

High-performance software package for Timepix3 data acquisition, online analysis and automation

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On the menu today...



Background: Timepix3

About the software:

- What is it?
- What can it do? (...for you?)
- How does it work?
- How is it better than competition?

Example applications of Track Lab Future development



Background: Timepix3

- Solid-state hybrid pixel detectors
 - 256 \times 256 pixels, 55 μ m pitch
 - Sensor materials: Si, GaAs, CdTe, ...
 - Typical sensor thickness: 100 μ m 5 mm
- Can measure simultaneously:
 - Time over Threshold: calibrate to keV using XRF
 - Time of Arrival: 1.56 ns resolution
 - In data-driven mode: 'zero' dead time
 - In Z-axis: using charge carrier drift model (ToA)







Background: Timepix3



• Z-coordinate reconstruction examples:



What is Track Lab?



- Data acquisition (DAQ) and analysis software
- Runs on all major platforms: 🐧 📒 🗯
- Originally aimed at pixel detectors, now can do much more...
- Focus on:
 - High performance
 - Versatility and extendibility
 - Live feedback



Photo credit: University of West Bohemia, Advacam, Standa LTD, Amptek Inc., Universal Robots A/S

What can Track Lab do?

Take data from detectors

Run analysis in real-time



Automate repetitive tasks





Data taking: device support



	Readout	Sensor(s)	Connection	Readout	Sensor(s)	Conn.	
	Katherine Gen1	1x Timepix3	1 Gbit Ethernet	Timepix2 Mini	1x Timepix2	USB 2	
		1x Timepix2	1 Gbit Ethernet	MiniPIX EDU	1x Timepix	USB 2	
A No al	Katherine Gen2	8x Timepix3	1 Gbit Ethernet	MiniPIX*	1x Timepix	USB 2	
Katherine readout for Timepix3			USB 3		1x Timepix2	USB 2	Ċ
			PCIe 3 x4		1x Timepix3	USB 2	
	HardPix	1x Timepix3	USB 3	AdvaPIX*	1x Timepix	USB 3	
	SPIDR4*	1x Timepix4	10 Gbit Ethernet		1x Timepix3	USB 3	
	COMBO+Spectrig*	1x SiPM	USB 2	WidePIX L*	10x Medipix3	1 Gb. E.	
	MicroDAQ	28x PMT	1 Gbit Ethernet	* e>	perimental support / w	ork in progress	







Real-time analysis



- Application of geometry, ToT calibration, time-walk correction
- Clustering and coincidence analysis
- Cuts on cluster attributes
- Live 1D and 2D plots
- Possibility to combine above elements into arbitrary data pipeline



Automation options

In the physical world:

- Motorized stages (rotation, linear)
- 3D positioning arms
- X-ray tubes

In software:

- Acquisition repetition
- Direct control from plug-ins (orchestration of multiple instruments)

IR

Scripting (experimental)





How does Track Lab work?





How does Track Lab work?



User builds data pipeline from many single-purpose elements.



User interface



User builds data pipeline from many single-purpose elements.



Data diagram



Front panel

User interface: extensibility



Panels can be detached, moved and docked into arbitrary grid layout by drag & dropping with mouse.



User interface: examples





I made all these layouts by dragging panels around in less than 5 min...

High performance



- Entire software written in C++20
- Horizontal scalability: each node runs on a separate CPU thread, simultaneously with others.
- Data connections facilitated by ZeroMQ "sockets".
 - Easy interoperability with other programs.
 - In-memory multiplexing at (nearly) no cost.
 - <u>Future:</u> real sockets, distribute over network
- File I/O facilitated by memory mapping.





Extendibility



- Anyone can make their own
 Control
 brick!
- <u>We do this too:</u> everything you saw implemented as plug-ins.
- API is well-defined, source code available to collaboration.
- More examples, consultations can be provided upon request.
- Requirements: C++20, Qt6 programming skills





Example applications

Example: PAN beam tests

(carried out in 2021-2022)

120 GeV/c hadron beam (90% pions) + setup:

- 2x Katherine Gen2 + 8x Timepix3 (2x Quad)
- 1x Standa rotation stage
- Trigger input (scintillator)
- Trigger out to other detectors

Software challenges:

- Pulsed large data rates
- Live analysis (e.g. cluster centroids to align in beam)
- GPIO time signals (input timestamping, out pulse gen.)





