NeXt Generation of Time-to-Digital Converters (NXGTDC)

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ABSTRACT
Conventional timing instruments make use of application specific integrated circuits to perform picosecond resolution time-to-digital conversion. This limits scalability in regard to the number of timing channels, increases cost and reduces flexibility. The NXGTDC project has developed a novel, FPGA based timing instrument that costs approximately two orders of magnitude less than commercially available offerings. The NXGTDC project has demonstrated a device with 32-input channels, 8-user programmable output channels, a resolution of 1.86ps and a precision of 15.56ps RMS which can be easily scaled to a larger number of timing channels.

Keywords: time-to-digital conversion; time correlated single photon counting; timing.

1. INTRODUCTION

Time-to-digital converters (TDCs) are a fundamental component in many applications and research fields, such as quantum key distribution (QKD), particle experiments, fluorescence lifetime imaging (FLIM), 3D imaging/laser imaging, detection, and ranging (LiDAR), positron emission tomography (PET) scanners etc. Such devices typically measure the time difference between the rising edges of START and STOP signals presented to the device and these time differences or 'timestamps' are then transferred to a personal computer (PC) for further processing and analysis. In a typical TDC instrument, picosecond resolution time measurements are performed by commercially available application specific integrated circuits (ASICs), such as those made by AMS [1]. Unfortunately, the use of such ASICs poses a significant challenge in regard to timing channel scalability, cost and flexibility. Such ASICs also typically require a field programmable gate array (FPGA) to buffer and transfer timestamps to the host PC. Hence, there would be considerable cost, scalability and flexibility benefits if the TDCs could be entirely implemented within an FPGA. However, the implementation of TDCs within FPGAs poses numerous technical challenges in regard to converter linearity, converter dead-time, resolution and precision due to the fixed architecture and resources available within an FPGA, which results in most FPGA based TDCs being outperformed by ASIC based systems.

The NXGTDC project has successfully developed a high resolution and high precision 32-channel FPGA based TDC which costs approximately two orders of magnitude less than comparable commercially available instruments. This cost reduction could enable widespread use of TDCs in many applications. In particular, the low-cost nature of the device could bring significant benefits to research laboratories due the instrument's cost falling under the capital expenditure limit in most universities and research institutions.

The NXGTDC prototype has 32-input timing channels, 8-user programmable output channels (for the control of external experimental components). The inherently flexible nature of the FPGA allows for the device to be operated in one of two modes: firstly the "timestamping" mode, where the TDC generates a timestamp for each input's rising edge with respect to the start of the measurement and secondly the time correlated single photon counting (TCSPC) mode, where correlations across 8-pairs of input timing channels can be calculated on-chip in real-time, which is an enabling technology for real-time imaging systems using single photon avalanche diode (SPAD) arrays. The instrument exhibits a precision of 15.56ps RMS on average and a calibrated resolution of 1.86ps.

2. STATE OF THE ART

Considerable research has been undertaken on FPGA based TDCs to improve the converter precision, resolution and linearity and to reduce resource utilisation. The vast majority of FPGA TDC's make use of the carry-chain, a linear and relatively predictable signal path which propagates throughout a column of FPGA slices. Despite being originally designed for arithmetic circuits, the carry-chain is used as a delay line, such that input edge's position within a particular clock cycle can be measured to a resolution of T_{DB}, where T_{DB} is the delay element size [2].

However, the carry-chain still suffers from a relatively large delays and considerable non-linearity caused by "ultra-wide bins" [3], where intra-slice bin delays are considerably smaller than inter-slice bin delays.

The "wave union" B method [4], proposes an approach of performing multiple measurements within the same delay line via an input controlled ring oscillator providing multiple edges to a delay line. This improves the performance of the TDC at the expense of increased converter dead-time, as multiple ring oscillator edges must be measured and post-processed. The wave union B method achieves a resolution of 2.44ps and a precision of 10ps RMS (with averaging across multiple TDCs) with a dead-time of ~45ns.

