Research into Open Architecture Systems

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1. INTRODUCTION

1.1 Changing Functional Expectations from CNC Machines

Manufacturing has undergone a major transformation since the advent of computer numerical control (CNC) technology nearly half a century ago. CNC enables a machine to act in accordance with the CNC part program input to it (see Figure 1.1). Part changeover is accomplished simply by changing the program. The resulting flexibility allows greater part variety at lower cost. This is the 'technology push'. On the side of 'market pull', owing to worldwide trends towards globalization of markets and growing customer affluence, the demand for increased part variety has grown rapidly. As a result, CNC machines have proliferated in batch production environments.

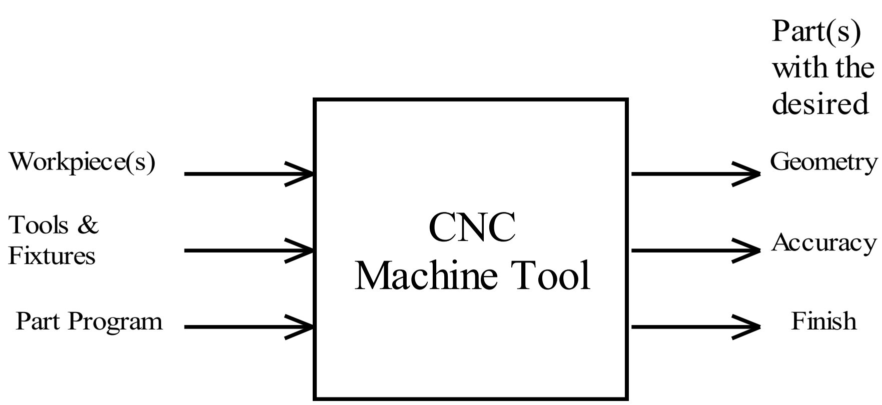

Figure 1.1 Functional view of a CNC machine tool on its own

The second major feature of CNC technology is its ability to cope with part complexity while maintaining high accuracy. In principle, parts with any geometry can be machined by a multi-axis CNC machine tool. Consequently, almost every tool room now utilizes a variety of CNC machine tools. Thus, CNC has become a basic technology for industries engaging in mass production too.

Meanwhile, the appetite for ever-greater flexibility and agility has grown dramatically in industry. The industrial response has been through the development of flexible manufacturing cells (FMC) and systems (FMS). In the new context, a CNC machine needs to be monitored closely through a range of sensors, controlled in new ways, and able to communicate in real time with numerous external devices and systems (e.g., handling robots, autonomous guided vehicles, shop floor computers, and, more recently, the Internet itself to permit collaborative manufacture)—see Figure 1.2.

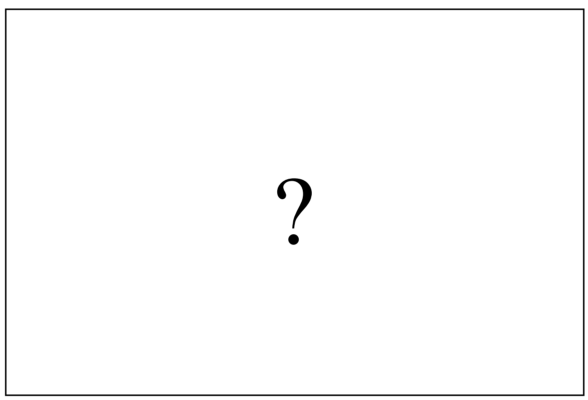

Figure 1.2 Extended Functional Expectations from a CNC Machine Tool

Unfortunately, most machines in operation on machining shop floors around the world had originally been designed with the functional paradigm illustrated in Figure 1.1. Although some newer machines incorporate some of the functions illustrated in Figure 1.2, very few are capable of the full range. For instance, “for the enhancement of the machining conditions to achieve higher accuracy and productivity, custom control functions may need to be introduced in addition to the conventional control functions implemented in the commercially available CNC controllers [Mori 2001]. The result is that there is a wide gap between user-needs and the functional features made available by machine tool manufacturers.

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1.2 The Movement Towards Open System Architectures for CNC Machines

Following the discussion presented in Section 1.2, it should not be surprising that many industrial as well as academic researchers working on enhanced CNC (Computer Numerical Control) machine tools and technologies are often frustrated by their inability to incorporate new functionalities into their existing CNC systems. In fact, the investigating team on the present project itself had experienced such frustration. For example, when we had found a new part probing technique called 'Fine Touch' to be particularly promising [Ostafiev 1997] and tried to integrate into a commercially available turning center, we had to overcome several difficulties. Although we finally managed to overcome these problems by taking advantage of the 'Q-setter' available on the machine, the solution was far from being elegant [Liu 1998]. A more elegant solution could have been found if the machine were capable of responding with instantaneous XYZ coordinates upon receiving a triggering signal from an external computer in close communication with Fine Touch. Likewise, we had recently demonstrated that the cutting forces arising in turning operations could simply be measured through the axis-motor current signals [Cheng 2001]. However, our technique had to use externally mounted Hall effect sensors to monitor motor current signals. On other machines utilizing a current-based control strategy this would not be necessary since the machine would already have a motor current sensing device. However, few manufacturers of turning centers make the motor current signals accessible to the end user. In practice, such 'closedness' could impede the industrial acceptance of the motor current based force estimation technology developed by us.

For example, "Most of the today's CNC machine tool systems are being equipped with CNC controller supplied by controller vendors as a "black box" and this makes it difficult for the machine tool builder to quickly develop and implement the custom control functions [Mori 2001]."