Example: calibration with XRF



Our in-house method for calibrating ToT. Setup:

- 1x Katherine Gen1 + 1x Timepix3 (varies)
- 1x Amptek Mini-X2 X-ray tube
- Set of foils (Ti, Cu, Zr,Cd)

V-ray tube Timepix3

Shielded enclosure with interlocks

Software challenges:

- Sustained large (but controllable) data rate \rightarrow performance tuning
- Feedback: pulse X-ray & measure until enough clusters are collected
- Foil rotation using motorized carousel (WIP)



Examples: detector networks



ATLAS-Timepix3

- 28x Timepix3 (sandwiched in pairs)
- 4x Katherine Gen2 (2 PCIe, 2 Eth)
- 4x Katherine Gen1

Software challenges:

- Demand on fast I/O (SSD RAID)
- Directional event reconstruction
- Timestamping LHC orbit clock

MoEDAL-Timepix3 (LHCb)

- 6x Timepix3 (sandwiched in pairs)
- 1x Katherine Gen2 (PCIe)

Software challenges:

• ML-powered anomaly detection





Examples: detector networks

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Example: tissue scanning







Collaboration with Czech National Radiation Protection Institute Positione <u>Objective:</u> map radioactive contamination of biological tissues in 2D <u>Time</u> Setup:

- Katherine Gen1 + 1x Timepix3 (Si, 300µm thick)
- COMBO + SiPM for γ-spectroscopy
- UR3 positioner arm (5 joints)

Software challenges:

- Orchestrating large number of instruments
- Integrating multiple types of data
- Aggregation over multiple sampling points









Conclusion

Summary



- Track Lab = versatile software for data acquisition and analysis
- Maturing over 3 years and 12 versions: moved from 1 to 20 devices.
- We would like to share it with the collaboration, and invite feedback.
 - Latest binaries available publicly at: https://software.utef.cvut.cz
 - Source code available at CERN GitLab to collaboration members upon request.
 - Happy to answer questions, organize workshops / demonstrations.

Why 2024 is not over yet:

- More hardware: Timepix4 is a priority, PCIe \rightarrow larger bandwidth
- More analysis: machine learning, imaging, calibration, scans



Thank you for listening!

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Try out Track Lab now:



Download v1.4 from https://software.utef.cvut.cz

Minimum requirements:

- 👌 glibc 2.35 [x86_64, aarch64]
- Hindows 10 [x86_64, arm64]
- macOS Monterey [x86_64, M1]

See article for details:



Available in J. Inst. or arXiv:2310.08974

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Backup slides

Supported operating systems





64-bit, glibc 2.35

64-bit (X64 or ARM)

macOS 14 Monterey Intel & M1 compatible

LEAP CTU

Version history

Date	Release
2020-11-04	v0.1 – initial release, very rudimentary DAQ for single readout
2021-03-10	v0.2 – multiple readouts, full configuration GUI, settings import
2021-05-05	v0.3 – pixel masking, beta threshold equalization, data flow monitor
2021-05-06	v0.3.1 – quick bug fix
2021-07-02	v0.4 – X-ray tubes, performance increase, temperature monitoring
2021-11-18	v0.5 – motor stages, real-time analysis, more file formats
2022-03-08	v0.6 – noise mean equalization, threshold scan, DAC scan, GaAs sensors
2022-07-31	v0.7 – mask patterns, file name wildcards, import/export of thresholds
2023-03-01*	v1.0 – new data core, completely new GUI, Gen2 and Quad support

Data element lifecycle



Color-coded states:



...formulated as a state machine: state of the system is aggregation of the states of its elements.

Added deterministic shutdown logic that was not previously present:

- Soft stop will finish processing data and terminate.
- Hard stop will terminate immediately useful in emergencies!



Example of THL equalization





Example of THL equalization



Reference software (UWB)



More screenshots

Readout settings: 192.168.1.37 [1]	
Acquisition Timing Trigger Chip geometry	
	Flip: X-axis Y-axis
	Rotate: 0° • 90° 0 180° 0 270°
	(all rotations counterclockwise)
	Offset X: 256 px 🗘 Y: 256 px 🗘
99 95 70000 53	Divide X: 1 🗘 Y: 1 🗘
E5000VV 01X C8 W00054	
Device will be automatically reconfigured before acquisition.	Close



More screenshots

Timepix3 settings: K10-W00053

Threshold	Mask	Calibration	All DACs
-----------	------	-------------	----------

DAC:	Configured value:		Monitor:
Ibias_Preamp_ON:	128	*	1.13 V
Ibias_Preamp_OFF:	8	*	1.29 V
VPreamp_NCAS:	128	+	0.60 V
Ibias_Ikrum:	15	*	0.89 V
Vfbk:	164	*	0.60 V
Vthreshold_fine:	470	*	0.73 V
Vthreshold_coarse:	8	+	0.73 V
Ibias_DiscS1_ON:	100	*	0.98 V
Ibias_DiscS1_OFF:	8	*	1.25 V
BandGap_output:	0	÷	0.61 V
Ibias_dac:	0	÷	1.16 V

