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Optical cyber-physical system embedded on an FPGA for 3D measurement in structural health monitoring tasks

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A R T I C L E I N F O

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A B S T R A C T

This paper presents the description of a cyber-physical system embedded on an FPGA for 3D measurement in structural health monitoring tasks. The implementation technique and performance evaluation demonstrate the contribution of this paper to the mathematical fundamentals adaptation of an on-site rotatory scanning system to a cyber-physical system. In particular, it is described in detail the design of a virtual angle measurement soft sensing technique based on the information conversion of an optoelectronic signal provided by a rotatory scanning system through an FPGA. Behaving the FPGA as the sensor controller and the actuator in the scanning system. Using the measurement of angles through the proposed embedded system, it can be calculated the coordinates and displacement of specific indicators distributed over a structure under observation. Providing online data exchange from on-site measurement to a remote computational station for real-time or posteriorly data analysis.

1. Introduction

Structures are susceptible to aging due to environmental and operational conditions. The monitoring of structures health status allows detection of damage. Materials degradation can lead to structure damages if not appropriate preventative maintenance is done. A continuous structural health monitoring (SHM) is essential to ensure structural integrity. To achieve this aim, an optical scanning system (OSS) has been developed, based on a rotatory scanning searching an optical signal of a light source previously mounted on the structure under observation, with the purpose to monitor the structure displacements.

Displacement is classified as a structural vibration-based response measurement. Traditional techniques typically comply the principle of system identification, which is based on the relationship of inputs (excitation) and outputs (measurements), as consequence by this technique, get the desired data from large-scale structures can result in a very expensive and difficult task [1].

On the other hand, the proposed OSS based on a rotatory scanning represents a continuous, low-cost and non-contact SHM system [2]. The displacement represents an indirect measurement using the coordinates measurements cross-correlation obtained with the OSS based in rotatory scanning. At the same time, the measured coordinates are calculated using a mathematical method based on the rotatory scanning system properties as previously described in [3]. Which provides the angle measurement through the use of an optoelectronic signal, involving the Pythagorean Theorem, mathematical proportions, and angular frequency.

Mathematical methods for angle measurement have been developed since the beginning of mankind civilization for multiple daily activities, in specially to solve engineering problems. Due to the electronics devices development, today a big variety of sophisticated transducers and application specific integrated circuits (ASIC) as well as field programmable gate arrays (FPGA), it is possible and increasingly common the development of virtual sensors based on soft sensing for physical magnitudes measurement [4].

The main purpose of present paper is to introduce a cyber-physical system embedded on an FPGA for 3D measurement in structural health monitoring tasks. Other purpose is to describe the implementation of a virtual angle measurement soft sensing technique based on the information conversion of an optoelectronic signal. The signal is provided by an optical scanning system (OSS) through an FPGA behaving as an actuator and/or the controller of actuators. After the introduction, the rest of the paper is organized as follows. Section 2 summarizes the basis of the angle measurement application. Section 3 describes related work and applications context of the proposed virtual sensor in OSS based in

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rotatory scanning. Section 4 introduces the angle measurement methods and OSS based on rotatory scanning overall. Section 5 covers the description, characteristics of the selected electronic device platform for the implementation of virtual sensing, as the achieved goals. Section 6 provides some details about the experimental methodology. Finally, experimentation results are analyzed and discussed, concluding with remarks for future work.

2. Mathematical methods applied to angle calculation for 3D measurement

3D coordinates measurement is fundamental to monitor structural health if the displacement is occurring. Methods for 3D coordinates measurement performed using dynamic triangulation require the measurement of angles for their calculation. The measurement of angles is the base of many concepts in geometry and trigonometry, which are used throughout almost all the disciplines of engineering. Angle measurements are needed for the simplest as for the most complex tasks. They have been performed through history using the most primitive's to the most sophisticated methods.

The development of instruments for angle measurements has been evolved in the search of increased accuracy and precision as well as for the adaptation of the angle measurement instrument to the applications. It is believed that the first measurement of angles was made matching the shade provoked by the sun over marked stones. The first instrument for measurement of angles was the Groma (four stones hanging from cords arranged at specific angles). Followed by the cross-staff and its improved versions (optical square, graphometer, the sextant, Abney level, etc.) [5]. Continued by the Dioptra, Astrolabe, Theodolite, Vernier, Dividing engine, and electronic instruments based on the measurement of binarily coded circles [6].

