A Modular, Multiple Sensor Embedded System CMM Motion Controller

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Abstract

This paper describes design, development, and implementation of an embedded system style CMM controller. A single Intel Pentium microprocessor performs all functions including real time motion control. Boot up is via a solid state IDE flash disk to the Phar Lap ETS real time, multi-threaded operating system. An FTP server is always active. Hence configuration parameters, and even the main executable, can quickly be replaced. Setup is performed using a special GUI program that is executed on a notebook computer attached via 100BaseTX Ethernet. Graphing of commanded and actual position, commanded velocity, etc. is available in real time. Tuning parameters can be changed and their effect observed on the fly.

A significant issue with new sensors is combining the CMM structure error compensation with that of the sensor. Experience with this combination is reported for a Hymarc laser digitizer. The CMM structure was equipped with thermocouples on each axis, the granite table, and the probe mount. Error compensation tables were then created at 20, 25, and 30 degrees Celsius. A special ball bar, with optically diffuse coatings on the spheres, was then located at the 20 ASME B89.4.1-1997 positions to evaluate the combined CMM structure and laser digitizer error compensation transformations. An average 75 percent reduction in ball bar length dispersion was obtained.

Keywords: Motion control; Embedded system; Laser digitizer; Error compensation

1. Introduction

A background of CMM technology is described in [1]. For a bridge style CMM, the main components include the granite table, the moving bridge and related structure, and a linear scale encoder system. Conventionally, a touch trigger probe is used to measure the part surface. When the probe touches the part, it deflects and opens an electrical switch. This latches the scale position within an integrated circuit counter. The CMM control computer adds any probe and geometric error compensation [2], and transmits the measured data to a higher level metrology software computer. For a Direct Computer Controlled (DCC) machine, electric motors and associated drive components are added so that, additionally, motion can be commanded from the metrology software. The metrology software provided by the CMM vendor is proprietary, and typically not portable. Support for new sensors requires significant upgrade to the CMM control, possibly including total replacement. This situation is awkward for the CMM owner, and hinders rapid and cost effective adoption of emerging measurement technologies.

To address these issues, the industry is again moving towards widespread adoption of the Dimensional Measuring Interface Standard (DMIS) [3] to interface Computer Aided Design (CAD) software with the CMM metrology software. The I++ proposal [4] is intended to provide a standard interface protocol between the metrology software and the CMM controller. For sensors, the Optical Sensor Interface Specification (OSIS) [5] is being developed. To meet these new requirements, it is neither economically sensible nor environmentally appropriate to replace a working machine. Instead, a CMM controller upgrade solution compatible with legacy applications but extensible to support new software and sensors is preferred.

The concept of open architecture control is well established, particularly for Computer Numerical Control (CNC) of machine tools [6]. Research implementations for CMMs include the NIST Enhanced Machine Controller, which can be programmed using DMIS [7]. Industrial aftermarket CMM controllers include the Renishaw UCC1 [8]. The Next Generation Inspection Systems (NGIS) project included specification of a Sensor Interface Module (SIM) and Application Programming Interface (API) for CMM sensors [9], but has not been widely adopted.

Omni-Tech Corporation offers the OTC5000 controller, and to date approximately 100 units of this product have been commercially installed. In conjunction with McMaster University, the second generation controller design has been developed and implemented. A description of this work is the subject of the remainder of the paper.