The problem is that most commercially available CNC systems are closed in nature, i.e., they do not facilitate access to the inner features of the CNC controllers and axis control systems. CNC machine control is still a developing field and no universally accepted standards exist for all its features. Hence it is not surprising that each machine tool brand (manufacturer) utilizes its own proprietary hardware and software. As a result, more often than not, this type of proprietary controller design does not allow the end user to autonomously install and interface any new indigenously developed or commercially acquired functional modules so as to enhance the functionality of the machine.

By the early 1990s, the frustration caused by the ‘black box’ nature of commercially available CNC controllers had reached such a magnitude as to prompt several industry support organizations worldwide to start a movement with the aim of promoting the development of open architecture system for CNC machines (OAS-CNC) that is capable of providing the maximum possible flexibility and expandability to the end user of the CNC machine. For instance, in Germany, as early as in 1993, Aachener Werkzeugmaschinen-Kolloquium (Aachen colloquium on machine tools, AWK) had noted the need for open systems for production engineering. Among the other examples is the OSACA (Open System Architecture for Controls within Automation systems; ESPRIT III project 6379) and OMAC (Open Modular Architecture Controls) of USA.

The OSACA project (19923-98) was started with the aim of specifying a system architecture for open control systems that is manufacturer independent The organization believes that its achievements “will reduce the time to market for new products as well as increasing the flexibility of customised control systems and reducing the cost of development, maintenance, training and writing of documentation [OSACA]”

OMAC was initiated with the publication of version 1.1 of "Requirements of Open, Modular Architecture Controllers for Applications in the Automotive Industry" on December 13, 1994, by Chrysler, Ford, and General Motors of USA. The document provided guidelines for a common set of API 's for U.S. Industry controllers to better address manufacturing needs for the automotive industry. Likewise, another group called ‘Architecture’ is in the process of developing a white paper stating the requirements of manufacturing control systems and an OMAC-based manufacturing system architecture [OMAC].

In parallel with the organizational efforts described above towards the development of OAS-CNC, there has been growing interest in the subject area from several academic researchers. Among these, the works of Altintas [Altintas 1990] [Altintas 1993] [Altintas 1996] [Altintas 1998], Erol [Erol 2000], , Koren [Koren 1996], Masahiko [Masahiko

2001] Proctor [Proctor 1993], Pritschow [Pritschow 1993], Teltz [Teltz 1994], Wright [Wright 1990], Yamazaki [Yamazaki 1990] [Yamazaki 1997]and Yellowley [Yellowley 1996] are particularly noteworthy.

1.3 What is Openness in the Context CNC Controllers?

'Openness' seems to mean differently to different people.

The AWK colloquim held in Germany in 1993 had identified three essential features of open CNC systems: interoperability, interchangeability, and portability.

In [Eversheim 1997], eight aspects of 'openness' were noted: Standardized communication, adaptable user interface, harmonized programming, uniform drive interface, opened-up software interfaces, access to process and control data, configurable software, and modular hardware (modular concept).

According to Yamazaki *et al* [Yaamazaki 1997], OAS-CNC should be 'transparent', 'transportable', 'transplantable', ''revivable', 'user-configurable' and 'evolving'.

According to Altintas *et al*, the CNC machine should have user-friendly, reconfigurable and modular monitoring and control system [Altintas 1997].

Erol *et al* say that openness involves satisfying the need for user reconfiguration and modification [Erol 2000]. For example, "one should be able to reconfigure a CNC system designed for a three-axes machine tool to a five-axes machining center control system rapidly by simply interchanging the kinematics-dependent interpolation function." Likewise, the "end users of the CNCs require the addition of new sensor-assisted application-specific modules to the CNC without violating the integrity and reliability of the core CNC functions."

1.4 Advantages of OAS-CNC

OAS-CNC is believed to bring several advantages to the machine tool manufacturers as well as the end users.

The following excerpts from [Eversheim 1997] clarify the advantages to machine tool manufacturers:

- “Machine manufacturers will also be able to assume a new role with the introduction of open systems. Anyone today, who wants to offer a machine with special capabilities or features, must often develop the required controller in-house. With the advance of open controllers this will change: only the functionality that is actually needed to control the special add-ons of the machine will have to be developed by the machine manufacturer. He can buy the necessary base functionality and hardware on the free market, easily integrating his functions using the standardized interfaces. This brings the machine manufacturer two advantages. First, he can now focus on his core competence, machine engineering. He does not have to invest in areas that have no market recognition for his company whatsoever since he is not selling controllers but machines with controllers. Second, he can now market the special controller functionality he developed as well. If, by chance, he has programmed a module for a specific pallet changer, he can sell it to a controller manufacturer who is in the process to solve a similar problem for a customer. Thanks to open interfaces, the type of controller is now of little significance. The benefit of this method is that software written for one application process has returns for many others. The reverse of this new market situation has advantages for the machine manufacturer as well. The development and machine concepts no longer means he has to use a lot of persuasion, time, and money to convince the controller manufacturer to make the functionality he needs available. In the new open market, it will be easy to find a supplier who already offers a controller module for this or a similar case, or one who will implement such a controller module quickly. It might be possible to achieve this function by configuring already existing controller modules which will significantly reduce time-to-market of a product for the machine manufacturer. He is gaining flexibility that will allow him to react to unusual customer requests as well and to improve his market position.
- The integration of machine-specific functionality into a controller will not only become less expensive but also more reliable for the machine manufacturer. With the availability of standardized interfaces, he can, for instance, perform the implementation of technology modules that contain his specialized and extensive

know-how entirely in-house. The exchange of relative material with his controller manufacturer is no longer necessary, which eliminates that his algorithms and strategies are revealed to a third party."

