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Development of modular machine tool structural monitoring system

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ABSTRACT

Although designed to be structurally stiff, machine tool deformation takes place due to the various sources of errors such as shifting mass, component weight, temperature etc. In order to facilitate research activities and acquire further scientific insight on the deformation process, a computer-based on-line monitoring system has been developed. A variety of sensors can be used to capture data for numerous parameters like temperature, displacement, strain etc.

This paper presents the design and implementation of a LabVIEW based multi-sensor data acquisition program. It was designed in a three layer modular structure. In addition to data acquisition, the program is also capable of data processing, logging and implementing various error reduction techniques using online communication between LabVIEW and the MATLAB run-time engine for computation purpose. These calculated compensation values are then transferred to the machine controller via Ethernet. This paper also describes an example of application of such a system for a 5-axis CNC machine tool.

KEYWORDS: Machine tool structural monitoring system, Multi-sensor data acquisition system, Modular structure, LabVIEW

1. INTRODUCTION

The primary goal of the machine tool is to automate the cutting process to achieve higher accuracy to meet the greater quality requirements. Several factors play a crucial role such as machining conditions, cutting tool, type of workpiece etc. Various sources of error like shifting mass, component weight, temperature etc., hinder the possibility of achieving strict accuracy demands for the manufacturing process. Errors arise during building of the machine or occur over the time [1, 2]. Error reduction requires greater understanding of the machine tool capabilities and error sources. This results in the need for a machine tool structural monitoring system. Studies have been carried out on monitoring techniques that are based on the application of single or multiple sensors [3, 4]. Application of different sensors provides the ability to detect a wide range of system parameters like temperature, displacement, strain etc.

Sensor fusion culminates in a more holistic view of the process and in turn the state of the machine[4]. For example by observing the change in the strain of the structure with respect to variation in temperature provides the response of the system, which would be difficult to obtain by simply monitoring either strain or temperature; change in strain can derive from several causes while explicit prediction of distribution from temperature is a major challenge. Synergetic combination of data available from multiple sensors is called sensor fusion [5]. It can provide more reliable and accurate information. Varieties of techniques are used for sensor fusion such as Kalman filter, algebraic functions, weighted average, Bayesian estimation etc. [5, 6]. For high performance operational systems neural network [7, 8] and fuzzy logic [9, 10] techniques are applied for fusion purposes.

Developing data acquisition software (DAQ) for machine tool monitoring sensor fusion is a major challenge. At the moment, any commercial sensor in the market has either some application provided by manufacturer or open source software for capturing and/or analysing data. There is no general DAQ software available for this purpose. Software provided by manufacturers has restricted usage for research application. They often lack the flexibility and extensibilty required for research.

The motivation for this work came from a practical application for a modular machine tool structural monitoring and compensation system requiring the development of a multi-sensor data capture system. This DAQ system can capture data from several sensors like digital temperature sensor, laser position sensor and Fibre Bragg Grating (FBG) sensor for measuring temperature, displacement and strain respectively. Data can be logged in a format that can be used off-line by third party applications such as MATLAB or Microsoft Excel. Apart from these tasks, this application is programmed to implement compensation techniques during the process using parameteric models and artificial intelligence techniques such as Artificial Neural Network (ANN) and Adaptive Neuro Fuzzy Inference System (ANFIS). Obtained compensation values are then transferred to the machine controller using Ethernet.

The Objectives of this paper are to design a simple, reliable and flexible DAQ system, to implement this program to integrate different sensors and test the application on a real machine application.

2. SYSTEM OVERVIEW

In this paper a computer based on-line monitoring system has been developed. A block diagram of this system is as shown in fig. 1. The system hardware consists of a number of sensors and a computer. The system communicates with a CNC machine tool Siemens 840D interface. The Sensors used are:

The digital temperature sensors used are 1-wire protocol and have programmable resolution of 12 bit (0.0625^{O}C) with response time of 750ms. They have a temperature range of -55^{O}C to +125^{O}C. To communicate with a computer, it additionally requires an adapter either USB or serial port.

The laser position sensors used are Riftek RF603. They are used for measuring displacement. They work on the principle of laser triangulation and have a base distance of 10mm with measurement range of 2 mm. Resolution of this sensor is 0.01% of its measurement range. This sensor uses a serial port interface to communicate with the computer, which in some cases requires a RS232-USB converter.