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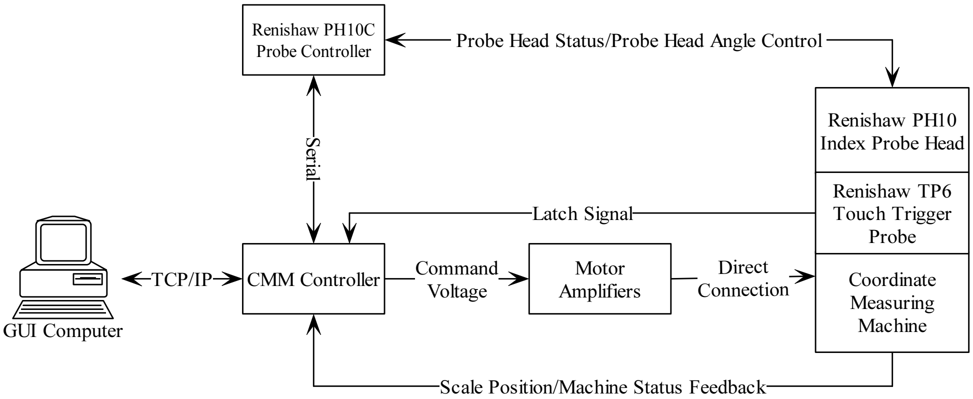
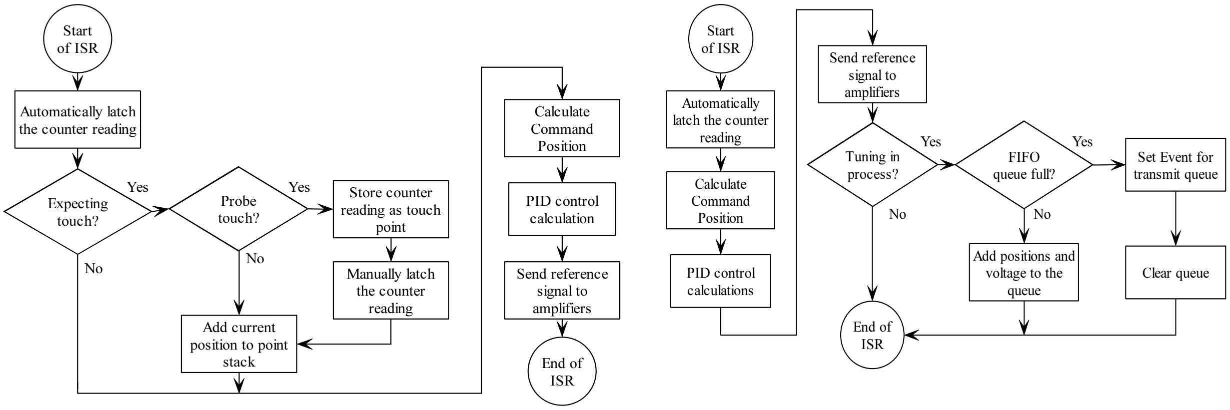


Fig. 1. CMM touch probe system architecture. The touch trigger probe architecture is shown. For an analog probe, the TP6 is replaced by an SP600 and a multiwire cable leads back to an AC2 interface card at the controller.



(a) (b)

Fig. 2. CMM software ISR flowcharts: (a) normal touch trigger probe operation; (b) motion control tuning.

2. System Architecture

2.1. Hardware

An overall system architecture schematic for the CMM controller is shown in Fig. 1. The CMM used for the initial implementation was a DEA IOTA 1102 with a Z on Y on X on granite table moving bridge configuration. Each axis is driven by pulse width modulated (PWM) amplifiers, rotary DC motors, and rack and pinion gearing. Motion control velocity feedback is provided by tachogenerators, and Renishaw RGH22 linear scales are used for one micrometer resolution position feedback. The touch trigger probe is a Renishaw TP6A mounted on a PH10M probe head. An SP600M analog probe with AC2 interface card [10] can be substituted. Non-contact laser digitizer interfacing is discussed below. A 133 MHz Intel Pentium I standard ISA/PCI motherboard with 64MB RAM was used. To avoid failure due to shock of vibration, a 16 MB IDE compatible flash disk is used for non-volatile storage. Because the controller is intended for used as an embedded system, RS-232 serial and 100BaseTX Ethernet are used for communication with the metrology interface computer. To simplify installation and remote maintenance, firmware upgrades are made using TCP/IP File Transfer Protocol (FTP).

Electrical interface to the CMM is via an 8 axis motion interface card [11]. This card provides 24 bit axis counters (extended to 32 bits in software), 13 bit analog to digital (A/D) input and digital to analog (D/A) output, as well as 32 bits of general TTL level input/output (I/O). The CMM linear scales are connected to the counters, the manual control joysticks are connected to the A/D inputs, and the motor amplifiers are driven by the D/A outputs. Additional multiplexing and buffering electronics connect the TTL I/O to limit switches, manual pushbutton switches, compressed air solenoid and pressure switch, etc. Probe debounce is implemented by connecting the normally closed switch touch trigger switch to an edge triggered D flip-flop that is in turn connected to the axis counter latch input. When trigger switch opens, the flip-flop output changes state. Time latency is negligible. To ensure that only the initial probe contact position is latched, a software re-arming of the flip-flop is required. For