The following excerpts from [Eversheim 1997] clarify the advantages to end users of machine tools:

- "The advantages for the end user are no less obvious... New opportunities for new suppliers mean more competition, better performance and lower prices. With interchangeable systems through standardized interfaces, a supplier can no longer tie his customer to his product with the argument of an expensive system change. He has to convince his customers over and over again with innovation and service challenging him to permanent maximum performance ~ with the customer in mind.
- The user of open systems will not only have the assurance that he is getting the best for his money. His special requests, such as integration of the controller into existing structures of his operation or realization of a special functionality, will be handled quickly and less costly. And, very crucial: with modularity and standardization of the systems, the customer can better compare what he is getting for his money. If everyone speaks the same language, and the functionalities of the individual modules are clearly identified, the user can easily reconstruct whether a certain configuration will either meet his expectations or not.
- It is of no significance, whether the user, judging from view, believes that he might need open systems. Even if he only uses standard applications in his production, has no special requests and is not interested in individual configuration, he will profit from the dynamics of these new market structures. Standard controllers will not develop detached from the high end area. A controller manufacturer who embraces open systems, will most certainly reuse as much of the software internally as possible - that includes his standard systems. Therefore, the user of such systems is going to profit as well from the

restructuring of the controller market because technical development will accelerate and prices will go down.

- The reusability of the software brings another, indirect but great benefit to the user: reusable software translates into the availability of modules that are not only stable but also have a proven track record in the field. It is to be expected that maintenance costs for controllers will decrease and the undesirable "teething troubles" of new systems will be much reduced.
- And the end user will finally profit from the new multitude of functional modules in a market of open systems. Thought processes are not only determined by the problems that must be solved but also by the opportunities that are offered. Individual modules that have entered the market partially based on the solution of very specific problems of a few customers, could expose improvement potential to another user who might otherwise never have envisioned it. Or he combines individual modules in an expected method to create new, innovative solutions for his manufacturing operation."

1.5 Problems Facing Widespread Implementation of OAS-CNC

However, as Eversheim has pointed out [2], open systems have so far remained just a marketing slogan. There are three basic reasons for this: (i) end user apathy, (ii) vendor resistance, and (iii) doubts about the undesirability of forcing standardization in a field that is still undergoing substantial technological development (partly owing to changes in computer and communication technologies).

The following excerpts from [Eversheim 1997] highlight the reasons for end user apathy:

- "The user often hesitates to make an expensive investment in the adaptation which appears necessary for the integration of open systems in a production plant. His interest does not focus on the internal processes of a system, he has to have a total one-stop operational solution.
- There are companies that are viewing this differently, but they are in the minority. Large customers in the automobile industry, for example, make very large demands regarding uniform programmability of the machines and a uniform

interface for graphical machine management and plant-wide diagnostic systems. This means that at this time a centralized collection of operational data for a transfer line with heterogeneous controller equipment is an unreasonably high expense. Each controller type must be specifically adapted in order to capture the targeted data. Even the various controllers of one an the same manufacturer are often equipped with different interfaces.

- There are also problems with retrofitting. At a time when controller hardware becomes outdate much faster than machine technology, it is quite common to improve the performance capability of a production system with the installation of a new controller. However, when switching to another manufacturer, it is often difficult to separate plant systems technology with drives and inputs/outputs from the NC and PLC hardware. Open, standardized system interfaces could remedy this problem."

The following excerpts from [Eversheim 1997] highlight the reasons for manufacturer resistance:

- "Many controller manufacturers do not want to open up their interfaces because they wrongly believe that competitors will be introduced to company –internal know-how, or because they hope that a closed concept will assure them a customer. Indeed, the creation of open system tools looks rather dim, in spite of tough predatory competition in today's market…
- Due to the large effort expended in the development of base functionality, the controller manufacturer will only have a relatively small share of his development resources available for the implementation of market-relevant special functionalities. Of course, a large controller manufacturer might be able to absorb this due to the high sales volume, but smaller manufacturers with respectively limited resources will encounter difficulties. Even if they can offer excellent functionality for certain fields which could be profitably marketed, they depend on the sale of large numbers of units in order to amortize the development of the base functionality…
- One solution to achieving enhanced or extended functionality from an existing machine is to retrofit it. At a time when controller hardware becomes outdate

much faster than machine technology, it is quite common to improve the performance capability of a production system with the installation of a new controller. However, when switching to another manufacturer, it is often difficult to separate plant systems technology with drives and inputs/outputs from the NC and PLC hardware. Open, standardized system interfaces could remedy this problem."

The following excerpts from [3] are worth noting:

- "Starting points for open solutions are primarily seen in the design of user interfaces of controller components. The latest trend is targeting PC based devices with a Microsoft Windows operating system. This openness gives the machine manufacturer a unique opportunity to deliver his machines with uniform user interfaces which is greatly appreciated. The user, in turn, has the opportunity, to configure different systems in his production with a uniform environment. The limits of flexibility, however, are often reached when process signals should be displayed for the user, but the controller manufacturer does not provide them under Windows."
- "Initiatives such as OMAC in the U.S. or OSACA and HÜMNOS in Europe show an interest in the definition of a manufacturer-crossing platform in the controller field, while the concrete conversion into products is still in progress. Even the standardization of interfaces for drives has received a new momentum since General Motors has declared SERCOS its system of choice. The consolidation of existing standards in the field bus area is continuing."
- "Even limited configuration possibilities in NC core functions are now available for newer products of some NC manufacturers. Such interfaces are strictly manufacturer-specific and the extent of allowed modifications is most often limited – it is an initial, though half-hearted start."

