# Virtual Computer Numerical Control System

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**Abstract**

This paper presents a comprehensive virtual simulation model for CNC systems. The Virtual CNC (VCNC) has a modular architecture, allowing a real CNC to be prototyped quickly from standard library functions for feed drive models, feedback devices, axis control laws, and trajectory interpolation. Additional CNC modules can easily be prototyped and integrated to the VCNC by the user. Various application examples are presented which include the prediction of contour errors, auto-tuning of feed drive controllers, toolpath and feed modification for improved cornering, and rapid identification of closed loop drive dynamics. Detailed experimental verification is presented for each algorithm.

**Keywords**:
Virtual, Simulation, Computer Numerical Control (CNC)

## 1 INTRODUCTION

The objective of Virtual Manufacturing technology is to design a completely digital factory, where the part is modeled, produced with optimized process parameters, and resulting errors are predicted with corrective actions being taken in a computer simulation environment. An essential step in achieving this goal is the construction of virtual prototypes that accurately represent the dynamics of machine tools and manufacturing processes [1]. This paper presents a virtual model for Computer Numerical Control systems used in machine tools.

The Virtual CNC (VCNC) enables the prediction and optimization of a machine's dynamic performance at the design stage. By running part programs on the virtual CNC and evaluating the contouring performance, the influence of various design choices such as guideway, drive, encoder, control law, and interpolation algorithm selection, can be assessed before the machine is actually built. The VCNC can also be used for tuning servo control and interpolation parameters, without taking up production time on the actual machine tool. Once the desired response and contouring accuracy are achieved in the virtual model, the parameters can be directly implemented on the real machine with minimal down time. In process planning, the VCNC can be employed to evaluate the contour errors to different part programs, and make necessary changes to the feedrate and toolpath, in order to avoid tolerance violations due to servo errors.

The simulation accuracy of VCNC relies on the utilization of realistic mathematical models to describe the dynamic behavior of each component. This is achieved through elaborate modeling of the feed drive dynamics [2], trajectory generation algorithms, control laws [3], [4], [5], [6], and nonlinear characteristics of the feed drive such as friction [7] and backlash [8], all of which influence the overall tool positioning accuracy. The VCNC, has been built on MATLAB® / SIMULINK® platform, and has an open architecture, thus allowing the user to add new modules or modify the existing algorithms as required.

Various applications have been developed, which take advantage of the Virtual CNC's accurate simulation capability in predicting and improving the dynamic performance of real CNC machine tools. These are:

- prediction of contour errors for part programs;
- auto-tuning of servo controllers for feed drives;
- sharp corner tracking using spline interpolation;
- rapid identification of virtual drive models.

Henceforth, the Virtual CNC architecture will be briefly introduced, followed by explanation and experimental validation of the developed VCNC applications.

## 2 VIRTUAL CNC ARCHITECTURE

The architecture of the Virtual CNC is shown in Figure 1, which resembles the real, reconfigurable and open CNC developed at the Manufacturing Automation Laboratory, UBC [9]. The Virtual CNC accepts reference toolpath commands generated on CAD/CAM systems in the form of industry standard Cutter Location (CL) format. The CL file is interpreted to realize the desired tool motion comprising of linear, circular, and spline segments. The axis trajectory commands are generated by imposing the desired feed profile on top of the toolpath commands. The feed profiling can be configured to employ piecewise constant, trapezoidal, or cubic acceleration transients.

The axis servo loops are closed by configuring the motion control, feed drive, and feedback modules. The motion controller can be selected from a library of frequently used control laws such as P, PI, PID, P-PI cascade, and lead-lag control, as well as more elaborate techniques proposed in literature like pole placement [3], generalized predictive [4], adaptive sliding mode [5], and feedforward control [6], as well as friction compensation [7].

The feed drive module can be configured to emulate the dynamics of direct or geared drives. Characteristics of the amplifier, motor, axis inertia, friction, and drive mechanism can be fully defined, including nonlinear effects such as quantization, current and voltage saturations, stick-slip friction, and axis backlash. Experimentally identified or analytically predicted high order drive models with structural resonances can also be incorporated. The

