

TOREO-P650

Software User Manual

Version 1.0.0

BECOM Systems GmbH
Gutheil-Schoder-Gasse 17
1230 Wien
AUSTRIA

office.systems@becom-group.com

<http://systems.becom-group.com>

TOREO-P650 – Software User Manual

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Information

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1 General Information

This guide applies to the TOREO-P650 from BECOM Systems. Follow this guide chapter by chapter to set up and understand your product. If a section of this document only applies to certain camera parts, this is indicated at the beginning of the respective section.

The document applies to product V0.9.x

1.1 Symbols Used

This guide makes use of a few symbols and conventions:



Warning

Indicates a situation which, if not avoided, could result in minor or moderate injury and/or property damage or damage to the device.



Caution

Indicates a situation which, if not avoided, may result in minor damage to the device, in malfunction of the device or in data loss.



Note

Notes provide information on special issues related to the device or provide information that will make operation of the device easier.

Procedures



A procedure always starts with a headline



1. The number indicates the step number of a certain procedure you are expected to follow.

Steps are numbered sequentially.

This sign ➤ indicates an expected result of your action.



References

This symbol ➡ indicates a cross reference to a different chapter of this manual or to an external document.

2 Overview

The document describes the necessary steps and settings to work with the TOREO-P650 and describes the firmware dependent interfaces.

This document applies to firmware version 0.9.x.

For a hardware compatibility list please refer to our support site.

Software and documentation

 <https://support.bluetechnix.at/index.html>

3 Interfacing

The TOREO-P650 provides control and data interfaces via Gigabit-Ethernet.

The control interface is used to set and read the configuration of the TOREO-P650 via a set of registers. Refer to TOREO-P650 _Register-Map for a detailed register description.

The data interface provides a continuous stream of ToF data depending on the configuration.



Note

BECOM Systems provides an abstraction of control and data interfaces by means of the *BltToFApi*. Refer to chapter 14.1 for the *BltToFApi*.

3.1 Data Interface

A UDP stream delivers ToF data from the TOREO-P650. BECOM Systems provides an abstraction of the data interfaces by means of the *BltToFApi*. Refer to chapter 14.1 for the *BltToFApi*.

3.2 Camera Discovery

The TOREO-P650 supports a discovery protocol via UDP/IP. It allows the discovery of the camera within the Ethernet network and the retrieval of camera properties.

The discovery service listens on UDP address 255.255.255.255 (broadcast) and port 11003.



Note

Discovery is supported by the *BltToFApi* and the *BltToFSuite*  Chapter 14

3.3 Secure Shell (SSH) Login

The TOREO-P650 camera features an OpenSSH server listening to TCP port 22.

| Root account | |
|------------------|-------|
| Username | becom |
| Default password | becom |

Table 1: Default login credentials

4 Register

The camera comes up according to the reset (default) values as described in the register description chapter (refer to TOREO-P650 _Register-Map).

Each camera has been pre-configured with a factory-default register map.

4.1 Save Registers

The entire register map can be saved into non-volatile flash using the register **CmdExec**. It will be restored from internal flash after a reboot or power cycle. Use this feature to save a user specific configuration.

4.2 Reset to Factory Default

The TOREO-P650 can be reset to factory default settings by deleting the saved register map. This can be done by writing a dedicated value to the register **CmdExec**.

Alternatively, a factory reset is executed via the camera's reset signal. (Please consult the Hardware User Manual for details.) It must be active until the firmware is completely booted and the data stream is present.

5 Data Format

The camera provides up to eight data channels via its data interface. The meaning of each data channel depends on the selected data format. The factory default setting provides an array of distance data and an array of amplitude data.

A channel can carry one of the following data types:

- Distance data from the ToF sensor, in millimeters, as 16-bit unsigned (UInt16) values
- Amplitude data from the ToF sensor, as 16-bit unsigned (UInt16) values
- Z coordinate values, in millimeters, as 16-bit signed (Int16) values
- X coordinate values, in millimeters, as 16-bit signed (Int16) values
- Y coordinate values: Same as X.
- Raw depth data (without scaling, corrections, and filters), as 16-bit unsigned (UInt16) values
- Raw phase data (0°, 90°, 180°, 270°), as 16-bit unsigned (UInt16) values
- Confidence, as 8-bit signed values (Int8)
- Amplitude8 data from the ToF sensor, as 8-bit unsigned (UInt8) values
- Color data from both RGB sensor, as YUV422, 8-bit grey scale, or JPEG
- Color overlay from both RGB sensors for the ToF sensor pixels, as YUV444

Which image format will be transferred can be selected by the register ***Image DataFormat***. It could either used predefined image modes or a user defined channel list.

