A FRAMEWORK FOR A VIRTUAL MACHINE TOOL (VMT)

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ABSTRACT
The ability to simulate cutting operations and obtain realistic predictions of its outcome is the vision motivating this paper. An initial framework for the realization of this capability, epitomized by the designation VMT, is defined. The underlying assumptions, interrelations between the necessary functions, and the envisioned methods and approaches to the discrete simulation of the functional elements of the VMT are addressed.

INTRODUCTION
In many areas of technology and industrial practice, well conceived and developed software systems are in existence for the simulation of manufacturing processes and equipment. These systems are an indispensable tool for evaluating and verifying the feasibility of contemplated processes for new products without costly trial and error runs with actual hardware. Examples include simulators for sheet metal working, casting, plastic injection molding, etc. Conspicuously absent are, however, systems for the simulation of metal cutting operations. The only exceptions are the widely used and very useful NC code verification and collision avoidance systems which account only for the nominal geometric and kinematic relationships of the process. However, these functions cannot be placed on equal footing with the previously mentioned systems. What would be of ultimate interest is the answer to the question whether the contemplated operation will result in parts with specified tolerances, form, and surface finish.

At the university research level, much work has been done in the past decade on machining process modeling. At the industry levels, companies like General Motors, Caterpillar, and Ford have recognized the value of process simulation tools and have internal programs directed toward developing and supporting such tools at the company level.

The authors believe that given the continued advances in the fundamental understanding of the cutting process coupled with new developments in computational models, it is feasible to re-examine the possibility of developing a true system-based machine tool simulator. This undertaking has been termed the "Virtual Machine Tool (VMT)" project to be conducted by the Machine Tool - Agile Manufacturing Research Institute (MT-AMRI) with participation from both universities and industry. The ultimate aim is the establishment of a system which will have the same impact on cutting as the other systems have on their respective processes. The paper presents a framework for undertaking this effort and summarizes current work toward this goals.

THE VIRTUAL MACHINE TOOL
In an abstract way a machine tool is a collection of connected bodies which perform a controlled relative motion for providing a precise relative temporal and spatial relationship between two points of the system associated with the tool and workpiece. Figure 1 shows the key entities of a system performing a cutting operation. T and W designate the tool and workpiece, respectively. The entities can be grouped in different ways to yield a particular functional representation. The following groupings can be easily recognized: (A) Basic Mechanical System: bodies B₁ and B₂ connected by the drive mechanism D, (B) Complete Machine Tool Hardware: system (A) plus the
actuator/amplifier package A and sensing system S, (C) Complete Operational Machine Tool: system (B) plus the CNC controller/computer C, and (D) Machine performing Cutting Operation: system (C) plus cutting process P. The machine is also referenced to a world coordinate frame W, and is acted upon by a force F and temperature field T respectively.

FIG. 1. MACHINING SYSTEM MODEL

Without going into further detail, we may now state the problem of simulating the operation of system (D). In its simplest terms it reduces to the need to compute the attributes of the workpiece, i.e., its geometric characteristics (tolerance, form, surface topography) and integrity (residual stresses, crystallographic changes, etc.) as a function of the system's characteristics (physical properties of the components of (D)), operational parameters imposed by external commands, influence of the imposed force and temperature fields, and of the governing physical mechanisms. It is clear that there are countless ways and methods by which this problem can be approached, however, by adopting a particular philosophy the choices can be narrowed down. For the development of the VMT we will take the standpoint that the principal factor that affects workpiece attributes is the relative displacement, D, between T and W, which can be expressed in generalized form as:

\[ D = f(F, T, R, t) \]  

where all quantities except for time, t, are vectors and vector functions respectively, and where \( R \) represents the command set supplied to the controller such as NC code, workpiece and tooling data, etc. To formulate (1), by considering all possible physical interactions, is a formidable task so that plausible alternatives need to be sought. One approach, which allows one to break down the problem into more tractable components, is to assume that \( D \) can be represented as a sum of component displacements, \( D_i \), caused by different physical mechanisms, e.g., structural deformations, thermal distortions, servo errors, etc. so that:

\[ D = \sum D_i \]  

where \( i \) designates the particular physical cause of the displacement. This also carries the implicit assumption that the various mechanisms may be considered to act independently. A closer reflection on the technical literature reveals that Eq. (2) characterizes the prevalent approaches taken by most researchers in the past when addressing particular aspects of the metal cutting operation.