The Fibre Bragg Grating (FBG) sensors are used for strain measurement purpose[11]. They are supplied by SMARTEC. They use Fabry-Perot Tuneable filter technology. Multiple FBG sensors are used in the wavelength range of 1510 to 1570 nm. FBG sensors have their own reading unit by Micron Optics, which can read at 2 Hz and has 4 optical channels expandable up to 16 channels. The reading unit communicates with the computer using the Ethernet protocol.

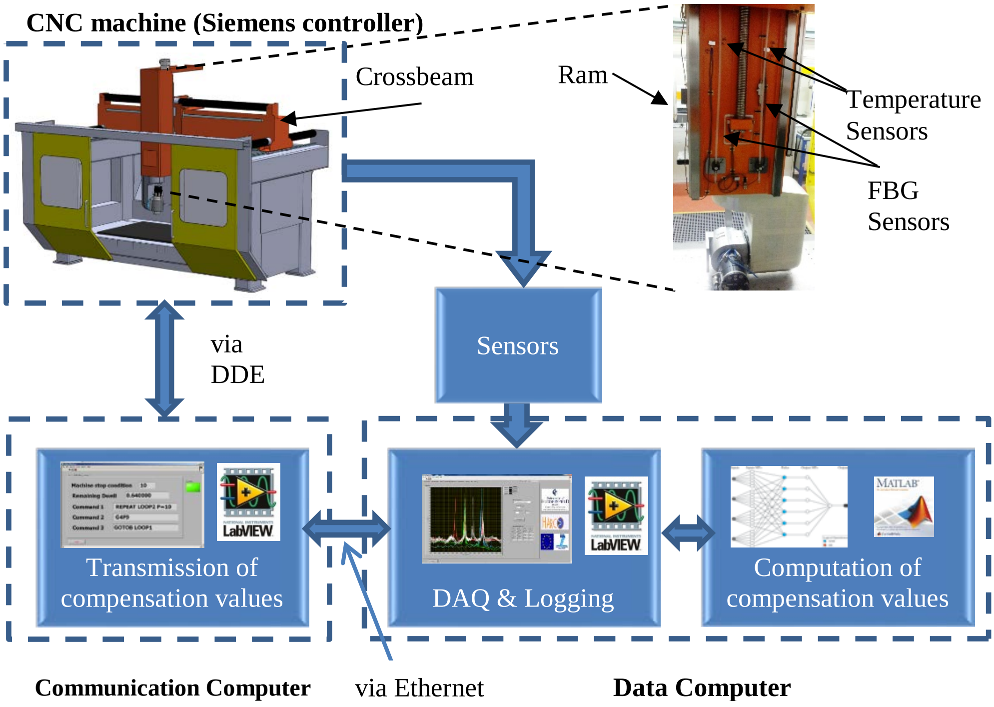

Fig. 1. System Overview

FBG sensors and temperature sensors can be used for structural monitoring of the machine tool for off-line and on-line research purposes. Strain values obtained from FBG and temperature values from temperature sensors can be captured and recorded over the desired time period. Logged data can be used for further off-line analysis purpose.

The software installed on the Data Computer (DC) performs all the major tasks like data acquisition, logging and processing. To make advanced on-line analysis and computation more efficient, the software includes a live interface with the MATLAB run time engine. This program computes the compensation values which are transferred to another LabVIEW program on the Communication Computer (CC). This communication is realized through the Ethernet protocol.

The Program on the CC uses a Dynamic Data Exchange (DDE) link to communicate with the machine controller via Ethernet. Finally compensation values are applied to the machining process by updating values in the part program. This rudimentary method of compensation is suitable for research purpose, but would be replaced by more robust methods in a commercial implementation.

3. SOFTWARE DESIGN

This section discusses the different criteria that were kept in the mind while designing the software. It also talks about the software architecture.

3.1. Design Criteria

The software was designed to provide a simple machine tool structural monitoring system for researchers using LabVIEW based multi sensor data acquisition program. Several aspects that were considered are mentioned as follows:

Usability: All the functions of the program can be performed under the required conditions reliably. Flexibility: It should be flexible enough to modify various parameters and configurations for different sensors. Reusability: Modules designed in this program should be able to be used by other programs without any modification or with trivial changes. Extensibilty: Additional features can be easily incorporated without any substantial alterations to the program structure. Cost-efficiency: Cost involved in the development and maintenance of the program should not be high.

