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Design of a Non-Contact Surface Profilometry System for Automated Geometrical Dimensioning and Tolerancing

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ABSTRACT: *A Non-Contact Surface Profilometry System has been developed for autonomous geometrical dimensioning and tolerancing quality control. Using embedded microcomputers and custom control circuits a cost effective system has been developed to provide high density sub-micron resolution 3-dimensional point clouds and meshes. With a data acquisition rate of up to 200,000 samples per second large data structures are developed quickly and manual data processing is infeasible. Software has been developed to automate the post processing of the acquired data to provide quality control of critical dimensions of various components.*
Keywords: Dimensioning, *tolerancing, automation, profiling, quality, control, measurement*.

I. INTRODUCTION

Geometrical dimensioning and inspection are critical for manufacturing quality control. Coordinate Measurement Machines (CMM) are the industry standard for geometrical dimension quality control. Modern industrial CMM machines do not offer a feasible method of performing 100% inspection on produced parts due to the cost, limited data collection rates, and lack of autonomous feature recognition and measurement systems. This explorative research attempts to establish a means of providing autonomous geometrical dimensioning and inspection at a high processing rate and high scan resolution while keeping costs within practical range for industrial application.

II. PRIOR RESEARCH

Previously, two non-contact surface profiling systems have been developed through this research. The first system was to prove the feasibility and concept of developing a low cost profiling system while maintaining high data resolution. The first system was built using an industrial programmable logic controller (PLC) and using a single point laser displacement sensor to provide the sub-micron resolution measurements. The first system was able to successfully generate 3 Dimensional point clouds of the scanned surface at a fraction of the cost of commercially available CMM equipment. The first prototype had a data acquisition rate of 100 data points per second.

The second prototype developed replaced the expensive PLC with an ATMega168eight bit microcontroller. With design improvements the new prototype was able to achieve 1000 data points per second. Issues with the commercial laser displacement sensor controller limited the overall number of data points that could be collected as well as created timing issues[1].

The latest prototype utilizes an AM335x 1GHz ARM Cortex-A8 processor running a linux OS along with a custom developed analog to digital converter to acquire data from the laser displacement sensor. With this design, data collection speeds have been achieved at 28,000 samples per second during operation and the maximum possible collection rate has been computed to be 200,000 samples per second. The low cost ARM processor enables the developed system to sustain complete synchronization between the laser displacement sensor data acquisition and positioning of the 3 axis traverse system.

III. OBJECTIVES

The list below describes the primary objectives to be achieved through this research and design. This research was sponsored by the Federal Railroad Association (FRA) for the analysis and quality control of steel reinforcements used within concrete railroad ties. As such the design is tailored to the needs of the quality control of these steel reinforcements; however, the design aspects of this research are practical for any generic geometry part.

- Acquire a sub-micron resolution point cloud of part geometries
- Develop autonomous processing algorithms to detect and measure surface geometries
- Achieve data acquisition rates practical for application in industrial production facilities
- Develop system at feasible price point for wide scale industrial application
- Use the developed prototype for the quality control and analysis for the Federal Railroad Association on real manufacturing quality control problems

IV. DESIGN OVERVIEW

The latest prototype development and design can be segregated into the following three sections, mechanical hardware design, electrical circuit design, and software design. For each aspect of the design process analyses were made to determine whether the needed component should be custom design or that commercially available components are available that meet the objective requirements.

V. HARDWARE DESIGN

The hardware design needed to achieve the following:

- Securely locate the part to be scanned by the profiling system
- Locate and control the position of the laser displacement sensor relative to the part
- Provide a smooth scanning path that allows for the entire part to be scanned continuously

The hardware chosen was specific to the needs of the parts scanned during the research. Two linear traverses and one rotary table were used to locate and control the motion of the part relative to the laser displacement sensor. The application of this research is the surface profiling of prestressing steel reinforcement wires used in concrete members. The wires in question are hardened steel with a diameter of 5.32mm. The surface of the reinforcement wire is covered in indentations which geometrical features are critical for the reinforcement steels performance in concrete members. In Fig. 1 the hardware layout is shown. The part in yellow is the 5.32 mm diameter wire to be scanned by the profiling system. The linear traverse and rotary table are shown in blue and the laser displacement sensor in green. During data collection the vertical linear traverse and rotary table are moved synchronously to achieve a helical scan path allowing the laser displacement sensor to cover the entire surface of the part.