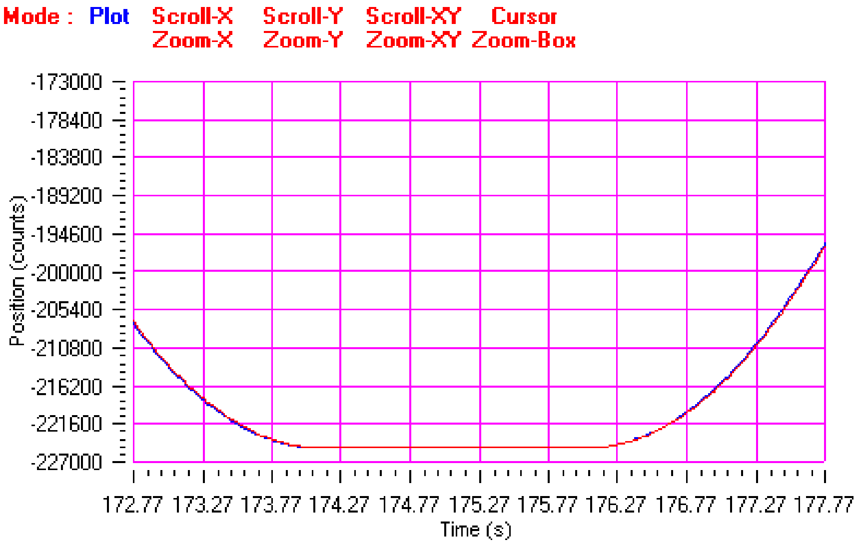


Fig. 3. X-axis tuning strip chart.

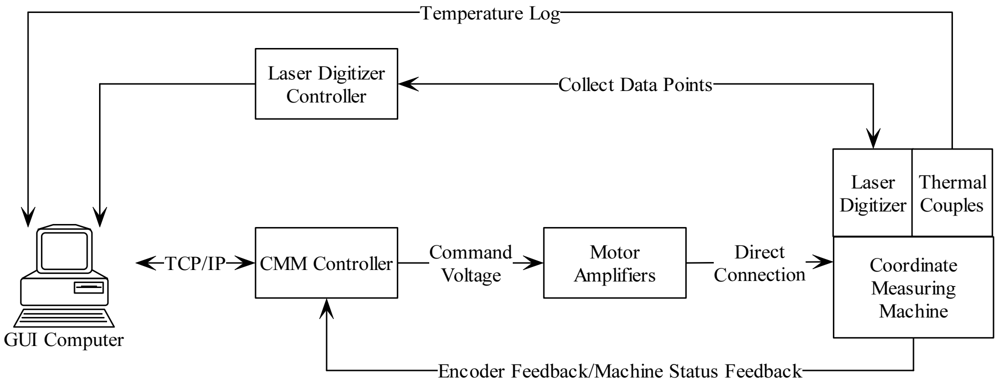


Fig. 4. CMM non-contact laser digitizer system architecture.

the analog probe, the analog deflection voltages are transmitted over a multiwire cable connected to a Renishaw AC2 A/D conversion card. The axis scale counters are latched and combined with the analog deflection voltages to obtain the actual part surface coordinates. For elevated temperature compensation, 11 type-E thermocouples were used. One thermocouple was attached to the granite table, one to the probe head, and 3 to each linear scale.

2.2. Software

The CMM controller software is based on the VenturCom Phar Lap ETS real time operating system [12]. After power up, the computer boots the ETS operating system from the flash disk, and then runs the CMM specific executable. An FTP server is included so that implementation specific startup parameters, motion tuning information, geometric error compensation tables, and even the executable itself can be updated by simply uploading the replacement file and rebooting. Separate execution threads handle RS-232 serial and TCP/IP Ethernet communication, probe and joystick monitoring, FTP commands, etc. Real time motion control uses interrupts generated by an 800 microsecond timer. As a safety precaution, a “watch dog” timer is included. Should the Interrupt Service Routine fail to reset the timer, the D/A outputs to the motor amplifiers are automatically set to zero volts.

The main program thread receives the OTC5000 [13] language command. Motion command profiles are pre-calculated just prior to real time execution. For a single point to point position move, a trapezoidal velocity profile is calculated. For joystick input, a velocity move with constant acceleration is used. Multi-point (DMIS GOTARG) contouring moves include constant acceleration at all interior corner points. Fig. 2(a) shows a condensed flowchart of normal touch trigger probe operation. Unless a touch is expected, the hardware automatically latches the counters when the interrupt occurs. If the controller is expecting a touch, it will latch the counters in real time when the touch actually occurs. To maintain consistent sample time spacing, the counters are again latched in software before the motion control algorithm is executed.

