Chapter 4
The University of Tokyo IMS

4.1 Introduction

Supported by TJTTP-OECF (Thailand-Japan Technology Transfer Project – The Overseas Economic Cooperation Fund), the author was sent to study the fundamental concepts of IMS at Nagao-Mitsuishi laboratory at The University of Tokyo, Japan during April 1^{st} – August 31^{st} 1997.

This chapter will describe the structure of IMS and an intelligent machining center implementing at the Department of Engineering Synthesis, The University of Tokyo, Japan.

Actually, there are many researches on IMS in many laboratories and schools of engineering throughout the world. It is indeed difficult to definitely make any conclusions about the fundamental concepts of IMS from a specific group of researchers or a laboratory. Since the concepts of IMS has not been completely developed yet, this thesis will be developed base on the research done at The University of Tokyo.

4.2 The University of Tokyo IMS

Since 1993, The University of Tokyo, Japan, has setup a workshop of IMS as shown in Figure 4.1 [30]. The system consists of the following machine tools.

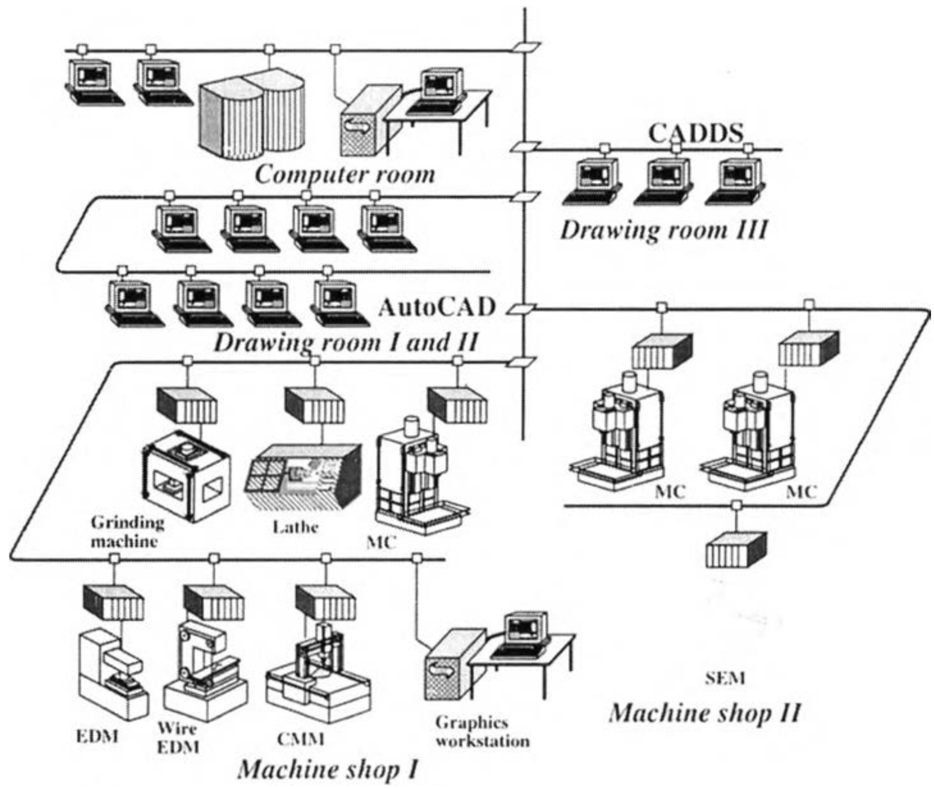

Figure 4.1 : The University of Tokyo Intelligent Manufacturing System

1. **a machining center** (power of spindle 5.5 kW, max.rotation 8000 rpm, taper of spindle ISO 7/24 taper#40, table 720 mm. × 40 mm., table shift 510 mm. × 410 mm. × 460 mm.) This machining center is equipped with deformation sensors, thermal distortion compensation, six-axis force sensing table. It was originally designed by Hatamura et al. [9][10][12][13] and developed by Hamai Co.,Ltd. See Figure 4.2.
2. **an NC lathe** (power of spindle 15 kW, max. rotation 4,500 rpm., max. size of workpiece ϕ370 mm. × 500 mm.) This is the first information-oriented lathe of Okuma Co., Ltd. which can be controlled via UNIX, MS-DOS and OSP (Okuma Works' Operating System). It is equipped with information

and force sensors to detect and automatically avoid chatter. It can compensate for thermal deformation. See Figure 4.3, 4.4, and 4.5.