5.1 Predefined Image Modes

The predefined Images Modes can be selected by writing the corresponding value into the Register ***ImageDataFormat***.



Note

Please refer to TOREO-P650 _Register_Map.pdf for the description of ***ImageDataFormat***.

The supported Image modes are:

- Distance and Amplitude
- Distance, Amplitude and Confidence

- XYZ Point Cloud
- XYZ Point Cloud and Amplitude
- XYZ Point Cloud and color overlay
- Raw Sensor Data (Raw Phases)
- Distance and XYZ Point Cloud
- Z values and Amplitudes
- Distance
- RawDistance and Amplitude
- Amplitude
- Distance, Amplitude and Color
- Distance and Color

5.2 User Defined Channel List

If none of the predefined data format matches the requirements offers the camera the possibility to configure a user defined channel list. The channels can be selected via the registers ChannelData0 – ChannelData7. The registers ChannelData0 – ChannelData7 define the data delivered by the camera. If a channel ID is selected twice the camera sends it only ones. If no channel ID is selected the camera sends a Distance channel as default. If the camera is not able to send a specific channel ID the channel gets skipped. The order of the selected channel IDs does not matter and does not correspond with the order the camera sends the channels.



Note

The ***ChannelDataX*** get applied by setting the ***ImageDataFormat*** register to "UserDefined".



Note

Please refer to TOREO-P650 _Register_Map.pdf for the description of ***ChannelDataX***.

6 Configuration

6.1 ToF Modulation Frequency

The modulation frequency of the illumination is set to 41.2 MHz per default. Other modulation frequencies can be set using registers **ModulationFrequency**, **ModFreqSeq1**, **ModFreqSeq2**, **ModFreqSeq3**. Be aware that this also changes the ambiguity range of the camera. On writing these registers, if inexact values are supplied, the camera searches for the next possible modulation frequency automatically.

The following modulation frequencies can be selected:

| Frequency | Unambiguity Range |
|-----------|-------------------|
| 21.2 MHz | ~7m |
| 41.2 MHz | ~3.5m |
| 60.24 MHz | ~2.5m |
| 80.32 MHz | ~1.8m |

Table 2: Pre-defined modulation frequencies

The register content is the frequency in 10-kHz-steps (frequency in Hz/10000). On a register read, the currently selected modulation frequency (again, in 10-kHz-steps), is returned.



Note

The BltToFSuite demo application displays and takes modulation frequencies in MHz and calculates the register content transparently!

6.2 Frame Rate and Integration Time

The frame rate and the integration time of the ToF sensor can be set by using the registers **Framerate** and **IntegrationTime/IntTimeSeq1/IntTimeSeq2/IntTimeSeq3** (for sequence 0/1/2/3).

The combination of frame rate and integration time influences the input current as well as the dissipated heat and will be characterized by the “Frame rate Integration Time Product”(FITP) which has been defined as follows:

$$FITP = t_{INT} [ms] \cdot fps \left[\frac{1}{s} \right] \cdot 4$$



Caution

Be careful in setting different integration times and frame rate combinations. Not all combinations are possible! Without appropriate cooling the device may be damaged! Refer to the Hardware User Manual for more information.

6.3 Sequencing

The TOREO-P650 allows the configuration of up to 4 sequences. These sequences are captured immediately after each other. Each sequence can be configured with individual integration time and modulation frequency.

If the camera's video mode is disabled (see register **Mode0**), and the camera is manually triggered, each trigger will generate as many sequences as currently configured.

The number of sequences can be configured in register **NofSequ**.

For sequence 0, use registers **IntegrationTime** and **ModulationFrequency** to set integration time and modulation frequency, respectively.

For sequence 1, use registers **IntTimeSeq1** and **ModFreqSeq1**.

For sequence 2, use registers **IntTimeSeq2** and **ModFreqSeq2**.

