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Response of a numerically controlled machine-tool to the modification of its position feedback using real-time solution

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Abstract

The dimensional accuracy of machined parts can be influenced by numerous factors, among which inaccuracies in the machine's structural loop and thermal expansion of components have the biggest impact. Hence, highly accurate machining requires effective error compensation. This motivates the development of a real-time compensation system implemented on a five-axis machine tool. In this study, a physical monitoring device is installed in the feedback loops of the machine's axial position control circuit, to intercept and modify linear encoder signals. It communicates with a custom software application that processes the data and generates corrected signals according to geometric model based on the rigid body assumption. The numerical controller (NC) is then induced to perform volumetric error correction based on its default programming. The key advantage of this software-based compensation strategy over the use of look-up tables or NC program modification is the total independence from the NC. The same real-time program is also used for the characterization of linear axis controls. This article outlines the behaviour of an NC machine when an axis displacement is generated via the modification of measuring systems feedback. The rate of change of the virtually added movement appears to be more of a limiting factor to the controller than the magnitude. Moreover, virtual displacements can be injected with discontinuous velocity profiles, resulting in unbounded acceleration and jerk.

Machining – Compensation – Positioning – Monitoring

1. Introduction

In machine-tools, many sources of errors, including geometric, thermal, loading, and servo errors may contribute to the inaccuracies during manufacturing processes. Quasi-static errors, such as link and motion errors, are highly responsible for the contouring error [1]. If they cannot be avoided during machine design, or mechanically corrected, the so-called volumetric error can be modelled by applying the rigid-body assumption for the elements in the machine structure [2]. The tool positioning is then modified accordingly, through a software compensation strategy. The main approaches are the use of compensation tables that can be filled with axis motion or link errors, the discretization and modification of NC program [3], and the interception and modification of feedback signal in the position control loop [4]. When a CNC is customizable enough, the addition and multiplication of look-up tables are available and compensation algorithms can run in real-time. This is, for instance, a Siemens 840D numerical controller feature [[5] – [6]].

Implementing the re-computation of tool path before machining is the easiest compensation method because it does not require extra hardware. However, it is not the best industrial strategy. Indeed, different programs are required for machining one type of part on different machines and each compensated program is referenced to a specific origin point within each workspace. Other compensation methods mostly rely on the CNC controller, whereas the modification of feedback signals strategy can be developed on any machine tool. It has the advantage of being independent of numerical controller algorithms, which are often proprietary and not exposed to the end-user. Nevertheless, the response of the controller to the

modification of its position feedback signals needs to be investigated, so as to determine kinematic limitations for the simulated displacement. Indeed, the feedback signal change induces a shift between the axis position deduced by the rotational velocity sensor and the linear position sent to the controller. This can be interpreted as the application of a virtual force on the axis, inducing a virtual displacement, to which the controller reacts. However, such multi-axis machines tend to have built-in restrictions on the response to such displacements, and if this is not properly considered, the machine's internal emergency stop may be triggered. This type of study has been done in the past with the use of a compensation register of a specific incremental encoder interface board [7]. The present article introduces a real-time system running on a dSPACE Scalexio *LabBox*, that is installed in the axis position control feedback loops. It intercepts and regenerates analog position signals and can be used for system identification. This report will first introduce the software's functionalities and architecture, before the measured magnitude, velocity, acceleration and jerk's limitations of the virtual displacement injected into the controller are presented. Finally, the proposed solution is used for the position control loops identification and its applicability in error compensation problems is discussed.

2. Materials and methods

The experimental setup is installed in a GFMS HSM600U 5-axis machine-tool with a [wC'B'XbYZ(C1)t] architecture. The associated CNC is a Heidenhain iTNC530 (cf. Figure 1). The linear position is estimated by the motor's rotary encoder but the value used in the position control loop is measured by a linear encoder closest of the linear guideway. To date, the proposed solution is developed for linear axes X, Y and Z.

