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BIMPLEMENTATION OF PC-BASED CONTROL ON A MODULAR OD/ID GRINDING MACHINE WITH AIR BEARINGS PRELOADED BY INCLINED IRON CORE LINEAR ELECTRIC MOTOR

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Abstract. A fundamentally precise, simple-to-manufacture, and modular grinding machine is presented where the core catalysts for rapid design and manufacture, the entire process took only 6 months, are preloading air bearings with linear motor magnets, and controlling the machine with a simple PC-Based control system. Customizing the control for the kinematics of the machine, as well as tuning the motors to optimize overall system performance, were done with relative ease and precision. The electronics of the machine were designed to be of 'plug and play' type, complimentary to the simple and easy to use PC control architecture. Grinding tests indicate that parts can be ground significantly faster and with better accuracy than conventional machines. This indicates that modular PC-based control can enable a precision machine tool to be created for a very low controller cost.

Keywords: PC Control, open architecture, CNC, grinding, linear motor, air bearings, preload

1. Introduction

Computer numerical controls (CNCs) are extensively used in today's machine tools. The advent of the PC and its introduction into the machine tool controls segment has provided the base for a robust, inexpensive, and reliable precision machine control. With advances in tooling materials such as carbide, diamond, cubic boron nitride, material removal rates have dramatically increased. This has made machine tool performance, in particular stiffness and motion control accuracy, the limiting factor in the exploitation of higher cutting speeds. Current CNC control technology is based on low to medium bandwidth motion of the de-coupled system. The coupled linear motor drive / air bearing system shown in Figures (1) & (2) of the new Overbeck® ID/OD grinder is complementary to the notion of higher federates and will require the use of a high bandwidth controller.

Figure 1 Overbeck® ID/OD grinding machine with PC-Based control..

A pair of orthogonal planes is a very accurate and low cost geometry that can be used to guide linear motion (Slocum, Basaran, Cortesi). By placing the motor at a desired position and angle with respect to the air bearing pads, a desired distribution of preload forces can be obtained on the pads; hence when a new machine is designed, the preload can compensate for large static weight distributions. Because the attractive forces are typically 5 times the axial force from the motor, the system is inherently stable even in the presence of externally applied forces and moments. An advantage of this type of design is that it can be rapidly assembled from modular components.

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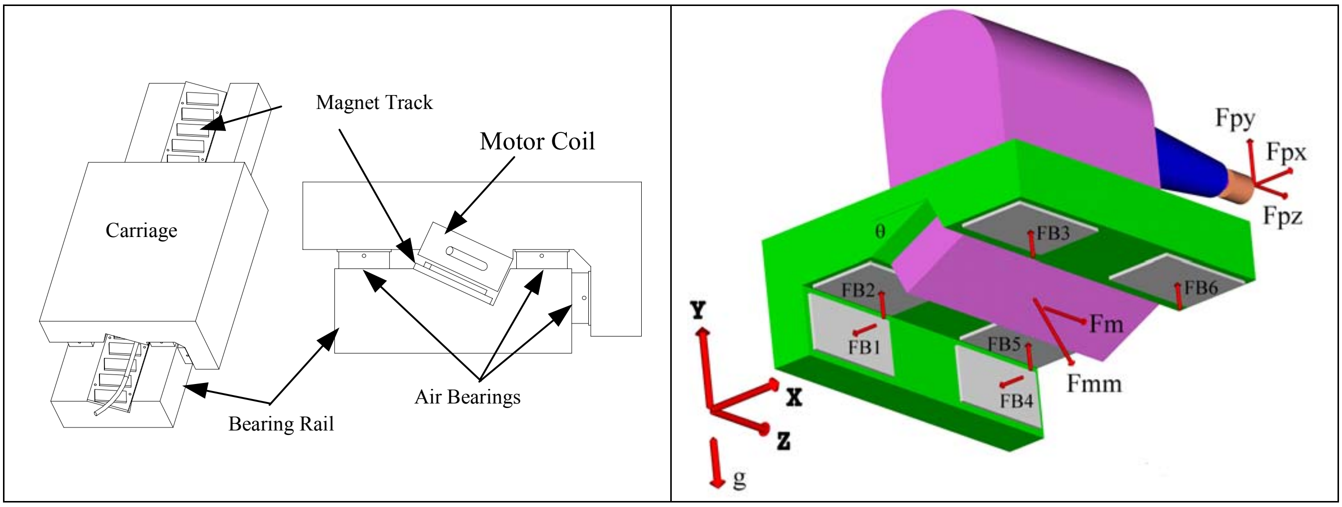