For each axis, a conventional Proportional-Integral-Derivative (PID) control law, with velocity and acceleration feed forward, is used to execute the real time motion. At the end of the ISR sample period n, the controller executes the PID update equation

$$O_n = K_R(K_p E_n + K_d(E_n - E_{n-1}) + K_i S_n + K_v V_n + 64 K_a A_n) + K_o$$

where

O_n	is the motor control output voltage	K_R	is the overall scale factor ($K_R = 2^{\text{shift}}$)
K_p	is the proportional gain	K_i	is the integral gain
K_d	is the derivative gain	K_v	is the velocity feed forward
K_a	is the acceleration feed forward	K_o	is the static offset
E_n	is the position error	V_n	is the command velocity
A_n	is the command acceleration ($*2^{-6}$)	S_n	is the integrated error,
		$S_{\max}$	is the maximum integrated error

$$S_n = \begin{cases} S_{n-1} + E_n & \text{if } \; -S_{\max} < S_n < S_{\max} \\ S_{\max} & \text{if } \quad S_n > S_{\max} \\ -S_{\max} & \text{if } \quad S_n < -S_{\max} \end{cases}$$

During joystick operation, the A/D inputs are polled, and motion occurs using the same PID method. This allows consistent choice of velocity and acceleration parameters for both joystick and DCC control. As well, geometric error compensation is included.

