ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-THMBCM024

TIME SYNCHRONIZATION AND TIMESTAMPING FOR THE ESS NEUTRON INSTRUMENTS

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Abstract

The European Spallation Source (ESS) will be a cutting-edge research facility that uses neutrons to study the properties of materials. This paper presents the timestamping strategy employed in the neutron instruments of the ESS, to enable efficient data correlation across subsystems and between different sources of experiment data.

ESS uses absolute timestamps for all data and a global source clock to synchronize and timestamp data at the lowest appropriate level from each subsystem. This way we control the impact of jitter, delays and latencies when transferring experiment data to the data storage. ESS utilizes three time synchronisation technologies. The Network Time Protocol (NTP) providing an expected accuracy of approximately 10 milliseconds, the Precision Time Protocol (PTP) delivering roughly 10 microsecond accuracy, and hardware timing using Micro Research Finland (MRF) Event Receivers (EVR) which can reach 10 nanoseconds of accuracy. Both NTP and PTP rely on network communication using common internet protocols, while the EVRs use physical input and output signals combined with timestamp latching in hardware. The selection of the timestamping technology for each device and subsystem is based on their timestamp accuracy requirements, available interfaces, and cost requirements.

This paper describes the different methods used for a number of device types, like neutron choppers, detectors or sample environment equipment, to synchronize operations and timestamp data.

INTRODUCTION

The European Spallation Source (ESS) will generate intense neutron beams for scientific experiments. Data from such different data producers is collected independently without synchronisation. Correlation between measurements from different devices happens via the timestamping in post processing. Accurate measurements of neutron interactions with samples require precise timestamping of events between the various instrument components, including the neutron source, choppers, sample environments, and detectors. That makes synchronisation of clocks and accurate tagging crucial for maintaining experimental data integrity and ensuring that the acquired data can be correctly interpreted and analyzed.

ESS employs a timestamping strategy that uses absolute timestamps, based on UTC, for all data and a single source oscillator used by all timing technologies. The strategy is also to ensure that each subsystem timestamps data at the lowest possible level. This eliminates the impact of jitter on delays and latencies when transferring experiment data to the data storage.

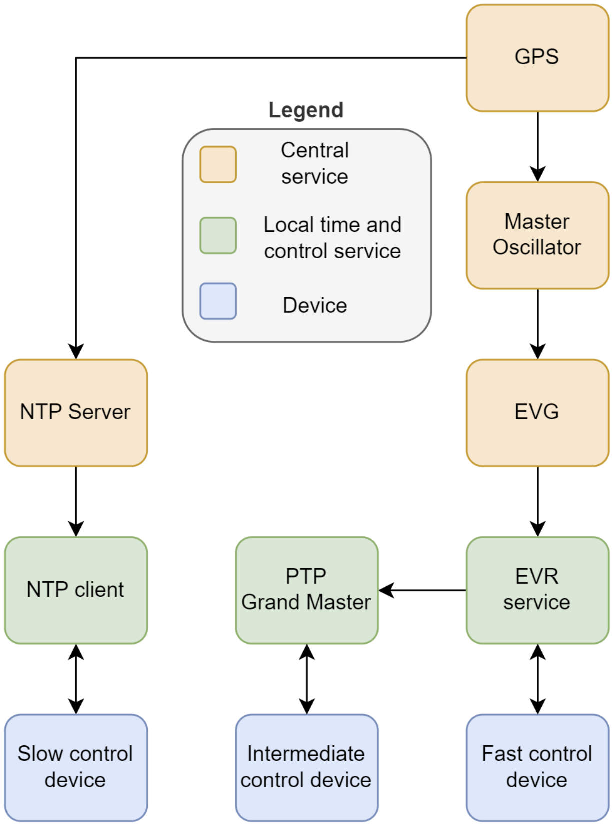

Figure 1: One central clock creates the foundation for all clocks and timestamps at the ESS facility

The selection of the timestamping technology for each device and subsystem is based on the accuracy requirements, available interfaces, and cost requirements. In this paper, we investigate how the three different technologies, NTP, PTP and EVR, are employed, see Fig. 1. Using a few examples, we also discuss which criteria are used to select synchronization and timestamping method and how this is implemented and verified for specific devices.