For sequence 3, use registers **IntTimeSeq3** and **ModFreqSeq3**.

Each sequence is processed and streamed by the camera as one individual frame. Each frame header contains the sequence number in field **SequenceNumber**.

6.4 Manual Frame Trigger

The default mode of the camera is video mode, where it streams continuously with configured frame rate. To use manual frame triggering, the video mode must be disabled in register **Mode0**.

A frame can be triggered by Software trigger (see register **Mode0**) or hardware (Please consult the Hardware User Manual for details).

A manual trigger will trigger the capturing of as many sequences on the ToF sensor, as is configured in register **NofSequ**.

7 ToF Image Enhancements

7.1 Plausibility Check

The Plausibility check verifies raw sensor data regarding their plausibility. Pixels which do not pass the test will be marked as invalid.

The following registers are used to enable the Phase symmetry check:

- **ImgProcConfig**: bit 14 to enable
- **PhaseSymetryLimit**: Limit for fine tuning. A lower value will make the filter more aggressive.



Note

Phase symmetry check is only supported if **NofPhases** is set to 4.

7.2 Low Motion Blur

To reduce artifacts due to movements the camera supports a mode that uses only 2 phases instead of 4 phases.

The following registers are used to enable the Low Motion Blur mode:

- **NofPhases**: 2.. enabled, 4.. disabled

7.3 Global Offset

Each TOREO-P650 is offset-calibrated out of factory.

For each pre-defined modulation frequency, there is an absolute offset in millimeters that all distance values are corrected with. The absolute offsets are stored in registers **DistOffset0** (for 21.2 MHz modulation frequency) to **DistOffset3** (for 80.32 MHz). Offsets can be modified by direct register writes.

Distance Offset correction is enabled or disabled in register **ImgProcConfig**.

7.4 Vernier

In order to combine the benefits of a smaller modulation frequency (higher unambiguity range) and a higher modulation frequency (higher precision and accuracy), the camera features the ability to combine two sequences with different modulation frequency into one frame.

The following registers are used to configure Vernier mode:

- **NofSequ**: To configure 2 or 4 sequences.
- **IntegrationTime, IntTimeSeq1, IntTimeSeq2, IntTimeSeq3**: To configure integration times of up to 4 sequences
- **ModulationFrequency, ModFreqSeq1, ModFreqSeq2, ModFreqSeq3**: To configure modulation frequencies of the sequences
- **ImgProcAdvanced**, bit 7: To enable combine mode

If **NofSequ** gets configured to 4, the first and the second sequence and the third and the fourth sequence get calculated to one frame.



Note

The modulation frequency of sequence 0 must be higher than the modulation frequency of sequence 1 and the modulation frequency of sequence 2 must be higher than the modulation frequency of sequence 3

7.5 HDR

In order to improve the accuracy of distance data, the camera features the ability to combine up to 4 sequences from the ToF sensor into one frame with improved accuracy. It uses the confidence values of the input frames to calculate a new distance value for each pixel of the output frame.

The following registers are used to configure Combine mode:

- **NofSequ**: To configure up to 4 sequences. Minimum of 2 required for Combine mode.
- **IntegrationTime, IntTimeSeq1, IntTimeSeq2, IntTimeSeq3**: To configure integration times of up to 4 sequences
- **ModulationFrequency, ModFreqSeq1, ModFreqSeq2, ModFreqSeq3**: To configure modulation frequencies of the sequences
- **ImgProcAdvanced**, bit 0: To enable combine mode

It is recommended that all sequences are recorded with identical modulation frequency when using Combine mode.

7.6 Vernier + HDR

Vernier and Combine sequences can be enabled together to get a high precision frame.

Example register settings:

- ***NofSeq***: 4.
- ***IntegrationTime***: 200
- ***IntTimeSeq1***: 200
- ***IntTimeSeq2***: 1000
- ***IntTimeSeq3***: 1000

- ***ModulationFrequency***: 80MHz
- ***ModFreqSeq1***: 20MHz
- ***ModFreqSeq2***: 80MHz
- ***ModFreqSeq3***: 20MHz
- ***ImgProcAdvanced***, set bit 0 and bit 7

7.7 Flying Pixel Filter

The flying pixel filter detects and invalidates flying at edge locations in the depth image.