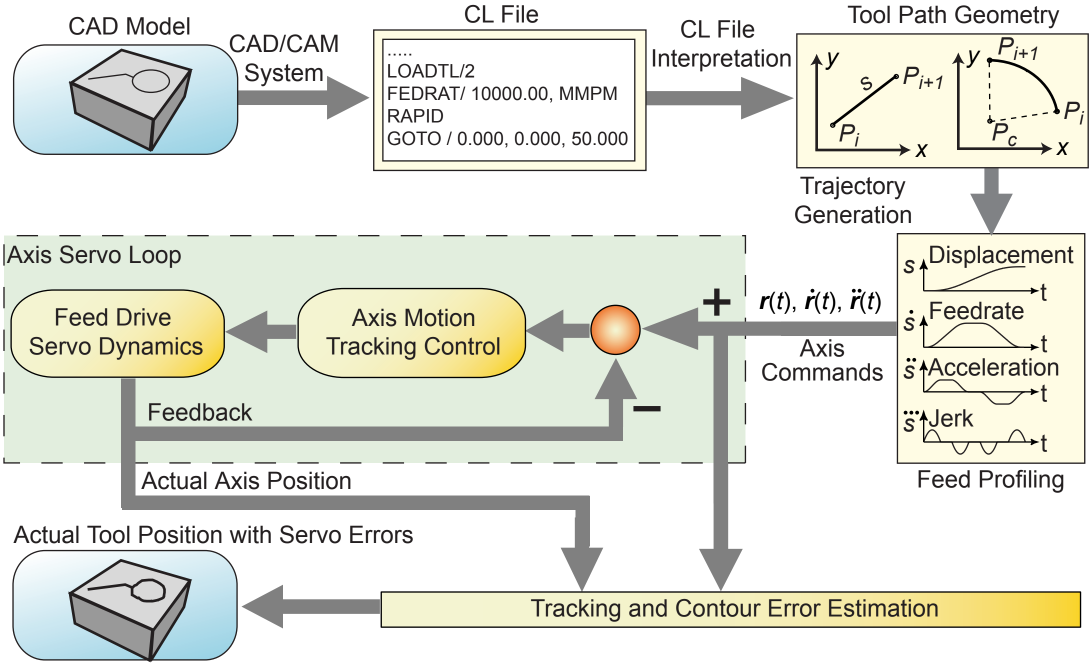


Figure 1: Virtual CNC system architecture.

feedback module can be configured from a combination of linear or angular position, velocity, and acceleration sensors, each with its user defined accuracy and noise characteristics. When the Virtual CNC is assembled, its performance can be assessed by running various part programs and evaluating the servo tracking and contour errors, as well as axis velocity, acceleration, and jerk profiles, and motor torque and power histories. It is also possible to conduct frequency and time domain analyses, which aid the user in evaluating and improving the stability margins and servo performance of the VCNC axes.

## 3 APPLICATION EXAMPLES

In the following, examples of Virtual CNC applications are presented. Each application is briefly explained followed by experimental validation.

### 3.1 Prediction of Contouring Accuracy

The contour and tracking error prediction accuracy of the VCNC was verified by conducting diamond and circle machining tests on a three axis machining center, controlled with an in house built CNC [9]. Simulations and experiments were conducted for cases involving closing the servo loops with PID and adaptive sliding mode control. An example result for tracking a diamond toolpath (50 mm side length, 200 mm/sec feed) with PID control is shown in Figure 2. The predicted and measured tracking and contour errors are in close agreement with each other. Similar results were obtained for other cases involving different toolpaths and controllers, which are not presented here for conciseness. In overall, the VCNC is able to predict servo errors within a few encoder counts.

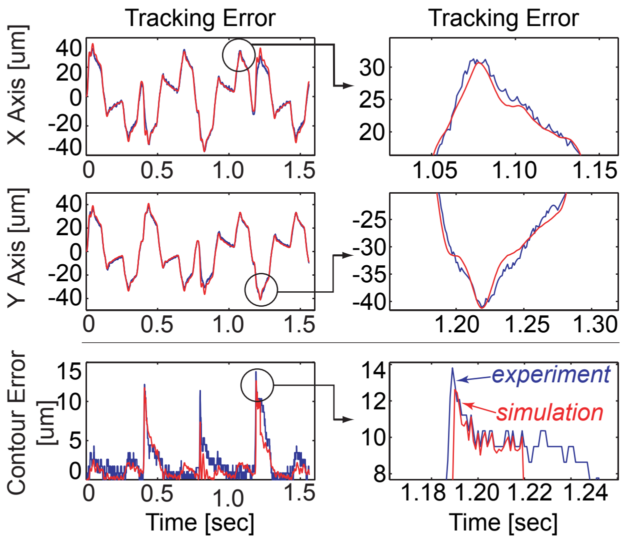


Figure 2: Predicted and experimentally verified tracking and contour errors for diamond shaped toolpath.