Eversheim notes in [2] that "the end user seems to have little interest in extensive intervention opportunities into a controller. His requirements for open systems is first and foremost a uniform user management of controllers made by different manufacturers. For this purpose there is no need for manufacturer-crossing openness. It suffices when the user environment has a certain configurability. The user often hesitates to make an expensive investment in the adaptation, which appears necessary for the integration of open systems in a production plant. His interest does not focus on the internal processes of a system, he has to have a total one-stop operational solution.

The following excerpts from [2] highlight the implications of vendor resistance:

- "Regarding the attitudes of CNC machine vendors, Eversheim notes that "[t]here are companies that are viewing this differently, but they are in the minority. Large customers in the automobile industry, for example, make very large demands regarding uniform programmability of the machines and a uniform interface for graphical machine management and plant-wide diagnostic systems. This means that at this time a centralized collection of operational data for a transfer line with heterogeneous controller equipment is an unreasonably high expense. Each controller type must be specifically adapted in order to capture the targeted data. Even the various controllers of one and the same manufacturer are often equipped with different interfaces. Many controller manufacturers do not want to open up their interfaces because they wrongly believe that competitors will be introduced to company –internal know-how, or because they hope that a closed concept will assure them a customer. Indeed, the creation of open system tools looks rather dim, in spite of tough predatory competition in today's market."

1.6 The Need for Facilitating 'Opening Up' of Existing Machines

According to Eversheim *et al* [Eversheim 1997], "an open system controller will always consists of a number of modules that can communicate interactively via defined functional interfaces." This poses a major problem with regard to the development of OAS-CNC. Assuming that a consensus has been arrived at amongst vendors, end users, and industry support organizations, what exactly should be the 'standard' features of OAS-CNC specification? This is a difficult question to answer given the rapidly changing technologies related to computers and communications that underpin CNC technology. A premature standardization of OAS-CNC will certainly become outdated quickly and could, even, impede the progress of CNC technology in general.

The summary presented in Section 1.3 of the prevailing interpretations of the term ‘openness’ suggests it is an ever-expanding term. There is no limit to the ‘openness’ of a CNC machine. An ‘open’ system designed to meet current needs may not be sufficient sometime in the future. The very specifications of openness may need to be redefined as the technological environment changes owing to developments in sensors, computer hardware and software, communications, the Internet, etc.

From the point of view manufacturers, the next generation machines could certainly be made more open but this does not solve the problems faced by end users of the thousands of existing machines. The users will always find the existing machines to be ‘closed’ albeit to varying degrees. Whatever the state of the worldwide movement towards OAS-CNC, a user interested in incorporating/interfacing one or more new technologies into/to CNC machines already in use in his/her shop floor will have to continue to undertake the task of ‘opening up’ to the required degree. However, experience shows that ‘opening up’ a sophisticated CNC machine control system is not a trivial task, particularly when, as is common problem, documentation supplied is sparse. CNC controllers are complex mechatronic systems whose ‘opening up’ requires interdisciplinary expertise that is well beyond what is usually available with in a manufacturing set up. However, a review of literature has shown that, although the characteristics of OAS-CNC have been discussed widely, little attention has been paid to the issues involved and the facilitating technologies needed in the process of ‘opening up’ an existing CNC machine. This project aims to explore ways of filling this gap.

1. 7 Project Aim

To explore the development of a generic, functional, modular, and expandable tool kit that facilitates rapid ‘opening up’ of the current generation of CNC machines. The tool kit should involve the minimum possible hardware by maximizing the use of software. It would be desirable, if the tool kit could also continually learn, i.e. enhance its performance through its own experiences.

Henceforth, the ‘tool kit’ will be referred to as the CNC-OTK (CNC-Opening Tool Kit).

1.8 Project Objectives and the Organization of the Rest of the Report

Whatever its final structure, the CNC-OTK is likely to include a small set of sensors, some necessary hardware, and software with many functional modules. Hence, the main objectives are:

1. Identify and analyze the general issues that need to be considered while developing a CNC-OTK (CNC-Opening Tool Kit). (See Chapter 2.)
2. Suggest a desirable CNC-OTK architecture. (See Chapter 2.)
3. Select a typical commonly used CNC machine tool, study it in detail, and choose the sensors needed to monitor voltage and current signals from selected tapping points of the machine's controller. (See Chapter 3.)
4. Develop the hardware to match the interfacing requirements of the computer. (See Chapter 3.)
5. Analyze the voltage and current signals using software such as MATLAB, SIMULINK and LABVIEW as appropriate with a view to extracting as much information (that, otherwise, would have been 'closed') information about the controller as possible. (See Chapter 4.)
6. Suggest an action plan for future development of CNC-OTK.

2. GENERIC ISSUES INVOLVED IN THE DEVELOPMENT OF A CNC-OTK

2.1 Prologue

We have noted in Section 1.6 that the problem of 'opening up' existing machines has received little attention in literature. This chapter will examine the problem from a high level viewpoint with a view to identifying the broad issues that need to be considered while developing a CNC-Opening Tool Kit (CNC-OTK).

There exist a large variety of CNC machine tools in use around the world. Indeed, it is unrealistic to assume *a priori* that it is possible to create a CNC-OTK that is capable of 'opening up' *all* these machines. It is more realistic to aim, at least initially, for a CNC-OTK that is capable of 'opening up' at least the majority (i.e., over 50%) of the machines belonging to a class of machines extensively used on machining shop floors worldwide to a degree (of 'opening up') that significantly facilitates the assimilation of new technologies within the shop floor.