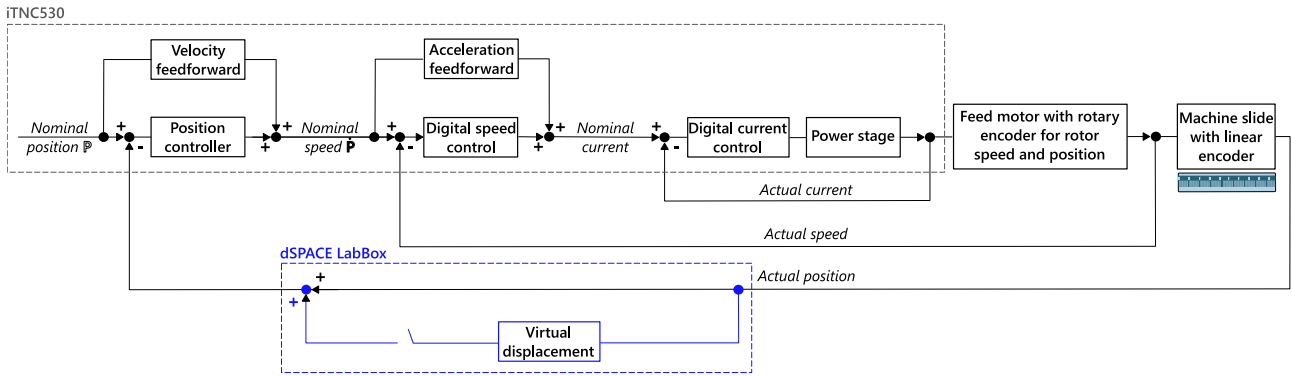


Figure 1. Cascade control loops of the iTNC530, for linear axes, with the addition of a feedback signal modification block. The usual configuration is shown in black (inspired by iTNC530 Technical Manual [8]).

2.1. Virtual encoder principle

The linear encoders mounted in the machine-tool used for experiments are Heidenhain DIADUR LS486C. The position information is obtained through the counting of individual increments from any set point of origin. Moreover, an additional track bears distance-coded reference marks. The distance between two marks is unique and provides the absolute reference. This distance is read by the NC during the homing procedure, but also each time the axis is moved.

The response of an NC machine-tool to the modification of its position feedback is studied by comparing the virtually added displacement (ΔX in Figure 2) to the actual compensation movement of the axis. The basic principle is to regenerate the sine analog signals of the linear encoders, simulating an axis movement whereas it is not caused by motor rotation. The NC then compensates for a linear positioning error by moving its axes. The virtual encoder principle is depicted in Figure 2 and can be summarised as follows:

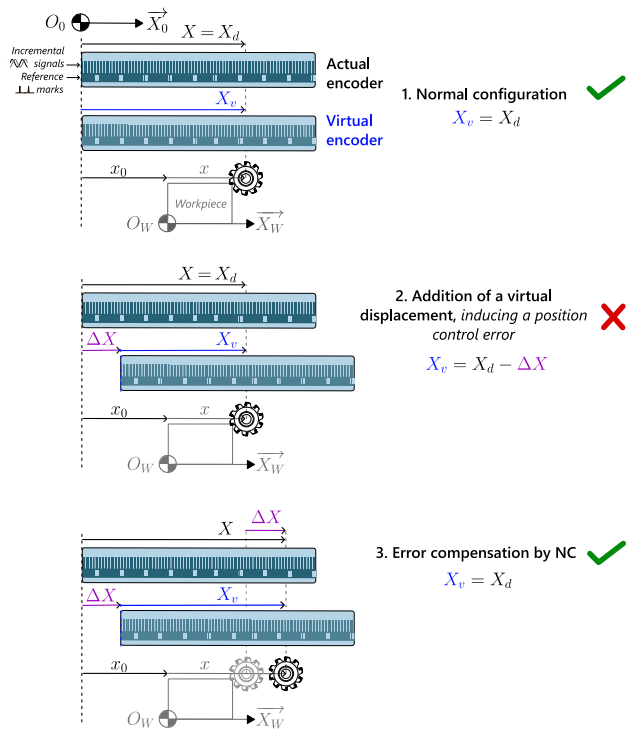


Figure 2. Virtual linear encoder principle: a virtual displacement of the linear encoder induces a real shift of the tool in the workspace (W frame).

1. In the normal configuration, the virtual encoder is read by NC and its value matches the desired joint coordinate X_d , set by the NC as the nominal position.

2. A gradual displacement is induced on the virtual encoder whereas the actual position X remains the same. The NC compares the command position X_d to the virtual encoder value X_v and measures a positioning error ΔX .
3. The NC signals for a linear displacement to compensate the previously estimated positioning error. Therefore, the tool is shifted by ΔX in workspace compared to the nominal configuration. The NC assumes that the actual axis position is $X = X_d$ while it is $X = X_d + \Delta X$.