### 3.2 Fuzzy Logic Tuning of Adaptive Sliding Mode Control (SMC)

A fuzzy logic based automatic tuning strategy [10] for adaptive sliding mode control of feed drives [5] has been developed on the VCNC platform. The tuning architecture is shown in Figure 3. During execution of smooth back and forth motion in the servo loop (Bottom Layer), performance descriptors such as maximum tracking error (TRE), control loop phase margin (PHA), and control signal oscillation level (OSC) are evaluated in the Intermediate Layer. These descriptors are passed on as fuzzy variables to the supervisory Upper Layer, where

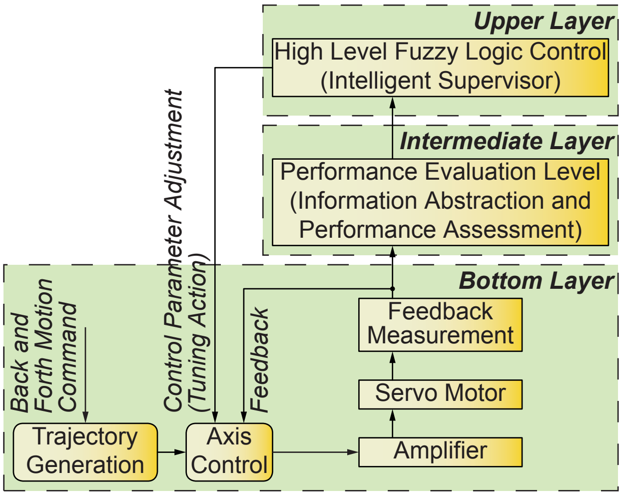


Figure 3: Fuzzy logic based auto-tuning strategy for SMC.

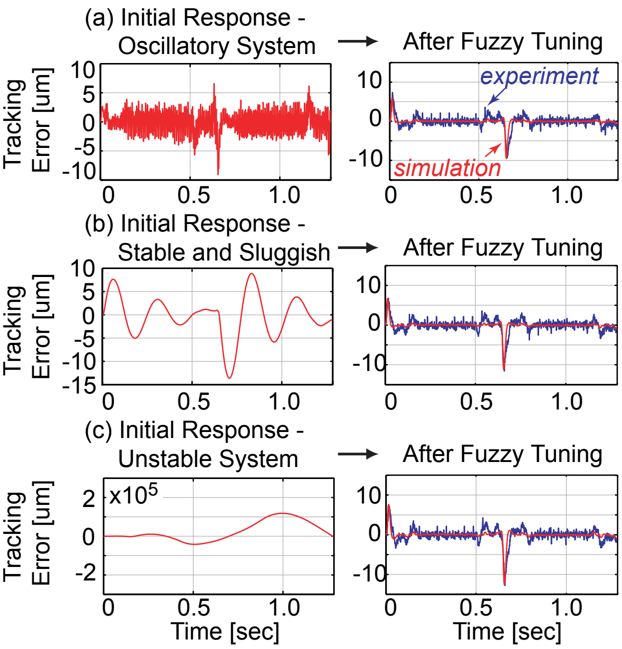
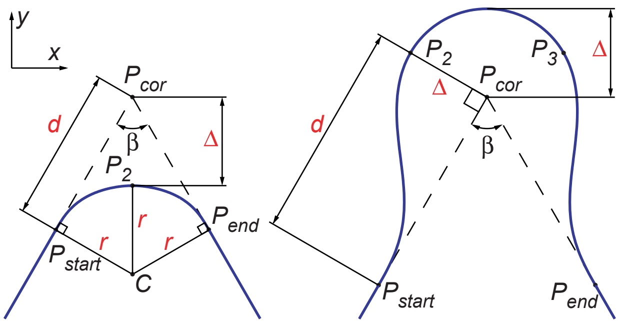


Figure 4: Drive performance before and after auto-tuning.

adequate tuning actions are taken in accordance with the tuning rule base, constructed from tuning experience. As a result, the SMC gains are varied until acceptable servo performance is obtained. Upon successful tuning in the VCNC, the control parameters are implemented on the actual CNC machine. Three cases for automatic tuning are presented in Figure 4. In case (a), the SMC is over-tuned and the response is highly oscillatory. In case (b), the initial SMC design is stable but sluggish (under-tuned). In case (c), the design is unstable due to the high disturbance adaptation (i.e. integral action) gain initially assigned. In all cases, the fuzzy logic tuner is able to recover the performance and yield acceptable tracking results, which have been verified on the actual machine.