Figure 2 Air bearing carriage preloaded by an inclined linear motor.

2. Benefits of a PC-Based controller

In following with the concept of modularity and simplicity of design, A PC-based CNC controller was chosen. This was provided by MachineMate® CNC Controls. When choosing a control system, it is important to keep in mind the following overall objectives:

- Will it handle the degree of precision that is necessary?
- What reliability issues will be present?
- What operating, maintenance costs are involved?
- How modular/upgradeable is it?
- What other limitations are there?

Given the dynamics of our system, as calculated in Figure (3) , and its error budget, a 0.1µm resolution encoder is an ideal choice for feedback precision. However a higher resolution encoder, which may be computationally feasible by the CNC, can be a limiting factor for the servo drive, because the internal scan rate of the servo amplifiers may not operate at a high enough frequency. Figure (4) shows the functional components of the PC-CNC in block diagram form. Running on a Windows 2000 operating system, which is heavily based on the long-running and stable NT operating system, instability issues with the CNC have not arisen. The price/performance ratio of such a PC-Based system surpasses that of current CNCs.

Maintenance of such a PC based system is identical to that of a standard Desktop PC. With a familiar windows user interface, operator training and overall learning curve is quite short. In addition, with a PC based controller, all of the machine parameter files and PLC are in separate files. When upgrading the hardware, all that is necessary to restore the original operating condition is to copy these parameter files to the new PC. Creating backups of all part programs, parameters, PLC ladder diagrams is very straightforward, and can be saved on a network. For multiple machine tool monitoring, several PC controls can be linked together on a wireless network, and through the use of Dynamic Data Exchange (DDE), a continuous flow of information can flow into a single server-type computer. This is especially useful for gathering machine data, from temperature to cycle times, and error frequency. These are perfect examples of exploiting the full functionality of the windows operating system environment.

Deflections at Process Point (microns, microradians)				
	Process only	Mass, Accel.	Angular	
δx	0.466	-0.12	Pitch (ε_x)	0.001
δy	0.242	-1.00	Yaw (ε_y)	-0.001
δz	-0.12	0.07	Roll (ε_Z)	-0.002

Results of Bearing Force and Deflection analysis											
All Loads				Preload only				Process Forces only			
Forces (N)		Defl. (microns)		Forces (N)		Defl. (microns)		Forces (N)		Defl. (microns)	
FB1	960	δ1	-5.04	FB1	950	δ1	-4.99	FB1	-5	δ1	0.03
FB2	833	δ2	-9.85	FB2	780	δ2	-9.22	FB2	-13	δ2	0.15
FB3	948	δ3	-11.21	FB3	865	δ3	-10.22	FB3	17	δ3	-0.20
FB4	960	δ4	-5.04	FB4	950	δ4	-4.99	FB4	25	δ4	-0.13
FB5	834	δ5	-9.86	FB5	780	δ5	-9.22	FB5	-27	δ5	0.32
FB6	949	δ6	-11.22	FB6	865	δ6	-10.22	FB6	3	δ6	-0.04
Fm	27	dservo	-0.05	Fm	0	dservo	0.00	Fm	-2	dservo	0.00

Location of Pitch, Yaw, Roll Axis					
Pitch Axis		Yaw Axis		Roll Axis	
		Xya	50	Xra	175
Ypa	175			Yra	175
Zpa	0	Zya	0		