Equivalent coding lines (ECL) [5] use knowledge from statistical measurement of the transfer function of several delay lines created within the FPGA to create an ECL. Due to process and placement variations, each delay line will have a unique transfer function. This allows for equivalent delay bins to be formed between the quantization steps of each real delay line, increasing the resolution and precision at the expense of resource utilisation. An ECL was demonstrated with a resolution of 2.87ps and a precision of ≤10ps RMS at the expense of resource utilisation from the instantiation of multiple delay lines.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The major contributions of the NXGTDC are threefold. Firstly, a novel low resource TDC has been developed which offers high linearity, high precision and low dead-time measurements whilst using minimal FPGA resources. The TDC achieves a calibrated resolution of 1.86ps and a precision of 15.56ps RMS. Linearity is also extremely high (as evidenced by the Gaussian like instrument response function shown in the results section), which insures that the shape of time correlations exhibited by experimental setups can be accurately recorded. Low resource utilisation also allows for a large number of TDC "time stampers" to be implemented in a singular FPGA, with 16 currently being demonstrated, which allows for 32 timing channels with multiplexing of non-temporally correlated input pairs into each TDC.

Secondly, a low-cost hardware platform has been developed that can easily be manufactured and can be easily modified to suit OEM applications, if needed.

Thirdly, on-chip real-time TCSPC has been demonstrated, with eight correlations being performed across any 8-pairs of input channels. This is a considerable contribution to the cutting edge as most timing instruments perform TCSPC via the post-processing of timestamps on a PC. TCSPC via post-processing of tags poses two technical limits. Firstly, the throughput of the communication medium (typically USB 3.0 or USB 2.0) limits the number of timestamps that can be transferred to the PC per second. This throughput is shared across all channels, hence, there is a limit on the number of events which can be measured per timing channel on average before the TDC's buffer overflows and measurements are lost. This creates a detrimental impact on experimental setups, as many TCSPC systems operate with a high excitation rate/START signal frequency. Secondly, the post-processing of timestamps to form correlations/histograms is a computationally demanding task to perform in real-time on a PC.

In the NXGTDC instrument, correlations are performed using dedicated digital circuits, exploiting the concurrent nature of the FPGA. The result of this is that timestamps do not need to be transferred to the PC, only the result of the correlations (histograms) which are approximately 16kB each. Hence, USB or communication throughput no longer limits the average maximum signal input frequency. This allows for the input signal frequencies to far exceed typical systems, with the limit now being determined by how fast the digital circuit can process time stamps.

Tab 1. Summarises the performance of the NXGTDC prototype to a commercially available instrument.

Tab. 1. A comparative table of the NXGTDC's performance.

Metric	NXGTDC	HydraHarp 400 [6]
Timing channels	32 (16 dedicated TDCs)	8
Calibrated resolution	1.86ps	1ps
Precision	15.56 / 12.95ps RMS	<8.5ps RMS
Dead-time	~11ns	<80ns

4. PROJECT RESULTS

Instrument hardware and design

The instrument developed shown in Fig. 1 has 32 50Ω terminated input channels, each with a user configurable constant level discriminator. This is designed such that readily available SPAD modules can be connected directly to the device. This is to keep costs low and it is assumed that if photomultiplier tubes (PMTs) or similar devices are to be connected, a separate constant fraction discriminator will be externally used. The device also exhibits 8 50Ω logic level output drivers to control or trigger experimental components, which can be controlled from the host PC.

Fig. 1. The 19" rack mounted 32-channel NXGTDC prototype instrument.

Fig. 2. The electronics behind the NXGTDC prototype instrument.

Expansion to a higher number of timing channels is also possible via the "daisy-chaining" of multiple instruments via the clock input and output ports present on each instrument. Fig. 2 demonstrates the construction of the prototype, which is based around a readily available Opal Kelly FPGA module. This will allow for the FPGA firmware and associated printed circuit board (PCB) to be easily customised for custom and potentially OEM applications in the future.

At present, each input channel pair is multiplexed into one TDC and as of such, non-temporally correlated inputs or temporally correlated inputs with a separation greater than the converter dead-time can be presented to such pairs.