With reference to Fig. 1 we will highlight generalized modeling approaches for some of the principal characteristics of this system. The structural dynamics, for example, is defined for system (A) by establishing a relation between a force \( F \) applied between points T and W and the resulting displacement, \( D_r \). By adopting a linear lumped parameter approximation one obtains:

\[ D_r(s) = H(s) F(s) \]  

where \( H(s) \) represents the structural transfer matrix. The kinematic model of system (A), in differential form, expressing the relationship between an actuator displacement at the drive input \( q \), and a corresponding displacement \( D_r \), between points T and W is expressed, under rigid body motion assumptions, as:

\[ D_r = J q \]  

where \( J \) is the Jacobian. The thermal model expresses the thermal deformation \( D_t \) between points T and W as:

\[ D_t = g(T) \]  

The accuracy model is similar to the kinematic model, but in addition to the nominal drive input, \( q \), also considers geometric and kinematic errors in the kinematic chain, Y:

\[ D_a = h(q, Y) \]  

The servo model gives the relation between the sensor readings, \( D_{sa} \), of the displacement/velocity between T and W by the sensor system S, and the command input, \( R \), from the computer to the actuator A, in the form

\[ D_{sa}(s) = G(s) R(s) \]  

where \( G(s) \) is the servo transfer function matrix.

Similar generalized relations can be derived for many other relevant aspects of the system's operation.
To completely characterize system \( D \) the modeling of the metal removal process \( P \) needs to be reflected upon as well. The process is, in general, formulated for evaluating one of its particular aspects, \( Q \), as a function of the chip cross-sectional area, either in a static or dynamic sense. Since the chip cross-section is a function of the relative displacement \( D \) one may write

\[
Q = p(D)
\]  

(8)

where \( Q \) most frequently represents the primary responses of the process, i.e., cutting forces and power, or tool and workpiece temperature. If \( Q \) in Eq. 8 is taken to be equivalent to the force \( F \) in Eq. 3, one arrives at the closed loop representation of the machining process.

In order, however, to reach our objective of simulating the metal cutting operation we need to establish a new set of models and algorithms for converting the influence of all the above expressed variables into workpiece attributes, \( U \), again expressed in a generalized form as

\[
U = q(D).
\]  

(9)

The determination of Eq. 9 is an area of research and development which has not received much attention in the past and it will and must constitute a fundamental thrust in the development of the VMT.

The approach for the establishment of an initial incarnation of the VMT will be based on the assumption expressed by Eq. 2 which will allow us to adopt and incorporate many of the existing solutions in the technical literature into the system. The advantages of this additive concept are that it (a) allows for simple models of the contributing phenomena, (b) allows for the coexistence of different types of models, (c) supports computational schemes that can be executed on parallel or distributed computer systems, and (d) allows for the independent development of missing functions.

Presently, MT-AMRI is working with STEP Tools, Inc. to develop CAD interfaces to various VMT modules, including the FIXMA program and FMSIM, a program for face milling simulation. Operating initially from a CAD environment such as ProEngineer, MT-AMRI researchers at the University of Illinois at Urbana-Champaign have developed a STEP translator that allows a ProSTEP file to be converted into two-dimensional-view GIF files that are then imported into FIXMA and FMSIM. This is an important first step toward realizing a practical solution to defining part surfaces for fixture planning and for machining simulations.

**CURRENT STATE OF DEVELOPMENT**

The aim of this Section is to concisely reflect upon the current work at the MT-AMRI Universities which is focused on providing basic VMT simulation capabilities.

**Machine Tool Behavioral Models**

The essence of this effort, summarized below, is the modeling of the machine tool (System C).

**Machine Topological Model.** The University of Michigan researchers are currently working on the development of methods to represent machine tool topologies. Examples of topological representation methods include symbolic, general kinematic chain, tree graph, and matrix representations and other graph theory based methods (Deo, 1974; Yan, 1992). Additional features of the machine tool topological model include the consideration of tool and workpiece requirements, motion constraints, and of other functional characteristics.

**Kinematics Model.** Researchers at both the University of Michigan and Northwestern University are working on the development of kinematic models for arbitrary machine tool topologies. The purpose of these models is to perform a kinematic simulation of the movement of the machine's axes (Lin, 1989; Wang and Ehrmann, 1994; Lo, et al, 1994). The emphasis here is to standardize the representation and notation for automatic model generation and evaluation.

**Machine Tool Control Model.** The prevailing controllers for current machine tool systems are of the PID type. Their shortcomings are well known and need to be overcome. Wright (1995) and Greenfield and Wright (1990) at the University of California, Berkeley, have developed a VME-bus based open-architecture controller that supports advanced controller algorithms and process monitoring. There is currently an on-going effort to incorporate process simulation into this controller and perform machining experiments at remote sites over the Internet (DeVor, 1996). Tomizuka (1989), Tomizuka and Tsao (1989), and Tsao and Tomizuka (1994) at the University of California, Berkeley have developed several control algorithms pertinent to machine tool systems including: preview, zero-phase error tracking, and repetitive control. Rober and Shin (1995) at Purdue designed a PC-based open architecture controller and used it for constant force control (Rober, et al, 1994 and 1996), and for adaptive cross-coupling control to improve contouring errors (Rober, et al, 1996). Alter and Tsao (1994) at the University of Illinois are currently working on servo control methods for high speed linear motors to improve stiffness characteristics, while Ehrmann (1986), Kim, et al (1986 and 1987), and Lin, et al (1995) at Northwestern have developed forecasting compensatory control methods for grinding, milling and boring operations.