Numerous factors need to be considered while selecting the programming language, such as programming skills of the developer, availability of the drivers for various sensors, time required for the development of the program, parallel programming capability, ease of debugging etc., [12, 13] Considering the above mentioned factors and due to the several other advantages of LabVIEW over other text based languages, it was selected for developing a data acquisition program [14, 15].

3.2. Software structure

For any software, well designed architecture is crucial for its success. This program was designed in a modular fashion to offer independent as well as interconnected control of various signals and the three tier structure was implemented for the development.

The top layer consists of graphical user interface developed using a LabVIEW user interface control. The low level tier is designed for the communication by means of hardware drivers and LabVIEW I/O commands to send and receive data from sensors and hardware devices. The middle tier connects top and bottom layer and provides platform for the development. It performs many tasks and is made up of some of the core modules: FBG Module, Temperature sensor module, laser position sensor module, Controller communication, LabVIEW and MATLAB online communication, data logging and error handling module. Each of these key modules are discussed in detail in later sections. All the principle modules are programmed in independent loops to improve the reusability of the program. The three tier structure is as shown in the fig.2.

A modular structure in the software allows integration of new types of sensors or additional sensors without making considerable modifications to the system architecture to easily achieve the desired extensibilty. Apart from sensors, extensibility permits the addition of new features in the software as per the requirement in the later stages of research.

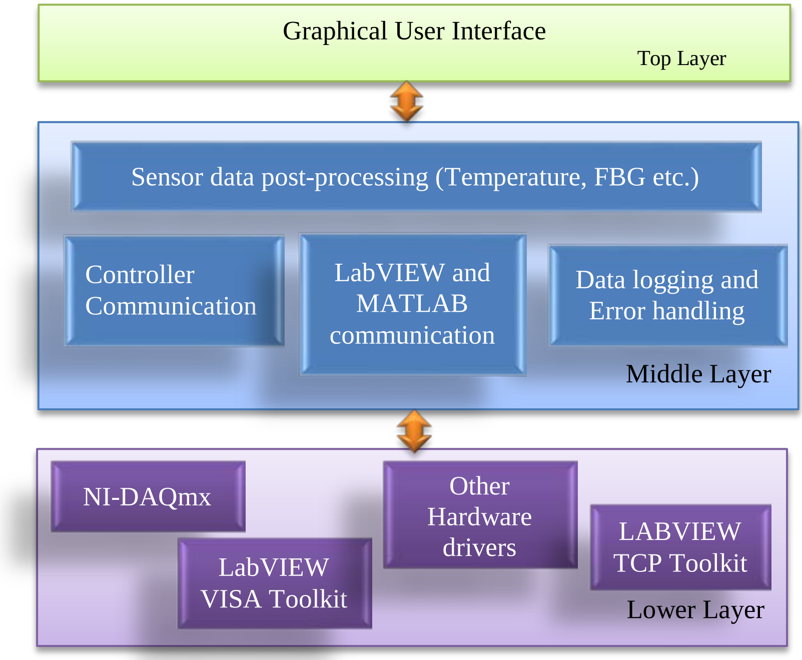

Fig. 2. Three tier structure of the program

3.3. Data acquisition process.

A typical data acquisition process is as illustrated in Fig. 3. The system is first initialised to establish a communication between computer and different sensors. In the second step, depending on the type of the sensor, the program either reads the raw data or sends configuration command. For example, in case of laser position sensor, it reads the raw data; for temperature sensor, a convert command is sent for temperature conversion and for FBG sensors, channels are configured. Subsequent steps in the flowchart are based on the parameters set by the user. Data acquisition process is started from capturing the data form the sensors. Sampling rate of each type of sensor can be controlled individually. Raw data is processed to obtain engineering values before displaying it and saving it to a file if required. After data is read from all the configured sensors, program completes the acquisition operation.

4. IMPLEMENTATION OF MAIN MODULES

4.1. Sensor data acquisition Module

Different modules are created for different sensors to maintain the modularity of the structure. Software Development kit (SDK) for programming these sensors is provided by their manufacturers. These SDK’s contain sample LabVIEW sub-VIs (Virtual Instrument) and drivers necessary to perform fundamental operations.