Among the various CNC-machine tools in use around the world, 3-axis machining centers seem to be in predominant use. Further, much of the previous work of the PI of the present work was related to the enhancement of the capabilities of 3-axis CNC machining centers. In Particular, the PI had worked on a Mazak H-400N 3-axis vertical machining center. However, because of difficulties in 'opening up' this machine, he could not integrate the newly found technological enhancements into the machine.

In view of the considerations described above, the rest of this report will refer frequently to Mazak 3-axis horizontal machining center (HMC) available in the laboratories of the Department of Manufacturing Engineering and Engineering Management of City University of Hong Kong. Appendix A1.1 shows some views of the HMC. Appendix A1.2 shows some details related to the operating panel of the machine. Appendix 1.3 lists the functional specifications of the machine. Appendix 1.4 shows several drawings outlining the control structure of the machine as given in the user manuals of the machine.

2.2 Opening Up a CNC System is Not a Trivial Task

If the opening up a CNC machine were a trivial task, there would not have been a need for the worldwide movement towards the development of OAS-CNC. However, in Chapter 1, we have noted that, whatever the state of OSA-CNC, there would be a continuing need for 'opening up' existing machines. In order to provide an appreciation of the difficulties involved in opening up a CNC machine, we will now narrate briefly the experience of the writer's team with respect to the Mazak H-400N HMC.

There were several reasons underlying our desire to open up the HMC. Firstly, in one of our research projects, we wanted to utilize a novel system called 'Fine Touch' in performing on-machine measurement of machined parts. This application required the HMC to receive a part contact trigger signal from the Fine Touch probe and transmit the instantaneous axis positions to an external PC. Secondly, in another research project, we needed to monitor the currents drawn by the axis motors in real cutting time. This required us to know whether there were any motor current sensors already incorporated into the machine's control system. If so, we needed to access the sensor terminals. Otherwise, we needed to slip external Hall effect sensors around the input lines to the motor. This, in turn, required us to locate the input terminals to each of the axis motors. In addition, for optimizing our motor current sensing technique, we needed to know certain electrical characteristics (the type of motor—dc, ac, etc.; the control strategy used—voltage control, frequency control, pulse-width modulation, etc.). Finally, in yet another project, we needed to understand the basic characteristics of the position and velocity control loops in order to implement certain new control strategies we had in our mind.

We had in our possession voluminous machine manuals supplied to us by the vendor. However, when we examined these manuals, we found that only a very small part of the information we needed (for implementing the above three CNC development projects) was available explicitly within the manuals. We then opened the control panel of the machine to see whether we could collect the needed information by examining the visible terminals and features of the controller. However, we quickly realized that the task required specialist expertise that we (qualified mechanical engineers) did not possess. We then wrote to the vendors seeking the missing information. The response was cursory and of little use to us. The vendor either did not have the information available (the machines were over 10 years old) or did not find it worthwhile to search through available documents for responding to our queries.

2.3 Defining the Task of CNC-OKT

Every system designer knows the *internal description* [Lathi 1992, p. 92] of the system he/she has designed. The designer often uses this internal description to create a model (analytical or computational) of the system that is capable of anticipating the outputs for a give set of inputs (See Figure 1.1). In other words, the model enables the designer to engage in a process of *deduction.*

There would not be a need for a CNC-OKT if the internal description were available to whatever machine interventions (technological enhancements) he/she is planning. Like the designer, he can anticipate the outputs from whatever machine interventions (technological enhancements) he/she is planning. Such an approach is not totally new. For instance, Yamazaki's group has utilized a 'parallel virtual machine' based on the designer's model [Kommareddy 2000].

However, unfortunately, few manufacturers release the internal description to the user for fear of disclosing some information that gives them a competitive edge. As a result, user-developers are forced to engage in tedious experimentation to obtain an *external description* of the system as seen from the system's input and output terminals [Lathi 2000, p. 92]. The present project aims to explore technologies that can be used to facilitate rapid generation of the external descriptions of diverse CNC machines. It is hoped that the work will eventually lead to the development of a CNC-Opening Tool Kit *(CNC-OKT) that is capable of generating external descriptions of CNC machines that are significantly richer than those that can be inferred explicitly from the machine manuals (normally released by machine vendors).*

However, it is well known in the field of systems engineering that the external description of a system need not always be equal to its internal description. The two descriptions will be equal only if the system is fully *controllable* and/or *observable* [Lathi 1992, p. 95].

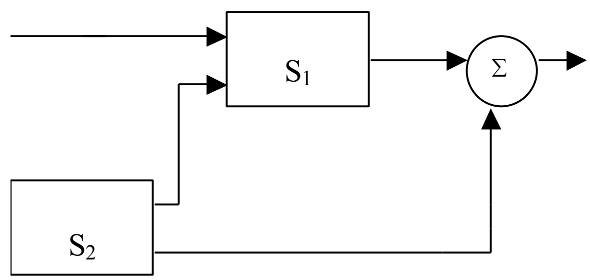

Figure 2.1 A system with an uncontrollable element (S_2)

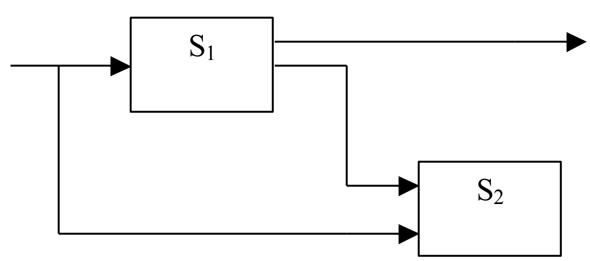

Figure 2.1 A system with an unobservable element (S_3)

In some systems, there could be certain internal elements that are not controlled by the external inputs to the system. In the system in Figure 2.1, the input {I} does not in any way control subsystem S_2. Hence, the external description cannot uncover aspects related to S_2. Likewise, only certain outputs from certainly elements within the system are observable in practice (in fact, many internal output terminals are not even physically accessible owing to modularization and/or protective encapsulation). For instance, Figure 2.2, the output from subsystem S_3 is not observable from the output {O} of the system.