**Geometric Error Model.** Evaluation of the relative position error between the tool and the workpiece, according to Eq. 6, is the objective of the effort performed at both Northwestern and the University of Michigan. The work so far has resulted in the formulation of generalized geometric error models for machines of both serial and parallel configuration (Wu, et al 1987; Lin and Ehrmann, 1993 and 1995; Wang and Ehrmann, 1994 and 1995; and Hal, 1995), and also algorithms which can be used for compensation of these errors (Wang and Ehrmann, 1992 and 1994a; Chen, et al, 1993; and Yang, et al, 1996).
Spindle Dynamics. In the majority of machining operations spindle dynamics dominates the process characteristics and its stability. Shin (1992), Chen, et al (1994), and Jorgensen and Shin (1995 and 1996) at Purdue are currently developing an integrated analytical model, similar to Eq. 3, and a computational tool to predict the static and dynamic response of the bearing-spindle system. The model is based on the influence coefficient method to enable a simplified and yet comprehensive modeling of the complex spindle geometry.

Thermal Error Model. Modeling of thermal error components of machine tools over the past several years has been an ongoing effort at the University of Michigan (Yang, et al, 1996; Chen, et al, 1996). The emphasis of the thermal error model is on the prediction of possible thermal errors corresponding to a known temperature field (Eq. 5). FEM and empirical modeling methods are used to study the sensitivities of thermal deformations due to different temperature fields, alternative machine topologies, etc.

Process Models
This work concentrates on the modeling of the cutting process $P$ with respect to two classes of outputs, i.e., primary responses $Q$, and of workpiece attributes $U$.

Cutting Process Model. MT-AMRI has been working to develop a comprehensive cutting process machining simulation module which has been implemented on the Internet to facilitate technology integration and industry access for beta testing. Currently, processes covered include end milling (EMSIM), drilling (DRSIM), and face milling (FMSIM). The process simulations provide process performance measures including cutting forces, vibration levels, stability analysis, i.e., relevant primary process responses in accordance to Eq. 8. The basis of these developments are the mechanistic process models developed at the University of Illinois at Urbana-Champaign over the past decade (Kline, et al, 1982 and 1982a; DeVor et al, 1988; Fu and DeVor, 1984; Sutherland and DeVor, 1986; Subramani, et al, 1987; Gu, et al, 1992; and Chandrasekharan, et al, 1996).

Workpiece Attribute Model. The ultimate impact of the VMT project will hinge on our ability to arrive at realistic predictions of workpiece attributes (Eq. 9). Solutions already exist for the computation of machined surface form errors based on cutter compliance (Kline, et al, 1982; Sutherland and DeVor, 1986) and for the evaluation of ideal surface texture/roughness based on tool errors, machine geometric and kinematics errors, and machine tool vibrations (You and Ehmhnann, 1989 and 1991; and Hong and Ehmnnann, 1994 and 1995). The algorithms are being refined and integrated with the other VMT modules.

Workplace/Fixture Module. A development that gives a glimpse of the overall implementation structure and philosophy of the VMT can be given with respect to MT-AMRI Agile Fixturing Project. While it represents a part of the VMT, alone it demonstrates the way of interconnecting and sharing of information between related functional models, and the way such a system can be implemented over a geographically and computationally distributed landscape.

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**Fig. 2. SCHEMATICS OF THE AGILE FIXTURING TESTBED**
The current WEB-enabled version of this module, FIXMA, resides at Pennsylvania State University (De Meter, http://tool.ie.psu.edu:80/~meter/) and provides rigid-body analysis for a user-defined set of locators and clamps (Hockenberger and DeVor 1996). Cutting forces are obtained through the Internet-based interaction of FIXMA with machining simulation users such as ESMIM for end milling (DeVor and Kapoor (http://mtamri.me.uiuc.edu/ESMIM/), located on a University of Illinois at Urbana-Champaign server. Locator and clamp optimization is provided through the Internet-based interaction of FIXMA with a program, OFixDesign, located on a server at the University of Michigan (Cai, et al 1996, 1996a, and 1997). Current research and technology integration activities include reaction force and contact region analysis at Georgia Tech and UIUC (Reams and Melkote, 1996; and Chandra, et al., 1996) and tolerance analysis at UM at PSU (Lee, et al 1996). Figure 2 provides a schematic representation of this module of the VMT system.

CONCLUSIONS
An outline of a concept for the development of a pragmatic simulator for metal cutting operations, designated as the Virtual Machine Tool, was given. The underlying assumptions and work already completed as part of its implementation were also addressed.

ACKNOWLEDGMENTS
The support of NSF and DARPA through the Machine Tool - Agile Manufacturing Research Institute (MT-AMRI) is gratefully acknowledged.

REFERENCES
Deo, N., (1974), "Graph Theory with Applications to Engineering and Computer Science," Prentice-Hall.
Kline, W. A., R. E. DeVor, and J. R. Lindberg, (1982), "A Mechanistic Model and Computer Program for the