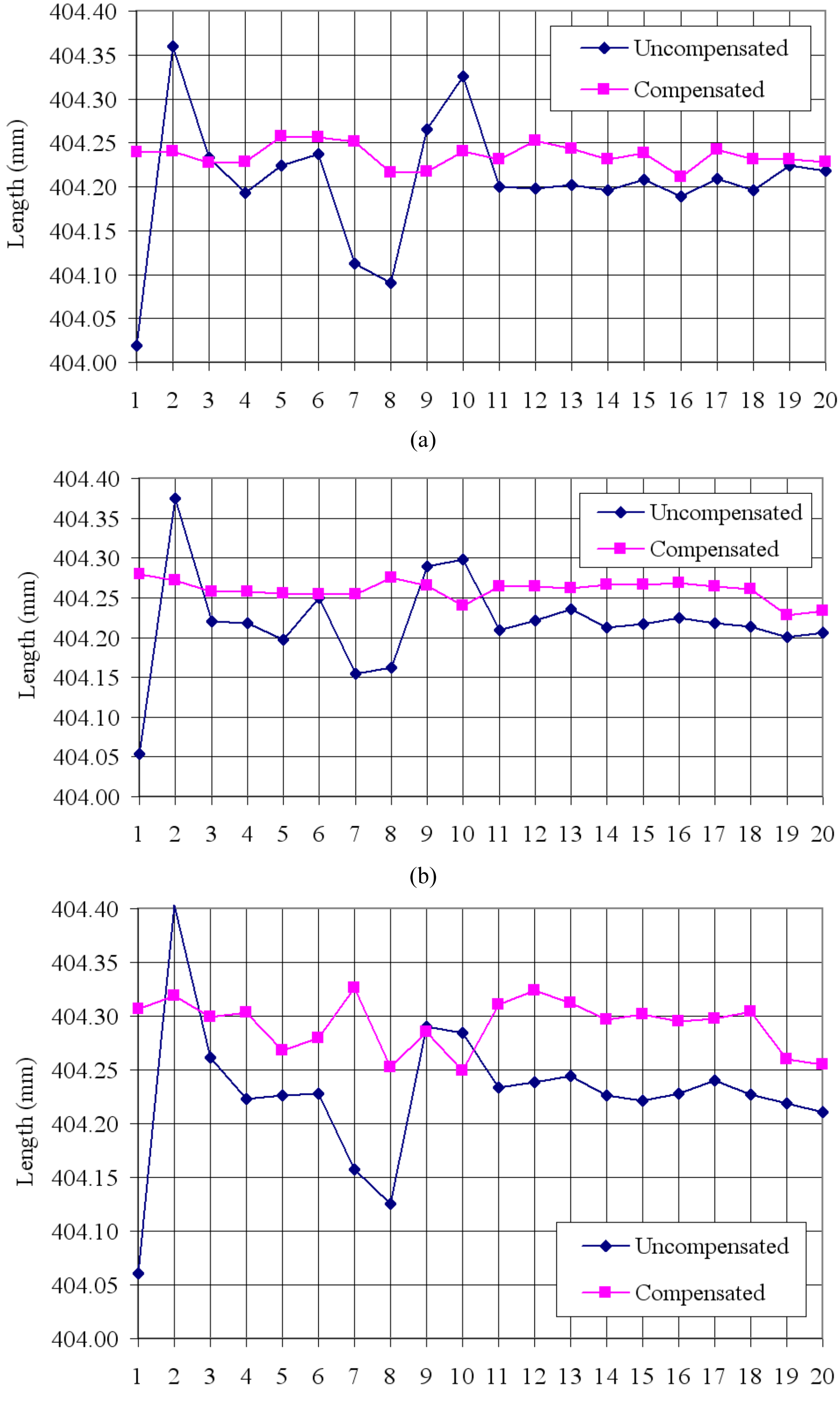
2.3. Motion Control Tuning

A key new feature of the CMM controller is a remote graphical interface for motion control tuning. The 100BaseTX Ethernet is connected from the controller to a remote computer that executes a special Microsoft VisualBASIC setup program. This program begins a back and forth motion on the selected CMM axis, and in real time the controller returns samples of the commanded position, actual position, and servo voltage. Samples are held in a First In First Out (FIFO) queue (Fig. 2(b)) and, to reduce communications overhead, are transmitted to the setup computer in groups of 5. For a 133 MHz Pentium, this task consumed less that 15 percent of the available processing time. The setup program plots the received samples as a strip chart (Fig. 3) [14], and the service engineer can instantly update the PID tuning parameters until the desired performance is obtained. Other capabilities of the setup program include CMM homing, digital readout and joystick operation, switch status information, and editing of geometric error compensation data.

2.4. Optical Probe Integration

A Hymarc Hyscan 45C [15] was used as the laser digitizer. It independently obtains linear scale coordinates using optoisolation electronics (Fig. 4). This situation is typical of new sensors in that the laser digitizer manufacturer and CMM manufacturer are two independent companies. As a rule, the CMM manufacturer geometric error compensation table is unavailable to the laser digitizer manufacturer. These digitizers are often used in less environmentally controlled surroundings, and hence temperature influence is significant.

To investigate the potential improvements that can be achieved by integrating the error compensation information, the CMM was error mapped for linear and squareness errors at 20, 25, and 30 degrees Celsius using a laser interferometer and conventional touch probed ball bar. The laser digitizer was then mounted on the CMM. A special ball bar was constructed by replacing the usual touch probed spheres with optically diffuse 76.25 mm diameter spheres, spaced approximately 404 mm apart. To emphasize the XY squareness correction, an error of 170 arc seconds was deliberately retained in the mechanical setup of the bridge. Plots of the uncompensated and compensated ball bar lengths for the 20 ASME B89.4.1-1997 locations ([16], Fig. 26) are shown in Fig. 5. The ball bar length dispersion was reduced by 82 percent (20 deg C), 79 percent (25 deg C), and 63 percent (30 deg C).



(a)

(b)

(c)

Fig. 5. Optical ball bar uncompensated and compensated lengths. Positions 1-20 correspond to [16], Fig. 26. (a) 20 deg C; (b) 25 deg C; (c) 30 deg C

2.5. Communication Standards

As new international communication standards are adopted, the control can be adapted without major revision. For example, I++ is supported by implementing a special TCP/IP bridge program on the metrology computer that converts I++ commands to/from the OTC5000 command language that the controller communicates with. This avoids the need to update the controller firmware. Interim support for OSIS can be implemented in a similar way.

3. Conclusions

This paper has described a new, embedded system style CMM controller. The unit uses a single Intel Pentium microprocessor for all functions including real-time motion control. The firmware is stored on flash disk, and is easily replaced using FTP. Setup, including real-time motion control tuning, is performed using 100BaseTX Ethernet, and a special GUI program that executes on a remote notebook computer. The controller is easily extended to support new analog touch and laser non-contact probes. Integration of CMM structure and laser digitizer geometric error compensation includes thermocouple based temperature compensation, and was evaluated using the ASME B89.4.1-1997 test with a special optically coated sphere ball bar. On average, a 75 percent reduction in ball bar length dispersion was attained.

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