The following register is used to enable the Phase symmetry check:

- ***ImgProcConfig3***: bit 13 to enable

7.8 Dead Pixel Filter

Dead sensor pixels get detected during production and are invalidated by this filter.

The following register is used to enable the Phase symmetry check:

- ***ImgProcConfig3***: bit 12 to enable

7.9 Saturation and Low Amplitude Filter

Under exposed or over exposed pixel get marked as invalid. The thresholds can be set via the following registers:

- ***ConfidenceThresLow***
- ***ConfidenceThresHigh***

7.10 Pixel invalidation

The TOREO-P650 provides an on-board check for invalid pixels:

- Underexposed pixels: The amplitude is too low for the distance value to be trustworthy. The threshold is set via register ***ConfidenceThresLow***.
- Overexposed pixels: The amplitude is too high for the distance value to be trustworthy. The threshold is set via register ***ConfidenceThresHigh***.
- Invalid pixels: The TOREO-P650 sets pixels to invalid when at least one measurement result is outside the sensor's linear range. The minimum/maximum thresholds are set via registers ***PhaseSaturationMin*** and ***PhaseSaturationMax***.
- Dead pixels: The TOREO-P650 sets dead pixels to invalid.
- Flying pixels: If the flying pixel filter is enabled the TOREO-P650 sets flying pixels to invalid.

| Channel ID | Invalid Values | Transmission error | Invalid | Underexposed | Over exposed | Dead Pixel | Flying Pixel |
|-------------------|----------------|--------------------|---------|--------------|--------------|------------|--------------|
| Distance | < 10 | 0 | 1 | 2 | 3 | 4 | 5 |
| Amplitude | 65535 | 65535 | | | | | |
| X | -32768 | -32768 | | | | | |
| Y | -32768 | -32768 | | | | | |
| Z | < -32758 | -32768 | -32767 | -32766 | -32765 | -32764 | -32763 |
| Confidence | 0 | 0 | | | | | |

Table 3: Invalidation of pixel values

7.11 Overlay

The overlay calculated by the TOREO-P650 is intended to extend the XYZ-Pointcloud by the color information. For each ToF-frame a color image is taken synchronously. This allows the TOREO-P650 to assign a color information to each pixel in the pointcloud.

The overlay mode can be activated by using Framemode XYZColor (ID: 5), or by selecting "Overlay lens2" (ID: 10) or "Overlay lens3" respectively.

The sensitivity of the hidden pixel invalidation can be adjusted by the two registers as described in

| Register | Default Value | Description |
|--|---------------|---|
| OverlayVectroLengthThreshold (0x0171) | 200 | A hidden pixel is determined by the distance between the pixel on the color sensor and the pixel in the pointcloud. This value specifies the length error margin. Therefore a higher value leads to less detected hidden pixels |
| OverlayOverlapClearnessLimit (0x0177) | 10 | Due to the higher resolution of the color sensor, one tof pixel is matched with an area of many pixels on the color sensor. This limit specifies the ratio from valid pixels to all matched pixels in the area. |

Table 4 Overlay Registers

8 ToF Image Filters

After the distance calculation, filters can be applied to the distance data. Each of the filters provides one or more configuration parameters. The iteration count for each filter can also be configured. The filters can be enabled or disabled by writing the **ImgProcConfig** registers. Enabling more than one filter is possible but each added filter reduces the maximum achievable frame rate (as does the number of iterations).

The filters are applied in the following order:

1. Frame Average filter
2. Sliding Average filter
3. Average filter
4. Median filter
5. Bilateral filter

8.1 Median Filter

A 3x3 median filter can be applied.

Register: **FilterMedianConfig**

The number of iterations is configurable.

8.2 Bilateral filter

Registers: **FilterBilateralConfig**, **FilterBilateralConfig2**

Configuration options are σ_R (Width of range kernel), σ_S (Width of spatial kernel), number of iterations, and window size.

8.3 Average filter

Registers: **FilterAverageConfig**

Configuration option is the filter size.

8.4 Sliding Average Filter

Register: **FilterSLAConfig**

A sliding average filter over up to 255 frames can be applied. The number of frames is configurable. An increasing number of frames will not decrease the frame rate but may add blurring effects.