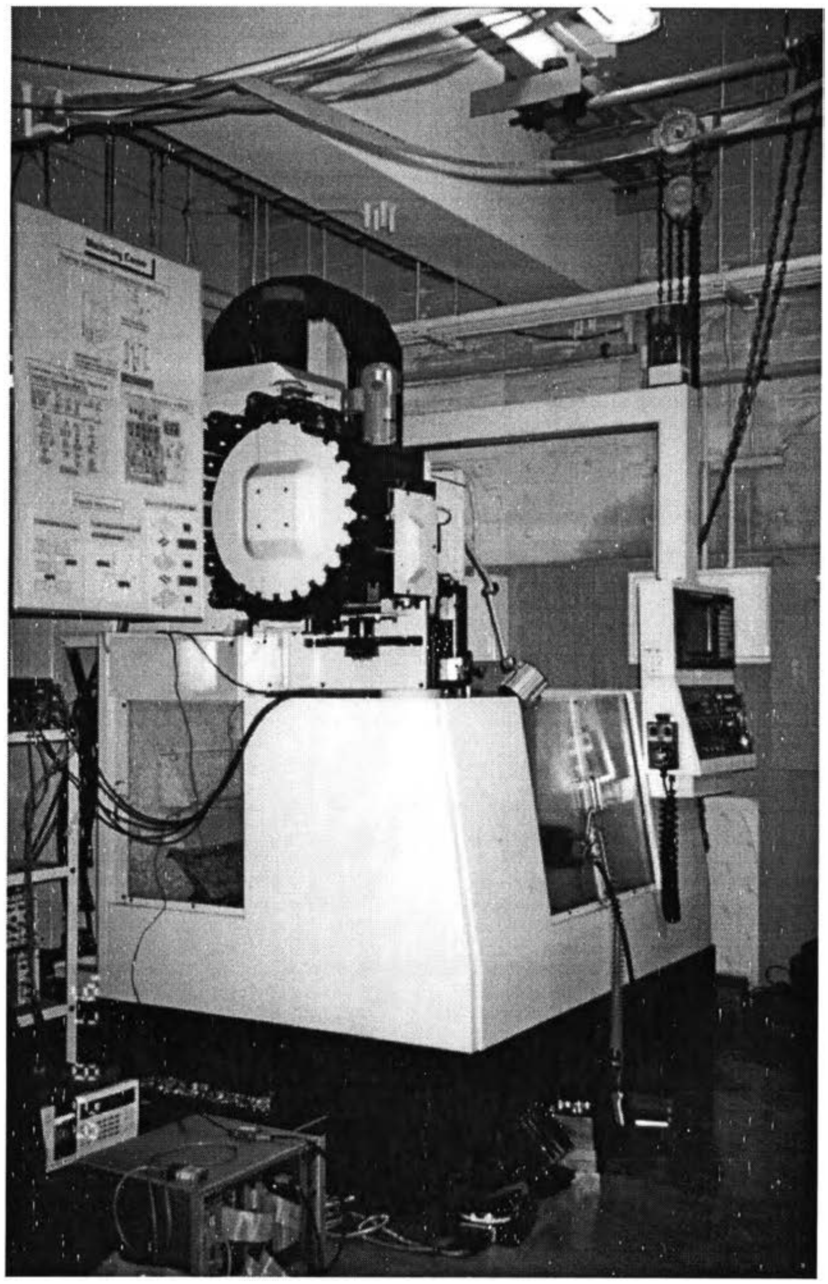

Figure 4.2 : An Intelligent Machining Center

3. **an NC precision face grinding machine** (power of spindle 1.5 kW, rated rotation 5,000 rpm., table shift 600 mm. × 350 mm. × 200 mm.) This

machine was design by Hatamura et al. [11] and developed by THK Co., Ltd. It is equipped with the deformation sensors to compensate its thermal and force deformation. It also has four columns and guides with piezo-driven adjusters to adjust each of their heights. The spindle has a remote-centered compliance mechanism (RCC) to avoid jamming of the wheel. This is ultra-precise for the grinding of waters and thin glass plates. See Figure 4.6 and 4.7.