Network Time Protocol Synchronisation

Network Time Protocol (NTP) is a widely used internet-based protocol for synchronizing clocks over a computer network, including neutron instruments. NTP can achieve millisecond-level accuracy, providing satisfactory time synchronization and timestamping for many applications that do not require ultra-high precision. It can be implemented in both hardware and software, allowing for diverse applica-

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tions and compatibility with various devices. NTP employs advanced algorithms to counteract network delays, packet loss, and other disruptions, ensuring reliable time synchronization and timestamping.

Precision Time Protocol Synchronisation

Precision Time Protocol (PTP) provides highly accurate time synchronization across distributed systems and also offers the capability for timestamping data. PTP employs hardware or software-based timestamping to accurately measure the time delays between the reference clock and receiver devices. Like NTP, PTP runs on standard commercial of the shelf hardware, but requires hardware support from the networking infrastructure and some care and attention to work reliably [1]. At ESS, only PTP hardware timestamping is used. The facility wide timing system, using an Event Generator (EVG) with downstream Event Receivers (EVR), time is transferred from the EVR to the PTP grand master, ensuring that the same Master oscillator is still the basis for all timestamps and all timing technologies. PTP can be used to synchronize data acquisition across multiple devices, ensuring consistent and accurate time-stamping of acquired data.

Timing System Event Receiver Integration

Event Receivers (EVR) are hardware devices that enable precise time synchronization and timestamping especially in accelerator based science facilities like ESS. They operate as part of a larger timing system that includes an Event Generator (EVG), Fanouts and EVRs. EVRs are designed to provide reliable and repeatable synchronization and timestamping and are straight forward to integrate with equipment that only use standard TTL inputs and outputs.

For the integration of instrument components, EVRs have been selected for critical, high demanding devices such as detectors, neutron choppers, and some sample environment equipment. They are typically implemented using dedicated hardware such as PCIe cards or FPGA modules and can generate and process timing signals with sub-microsecond precision; in the case of ESS, the resolution is 11.36 ns [2].

DEVICE INTEGRATION EXAMPLES

In the following we will go over a few example to illustrate the implementation of the different schemes. The main communications or synchronsation routes between devices involve UDP or TCP network communication or hardware TTL pulses. These will be details in the device integration figures. A common legend is provided in Fig. 2, that also differentiates the different control domains.

Neutron Detectors

Detectors, such as Timepix3 (TPX3, [3]) and cameras, for example Orca, [4]), are responsible for capturing the scattered neutrons and converting them into digital signals for data acquisition and analysis. The typical expected time resolution of a neutron event is on the order of 1 µs. Synchronizing these devices using EVR ensures that the acquired data is accurately timestamped. ESS will operate with a number of custom built detectors with bespoke readout systems as well as commercially available hardware. Both types can provide challenges for the timing integration, because injecting absolute time is not normally foreseen and requires special integration effort.

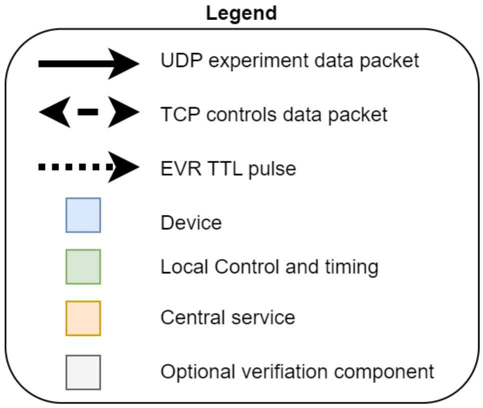

Figure 2: Legend for the device integration figures.

Event Based Detectors: Timepix3 The TPX3 is a time resolving, light sensitive detector with a single pixel readout streaming capability. Together with scintillation screens that convert neutrons to photons, it will be used as a neutron event detector at ESS in a few different neutron instruments, see Fig. 3. To make maximum use of the high performance hardware that the TPX3 is, the requirements on the timestamp has been to be better than 1 microsecond. Combined with the TTL I/Os on the TPX3, the EVR solution became the most suitable choice.