On-chip non-linearity calibration

As discussed in section 2, delay line non-linearity is experienced by all FPGA carry-chain based TDCs. Using non-calibrated timestamps results in considerable distortion in measurements and to enable on-chip TCSPC, calibration must be performed in-real time rather than in post processing on a PC. A low resource method (discussed in detail in [2]) has been utilised to statistically measure each delay line's transfer function to calibrate for delay line non-linearity in real-time as each timestamp is produced. This process calibrates each TDC's non-linearity to a resolution of 1.86ps.

Instrument precision

The NXGTDC's instrument precision, commonly known as single shot precision (SSP) was measured across all channel pairs with respect to channel 1. This was achieved by using a HP8082A pulse generator and a Mini-Circuits ZFRSC-42-S+ 50Ω splitter. This essentially presents a fixed delay between the timing channels. A series of approximately 64k timestamps pairs was then transferred to a PC and the time differences between each pair calculated and then histogrammed. This allows for the instrument's precision or the amount of timing error the TDCs introduce to be measured. A typical SSP is shown in Fig. 3, which demonstrates a SSP of 18.87ps RMS for a particular channel pair or 13.2ps RMS single channel SSP, with the average SSP across all TDC pairs being equal to 15.56ps RMS.

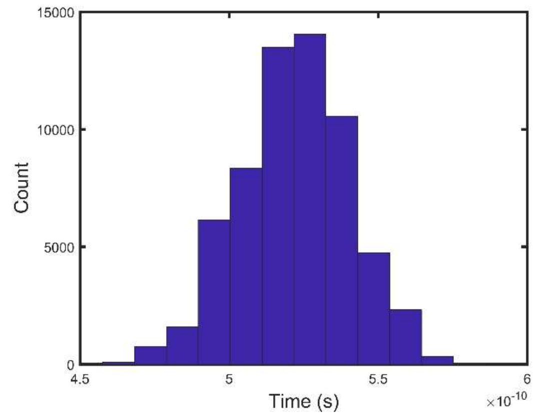

Fig. 3. The single shot precision or precision of a typical NXGTDC channel pair.

Instrument TCSPC

Custom digital circuits have been developed to perform 8 concurrently executing TCSPC on-chip across any 8 input signal pairs. This allows for input event rates of up to approximately $20x10^6$ events/sec per TCSPC or an input event rate of approx. $160x10^6$ events/sec, which far exceeds the USB 3.0 throughput limit of $44x10^6$ events/sec if time tagging and post processing was performed.

Novel TDC architecture

To reduce converter dead-time and to increase converter precision and linearity performance, a novel architecture has been developed during the NXTDC project and is documented in [7].

The largest bottleneck in most TDC designs is the priority encoder, a combinatorial logic circuit which converts an N-bit wide thermometer code, where N is the number of sampling bins in the delay line to a more manageable $\log_2(N)$-bit wide code.

The thermometer code will contain a singular 0-to-1 transition which represents where the input edge occurred within a clock cycle and the propagation delay in this combinatorial logic circuit typically necessitates long clock periods and long delay lines. This novel approach essentially shifts the priority encoder onto a slower, separate clock domain, allowing the TDC to operate in a higher frequency clock domain. It has been demonstrated that TDC SSP scales to $\sqrt{N}$ and the novel architecture allowed for an increase of 38.1% in clock frequency, reducing N by 114 and the SSP by 12.9% to 12.95ps RMS. This NXGTDC hardware/firmware is currently being updated with this method.

5. FUTURE PROJECT VISION

It is envisioned that the NXGTDC project will progress towards the incorporation of the NXGTDC within a novel photon counting greenhouse gas monitoring system in an ATTRACT Phase 2 project, if awarded. This will involve the research, development and commercialisation of a novel solid-state LiDAR system, exploiting the real-time nature of on-chip TCSPC.

Note that further development of the NXGTDC platform will also be undertaken to assist with research community.

5.1. Technology Scaling

The NXGTDC platform has already reached Technology Readiness Level (TRL) 4 via laboratory characterisation of the device's performance. A prototype device is currently being evaluated by the QLM (an industrial partner in the NXGTDC project) in regard to its suitability for gas detection, as such, it is expected that the NXTDC platform to reach TRL 5/6 by the end of the NXGTDC project.