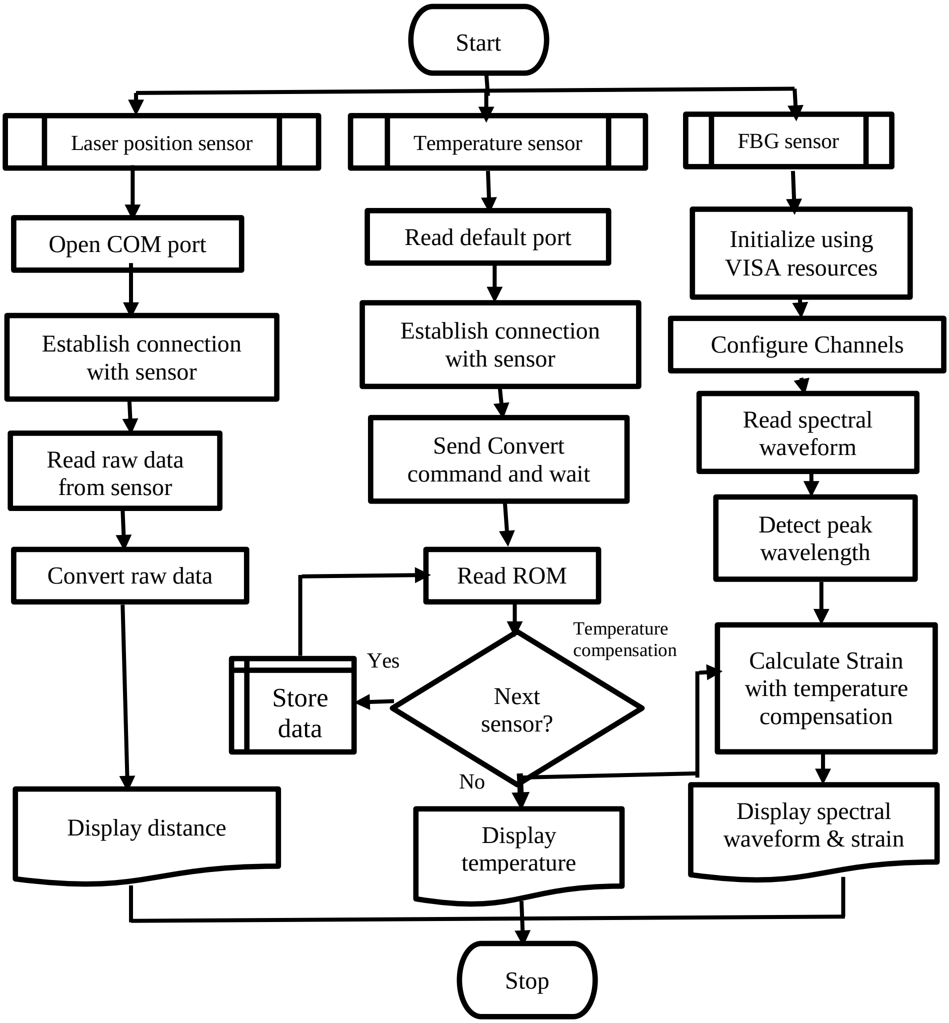

Fig. 3. Flowchart for data acquisition system

4.2. LabVIEW and MATLAB interface module

This LabVIEW DAQ program is designed to implement various machine tool error compensation algorithms based on ANFIS, ANN and physical models. Modelling, training and analysis of these compensation techniques was carried out in MATLAB. Due to this many complex inherent functions of the MATLAB were utilized during the design phase. It was observed that direct conversion of MATLAB code into the LabVIEW was time consuming and prone to error during translation which potentially could generate different output for the same input. Thus an interface between LabVIEW and MATLAB was used to simplify the adoption of off-line optimised model with reduced uncertainties that would be involved in the code conversion.

This interface was achieved using LabVIEW's MATLAB Script module. It uses Microsoft ActiveX technology for communication. Thus .m file generated by MATLAB can be directly imported into the LabVIEW eliminating the need for code conversion. Some of the off-line models such as ANFIS generate files in ".fis" format. Such a files can be called in the LabVIEW code without any recompilation.

Data captured from various sensors by LabVIEW is passed in the MATLAB Script code containing compensation model, which in turn generates the corresponding output. This output is returned backed to LabVIEW which is passed to the machine controller.