The detector internally runs with it's own oscillator and clock, in fact two counters. Every pixel hit receives its event timestamp using the local TimePix3 time. To reference this clock to the ESS time and account for oscillator drifts, the detector receives a hardware TTL signal from an EVR at fixed intervals. When this pulse is received one of the counters is reset and a UDP packet with the information of the other counter or clock is sent out. In an Event Formation Unit (EFU) [5], that is part of the experiment data chain, the information about the EVR TTL pulse time is paired up with the TPX3 UDP clock information. This way the the TimePix3 local clock timestamp can be aligned with the EVR clock timestamp and an absolute timestamp can be set to every pixel event hit. The drift of the TimePix3 oscillator, compared to the EVR time, can, as a first approximation be considered constant and negligible between TDC packets, since the pulse period is 1/14s, the same period time as the neutron pulses. However it is absolutely possible to reconstruct and correct for any drift with the information available to the EFU processing.

This synchronisation scheme has been implemented and

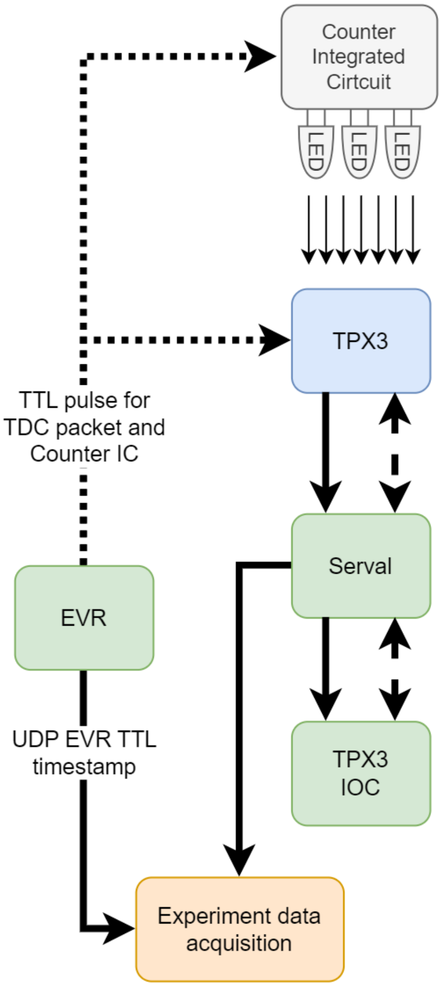

Figure 3: TimePix3 data flow and timestamping synchronization with LED counter timestamp verification setup. Serval is the software provided by the detector vendor, that communicates directly with the device.

tested for accuracy. The verification has been performed by presenting the TPX3 a known light pattern at short intervals and comparing the detected result with expectations. A counter circuit connected to multiple LEDs, was triggered by the EVR at relatively high frequency. The pixel data generated after the EFU clock alignment gave the expected results. However the long term reliability of the whole system is still under test.

Detector Readout Master Module

The custom developed ESS Readout Master Module (RMM) is used for the data readout, timing synchronisation and controls interface for almost all event based detectors, see Fig. 4, the TPX3 above being a prominent exception. The RMM provides a standardised common platform that can host a large number ADC frontends from a handful of different options. It provides a central 2x100 GBit interface for the data acquisition on commercial of the shelf hardware. For timing the RMM includes an integrated open-source EVR solution that allows for time synchronization of the different kinds of front ends in the ESS neutron instruments. At the RMM the accuracy and resolution of the timestamps are basically the same as using a dedicated EVR hardware. This can be somewhat reduced by limitations at in the frontend FPGA. The requirements on the timestamp is to be better than 1 microsecond. Verification and testing of this concept at ESS has come a long way and all the results with the designed and produced hardware points that the product behaves in an expected and reliable way.

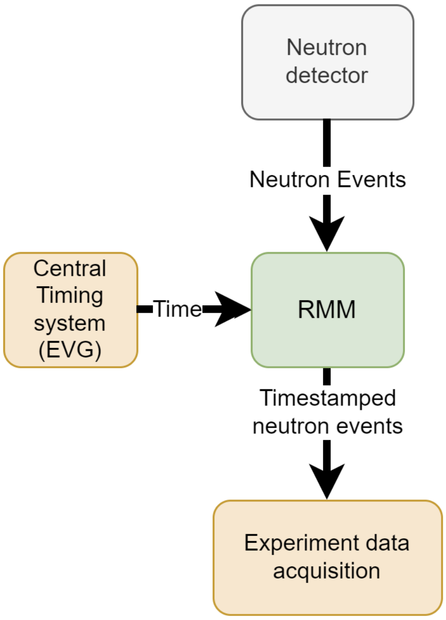

Figure 4: Timestamping of neutron detector events in the RMM.