If an ATTRACT Phase 2 project is awarded, it is expected for the NXGTDC platform to realise TRL 5-7 during the course of the project, via the integration and testing into real-life LiDAR systems and system validation in comparison to established systems before being deployed in actual products with the industrial partner.

Project Synergies and Outreach

To develop novel LiDAR systems for greenhouse gas monitoring will require additional skills which are currently not covered by the NXGTDC team (Aston University and QLM). These are as follows:

- Development of novel detector arrays or detectors capable of operating at near-infrared (NIR).
- Solid-state (i.e. no mechanical scanning) LiDAR system development.
- Exploration of novel optical elements for increasing sensitivity or solid state beam steering.

In regard to the first skill set, there is an ATTRACT Phase 1 project which is working on developing SIPM technologies for near-infrared (NIR), of which we plan on contacting in order to collaborate for a potential ATTRACT Phase 2 bid. In addition this, we plan to build further working relationships with other universities which are currently working on similar technologies to ensure this area is well covered in the Phase 2 bid.

In regard to the second and third skillsets, it is planned that two well-known universities and academics will contribute towards these topics and skillsets.

In regard to outreach, the NXGTDC project has currently published one conference paper and a journal paper is currently being written. In addition to this, the NXGTDC website has gained considerable interest from numerous UK academic institutions looking at using TDCs in quantum optics and LiDAR experiments. It is envisaged that considerable outreach and publications can be garnered in Phase 2 due to the vast potential impact from greenhouse gas monitoring.

5.2. Technology application and demonstration cases

The ATTRACT Phase 2 project will focus on the development of novel photon counting LiDAR. This is something the industrial project partner QLM already has significant experience and industrial presence in. It is envisaged that the TDC and TCSPC technology will be utilised to perform real-time LiDAR measurement and localisation of greenhouse gases to an unprecedented level of accuracy, precision and acquisition speed. This aligns strongly with the "*Climate action, environment, resource efficiency and raw materials*" societal challenges set out by H2020 and EU strategy.

The TDC and TCSPC technology will also be commercialised such that this research can contribute towards assisting the research community. The cost of the NXGTDC platform is approximately two orders magnitude cheaper than competing commercially available instruments and would fall below the capital expenditure limit present in most universities and research institutions, allowing for a greater penetration of timing instrumentation within research.

5.3. Technology commercialization

This technology was proven by QLM to improve their photon counting gas sensing system performance, enhancing resolution and signal dynamic range. This technology will be explored for commercialisation via licensing in the next generation of QLM products. In ATTRACT Phase 2, if awarded, a novel gas-sensing system will be developed exploiting real-time TDC and TCSPC. TDC and TCSPC instruments will also be explored as a university spin-out in conjunction with other collaborating consortium members.

5.4. Envisioned risks

The TDC and TCSPC technology has already been proven via characterisation of the device. However, there are risks involved with the development of a new LiDAR system for gas monitoring. The main core risks and mitigation strategies are:

- the inability to work collaboratively on physical lab due to COVID-19 imposed social distancing, this can be mitigated by approaching the project's components in modular and well documented fashion;

- the performance of the novel approaches do not outperform other approaches, this can be mitigated by a stage of analysis and modelling.

5.5. Liaison with Student Teams and Socio-Economic Study

The NXGTDC project has supervised a MEng project student locally to develop a low cost hardware random number generator using photon counting technology. The use of photon counting and TCSPC will be explored with the MSc student teams in ATTRACT Phase 2, if awarded, as it is believed that photon counting related projects could inspire such students to address societal challenges. Photon counting based systems could be used for automotive LiDAR, quantum cryptography, quantum computation, food evaluation and many more applications.

Dr. Richard Nock will lead in the development and facilitation of MSc level materials, lectures and potential projects on the use of photon counting technology.

It is expected that the project will be able to contribute news pieces, academic papers and evaluations on the impact of the technology in various applications for the Phase 2 socio-economic study.

6. ACKNOWLEDGEMENT

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