DAC:	Configured value:		Monitor:
Ibias_DiscS2_ON:	1	28 🗘	0.33 V
Ibias_DiscS2_OFF:		8 ‡	0.16 V
Ibias_PixelDAC:	1	40 🗘	0.91 V
Ibias_TPbufferIn:	1	28 🗘	1.09 V
Ibias_TPbufferOut:	1	28 🗘	1.00 V
VTP_coarse:	1	28 🗘	0.61 V
VTP_fine:	2	56 🗘	0.60 V
Ibias_CP_PLL:	1	28 🗘	0.50 V
PLL_Vcntrl:	1	28 🗘	0.63 V
BandGap_temp:		0 🤤	0.64 V
Ibias_dac_cas:		0	0.94 V
Apply DAC settings no	w Refresh monitors	Reset	to defaults
			Close

Device will be automatically reconfigured before acquisition.

Even more screenshots





Begin	acquisition	Read	у 35.8 ТЕМР
Duration:			10 s
Mode:	ToA + ToT		▼ ✓ Data-driv
Calibrate:	ToT Tir	ne-walk	
Advanced:	Acquisition	Trigger	Pulse generator
	GPIO	Timestamping	Geometry
 Bias V Channel 1 	oltage Supply	μΑ 100.0 V Μολιτοκ	100 V 🗘 🕣
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Event 2	feedback	GPIO 2	•	● Rising edge ○ Falling edge
Event 3	Name this event	GPIO 1	•	Rising edge Falling edge
Event 4	Name this event	GPIO 1	•	● Rising edge ○ Falling edge
Event 5	Name this event	GPIO 1	-	Rising edge Falling edge



Acquisition Trigger	Pulse generator GPIO Timestamping Geometry
Acquisition start tr	igger
Input signal:	Software start 👻
Trigger event:	Rising edge Falling edge
Delay:	0 μs 🜲
Acquisition stop tr	igger
Input signal:	Timer (counts to frame duration) 🔻
Trigger event:	Rising edge Falling edge
Delay:	0 μs 🜲
Ready signal comp	osition
Composed ready	= Local ready A GPIO1 A GPIO2 A GPIO3 A GPIO4

cquisition	Trigger	Pulse generato	r GPIO Timestam	ping Geometr	y
Signal ma	pping				
Port:	Map to sig	gnal:		Termination:	Monitor:
GPIO 1:	Input		-	100 Ω	Constant low MONITOR
GPIO 2:	Input		-	100 Ω	Constant low MONITOR
GPIO 3:	Input		•	100 Ω	Constant low MONITOR
GPIO 4:	Input		•	100 Ω	Constant low MONITOR
GPIO 5:*	Input		•		MONITOR
GPIO 6:*	Input		•		MONITOR
GPIO 7:*	Input		•		MONITOR
GPIO 8:*	Input		•		MONITOR
*Some por	ts may not	be accessible fr	om outside of the e	nclosure.	
		Apply	GPIO settings now	Refresh mon	itors Reset to defaults

Even more screenshots









Multi-chip configurations



Description (agreed with LM & PB):

- Multiple layers:
 - [X;Y;Z] position in 3D space
 - Orientation in 3D space \rightarrow not necessarily parallel to each other
- Each unit comprised of multiple chips:
 - All in the same plane
 - Position described in the unit of chip size
 - Orientation: increment of 90°

Multi-chip configurations



Example: telescope with 3 chips

- Layer #1: [X;Y;Z]
 - Chip, [0;0], 0° rotation
- Layer #2: [X;Y;Z+dz]
 - Chip, [0;0], 0° rotation
- Layer #3: [X;Y;Z+2dz]
 - Chip, [0;0], 0° rotation



Multi-chip configurations



Example: 4-chip quad

- Layer #1: [X;Y;Z]
 - Chip A, [0;0], 0° rotation
 - Chip B, [1;0], 0° rotation
 - Chip C, [1;0], 180° rotation
 - Chip D, [1;1], 180° rotation

Y=0B

Y=1

X=1

ATLAS-TPX3 network

- Run-3 continuation of the ATLAS-MPX and ATLAS-TPX projects.
- 14 detector units (each 2x Timepix3) installed in the ATLAS machine.
- Challenges:
 - Complex DAQ architecture, high data rates
 - Synchronization with LHC orbit clock
 - Real-time analysis (luminosity, radiation field characterization, neutron fluxes)









First data! (autumn 2022)



...this is just a very preliminary taste, more analysis is currently ongoing (help wanted!)



Thank you for listening!

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