8.5 Frame Average Filter

Register: ***FilterFrameAverageConfig***

A frame average filter over up to 255 frames can be applied. The number of frames is configurable.

The frame rate of the data interface will be divided by the number of configured frames to be averaged, e.g., if the camera is configured to 40 frames per second, and the frame average filter with config 4 is used, the resulting output frame rate will be 10.

9 Network Configuration

9.1 MAC Address

The TOREO-P650 gets delivered with a dedicated Ethernet MAC address.

The user is allowed to assign the camera another MAC address using the registers **Eth0Mac0** to **Eth0Mac2**. Be aware that in order to make the changes persistent, the register map must be saved to flash using register **CmdExec**, otherwise the changes will be lost on a reboot or power cycle.

If the register map in the flash will be cleared the default MAC address from will be loaded.

9.2 IP/TCP/UDP Settings

The IP Settings of the TOREO-P650 can be changes via the **Eth0_*** registers. A change of the IP settings (IP address, subnet mask, default gateway) will take effect on writing the latter one. Port settings will take effect immediately. UDP destination IP addresses will take effect immediately. Please see the register description for details.

To make the changes persistent the register map must be saved to flash by writing a dedicated value to the **CmdExec** register.

10 Error Indication

The TOREO-P650 indicates detected errors mainly in the **Status** register:

- Bit 3: Indicates a temperature measurement error on the illumination. The bit is automatically cleared if the error disappears.
- Bit 4: Indicates a temperature measurement error on the main board. The bit is automatically cleared if the error disappears.
- Bit 5: Indicates that calibration data are missing, refer to **CalibStatus** and **CalibStatus2**.
- Bit 9: Indicates the illumination temperature has exceeded the maximum tolerable value
- Bit 13: Indicates a color sensor error
- Bit 14: Indicates a temperature measurement error on the base board. The bit is automatically cleared if the error disappears.
- Bit 15: Indicates a communication error with the ToF sensor, or an error with triggering the TIM. This bit is automatically cleared if the error disappears.

11 Camera Coordinate System

The camera coordinate system is depicted in Figure 11-1.

Pixel numbering starts in the upper left corner of the pixel array, seen from the camera's point of view.

Distance data always contains the measured distance from the ToF sensor to the viewed scene.

Point cloud data contains X, Y and Z coordinates for each ToF pixel. Point cloud data is calculated via intrinsic lens parameters for the ToF sensor and optical system, and via extrinsic parameters. The reference point of the camera coordinate system, where $X=Y=Z=0$, is the front-bottom-left edge of the camera, seen from the camera's point of view.