Deflections (microns, microradians) at approximate center of stiffness											
Mass, Acceleration, Process				Preload Only				Process Only			
δx	0.05	Pitch (ε_x)	0.000	δx	4.990	Pitch (ε_x)	0.000	δx	0.053	Pitch (ε_x)	0.001
δy	-0.81	Yaw (ε_y)	0.000	δy	-9.723	Yaw (ε_y)	0.000	δy	0.059	Yaw (ε_y)	-0.001
δz	-0.05	Roll (ε_Z)	-0.002	δz	0.00	Roll (ε_Z)	-0.007	δz	0.00	Roll (ε_Z)	-0.002

Figure. 3 Motor-preloaded-bearing Design Spreadsheet Outputs

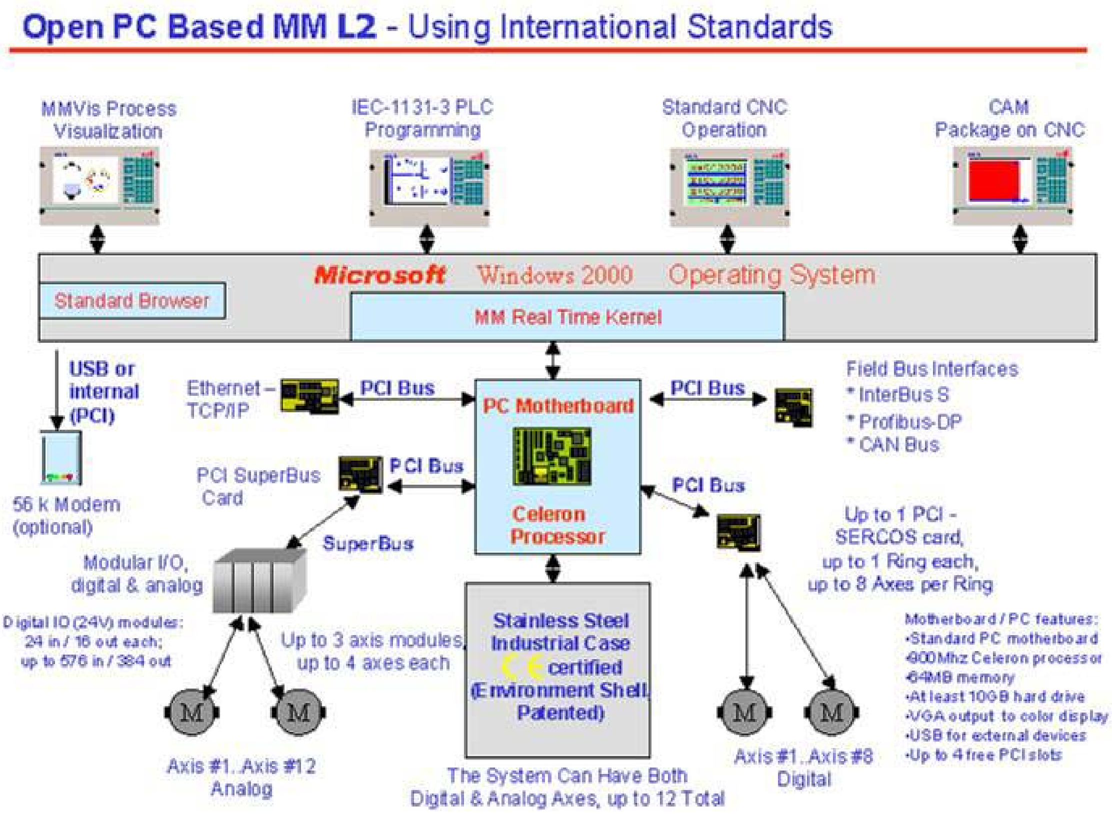

Figure 4. PC-Based CNC Architecture (MachineMate® PC-Based CNC Controls)