2.2. Real-time software and hardware architecture

The signal interception and modification block, shown in blue in Figure 1, is a real-time software running on a dSPACE real-time platform (i.e. Scalexio LabBox), equipped with a DS6001 processor board. To achieve the signal manipulation, a block diagram is constructed within MATLAB Simulink© and signal conditioning is performed with ConfigurationDesk© software. Afterwards, the C code is generated with Matlab and uploaded to the LabBox. The signal acquisition is enabled by DS6121 Multi I/O and DS6221 A/D boards while the signal generation is performed by a DS6241 D/A board.

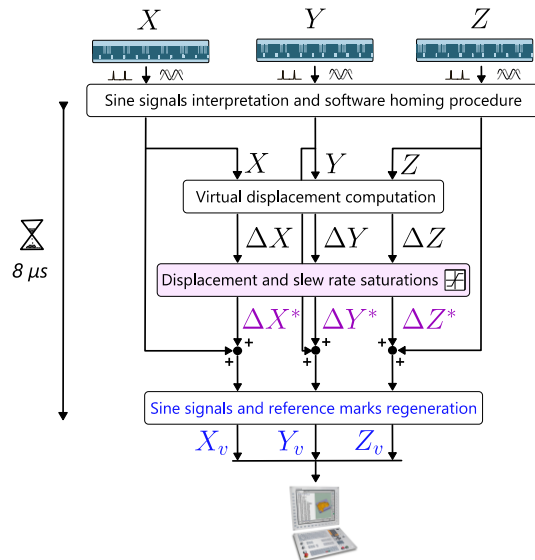


Figure 3. Real-time developed software architecture.

The software reads the sine analog signals of each linear encoder. It interpolates the actual axes positions, and regenerates the analog signals with a possible additional shift. This virtual displacement is also called “virtual perturbation”. It can be controlled by the operator thanks to a computer connected to the LabBox on which runs the software interface (i.e. ControlDesk©). Any other signal or program’s variables can be monitored with this real-time interface. The global

architecture of the Simulink block diagram is depicted in Figure 3.

Multiple tasks are running simultaneously when the real-time system is on. For instance, the virtual displacement computation can take more time, and therefore has a lower priority, than the basic task which has to copy the positions from the actual encoders towards the NC. This task has a 125 kHz running frequency, meaning that the signal delay induced by the LabBox is about 8 μ s and could represent a following error of 1 μ m if the axis moves at 10 m/min. This delay is mostly negligible for the presented purpose.

3. Solution performance: results and discussion

The proposed solution is characterised by firstly investigating the kinematic and temporal response of the NC to virtual displacements. The performance of the solution for error compensation is then analysed.

3.1. Kinematic properties of the simulated displacement

As emphasized in Figure 3, virtual perturbations must be inserted carefully into the feedback loop to avoid triggering an emergency stop. Their computation can depend on axis position, to perform volumetric error compensation for instance. It can also be configured in the real-time interface as, for example, a sine wave or a step command. The following precautions must be taken when generating virtual displacements:

- **Magnitude:** When a virtual displacement is simulated, the NC measures a gap between the axis position estimated by the motor's rotary encoder and its feedback position, sent by the virtual encoder. This difference can reach 10 mm, as set by the CNC provider, which is a substantial compensation range. Nevertheless, a range limit of ± 2 mm is imposed on the displacement computation, in case of the compensation algorithm diverging.
- **Velocity:** Virtual incremental travel speeds were tested until the emergency stop was triggered. The maximum velocity was found to be 35 mm/s. For safety purpose, a rate of change limiter is installed after the magnitude limiter. Its limit is chosen to be set to 10 mm/s for linear axes.
- **Acceleration and jerk:** Virtual displacement can be injected with discontinuous velocity profiles, resulting in unbounded acceleration and jerk. As shown in Figure 4, the jerk measured by the NC integrated oscilloscope exceed the limits (i.e. 100 m/s^3) used for the tool-path generation, without causing any internal errors, because actual acceleration is filtered by the axis control-loop.

As shown in Figure 5, the compensation reaction of the NC is particularly slow. Indeed, a delay is induced by the position controller's cycle time which is equal to 2 ms. Moreover, the acceleration at which the axis reacts does not reach the maximum value set for trajectory generation (i.e. 10 m/s^2).

