Adaptive Embedded Digital System for Plasma Diagnostics

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Abstract. An Adaptive Embedded Digital System to perform plasma diagnostics using electrostatic probes was developed at the Plasma Engineering Laboratory at Polytechnic University of Puerto Rico. The system will replace the existing instrumentation at the Laboratory, using reconfigurable hardware to minimize the equipment and software needed to perform diagnostics. The adaptability of the design resides on the possibility of replacing the computational algorithm on the fly, allowing to use the same hardware for different probes. The system was prototyped using Very High Speed Integrated Circuits Hardware Description Language (VHDL) into an Field Programmable Gate Array (FPGA) board. The design of the Embedded Digital System includes a Zero Phase Digital Filter, a Derivative Unit, and a Computational Unit designed using the VHDL-2008 Support Library. The prototype is able to compute the Plasma Electron Temperature and Density from a Single Langmuir probe. The system was tested using real data previously acquired from a single Langmuir probe. The plasma parameters obtained from the embedded system were compared with results computed using matlab yielding excellent matching. The new embedded system operates on 4096 samples versus 500 on the previous system, and completes its computations in 26 milliseconds compared with about 15 seconds on the previous system.

Introduction
This work reports the design and implementation of an Adaptive Embedded Digital System (AEDS) to perform plasma diagnostics using electrostatic probes [1]. The Plasma Engineering Laboratory at Polytechnic University of Puerto Rico (PUPR) currently performs plasma diagnostics using a Keithley 2400 source-meter [2] to apply a ramp voltage to the probe and capture the probe’s current, and a digital computer running a LabView [3] program that performs the diagnostics computations. The existing system is able to compute plasma parameters for Single and Double Langmuir probes, Emissive probe, and Ion/Electron Energy Analyzers[4]. The system is notoriously slow and difficult to maintain. The new System improves the speed, size and cost, and flexibility of the system. The main components of the AEDS are a 12-bit Digital To Analog Converter (DAC), a 14-bits Analog to Digital Converter (ADC), a Zero Phase Digital Filter, an Exponential Unit (EU), a Computational Unit (CU). A key feature of the design is the possibility of replacing the Computational Unit on-the-fly, allowing to use of the same hardware for probes with different computational algorithms. The system was prototyped using an Xilinx Spartan-3A FPGA Starter Kit board [5] for the Single Langmuir probe, and is able to compute the Plasma Electron Temperature and Density.
Description of the Hardware
This section describes the main components of the system. The hardware was designed using VHDL [6], and using the new VHDL-2008 Support Library [7], which provides for fixed-point and floating-point types required by the design. Figure 1 shows the system block diagram. The system is developed in a modular fashion to enable the substitution of the Computational Unit depending on the type of probe being used.

Zero Phase Digital Filter
Noise degradation of the I-V characteristic causes computational errors. A Zero Phase Digital Low Pass Filter was used in this project to remove the noise from the input signal avoiding phase distortion. This filter performs its function by processing the input data forward and reverse directions, canceling the phase shift produced by the filtering. Figure 2 shows the digital filter block diagram, consisting of a Filter Module, and a Dual-Port RAM module for storing the intermediate and final filtered values.

Exponential Section Unit
The Exponential Section Unit identifies the boundaries of that section, by detecting the zero crossing point of the probe current (leftmost boundary) and the maximum of the derivative of the probe current where the probe voltage equals the space potential (the rightmost boundary).
The Exponential Section Unit also identifies three type of errors that could be present in the signals:

(i) No zero crossing;
(ii) Multiple zero crossings;
(iii) Index of the maximum derivative before the index of the zero crossing.

Each error is specifically associated with a control signal to indicate the Response Monitor of the error that has occurred.

**Computational Unit**
The Computational Unit performs the computations to obtain the parameters, from the I-V characteristic of the probe. The prototype uses equations 1 and 2 for the Electron Temperature $KT_e$ and Density $n_e$ respectively [8].

$$KT_e = \frac{1}{\max \frac{d \ln |I|}{dt}} \quad (1)$$

$$n_e = -\frac{I_{es}}{eA\sqrt{KT_e \pi m_e}} \quad (2)$$

where $m_e$ is the electron mass, $e$ is the electron charge, and $A$ is the probe area.

**Main Finite State Machine (FSM) Controller**
The Main FSM Controller controls and coordinates the system operation.

**Response Monitor**
The Response Monitor is responsible of receiving any errors signals from the EU and alert the user about them.
Simulations and Results
Simulations were performed for each individual module, as well as for the complete system. The design was loaded into the FPGA and its functionality validated in hardware. Figure 3 shows $K_T e$ and $n_e$ obtained from the system using data previously acquired. These experimental parameters were compared with theoretical results, with and error of 0.000858115% for $K_T e$ and 1.07902% for $n_e$. Several signals were used as stimulus to the system; the average error percent was 2.644% for $K_T e$ and 2.13% for $n_e$. The accuracy of the results is a function of the number of bits used for the calculations. This project used 27-bits words for the data because of the size of the FPGA used for prototype. Notice that this is not a design limitation: by increasing the quantity of bits for the number scheme in the system the results will be more accurate. Figure 4 depicts a graph showing the relationship between the number of bits in the fixed point numbers of the system and the error percents of the Plasma Electron Temperature and Density.

The new embedded system operates on 4096 samples versus 500 on the previous system, and completes its computations in 26 milliseconds compared with about 15 seconds on the previous system.

Conclusions
An Adaptive Embedded Digital System was designed, implemented and tested to perform plasma diagnostics with electrostatic probes. Two novel features are included in this design: The adaptability of the computational unit for various probe types, and the use of a zero phase filter to remove the undesired noise from the current signal from the probe. The system was tested with data previously acquired from a Single Langmuir probe showing an acceptable accuracy when compared with computations made with software. The system is able to detect errors in
the data acquisition, and interrupt the measurement in those events. Further advantages of the new system are: low hardware cost, minimum size, high scalability, portability, and very high speed computations capabilities.

References
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Figure 4. Relation between quantity of bits and the error percent in results