hours (24 hours format)
    b. mm = minutes
    c. ss = seconds
4. **Line Number:** This number is a unique sample number. It increments with 1 for each new sample. In this way, it can be checked if some samples are missing. When the sampling rate is too large for the shape software to follow, some line numbers will be missing at regular intervals. In this case, the sampling rate of the ILLumiSense can be reduced to eliminate this effect.
5. **Quantity of Optical Lines (channels) Measured:** The number of optical channels that is read out (enabled) during the measurement of 1 sample. For each optical channel, the following information will be provided:

    a. **Optical Line Number:** The optical channel. This value sweeps over all the active channels.
    b. **Qty of FBG's:** Number of FBG-sensors detected in the current optical channel.
    c. **Error status (A, B, C, D):** 4 space separated integers specifying different types of detected errors.
    d. **Peak Wavelengths:** Array of the peak wavelengths. One wavelength per detected sensor.
    e. **Peak Powers:** Array of the peak powers. One power value per detected sensor.

6. **Curvature data:** the calculated curvature (in 1/cm) for all detected sensors, preceded with 'Curvature [1/cm]'. There will be as much values as the number of FBG-sensors detected (as indicated by the 'quantity of FBGs' from above)
7. **Curvature angles:** the calculated curvature angles (in radians) for all detected sensors, preceded with 'Curvature angles [rad]'. There will be as much values as the number of FBG-sensors detected (as indicated by the 'quantity of FBGs' from above)
8. **Shape:** the x, y and z coordinates for the calculated 3D-shape with 1 mm resolution in the arc length. (Note that the arc length can be slightly different from 1 mm in case the entered sensor spacing has higher precision than one millimeter. In such cases, the arc length is adapted so that the accumulated distance between 2 sensors corresponds to the entered distance. For example: if the spacing between adjacent sensors is entered as 2.25 cm = 22.5 mm (i.e. precision of 0.5 mm < 1 mm), the step size is 22.5 / 22 = 1.0227 mm so that after 22 steps the accumulated distance is 22.5 mm.) It contains 3 groups:

    a. **Shape x [cm]:** all the x-coordinates, preceded with 'Shape x [cm]' and the number of x-values. The number of values depends on the number of sensors and on their physical spacing.
    b. **Shape y [cm]:** all the y-coordinates, preceded with 'Shape y [cm]' and the number of y-values. The number of values depends on the number of sensors and on their physical spacing.
    c. **Shape z [cm]:** all the z-coordinates, preceded with 'Shape z [cm]' and the number of z-values. The number of values depends on the number of sensors and on their physical spacing.

The same TCP-receiver program as used for the ILLumiSense can be used to visualize the data string send out by the Shape sensing software but the port should be changed to 5000.

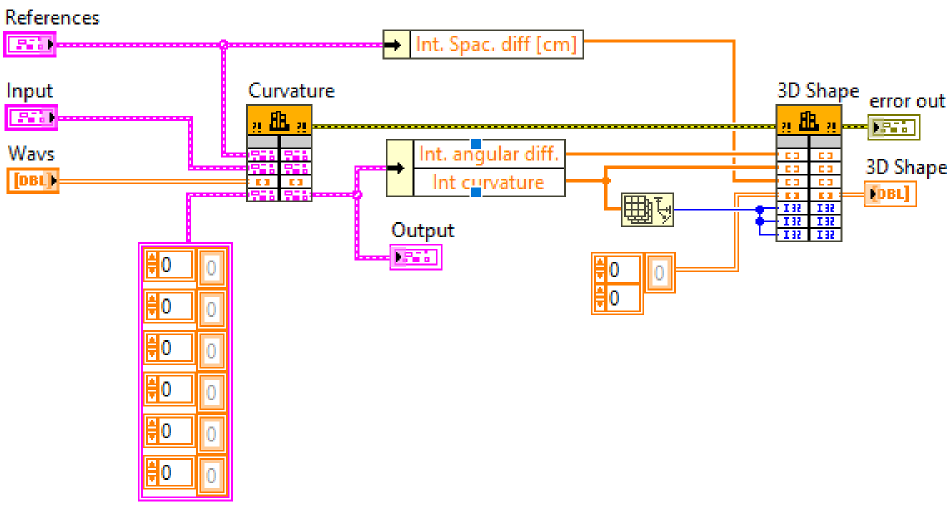
4.5 Software Development Kit

In order to integrate the Shape Sensing software into customer specific applications, there exists also a basic Software Development Kit or 'SDK', based on a Dynamic Link Library or 'DLL'. It is not standardly supplied with the Shape software but can be delivered on demand. The DLL contains several functions, amongst which:

- **Curvature calculation:**
  - **Inputs:** actual wavelengths, reference values, general settings, configuration settings
  - **Output:** curvature and curvature angle

- **3D-shape calculation:**
  - **Inputs:** Curvature, curvature angle, sensor distances
  - **Output:** 3D-shape coordinates.

A more detailed description of the functions and their inputs and outputs can be provided, together with some basic example LabVIEW programs in order to get started. The SDK is not limited to LabVIEW but can also be used in other programming languages (C, C++, C#, …).



For more technical and commercial information about the SDK, please contact FBGS.