4.3. Controller communication module

The purpose of this module is to establish a bi-directional communication between the machine tool controller and the CC. This communication link is established in two steps. In the first step calculated compensation value is transferred from the DC to CC using Ethernet. Standard TCP (Transmission Control Protocol) toolkit is used for this purpose. In the second step the DDE link using Ethernet is used to communicate with the controller. These compensation values are then used to modify the parameters in the controller which are subsequently used by the CNC code to modify the values of Machine Co-ordinate System (MCS) during the machining process. MCS values can be transferred from the controller back to the LabVIEW program for analysis.

4.4. Data logging module

Data captured from all the sensors as well as MCS values with absolute time can be logged using this module. This is achieved with the help of LabVIEW file I/O functions. Data is saved in ".CSV" (comma separated values) format. This format was chosen because it can be easily imported in other applications for further analysis purpose. Data logging time is programmable.

5. DEMONSTRATION OF THE SOFTWARE

5.1. Program overview

In this section a brief introduction to the developed LabVIEW program is provided. Screenshots of the front panel of the software are illustrated in Fig. 5. For each individual module such as for different sensors, compensation, communication and data logging separate tab is created. This way modularity of the structure is maintained in the front panel as well.

The front user interface contains 7 key segments: FBG spectrum, strain, temperature, laser sensor, compensation, communication and data log. Various configuration settings and sampling time for each type of sensor is programmable. Data for each sensor can be plotted live. Different compensation models can be configured as per the required parameters and their output can be plotted and observed in continuous manner.

5.2. Example of the software application

In this section three brief examples of the software application are mentioned. In the first two examples tests were performed on a 5-axis Geiss machine tool. Third example discusses about the performance evaluation test of the laser tracker (LT).

Test 1 was performed for the period of 14 days and machine was not in operation during this period. The purpose of this test was to monitor the thermal response of the crossbeam structure of the machine tool with change in environmental temperature. FBG sensors were mounted on the crossbeam structure (refer fig 1) with digital temperature sensor to observe the thermal response. Data for all the sensors was logged every minute. All the measured data was used for the post analysis purpose. Test result is shown in fig. 4.

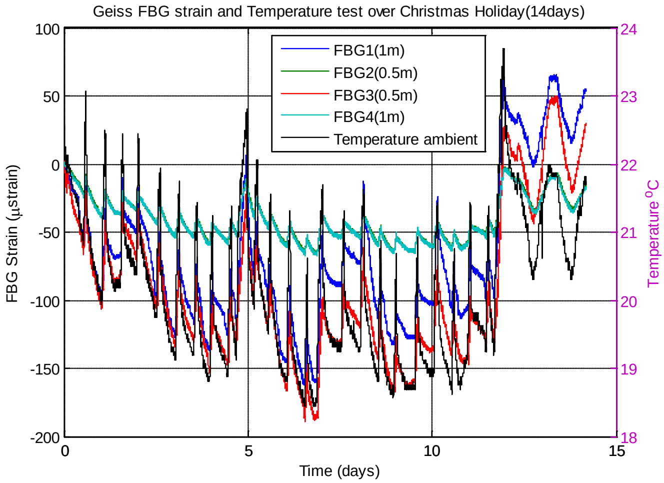

Fig. 4 Test results for environmental thermal response of crossbeam

The primary motive of the 2nd test was to observe the deformation taking place in the ram of the machine along the Z-axis direction due to the heating of the C-axis motor during prolonged operation and to compensate it during the running process itself.

FBG sensors were mounted on each side of the ram structure (refer fig 1). Output of the FBG sensors was used by the ANFIS compensation model. Calculated compensation values were used to modify the CNC code to maintain the position of the ram. Laser position sensors were used for the validation purpose. Data for all the sensors was logged at every 1 second. On-line screenshots of the output of the compensation model and laser sensor are shown in fig 5 and test results are shown in fig 6. Residual error in the range of 10 µm was observed during the test.