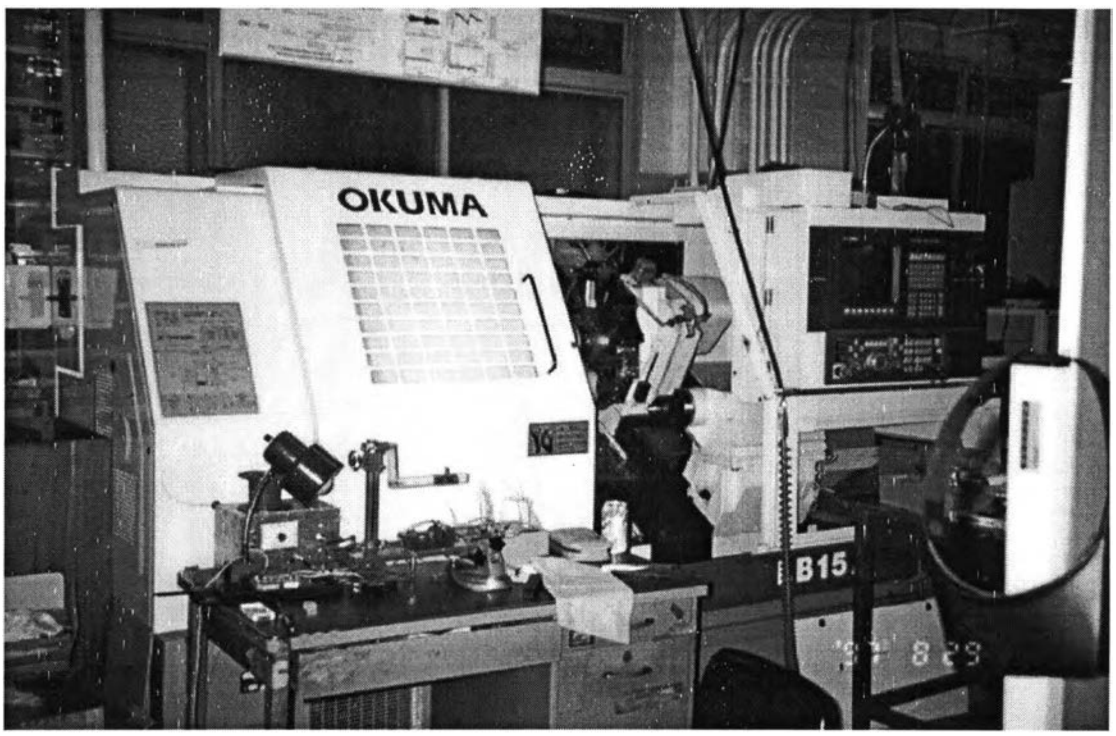

Figure 4.3 : An Intelligent Lathe

4. **an Electrical Discharge Machine (EDM)** (max. size of workpiece 750 mm. × 550 mm. × 210 mm., max. current 150 A, min. resolution of angle 0.001°, min. resolution 0.1 μm) See Figure 4.8.