3 IMPLEMENTING THE PC-BASED CNC

Overall implementation is fairly straightforward. Our PC CNC was equipped a SERCOS fiber optic axis card with 8 axis capabilities per ring. SERCOS was chosen over the conventional +/-10V analog system due to the nature of the control architecture as well as the excellent noise immunity qualities it offers. The difference in control architecture is straightforward; SERCOS is a high speed (up to 8Mbps) communication protocol used to communicate in real time between the PC and the servo drive amplifiers. On a SERCOS drive, position commands are sent from the PC and 100% of the PID control algorithm processing is computed directly on the servo drive itself, and position, machine status, and other information are relayed back to the PC.

As with any control system, calculating and experimenting with gain values is crucial for overall system performance. This next section will discuss the velocity and position gains, which were modified through the servo amplifier's tuning software. Figure (5) shows a simplified model of our system in block diagram format.

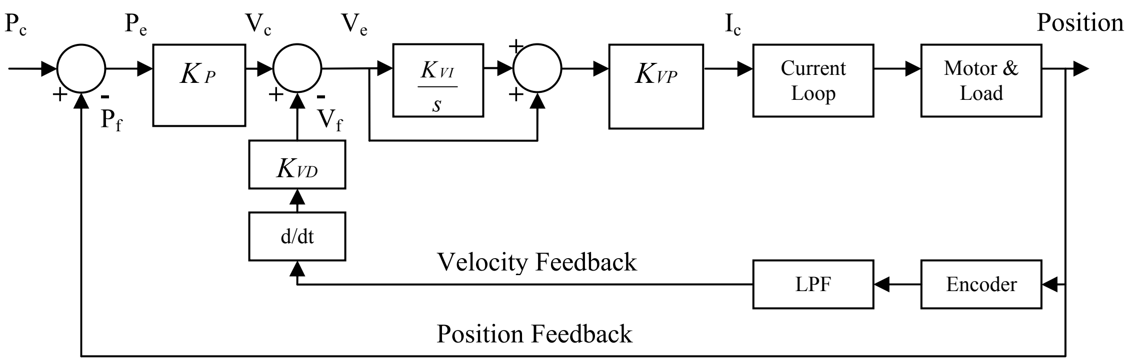

Figure 5. A simplified block diagram of cascaded position-velocity loops.

3. 1 TUNING OF THE VELOCITY LOOP

Three velocity gains are present in the system, K_{VP} K_{VI} $K_{VD,}$ proportional, integral, and derivative respectively. Tuning of the velocity loop was done through tuning software provided by the manufacturer. Since our design takes advantage of low-friction air bearings and linear brushless servo motors, it is not a surprise that our system will have a unique and perhaps extraordinary set of Proportional, Integral, and Derivative gain values[2]. A common method for calculating a rough estimate of PID values is the Ziegler Nichols method. The Closed Loop method determines the gain at which a loop with proportional only control will oscillate, and then derives the controller gain, reset, and derivative values from the gain at which the oscillations are sustained and the period of oscillation at that gain.

This method should produce tuning parameters which will obtain quarter wave decay. This is considered good tuning but is not necessarily optimum tuning. However, tuning of the velocity loop, in our system, was done by obtaining estimate gain values by running the auto-tune feature and experimentally determining the most stable condition by decreasing or increasing the respective PID values.

To decrease the audible noise to a comfortable level, setting the low-pass filter (LPF) to 75Hz eliminates any noise, which tends to be high frequency, or disturbances that may be contaminating the control system. It must be noted that lowering the low-pass filter frequency will cut off the bandwidth to the control. However, since noise tends to be of high frequency, we can safely implement at 75Hz LPF.

3.2 TUNING OF THE POSITION LOOP

With a properly tuned velocity loop, the final step was to set the gain parameters for the K_P, K_{ff}, K_D, K_I, and K_I zone; proportional, feed forward, derivative, integral and integral active zone.