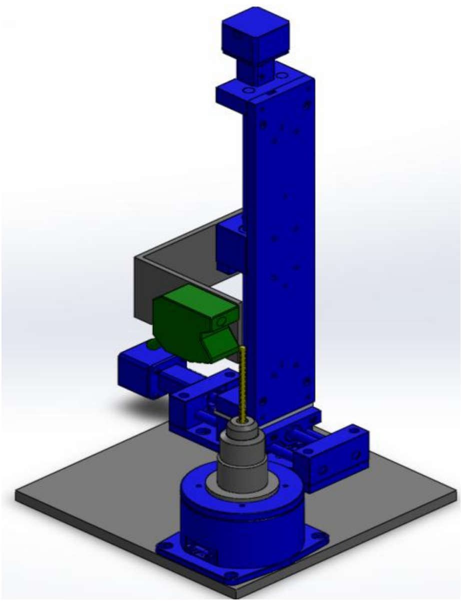

Figure 1. Hardware design

VI. CIRCUIT DESIGN

The mechanical hardware for the non-contact profiling system is application specific. However, the circuit design and software is universally applicable for any given part geometry and size. The circuit design needed to achieve the following:

- Support high speed analog to digital conversion(ADC) of at least 16 bit resolution.
- Synchronize ADC control with control of traverse motor positions
- Output the data to a personal computer for analysis

Fig. 2 shows the functional block diagram for the circuit design. The scanning process is initiated by a user at the desktop interface. The desktop computer communicates to the AM335x processer via an Ethernet connection. The AM335x begins the scanning process by sending the scanning instructions to the Programmable Real-time Unit Sub-System (PRUSS). The PRUSS consists of two 32 bit microcontroller co processors dedicated to real time applications. The PRUSS then communicates with the AD997A ADC converter via Serial Peripheral Interface (SPI) while simultaneously sending step and direction signals to the stepper motor drivers synchronizing the rotary table and linear traverse to the ADC conversion. A buffer is used to pass the retrieved ADC data from the PRUSS to AM335x processor which can either store the information in a USB storage device or send via Ethernet to the desktop computer.

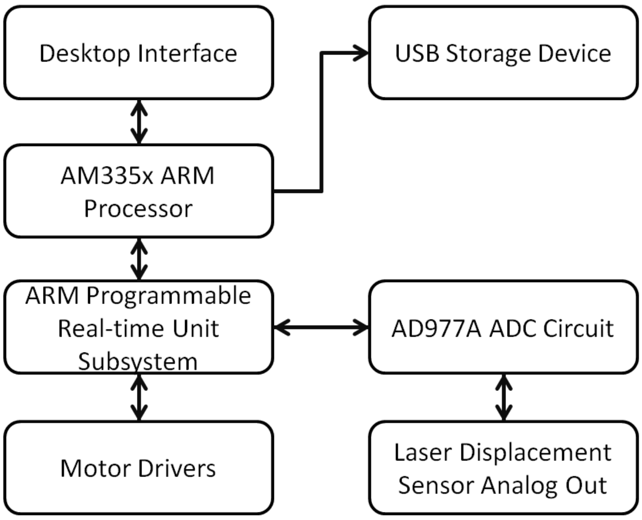

Figure 2. Function block diagram

Prior to this design, prototypes had limited buffer spaces limiting the amount of data that could be collected within a single scan. Due to the high resolution and spatially dense point clouds generated by the profiling process, the data requirements are relatively large compared the performance capabilities of modern industrial laser displacement controllers. By developing a custom ADC circuit, limited buffer space problems are mitigated. In addition the custom ADC allows for a high speed synchronization of the laser sampling with the motion control system, this is also not achievable with modern single point laser displacement sensor controllers.

Fig. 3 shows the circuit used with the AD977A. The circuit utilizes the AD8031 – a high speed op amp – to configure the AD977A for bipolar operation between ± 10 volts. This voltage range is a standard for industrial analog output which is used on the output of the laser displacement sensor utilized within this development. The data clock and R/C (read/convert) pins are driven by the PRUSS. Data received by PRUSS is stored in a temporary buffer until it is retrieved by the AM335x processor.