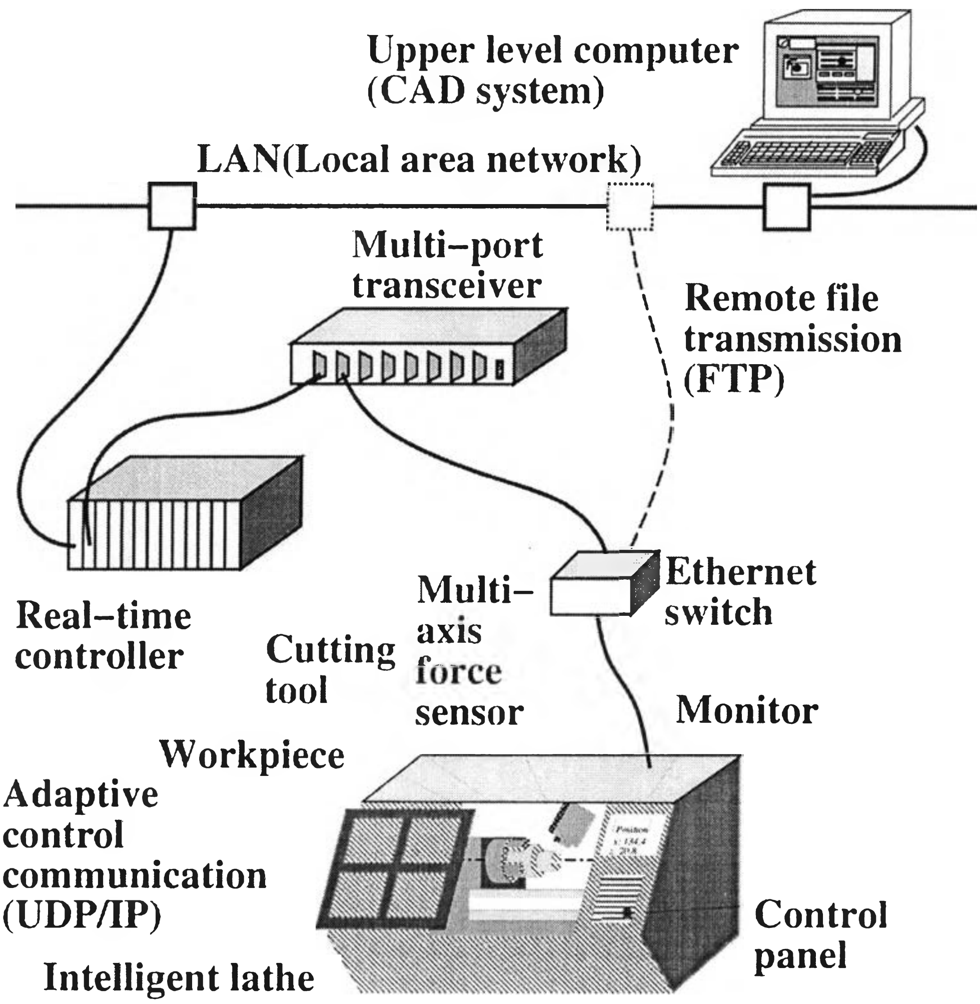

Figure 4.4 : Connection between upper level computer and real-time controller with Intelligent Lathe

5. **a Wire-Cutting EDM** (max. size of workpiece 690 mm. × 530 mm. × 260 mm., diameter of wire ϕ0.1-0.3 mm., min. resolution 0.1 μm.) This machine can make a plate thinner than 50 μm or a force sensor with a few mN of rated force which is necessary to detect force and control a micromachining device. See Figure 4.9.

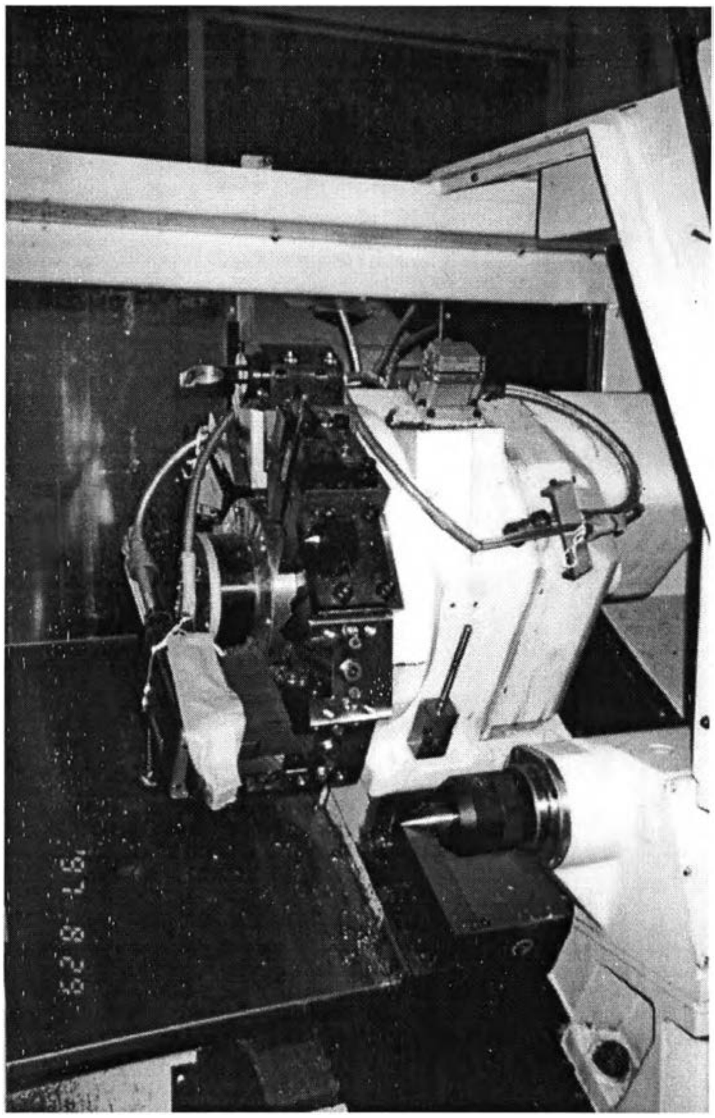

Figure 4.5 : The Spindle Head of Intelligent Lathe

6. **a 3D Coordinate Measuring Machine (CMM)** This CMM is equipped with the deformation sensors as shown in Figure 4.10, 4.11, and 4.12.