3.2. Position control closed-loop behaviour and identification

In order to improve the response time of the NC to a virtual displacement with a corrector, a transfer function of the position control closed loop needs to be identified. Models were fitted for each linear axis, with the virtual displacement as input and the actual position as output, meaning that the function includes every filter, NC algorithms, feed drives and physical behaviour of the axis (according to the parameters of Figure 1). A series of time- and frequency- domain experiments were conducted so as to identify a transfer function.

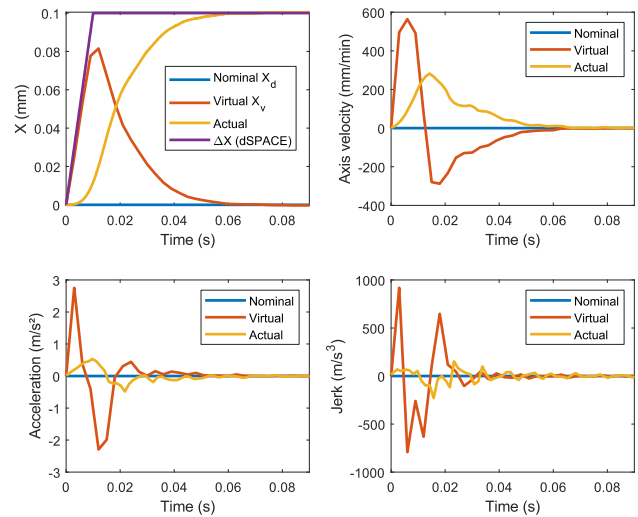


Figure 4. Kinematic measurements of a 100 μ m virtual displacement (NC integrated oscilloscope measurements for the nominal and virtual curves, dSPACE measurements for the actual ones).

On the one hand, gain and phase of the position control closed-loop system were measured using sine displacements injection. On the other hand, a transfer function was estimated with time-domain measurements like those displayed in Figure 5.

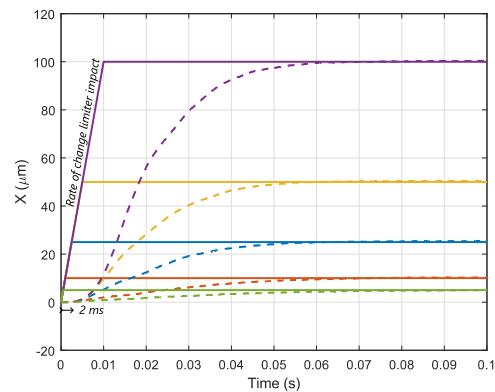


Figure 5. Virtual displacements (continuous lines) and machine response (dashed lines) for various step magnitudes.

The transfer function estimation algorithm is the Simplified Refined Instrumental Variable method for Continuous-time systems (SRIVC) with the implementation in the System Identification Toolbox in MATLAB [9]. Results of the two types of identification experiments are superposed on Figure 6. The differences between the two identification methods, particularly in terms of gain, are due to the numerous non-linearities of the system modelled (e.g. NC algorithm, axes mechanical behavior).

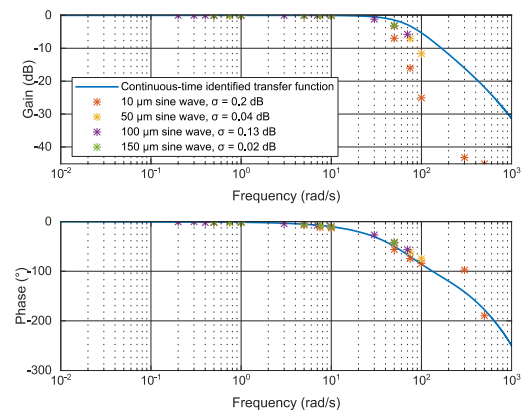


Figure 6. Bode diagrams of X-axis position control-loop.