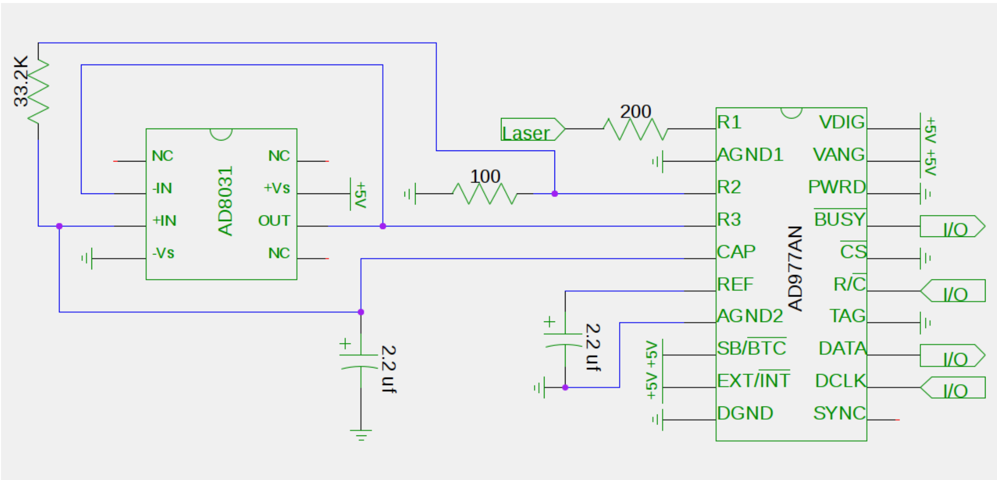

Figure 3. ADC circuit diagram

VII. SOFTWARE DESIGN

The designed software can be separated into the following three categories.

- PRUSS assembly for data acquisition and motion control
- AM335x C code for data transfer and interfacing the desktop computer
- Desktop C/C++ code for processing collected data and performing autonomous geometrical feature measurements

The PRUSS assembly instruction set is specifically tailored for developing real time systems where precise timing is critical. The assembly code developed for the PRUSS assembly code is written to receive instruction sets via a buffer from the AM335x processor. Upon receiving instructions for a scan the assembler code generates the necessary step and direction signals for the stepper motors while processing the SPI for the ADC. The assembly code stores ADC data in a buffer to be retrieved by the AM335x processor.

The AM335x C code provides a means of communication and data storage in-between the desktop computer and the PRUSS. Data pulled from the PRUSS buffer is stored on a flash memory device until it is unloaded to the desktop computer. The AM335x software additionally receives and processes all commands from the user and desktop computer.

The last and most intricate of the software development is in creating autonomous geometrical feature measuring algorithms capable of processing the data and obtaining surface profile measurements. Much of this development can be seen in greater detail in "Automated real-time search and analysis algorithms for a non-contact 3D profiling system"[2].

Each geometrical feature to be measured requires unique processing to obtain the desired measurement. A combination of spatial correlation, non-linear search algorithms, and procedural programming methodologies leads to automated measurement extraction[3].

VIII. RESULTS

The developed system was utilized for the surface profiling of pre stressing steel reinforcement wires to determine the geometrical features that influence performance when the steel is used in concrete members. With this system new geometrical features were discovered as having critical influences on concrete members whose measurements were not obtained until this development[4]. Fig. 4 below shows a resulting 3D model(right) of a microscope image capture of the same wire(left).

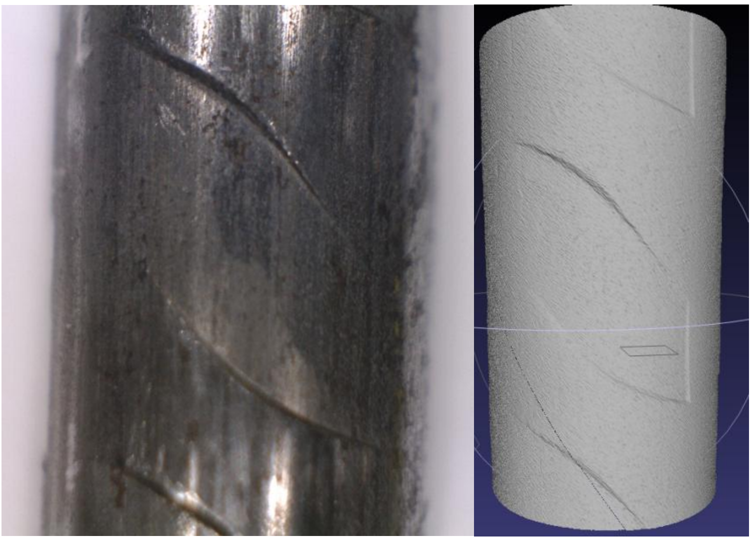

Figure 4. Microscope image (left) of part compared acquired scanned surface profile(right)

IX. CONCLUSSION

The developed system was used successfully for the analysis and quality control of prestressing steel reinforcement wire geometry[5]. The non-contact profiling system was able to identify critical geometrical features and their influence on reinforcement wire performance in concrete members[6,7]. The designed system maintains a sub-micron resolution and state of the art sampling rates while being at a fraction of the cost of commercially available systems. Additionally, the developed software allows for autonomous geometrical feature measurements making autonomous 100% inspection of geometrical measurements practical for industrial applications. System limitations consist of the mechanical hardware and the specialization requirements for the autonomous geometrical feature measurements. The mechanical hardware is part specific and performing automated surface profiling on different part geometries will require a different hardware arrangement. Each geometrical feature measurement extracted by the software requires specialized software development to achieve robust feature extraction.

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