Image-Based Cameras: Orca In contrast to above mentioned detectors that deal with neutron *events*, the smallest data unit of a *camera* is an image of an often configurable size. The image has a number of counts per pixel and no timing information on the individual count. Only the overall image has an exposure time, exposure start and end timestamp. An example for a *camera* is the Hamamatsu Orca-Flash4.0 V3 (Orca). The camera will be used as a neutron event recorder in multiple neutron instruments. The target requirements for the image timestamp accuracy has been specified to be better than 1 microsecond. For longer exposure times, this will obviously be more relaxed. Since the camera has TTL signal I/Os, the EVR technology meet both those requirements. ESS instruments use the EPICS area detector (AD) framework for camera integration with the AD Kafka Forwarder plugin to submit images to a Kafka Cluster for further processing and file writing.

To get an accurate timestamp of every image, the camera is operated to run externally triggered acquisition. For that a TTL pulse is sent from an EVR to the Orca at a time configured by the data acquisition system. Often this will have to be synchronised with the operations of the ESS source. For the resulting image the camera will provide a local timestamp, based on the local oscillator in the camera. The Orca and the EVR are driven by different oscillators, which means that the clocks and corresponding time reported by each device will drift apart. It is not possible to set/reset the camera clock using any external or internal signal.

Therefore the timestamp of each needs to be corrected by the EPICS area detector IOC [6] after transfer. The IOC knows about the trigger pulse timestamps and can overwrite the existing local timestamp meta data in the image. The local timestamp can, however, be used to verify that no images were dropped or other errors led to a misalignment of trigger pulses and EVR timestamps. If the local counter numbers does not match the expected range when the data arrives at the AD IOC, an interrupt is set and a re-synchronisation can be initiated.

This concept of timestamping has been used successfully at ESS to record images and reconstruct 3d representations of different objects using visible light and transparent objects. To more formally verify that the timestamps align, a counter circuit is connected to several LEDs, where the LED represents a binary bit pattern, e.g. 1 is 001, 2 is 010 etc. Every time the Orca is triggered to acquire an image, the counter IC also gets a pulse. All three counters are starting from zero, and the pattern of the LEDs can then be compared and confirmed to match with the image and the EVR TTL timestamp counter and the image counter, as seen in Fig. 5. This methods is being further developed to fully verify that the start and stop time of the acquisition matches the EVR timestamp. Additional tests are going to be conducted.

Neutron Choppers

Neutron choppers are vital components in neutron instruments. A neutron chopper generally consists of a rotating neutron blocking disc, with an aperture for allowing neutrons through at precise times. That imposes a time structure on the neutron beam and at a distance from the chopper the time of flight of the neutron can be used to determine its speed and by that its wavelength.

For control, a CHopper Integration Controller (CHIC) is used [7] at ESS. The CHIC controls the speed and phase of the chopper rotation against a reference signal. EVRs are configured, using the built in sequencer, to generate reference TTL pulses for the neutron choppers. The chopper returns a TTL pulse, a Top Dead Center pulse (TDC), which is fed to an EVR input for accurate timestamping, see Fig. 6. The timestamp of the TDC for each chopper is sent as experiment data and describes the exact phase and speed of the choppers (for convenience those parameters are also available as EPICS PVs). This type of controls setup has been demonstrated to be working reliably at the V20 instrument at HZB [8] and in early cold commissioning at ESS. The implementation exceeds the accuracy requirements from the neutron instruments was to be better than 100 nanoseconds, which in combination with the TTL control for reference pulses and timestamping.