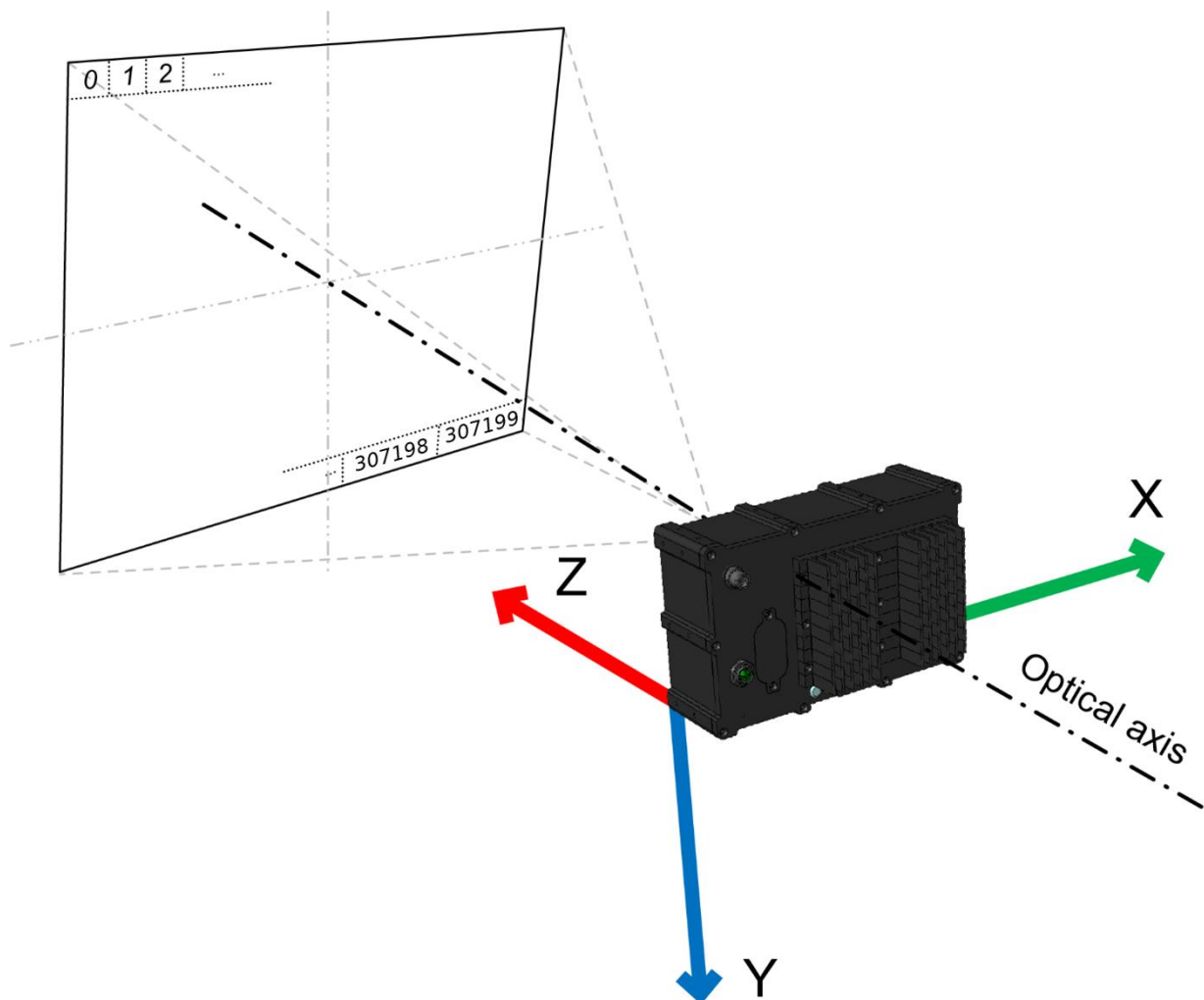


Figure 11-1: TOREO-P650 Default Coordinate System

12 Color Sensors

The TOREO-P650 has two 13M pixel RGB sensors. The Sensors support Auto Exposure/ Auto Gain control (AEC/AEG), Auto White Balance (AWB) and High Dynamic Range (HDR). Parameters like Sharpness, Gamma value, Brightness, Contrast and Contrast can be configured to fit the user's application the best.

12.1 Resolution

The camera supports four different pre-defined Resolution configurations. To allow maximum flexibility a custom configure ROI and Binning can be applied to each of the Resolutions.

| Index | Resolution | Max Frame rate | Max Exposure (@max fps) | Horiz. Opening Angle1) | Vert. Opening Angle1) |
|-------|------------|----------------|----------------------------|---------------------------|--------------------------|
| 3 | 640x480 | 100 | 9.8ms | 85° | 62° |
| 7 | 1920x1080 | 72 | 13.6ms | 85° | 48° |
| 9 | 3840x2160 | 29 | 33.2ms | 85° | 48° |
| 10 | 4192x3120 | 18 | 53.5ms | 86° | 63° |

Table 5: RGB sensor resolution overview

12.1.1 ROI

The ROI can be configured using the registers **ColorRoiStartX**, **ColorRoiStartY**, **ColorRoiEndX** and **ColorRoiEndY**. The ROI values get updated with writing **ColorRoiEndY**. **ColorRoiEndX** and **ColorRoiEndY** set to 0 means ROI is disabled. The ROI gets applied to both sensors.



Note

There are some restrictions when configuring the ROI:

- both sensor's resolutions must be the same (**ColorStreamParams** and **ColorStream2Params**)
- **ColorRoiStatX** must be even
- **ColorRoiEndX** must be odd

12.1.2 Binning

The supported binning modes are 2x2, 4x4 and 8x8 and can be selected via register **ColorImgProc**.

