TransferTech
SHERBROOKE

200-35, Radisson
Sherbrooke QC J1L 1E2
CANADA
t 819 821-7961

5 PICOSECONDS AND COUNTING DOWN!

A novel Time-to-Digital Converter (TDC) architecture – a TDC with multiple successive Vernier cycles and multiple ring oscillators

Context

A time-to-digital converter (TDC) is an electronic circuit that converts time to a digital code used by digital circuits (a very precise stopwatch). The objective is to measure time with the best possible accuracy, in the order of magnitude of 1 picosecond, or one thousand billionth of a second (10e-12 seconds). There are multiple architectures of TDCs, but few can provide good performance for all five key requirements of low area, low power consumption, low timing jitter, low dead time, and low cost.

Description

This invention is a game changer for TDCs. Its objective is to reach benchtop performance for temporal accuracy while benefitting from the integrated circuit advantages of low cost and low power consumption. The preferred architecture is the ring oscillator-based Vernier TDC. Modifications to current architectures are necessary to minimize the number of cycles while reducing circuit size. This invention uses several successive Vernier processes based on a single reference oscillator. It offers a reference oscillator + 1 additional oscillator per Vernier process. This multiple Vernier concept significantly minimizes the number of Vernier cycles (reduction factor up to 50) which is critical for low timing jitter measurements. It will therefore make it possible to reduce the number of revolutions carried out, to improve the temporal precision and to reduce the conversion time, without losing the “timing” information.

Applications

- The applications that will benefit from the enhanced features of this new TDC are numerous:
  - Medical imaging
    - Benefits – Lower dose to the patient, better contrast, higher throughput, and 3D reconstruction in real time.
  - Proximity sensors, 3D cameras, and automotive LiDAR
    - Benefits – Better spatial resolution from better temporal accuracy.
  - Quantum cryptography
    - Benefits – System miniaturization for large-scale production.
  - Benchtop laboratory equipment
    - Benefits – Significant reduction in manufacturing costs.
- The markets for TDCs are varied and huge:
  - Consumer 3D Cameras – ~US$13.8B by 2023
  - Industrial and Automotive LiDAR – ~$6.3B by 2023
  - Medical Imaging – ~$35B by 2022
  - Quantum Cryptography – ~$0.94B by 2022
  - Fluorescence Microscopy – ~$0.53B by 2023

Advantages

- Considerable reduction in number of Vernier cycles compared to a single-Vernier TDC
- Improved temporal accuracy (~1ps)
- Circuit miniaturization (e.g.: 256 TDCs in a 1mm2 detector)

- Reduced conversion time. Lower power consumption
- A faster TDC at a better price – see Figure 1.
- Temporal accuracy similar to benchtop TDCs, but with minimal power consumption and lower cost – Enabling competition in the LiDAR and 3D imaging systems markets.
- More accurate than all other integrated circuit TDCs
- Much cheaper than all other TDCs in laboratory equipment

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Products	Specifications							
	1) Timing Jitter (RMS)	2) Dead Time	3) Area		4) Power Consumption	5) Cost (CAD)/Unit	5) Cost/CH	Number of channels
			Silicon Area	Packaged Size				
Integrated Circuits								
Patent Pending TDC (expected results)	**< 5 ps (1 ps bin)**	**15 ns**	**0.0025 mm^2**	**6 × 6 mm^2**	**< 0.1 mW**	**22.50 $ ***	**2.82 $**	**8**
Current TDC	**5.5 ps (5.1 ps bin)**	**50 ns**	**0.0025 mm^3**	**6 × 6 mm^2**	**0.022 mW**	**22.50 $ ***	**2.82 $**	**8**
B. Markovic, 2017	17.2 ps (10 ps bin)	150 ns	0.3 mm^2	N/A	15 mW	N/A	N/A	1
TI - TDC7201	35 ps (55 ps bin)	N/A	N/A	4 × 4 mm^2	~10 mW	6.69 $	3.35$	2
MAX35101	20 ps (3.8 ps bin)	N/A	N/A	5 × 5 mm^2	~21 mW	8.70 $	4.35$	1
AMS - AS6500	20 ps (1 ps bin)	20 ns	N/A	6 × 6 mm^2	~108 mW	23.80 $	5.95$	4
AMS - AS6501	20 ps (1 ps bin)	20 ns	N/A	9 × 9 mm^2	~212 mW	26.00 $	13.00$	2
AMS - TDC-GPX	75 ps (81 ps bin)	100 ns	N/A	9 × 9 mm^2	~79 mW	241.27 $	30.16 $	8
AMS - TDC-GPX2	20 ps (1 ps bin)	20 ns	N/A	9 × 9 mm^2	~212 mW	82.82 $	20.71 $	4
Bench Top Equipments								
Bench top with patent pending TDC	**< 5 ps (1 ps bin)**	**15 ns**		**N/A**	**N/A**	**6k$**	**750 $**	**8**
Becker-Hickl SPC-150NXX	1 ps (200 fs bin)	100 ns		24 cm × 13 cm × 1.5 cm	12 W	33k$	33k$	1
Swabian Instruments - Time Tagger UH	9 ps (1 ps bin)	16 ns		19 cm × 14 cm × 6 cm	N/A	55.4k$	6.9k$	8
Qutools - quTAG	10 ps (1 ps bin)	40 ns		44 cm × 30 cm × 5 cm	N/A	22.2k$	5.5k$	4
Picoquant - HydraHarp 400	12 ps (1 ps bin)	80 ns		N/A	50 W	72k$	18k$	4

Figure 1 – This invention vs. competing integrated circuit TDCs and benchtop TDCs.

Keywords

- Vernier, ring oscillator, dual interpolation, successive measurement, time interval measurement, Fluorescence Lifetime Imaging (FLIM), Phosphorescence Lifetime Imaging (PLIM), Time-resolved Fluorescence, Diffuse Optical Tomography (DOT), Time correlated Single Photon Timing (TCSPC), Advanced Driver-assistance Systems (ADAS).

Technology Readiness Level (TRL)

- TRL 5-6
    - Solution ready for transfer to industry.
    - 1 picosecond goal – Inventors continue to work on performance improvements with a goal of 1ps.
    - Latest prototype contains several Vernier processes and is ready for demonstration to interested partners.
    - Also developing systems containing these TDCs with related circuits such as single-photon avalanche diodes (SPADs) and other applications.
- Targeted companies
    - Texas Instruments, Swabian Instruments, AMS Electronics, Teledyne Dalsa, Becker-Nickels, Canberra Packard, Analog Devices, TSMC, others.

Intellectual Property

- International PCT patent filed.

Seeking

- Development and collaboration partners. Commercial partners. Licensing. Investments.

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Inventor Contact

Professor Jean-François Pratte
Université de Sherbrooke
Jean-Francois.Pratte@USherbrooke.ca

TransferTech Sherbrooke Contact

François Nadeau
f.nadeau@transfertech.ca
873 339-2028
www.transfertech.ca