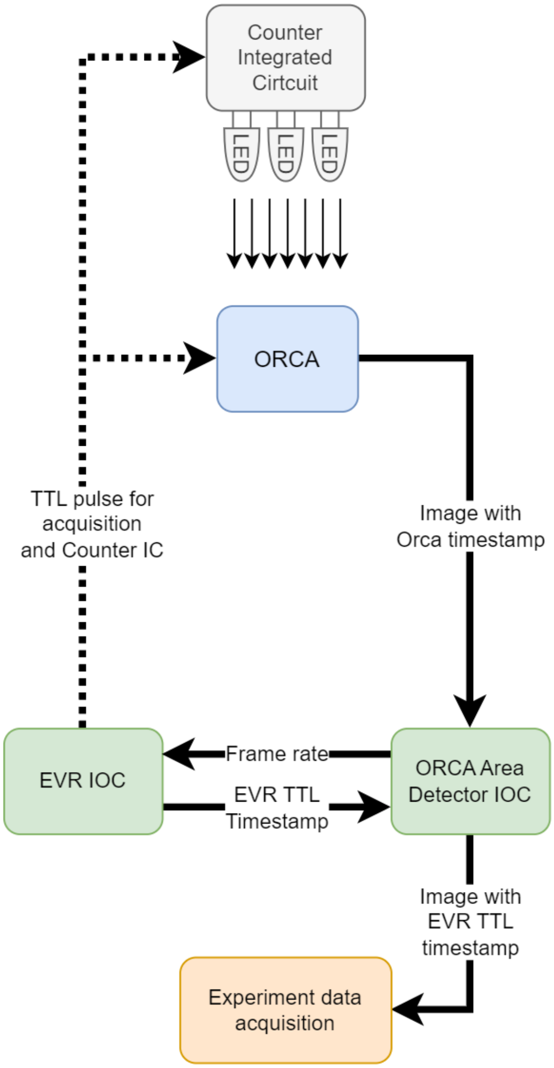

Figure 5: Orca data flow and timestamping synchronization with LED timestamp matching verification. The Orca Area Detector IOC controls both the camera, configures the EVR TTL pulse and applies the EVR TTL timestamp to each image.

Motion Control

Motion control is used for any application that requires physical movement, be it rotational or linear. PTP is the preferred method to synchronize motion devices. The standard motion control PLC for instruments is a Beckhoff PLC [9] with a PTP module, see Fig. 7. The existing design has allowed characterisation of motion data timestamping at ESS [10] and will likely improve the integration efforts in many areas in the years to come. Since the Beckhoff PLC is fully synchronized with the global time, it would then in theory also be possible to run the motor synchronously with anything integrated with the ESS timing service.

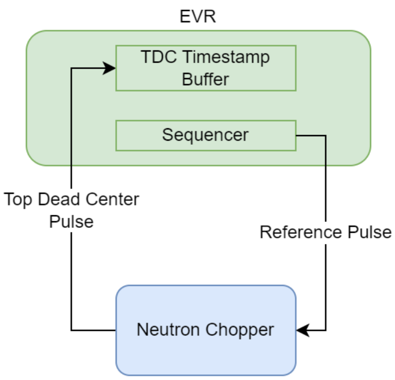

Figure 6: Neutron chopper input and output to an EVR.

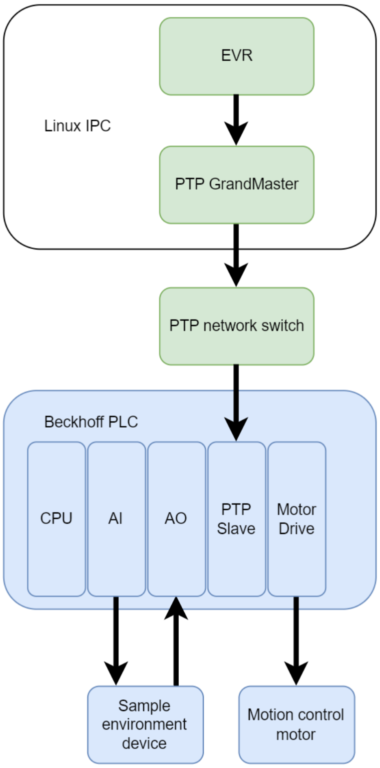

Figure 7: Generic motion or sample environment devices connected via a Beckhoff PLC, synchronised with PTP.

Sample Environment

The sample environment in neutron instruments consists of various devices controlling the sample's specific conditions, such as temperature, pressure, and magnetic field. Often, for example with process control, NTP meets the general requirements for timestamping of data, being better than 100 ms in accuracy. In that case the time stamping can also be performed in the IOC, i.e. often at the end of a serial or network connection to the sample environment hardware. It should be noted however that in order to achieve the 100 ms NTP timing precision, a physical machine must be used to synchronise and provide the timestamps. The default platform for deployment of IOCs is a virtual machine. Since the virtual machine can be suspended by the host at any moment for random amounts of time, an NTP client cannot reliably control the local realtime clock.