2.4 The Principle of Functional Decomposition: Levels of 'Opening Up'

It is a truism that every machine has been designed to meet certain functional requirements. Figure 1.1 shows the functional view of a CNC machine as perceived, say, by a process planner or a shop floor manager. At this coarse level (say, Level 0), the process planner is not concerned with the inner working details of the machine. All he is interested is in how to input his CNC program to the machine and how he may extract certain rudimentary output signals (such as an overload alarm) from the machine. If the shop is operating in a CNC environment, the input and output signals may need to be interfaced with appropriate shop floor computers and other standard (well-known) external devices. In short, all that is 'visible' to the planner/manger are the terminals for inputting the CNC commands and outputting the desired monitoring signals. These terminals are usually identified explicitly in the machine's user manual. Table 2.1 lists the Level 0 terminals specific to Mazak 400N HMC. The rest of the machine, however, is a 'black box' [Mori 2001] to a user at Level 0—as illustrated in Figure 2.3.

Table 2.1 Level 0 interfacing ports (terminals) of Mazak H-400N HMC

S. no.	Name of interface with operator	Description
1	MDI	This is a keyboard for manual data input
2	CRT display	To display parameters, part programs, and alarm indications.
3	DNC interface	It is RS232C connecter to establish communication between CNC and host CPU (External computer).
4	Mazak micro-disk system	To download information in CNC controller.
5	Magnetic tape reader	To input program using magnetic tape reader

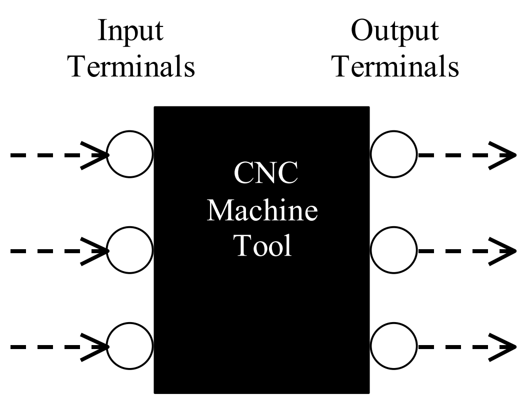

Figure 2.3 CNC machine tool as a 'black box'

Intuitively, it would appear that it should be possible to decompose the black box in the Level 0 representation shown in Figure 2.3 into a set of coarse elements shown in Figure 2.4 where each element is devoted to a certain sub-function of the Level 0 functional black box. In the Level 1 view, all that is 'visible' to the user are the accessible terminals of the decomposed modular elements.

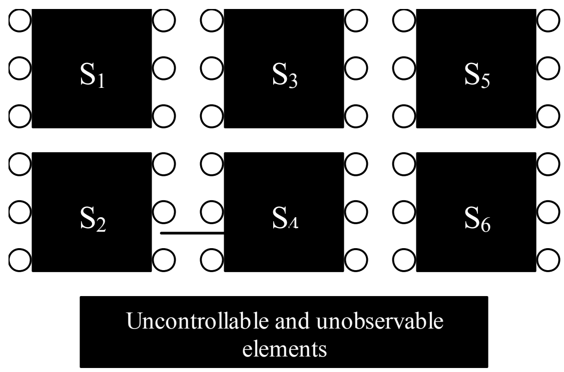

Figure 2.4 Level 1 decomposition

Figure 2.5 shows the Level 1 functional view of Mazak H-400N HMC. Now, it turns out that a large subset of CNC machines in use around the world have Level 1 functional views that, in essence, are similar to that shown in Figure 2.5—the only differences being in the number and natures of axes, the variety of auxiliary functions, and the way the Level 1 sub-functions are implemented internally in each modular element. In principle, it should be possible to systematically classify currently available CNC machines into certain types of Level 1 implementations. For the moment, we will assume that such taxonomy of CNC machines has been developed through further research.

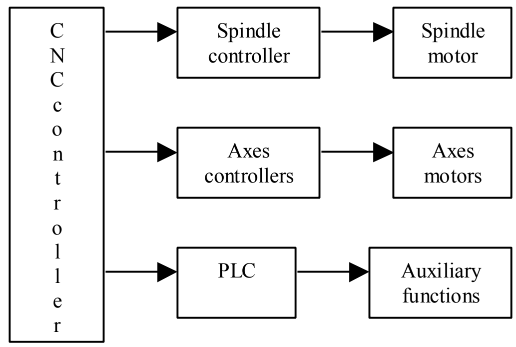

Figure 2.5 Level 1 functional view of Mazak H-400N HMC.

Note that level 1 has finer granularity than Level 0. This insight leads to the possibility of repeating the above procedure to generate higher (finer) levels of functional representation of CNC machines.

Figure 2.6 shows the Level 2 representation of the X-axis (feed) drive of Mazak H-400N HMC. Figure 2.7 shows the Level 3 representation of the X-axis servo-amplifier. Note that one of the functional elements in this representation is 'axis servo amplifier'.