### 3.3 Sharp Corner Tracking with Spline Interpolation

Another idea which has been implemented on the VCNC is sharp corner tracking using quintic spline interpolation [11]. Two approaches have been tested, shown in Figure 5. In the under-corner approach (Figure 5(a)), the toolpath length and cornering time is slightly reduced without violating the contouring tolerance ( Δ ). This is applicable when high bandwidth servo controllers are used, which can accurately track the modified toolpath. In the over-corner approach (Figure 5(b)), the toolpath is slightly stretched to counteract the under-cut, typically caused by the large phase lag in low bandwidth controllers. In both approaches, the toolpath is parameterized using appropriate tangent and normal boundary conditions and the cornering feedrate is adjusted iteratively in the VCNC, to ensure that the cornering time is minimized while the tolerance Δ is maintained around the original corner.



(a) Under-Corner Spline (b) Over-Corner Spline

*Δ: Toolpath Tolerance, d: Clearance, r: Radius*

Figure 5: Under-corner and over-corner spline techniques.

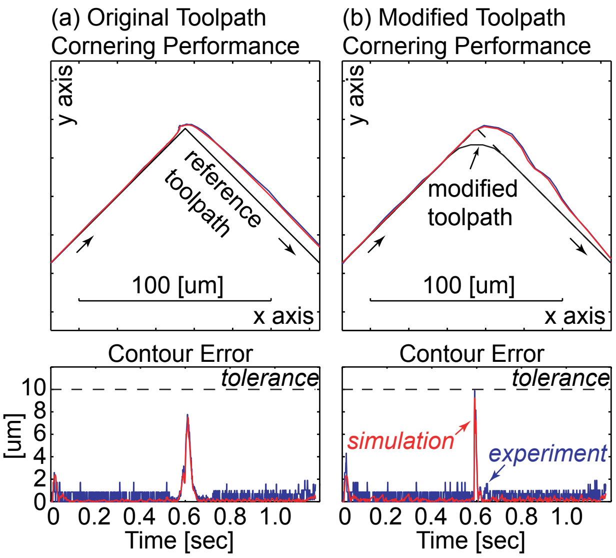


Figure 6: Contouring performance for 90° under-corner spline with sliding mode control.

Implementation results for the two cornering strategies are shown in Figures 6 and 7. In Figure 6, the cycle time has been reduced from 185 to 181 msec for a sliding mode controlled drive system, without causing tolerance violation. In Figure 7, the 350 um under-cut type of contour error, caused by the large phase lag of the P-PI servo controller, is eliminated and the contour error is brought below the limit of Δ =30 um. Following VCNC simulations, both cornering cases were experimentally verified on the CNC machining center.

### 3.4 Rapid Identification of Virtual Drive Models

The VCNC can be a useful tool for predicting and improving the performance of CNC machines. However, the prediction accuracy depends closely on the feed drive model, which is determined by disconnecting the servo loop and conducting a series of identification tests. This is usually time consuming and not always practical to apply on production machinery. As an alternative approach, a rapid identification strategy has been devised for constructing virtual drive models, as shown in Figure 8.

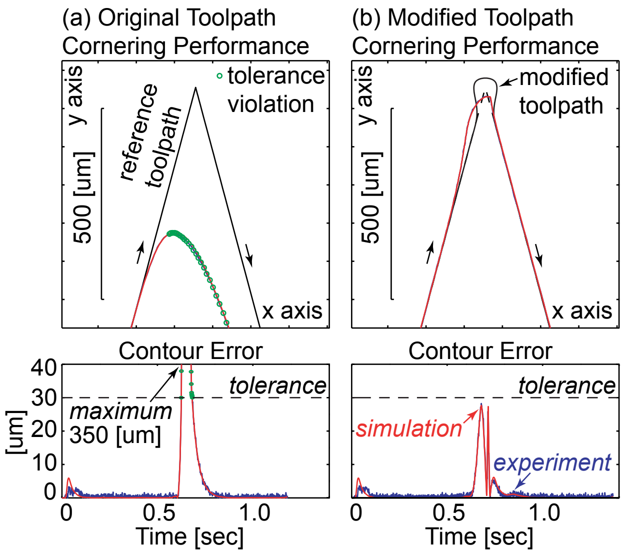
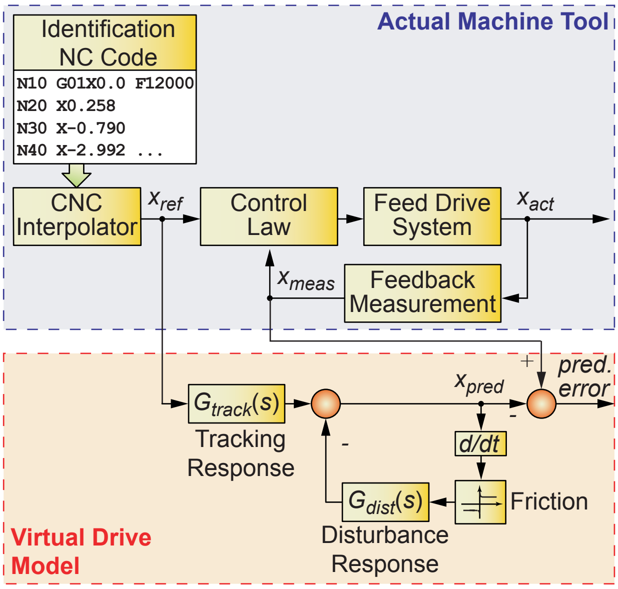