The K_P gain generates a control signal proportional to the position error. Increasing the K_P gain improves response time and increases the "stiffness" of the system. Too high a K_P gain value causes instability; too low a K_P gain value results in "loose" or "sloppy" system dynamics. With other position gains set to zero, K_P was increased until the system became unstable.

The K_D gain generates a control signal proportional to measured velocity. K_D gain provides damping to the position loop, which can reduce overshoot.

The K_{ff} gain generates a feed forward signal proportional to the commanded speed. K_{ff} gain reduces position following error. However high values can cause position overshoot.

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[2] A detailed description of PID closed loop feedback can be found in a textbook by John Van de Vegte. Feedback Control Systems, 3rd Edition, Prentice-Hall, 1994.

K_I gain generates a control signal proportional to the integral of the position error. K_I gain improves the steady-state positioning performance of the system and eliminates steady-state positioning errors. It affects the ability to reject load disturbances. Increasing the integral gain generally increases the ultimate positioning accuracy of the system. However excessive integral gain results in system instability.

The K_I Zone is the region, in counts, around the commanded position where integral gain is active. If the position error is greater than K_I Zone, the integrator is not active.

Following successful tuning of the axes, the machine was ready to be used in grinding.

4. Adaptive Control

Adaptive control implies dynamic monitoring of several elements during a specific process, and applying corrective controlling action to provide desired behavior. Naturally this is a computationally intensive task, as and an array of sensors and software drivers must be written to make such a system work. Much research has been done on this topic including thermal monitoring (Mou, Donmez) and force-feedback control (Cowen, Shertz, Kurfess). In our grinding system, air-pressure sensors, coupled with thermal, and force feedback would provide the building blocks for a sophisticated high-precision adaptive control system.

Compared with expensive CNCs, integrating adaptive monitoring instruments into the PC is relatively simple and inexpensive. Separate proprietary Data Acquisition Cards (DAQ) and hardware drivers can be avoided by using standard DAQ cards. Most of the hardware found off the shelf are windows compatible and are thus candidates for a functional role in the PC-based CNC. A simple program, written in C++, VB, or Java, will take care of the handshake communications with the open architecture PC-based CNC. For an inexperienced user, this can all be done in a relatively shorter period of time and with great success with respect to a similar implementation in a higher level, proprietary control.

5. Linear Motor Considerations

The linear motor pre-loaded air bearing concept is based heavily on the linear motor; using it for actuation as well as pre-loading the air bearings. Sizing of the motor is an absolute crucial step must be taken into careful consideration. For this system to work, a high magnetic pre-load is necessary. This generally tends to be 3 -5 times the axial force, resulting in an inherently stable system. The motors used in our system provided a pre-load force of 2300N and a peak axial force of 800N. 15 Amp servo drives were selected to drive our 7 Amp continuous current linear motors. Motor electrical parameters such as flux density, coil resistance, encoder resolution, and electric cycle, all need to be calculated and loaded into the onboard ROM of the servos. These parameters are almost always supplied by the motor manufacturer.

6. Discussion and Conclusions

A PC based control can be a practical and elegant solution for a direct-driven linear motor, air bearing ID/OD grinder. For the air-bearing/linear motor actuator technology, a young and new machine concept, the PC-Based control offers a robust and flexible method for precision control. Its Windows platform allows the addition of several other peripheral components which are not ordinarily found in current controls. As mentioned before, these can include adaptive measuring instruments feeding directly into a DAQ or serial port, wireless networking, and even remote assistance. The common windows user interface, coupled with simple and easily customizable CNC operators menu, enable this new technology to emerge as a true leader. As the PC grows and matures into an even more powerful computing machine, CNC controls in the future will surpass today's common-ground CNCs in terms of performance, reliability, and cost. This should enable Overbeck® to offer customers a complete grinding solution in a fraction of the time traditionally required. Any changes in production can be easily transferred to the grinder, whether it is part changeover, or grinding layout. Overbeck® believes that this approach should be particularly well-suited to the bearing industry as well as to automotive and small job shops applications.

7. Acknowledgements

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