The discovery of the photovoltaic effect and the photoconductivity in solids introduced the development of integrated circuits composed of semiconductors, and with constantly reducing the scaling size, the field of nanotechnology originated [7]. Where both, (a) nanotechnology and (b) need of measure dimensions, which are inaccessible, surged the indirect measurement methods supported by a new design of sensors and transducers with high performance in characteristics such as sensitivity, frequency response, and dynamic range; from where optoelectronic and photonic sensors have benefited and improved a wide range of applications [8].

On the other hand, semiconductor nanotechnology has not only revolutionized the design and production of sensor and transducer, but also the electronic control systems for actuators. Controllers are devices that receive input signals from sensors and transducers to compare the inputs values before and/or after analog-digital signal processing versus previously stored or adaptive control point values, to determine the output signals for actuators. The signal control algorithms can be executed in any electronic device, such as a microcontroller, ASIC, FPGA or a PC using special engineering software (Quartus, LabView, Matlab, OpenCL, to mention some).

For these and more reasons, the development of virtual sensors based on soft sensing for physical magnitudes measurement is possible and increasingly common. Transducers and sensors provide converted information from physical magnitudes to processable data, commonly represented as analogic and/or digital signals. However, such conversion does not directly provide the value of the physical magnitude; a signal processing is required to estimate the value of interest with a level of accuracy and precision defined by the specific application.

The biggest challenge on virtual sensing is the implementation of signal processing through an electronic device platform, which usually implicates a mathematical method adaptation depending on the electronic device platform characteristics and resources [9].

The complexity of such devices consists in the integration of its powerful and general purpose elements, like as the processor and/or the programmable logic elements array, embedded memory, memory interfaces, peripherals, video and audio, Ethernet networking, peripheral component interconnect (PCI), analogic-digital/digital-analogic converter (AD/DA), etc. The influence of all these hardware elements in the low-level programming language abstraction to achieve the desired system on chip (embedded system), results that only a few software engineers have experience in hardware description language (HDL). Besides there exists no standardization of the features supported by different and also time-consuming electronic design automation tools (EDA), due to each signal processing step is represented as a waveform.

Furthermore, debugging can be a complex task, due to limited memory resources, compared to the requirement of project design size for the debugging tasks, where it is often necessary to analyze inputs, outputs and some nodes simultaneously [10]. Using the virtual angle measurement soft sensing technique, based on the information conversion of an optoelectronic signal, provided by the OSS based on a rotatory scanning using an FPGA, an on-site rotatory scanning system has been upgraded to a cyber-physical system to estimate physical magnitudes under interest [11].

3. Virtual sensors on optical cyber-systems related work

Virtual sensors, also called soft sensors are favorable alternatives to replace physical measurement sensors, since they can be used to implement mathematically and physically, to estimate the value of magnitudes under interest. Even if the mathematical and physical model is not completely known, it can be estimated using supervised machine learning algorithms [12], enabling also actuators in some applications to be used as devices with dual function (sensor and actuator) [13]. Nowadays virtual sensors are present in systems for multiplies engineering fields: information technology [14], electromagnetics [15], mechatronics [16], metrology and calibration [17], and much more.

In particular for optical scanning systems virtual sensors are present in a wide range of applications, such as (a) Autonomous navigation of robots, where a laser-based scanning is integrated to the planning and control systems for navigation using the scanning of environment as input to a controller that decides the sequences of positions commands sent to the robot [18]. (b) Multimedia, where 3D vision systems have a wide range of commercial applications, and depth maps captured from a real scene are enhanced by rendered virtual viewpoint [19]. (c) Medical imaging, where virtual reality provide augmented visualization to develop clinical technics [20]. (d) Industrial equipment measurement and calibration, where laser vision sensors are part of quality control in manufacturing processes [21]. (e) Structural Health Monitoring, where optical linear variable displacement virtual sensors serve as a viable non-contact alternative to physical measurements of structure displacement [22], to mention some.

Regarding virtual angle measurement: they are implicit used in scanning systems, based on optical sensors for 3D/2D image construction like in [23] and [24], coordinates and displacement measurements [25], and other applications, as describes paper [26] the importance of energy and angular resolutions in top-hat electrostatic analyzers for solar wind proton measurements.

4. Angle measurements method for 3D coordinates scanning

As geometric methods are based on the Euclidean geometric circular arc, and trigonometric methods are based on the grade of a slope, there exist also other methods based on specific references inherent to the application. For example the use of the equator in geographic coordinate location, or the use of a selected point on the celestial sphere in the astronomical coordinate systems. At the moment of integration of an optic-based transducers, several novel alternatives to measuring the size of an angle are possible using the angle of rotation of scanning systems, as the proposed virtual angle measurement.