There is a large variety of sample environments, with the majority running relatively slow. But for more demanding applications, where better accuracy PTP is more suitable. Beckhoff solutions like for motion are also in use. There are also plans for EVR integrated sample environments, for example for magnetic or electric fields.

CONCLUSION

Timestamping neutron events and sensor readouts with the appropriate accuracy is a critical requirement for the scientific success of ESS. With the three presented options of EVR, PTP, and NTP based clock distribution and integration the neutron instruments have an arsenal of tools available that cover the known use cases appropriately regarding timestamping accuracy, cost and integration effort.

EVR-based synchronization allows for nanosecond-level accuracy for critical components such as choppers and detector imaging devices. Similarly, PTP gives microsecond-level timestamping accuracy for sample environment devices and motion controllers, where necessary. NTP, being the cheapest and most straight forward to deploy technology, provides millisecond-level timestamping accuracy for less demanding applications. These timestamping techniques can be integrated with existing and planned components and devices, allowing researchers to optimize their experimental configurations and achieve the desired level of timestamping accuracy. They have also has demonstrated scalability and flexibility in accommodating various experimental setups and requirements.

A distributed global clock that provides timestamps to all acquired data enables users to freely and fairly accurately correlate events from different devices. The correlation can be established in downstream processing after the experiment, without the need to setup hardware triggers in advance, for example. This freedom comes at a cost. All devices need to be integrated into the timing system and it needs to be verified that time synchronisation meets the required level and is reliable under all operational circumstances. Scenarios where incorrect timestamps lead to a wrong interpretation of the experimental data are quite easy to imagine. Hence a significant amount of work by ESS teams has gone into implementing the device level data timestamping and the corresponding verification. This effort will continue as more devices are being installed at ESS. It cannot cease during operations as neutron instruments will received upgrades in the form of new hardware, software or firmware on a frequent basis, which will necessitate a verification of the timing performance. As this paper shows, though there is a toolbox of implemetation methods, verification schemes and a drive to standardised solutions (e.g. RMM, CHIC) that help to keep the efforts manageable.

REFERENCES

[1] How Precision Time Protocol is being deployed at Meta, `https://engineering.fb.com/2022/11/21/production-engineering/precision-time-protocol-at-meta/`

[2] J. C. García, T. Korhonen, and J. Lee, “Timing System at ESS”, in *Proc. ICALEPCS’17*, Barcelona, Spain, 2017, pp. 618–621. `doi:10.18429/JACoW-ICALEPCS2017-TUPHA088`

[3] T. Poikela *et al.*, “Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout”, *J. Instrum.*, vol. 9, p. C05013, 2014. `doi:10.1088/1748-0221/9/05/C05013`

[4] `https://www.hamamatsu.com/us/en/product/cameras/cmos-cameras/C13440-20CU.html`.

[5] M. Christensen *et al.*, “Software-based data acquisition and processing for neutron detectors at european spallation source—early experience from four detector designs”, *J. Instrum.*, vol. 13, p. T11002, 2018. `doi:10.1088/1748-0221/13/11/T11002`

[6] EPICS Area detector, `https://github.com/areaDetector/areaDetector`

[7] D. P. Brodrick, T. Brys, T. Korhonen, and J. E. Sparger, “EPICS Architecture for Neutron Instrument Control at the European Spallation Source”, in *Proc. ICALEPCS’17*, Barcelona, Spain, 2017, pp. 1043–1047. `doi:10.18429/JACoW-ICALEPCS2017-WEBPL01`

[8] V. Maulerova *et al.*, “First neutron data recorded at the v20 test instrument utilizing prototype chopper systems and beam monitors planned for ess”, *Europhys. Lett.*, vol. 128, no. 5, p. 52 001, 2020. `doi:10.1209/0295-5075/128/52001`

[9] Beckhoff, `https://www.beckhoff.com/`

[10] J. Petersson, T. Bögershausen, N. Holmberg, M. Olsson, T. Richter, F. Rojas, *et al.*, “Characterizing Motion Control Systems to Enable Accurate Continuous and Event-Based Scans”, presented at ICALEPCS’23, Cape Town, South Africa, 2023, paper THPDP052, this conference.