3.3. Error compensation application

The main objective of studying the response of the NC to the modification of its position feedback is the development of a new software geometric error compensation method. However, dynamics of the studied response is slow and could induce volumetric error. This is why modelling of linear axes position control loops helps predicting the residual tracking error. This error depends on the compensation geometric rate $\frac{dC}{dX}$ and on the axis feed rate $\frac{dX}{dt}$, with C the necessary virtual displacement for a given volumetric error compensation. Kinematic properties specified in the previous section bound the rate of change of the virtual displacement to be:

$$\frac{dC}{dt} = \frac{dC}{dX} \frac{dX}{dt} < 10 \text{ mm/s} \quad (1)$$

A surface predicting the tracking error on a linear axis is plotted in Figure 7, and compared to experimental points. For example, for a finishing operation in an aluminium alloy, the linear axes can move at up to 6000 mm/min. For a compensation slope of 10 $\mu\text{m}/\text{mm}$, the expected maximum tracking error reaches 22 μm .

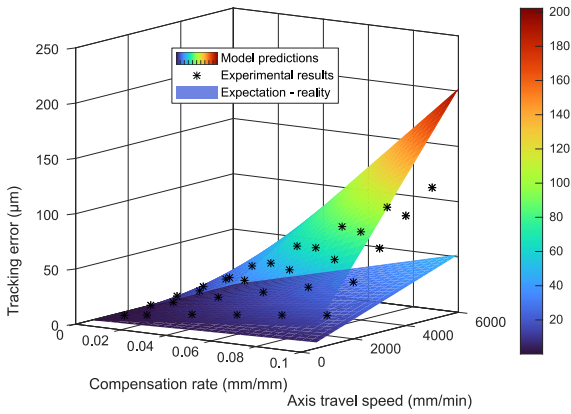


Figure 7. Estimation of the tracking error along a linear axis (X), superimposed with experimental results.

Despite a low-performance modelling (the difference between experiments and expectations can reach 50 μm in the tested - speed and compensation rate - area, especially in unrealistic compensation conditions), the tracking error can be reduced with the addition of a feed-forward controller H_{FC} [10] just after the virtual displacement computation block (Figure 3). Its coefficients are estimated via the axis model H_X and the desired NC response H_{ideal} as:

$$H_{FC} \cdot H_X = H_{ideal} \quad (2)$$

Because of the 2 ms delay and the fact that the trajectory of command is not known by the LabBox in advance, H_{ideal} cannot be equal to 1. Nevertheless, this feed-forward controller gives promising performances as shown in Figure 8, where the maximum measured tracking error was reduced from 31.6% to 4.7% of the set point.

4. Conclusion and outlook

A device for modifying the axis position signal in real-time has been introduced and tested in a CNC machine-tool. The linear position control closed-loops were modelled via the virtual encoder principle. Feed-forward controllers were then added to the software solution so as to ensure better virtual displacement tracking performances. Moreover, no noticeable slowdown was measured due to any coupling between the axes. For the future work, geometric errors of the machine must be identified.

Afterwards, the real-time compensation solution can be applied to the machining of a part, using three-axis milling first, before extending to 5-axis machines via including both swivel and rotational degrees of freedom in the software and develop multi-axis compensation strategy.

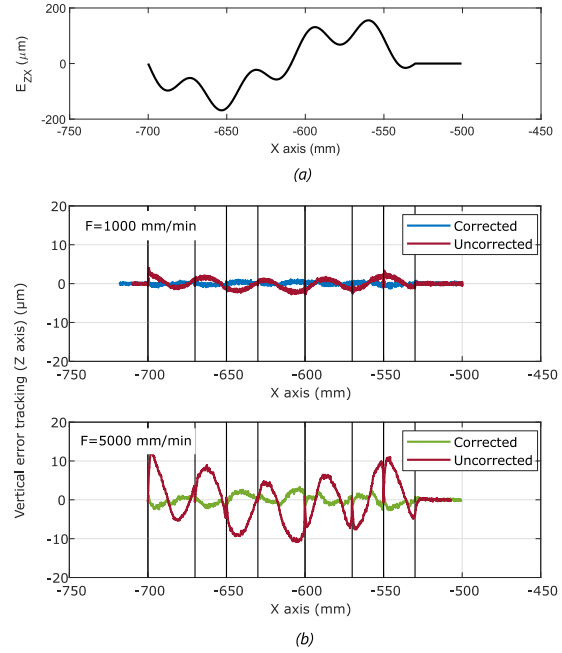


Figure 8. (a) Vertical straightness error supposed along X-axis – (b) Tracking error before and after inserting a feed-forward controller, for two different feedrates F . Vertical black lines correspond to X-axis stops.

Acknowledgments

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