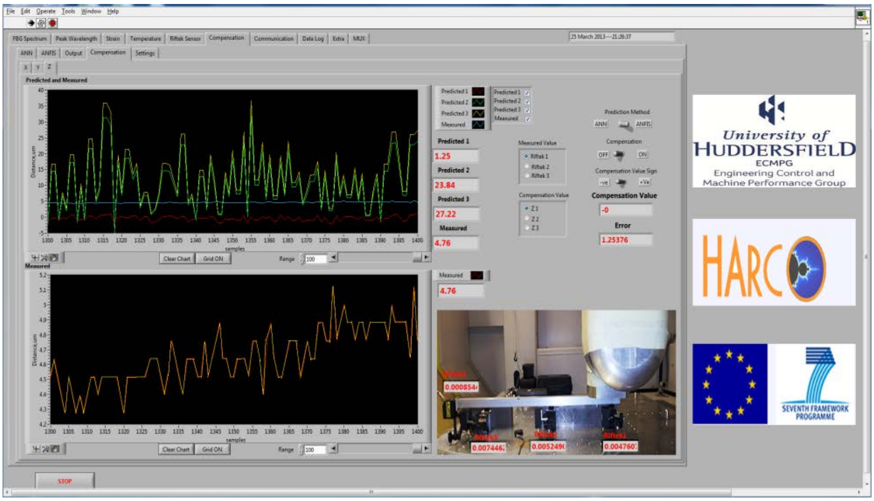

Fig. 5 Compensation model output during the operation

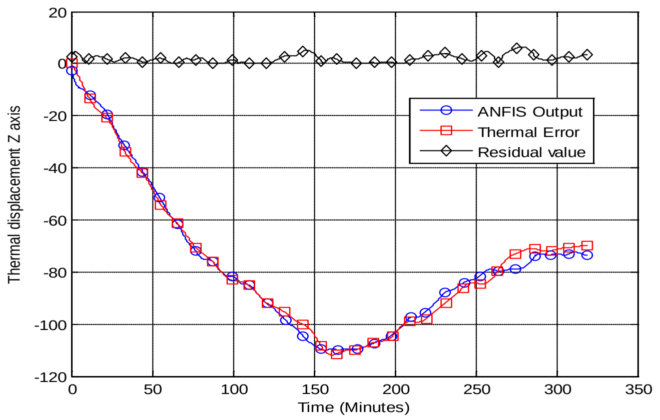

Fig. 6. Test Results for thermal displacement of Z-axis

In the third example only temperature measurement module of the software was used for performance evolution of the laser tracker. This test was carried out for the period of 14 hours and data was logged at every 25 sec. Data acquisition for temperature and LT was carried out using different softwares. Fig 7 illustrates test results showing effect of temperature variation on reparability of LT.

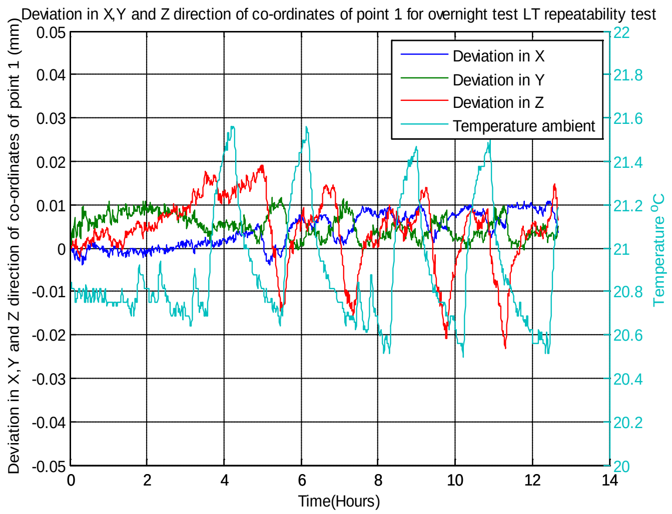

Fig. 7. Test results for thermal response of laser tracker

In addition this software was used for several other similar tests for structural monitoring of the Geiss machine tool. As this program can be used for data acquisition from various types of sensors, it has wide range of applications.

6. CONCLUSION

Using the LabVIEW environment a machine tool structural monitoring application was developed, offering researchers the prospect of using computer based data processing to expedite the development path. This program was created in the modular structure to provide user friendly software and to allow desired flexibility and extensibility. Various modules prepared in this program can be easily used for other applications with minimal or no alterations.

This paper also describes an example of application of such a system for data monitoring, logging, control model calculation and communication for compensation values for a 5-axis CNC machine tool. The system is now being used to facilitate data fusion and assist with improving performance of the machining. The extensibility of the design is of paramount importance to efficient development.

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