In theory, the above multi-level decomposition strategy can be carried through to many levels. However, at a certain level, the decomposition process must stop because of the requirement that the input/output terminals of the sub-unit in question are accessible, i.e., the user can physically locate and access them for the purpose of tapping voltage/current signals (this feature will be explained later) at the terminals. (Thus, it is unlikely, that the decomposition will proceed to the level of individual electrical components such as resistors and capacitors. In fact, with the growing trend towards modularization of CNC control units, it is unlikely that we would ever need to go beyond Level 4 or Level 5. This report will attempt to study the Mazak HMC up to Level 2.)

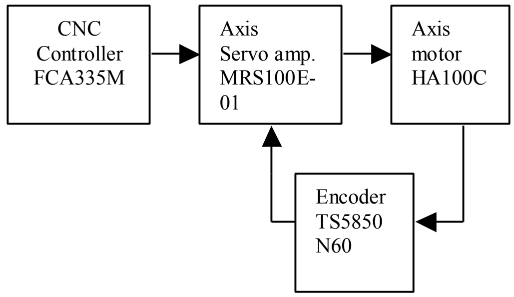

Figure 2.6 Level 2 functional view of Mazak H-400N HMC.

What is the significance of the Principle of Functional Decomposition described above in the implementation of CNC-OTK? Recall that each functional element at Level (x) representation fulfills a certain sub-function of the parent element in Level (x-1). Further, it is assumed that each representation belongs to one specific type of predetermined class of elements satisfying the particular sub-function in question. For instance, the Level 2 representation of the Mazak HMC has an element called 'X-axis motor'. The sub-function of this element is 'apply torque to rotate the input shaft to the X-axis feed box'. There certainly are many ways of implementing this sub-function. Some may use dc servomotors. Others may use 3-phase ac servomotors. However, at any particular time, the number of technological entities available for satisfying this specific sub-function are finite. Further, the specification of an ac motor necessarily constrains the variety of ways in which the other elements at the same level (e.g., the 'axis servo amplifier' in Figure 2.6). These two insights lead us to the possibility of coping with the apparently enormous variety of CNC machines around the world into a finite number of broad architectures each of which has substantial commonalities (similar features) at each level of decomposition. Arriving at this scenario will of course depend on how systematically we have been able to classify CNC machines in terms of their multi-level architectures. Achieving this objective will require substantial further research and is outside the scope of the present project. The main point to emphasize here however is that the principle of functional decomposition gives one the hope that it should be possible to develop a CNC-

OKT that can enable the ‘opening up’ of at least the majority of the commonly used CNC machines in industry (See Section 2.1).

2.5 Functional ‘Graying’ the Black Boxes by Monitoring V-I Patterns

Once the multiple-level decomposition has been effected, we would have arrived at a set of controllable and observable sub-systems along with the physical locations of the corresponding input-output terminals. Since we had decomposed the system using a functional viewpoint, we would already have some idea of the function and type of the specific subsystem in question. In other words, we know the nature of the subsystem, e.g., that is a motor, encoder, etc. However, the system will still appears as a ’black box’. We now need to ‘gray’ them, i.e., obtain as many insights as possible into the internal characteristics of the systems.

As an example, consider the Level 2 representation of the X-axis feed drive of the Mazak HMC (See Figure 2.6.) that we had arrived at by perusing the machine manuals. At this stage we could identify the following specifications of the motor: ‘Mitsubishi HA103C, 3-phase, star-connected servomotor, maximum speed = 2500 rpm, rotor current (I_r) = 10A, stator current (I_s) = 14A, armature resistance (R_a) = 0.31 ohm. This information was inadequate for our purposes (we had wanted to identify the current-torque relationship of the motor for the purpose of cutting force monitoring). We then approached the respective manufacturers for detailed information. However, the vendors did not divulge any information since the units were “obsolete”. In other words, these two units remained as ‘black boxes’ to us. We needed next to ‘gray’ them.

Note that CNC controller elements are all usually electrical and/or electronic in nature. Hence, all that happens at each pair of terminals is that a voltage is applied and a current is transmitted. Hence, everything that is observable at the terminals can be inferred from the voltage and current signals and the relationships between them. One can also compare the voltage and current signals at the input and output terminals so as to determine the ‘transfer function’ of the sub-system [McCarthy 1972]. The inferences thus derived present an external description of the sub-system.

It is important to emphasize that the functional view should be maintained while 'graying' the subsystems. The voltage/current patterns must be observed while the functional unit is performing under a functional command issued at Level 0. This principle ensures that the process of 'opening up' has not, in anyway, changed the machine— thus maintaining the operational integrity of the machine on the shop floor. This procedure therefore differs from the 'reverse engineering' techniques usually followed by product development teams. In reverse engineering, one dismantles the machine into subsystems and component parts of interest and perform specific tests (electrical or otherwise) that are not necessarily related to the operational function of the subsystem. Such an intrusive and possibly destructive approach is untenable in the context of 'opening up'. The merit of functional decomposition and functional graying lies in avoiding this danger.

The specific voltage/ current patterns to look for and the signal processing techniques that are able to reveal these patterns will differ from one type of subsystem to another. For instance a resolve would exhibit continuous sinusoidal voltage pattern whereas a digital encoder will exhibit a train of voltage pulses whose pattern will depend upon the specific type of encoder. However, fortunately, the variety of position measurement devices in use in CNC machines are finite and the voltage/current patterns associated with each type are well documented in literature. Hence, in principle, following a targeted literature review, it is possible to identify the basic characteristics of voltage/current signals associated with each type of subsystem. It should be possible then to create a structured knowledgebase that encodes the patterns associated with different subsystem types in industrial use along with the arrays of test procedures (signal processing techniques) needed for revealing those patterns.