Figure 7: Contouring performance for 30° over-corner spline with P-PI cascade control.



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N10 G01X0.0 F12000
N20 X0.258
N30 X-0.790
N40 X-2.992 ...
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Figure 8: Rapid identification technique.

The excitation is delivered by executing a G-code comprising of pseudo-random motion commands, tailored to reveal the closed loop dynamics as much as possible. The equivalent tracking and disturbance transfer functions, and friction model, are identified by monitoring the time stamped position commands and the encoder readings such that the inconsistency between measured and predicted axis movements is minimized in a Least Squares sense. Since the motion commands generated by the interpolator are smooth, they lack the persistence of excitation required to estimate full dynamic models. Hence, only the rigid body dynamics are identified. Stability of the closed loop model is guaranteed by setting bounds on the pole locations. Although there is no guarantee that the parameters will converge to their true values, the identified transfer functions are successful in capturing the key dynamic characteristics of feed drives. Third order transfer function models are used in the form,

$$\left.\begin{aligned} G_{track}(s) &= \frac{b_0 s^3 + b_1 s^2 + b_2 s + a_3}{s^3 + a_1 s^2 + a_2 s + a_3} \\ G_{dist}(s) &= \frac{s}{s^3 + a_1 s^2 + a_2 s + a_3} \end{aligned}\right\} \qquad (1)$$

Only Coulomb friction is considered. The virtual drive models constructed with the developed rapid identification technique were verified in contour tracking tests. An example result is shown in Figure 9, where the actual drive system is controlled with Zero Phase Error Tracking Control [6], and a circular toolpath with 20 mm radius is commanded at 100 mm/sec feed. Comparison of the virtual CNC predicted and experimentally measured tracking and contour error profiles are shown in Figure 9, which are in agreement, thus demonstrating the effectiveness of the developed identification strategy.

## 4 CONCLUSIONS

The VCNC allows the dynamic behavior of machine tool CNC systems to be prototyped, evaluated, and optimized in a virtual environment. It can be used as a tool in designing machine tools, developing and tuning control and interpolation algorithms, as well as planning manufacturing operations. Application examples have been presented, including contour error prediction, controller auto-tuning, sharp corner path planning, and rapid drive identification, which demonstrate the benefits of VCNC.

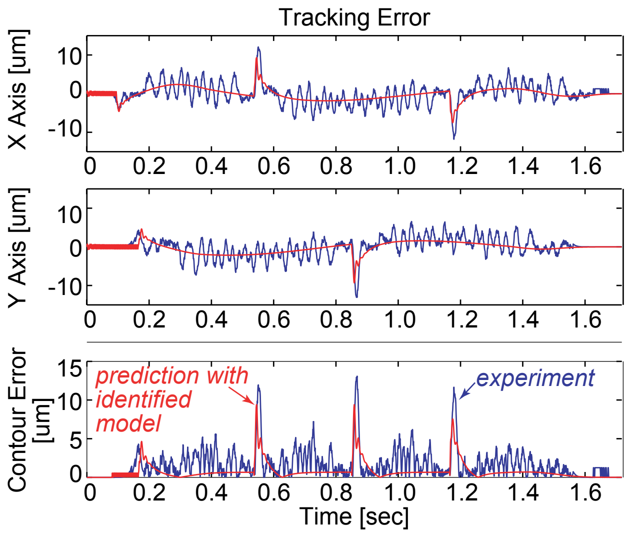

Figure 9: Tracking and contour errors for circular toolpath.

## 5 ACKNOWLEDGMENT

This research is sponsored by NSERC and Pratt & Whitney Canada under research chair and strategic grant agreements.

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