12.2 Data Format

The default color data format is YUV422 (UYVY interleaved). Via the register ***ColorStreamParams*** or ***ColorStream2Params*** a JPEG compression or and 8-bit gray scale mode can be activated. The quality of the JPEG compression is configurable via registers ***ColorJpegQuality*** and ***Color2JpegQuality***.

12.3 Synchronization

The color sensors can be configured to run in a free run mode or in a synchronized trigger mode. The synchronization can be activated via Bit 2 – FrameSync in register ***ColorSensorControl*** and ***ColorSensor2Control***. In the free run mode, the frame rate is the maximum possible. In the synchronized mode the frame rate can be configured via register ***ColorSensorFrameRate***. Please contact the BECOM System support to get an optimized configuration for your use case.

13 Firmware History

13.1 Version Information

| Firmware Version | Status | Release date | Changes |
|------------------|----------|--------------|--|
| 0.3.0 | Released | 21.12.2021 | <ul style="list-style-type: none"> Initial Firmware for the TOREO-P650 |
| 0.5.0 | Released | 05.09.2022 | <ul style="list-style-type: none"> Error in ToF sensor configuration of the second camera sequence (Seq1). Changed the color of the RGB status LED. White color means status OK. |
| 0.8.0 | Released | 05.09.2022 | <ul style="list-style-type: none"> Fixed some small bugs. New register for controlling the ethernet MTU size (max transmission unit) which allows to use Jumbo Frames. |
| 0.9.4 | Released | 20.04.2023 | <ul style="list-style-type: none"> Add JPEG compression for RGB images. Add grey scale mode for RGB sensors. Fixed: ColorStreamParams and ColorStream2Params must have the exact same value (not only the resolution) to enable ROI. Color Sensor ROI speed optimization. Application log files gets rotated after each restart. Last five logfiles get kept. Improved stability |

Table 6: Overview TOREO-P650 firmware changes



Note

Please refer to our support site for additional information about product changes.

13.2 Anomalies

| Applies to | Date | Description |
|------------|------------|--|
| V0.3.0 | 21.12.2021 | The single trigger has a delay of 1 frame |
| V0.3.0 | 21.12.2021 | Switching back from shared memory streaming mode to socket based streaming mode causes a crash |
| V0.3.0 | 21.12.2021 | Stability issues when randomly changing between frame modes |
| V0.4.0 | 10.06.2022 | Error in ToF sensor configuration of the second camera sequence (Seq1). |
| V0.8.0 | 10.03.2023 | ColorStreamParams and ColorStream2Params must have the exact same value (not only the resolution) to enable ROI. |

Table 7: Firmware anomalies

14 Software

14.1 BltTofApi

SDK for ToF products: Blt 'Time of Flight' API

In order to create a common interface for our products we define the interfaces between a ToF device and an application. The main part of this model is the *BltTofApi* which is written in C for platform independency.

The library which provides this API for Ethernet-based devices as the TOREO-P650 is the *BtaEthLib* (*BltTofApi* Ethernet Library).

Please visit our support Wiki to get information and to download the SDK.

Blt 'Time of Flight' API

 <https://support.bluetechnix.at/wiki/> (Section Software)

14.2 BltTofSuite

For the first evaluation of the camera and to evaluate different settings and configurations a .NET demo application for Microsoft Windows is provided: *BltTofSuite*. The demo application can be downloaded from our support web site.

Software and documentation

 <https://support.bluetechnix.at/index.html>

15 Support

15.1 General Support

General support for products can be found at BECOM Systems' support site

Support Link

 <https://support.bluetechnix.at/index.html>

15.2 Software Downloads

Camera support packages are available for registered customers only. Please contact BECOM Systems support if you do not yet have an account.

Software Download Portal

 <https://support.bluetechnix.at/software/>

15.3 Camera Development Package

The camera offers the possibility to bring your own application onto the TOREO-P650.

The TOREO-P650 is based on an embedded ARM Linux system based on the Jetson TX2 from Nvidia.

Please contact BECOM Systems support for more information.

16 Document Revision History

| Version | Date | Document Revision |
|---------|------------|--|
| 1.0.0 | 21.12.2021 | Initial SUM for Firmware Version 0.3.0 |
| 2.0.0 | 20.04.2023 | Updated to Firmware version 0.9.4 Added chapter Color Sensors |

Table 8: Revision history

A List of Figures and Tables

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