Table 2.2 summarizes the generic manual procedure for opening up CNC machines resulting from Sections 2.4 and 2.5.

Table 2.2 A generic manual procedure for opening up CNC machines

Step 1	Study the user manual and the electrical circuit diagrams
Step 2	(a) Perform functional decomposition into Levels 0, 1, 2, 3, on the basis of electrical circuit diagrams (See Section 2.4). (b) Identify the type of each subsystem at each level.

Step 3	Examine the machine manual to check whether a rich enough description of each subsystem is available. If so, note the information and terminate the further 'opening up' of the 'richly described' subsystems.
Step 4	(a) Reexamine the machine manual to identify the maker's labels of the remaining subsystems. (b) If the label is available, obtain relevant manuals from vendors and examine them to whether a rich enough description of each subsystem is available. If so, note the information and terminate the further 'opening up' of the 'richly described' subsystems.
Step 5	Study the machine manual and locate the input and output terminals for each of the remaining subsystems
Step 6	(a) Study relevant literature and identify appropriate functional test procedures and the resulting voltage/current patterns of potential interest with respect to each remaining subsystem. (b) Prepare test process plans for each test identified in Step 5(a). Note: Step (b) may involve a variety of decisions concerning the sensors required, data acquisition techniques, signal processing techniques—time and frequency domain analyses, wavelet-based de-noising and decomposition techniques, and signal pattern recognition techniques.
Step 7	(a) Perform each of the tests identified in Step 5(b) according to the test process plan and note the characteristic parameters and features of each remaining subsystem. (b) Prepare a report summarizing the findings from the 'opening up' exercise.

2.7 An Architecture for CNC-OTK

Clearly, the generic manual procedure shown in Table 2.2 for opening up CNC machines is quite tedious. This is the reason why most user-developers are reticent to undertake CNC machine 'opening up' exercises even though they have a pressing need for the same. The traditional response to this problem has been through organizational efforts promoting ever more open CNC systems (CNC-OAS). However, as we have already noted, the need for opening will always remain. It is therefore useful to examine how we could reduce the tedium and expertise involved in implementing the generic opening up procedure outlined in Table 2.2.

Note that Steps 1 to 5 in Table 2.2 involve browsing through hard copies of machine manuals and/or literature collected from component specific vendors. Hence, it is impractical (with present day technologies) to partially or fully automate these processes using computerization. However, the most tedious part of Table 2.2 is Steps 6 and 7. These are also the steps that require the user-developer to possess or acquire substantial technical knowledge and expertise. A review of the current status of knowledge systems [Coyne 1990], expert system [Giarratano 1994], automatic testing test equipment (ATE) [Brindley 1991] [Ligori 1974] and diagnostics [Simpson 1994] of electrical/electronic assemblies indicates that it should be technologically feasible to computerize much of the effort involved in Steps 6 and 7.

Step	Activity	Input from	Db	Kb	Reasoning module	Output to
1	Receive specific machine functional capabilities	User through *HMI*	Machine Functional Capabilities Db	-	Gets required input/information from the user using dialog box	
2	Identifying specific subsystem details	-	Searches subsystem database	Consults subsystem knowledgebase	Identifies subsystem using report generation software module	Communicates with user via HMI.
3	Preparation of interfaces with OTK's	-	Consults CNC machine database	Consults CNC machine knowledgebase	Prepares wiring diagrams using wiring diagram generation	Communicates with user via HMI

	interfacing hardware				software module	
4	Preparation of machining process Collecting data.		Machine functional capabilities database and subsystem database	Machine functional capabilities knowledgebase and subsystem knowledgebase	Prepares plan for machining process using machining process software module. Data collection software module	Communicates with the user to perform machining Initiates the data acquisition system module to collect data
5	Generating reports		Consults process database and subsystem database	Consults process knowledgebase and subsystem knowledgebase.	OTK's analysis software module such as time domain analysis, frequency domain, wavelet modules ete.	Displays summary report.

Before starting	User performs Steps 1 to 5 in Table 2.2 to, identifies the specific CNC subsystem to be 'opened up' and its basic characteristics and starts OTK.

↓

Step 1	OTK's *HMI* displays input dialog screen. *User* communicates CNC machine functional capabilities and known details of CNC subsystem to be opened up.
Step 2	OTK's Report generation Module searches *CNC subsystem database* to match the specific subsystem at to be 'opened' up. If there is a match, the module displays the appropriate *Report template* and the exercise is terminated.
Step 3	OTK's *wiring diagram generation* module consults *CNC machine database* for a match with the specific machine. If there is a match, it issues explicit instructions to the user indicating the *terminal connection procedures*. If no match is found, OTK communicates connection requirements from its side and seeks confirmation that the connections have been made.
Step 4	OTK reasons on the basis of the functional capabilities of the CNC machine and the specific *subsystem knowledgebase* to decide the required conditions of the subsystem intended to be opened up. Upon receiving confirmation, OTK asks the user to start machining operation. After the machining is started, it collects data through *data acquisition hardware and software.* Then, OTK's data acquisition module asks the user to stop machining.
Step 5	OTK's analysis module processes the acquired data using *software programs* in time domain, frequency domain, and wavelet de-noising.
Step 6	OTK performs software programs to find out parameters related to subsystem and process using subsystem and process database
Step 7	OTK displays summary report and prints the report and keeps the summary for its future use in *knowledge base*

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Knowledge is a fluid mix of framed experience, values, contextual information, expert insight and grounded intuition that provides an environment and framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of knowers. In organizations, it often becomes embedded not only in documents or repositories but also in organizational routines, processes, practices, and norms.
- by Thomas Davenport and Laurence Prusak