Those aforementioned machines are modified to be information-oriented which connected to the computer network (and also to the internet) and each exchanges information with a real-time controller and a workstation implementing adaptive control.

Figure 4.6 : An NC Precision Face Grinding Machine

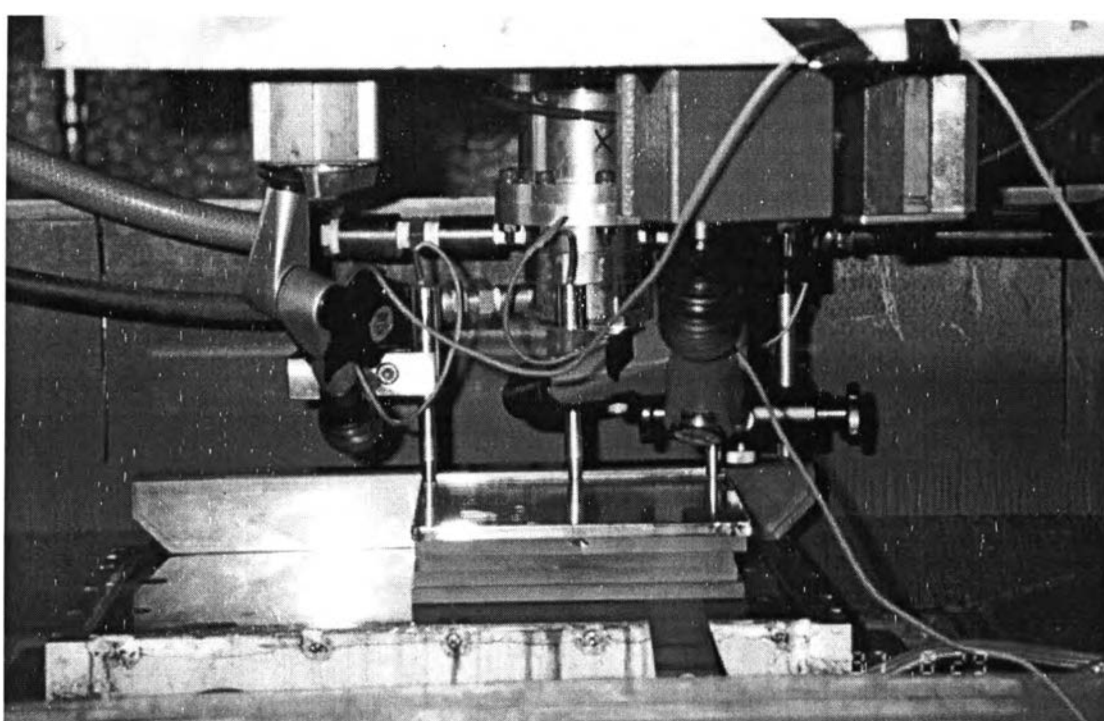

Figure 4.7 : An NC Precision Face Grinding Machine while working

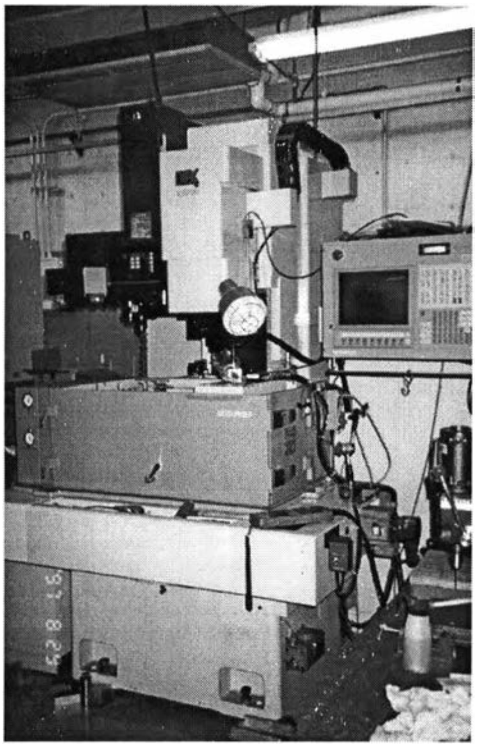

Figure 4.8 : An Electrical Discharge Machine (EDM)

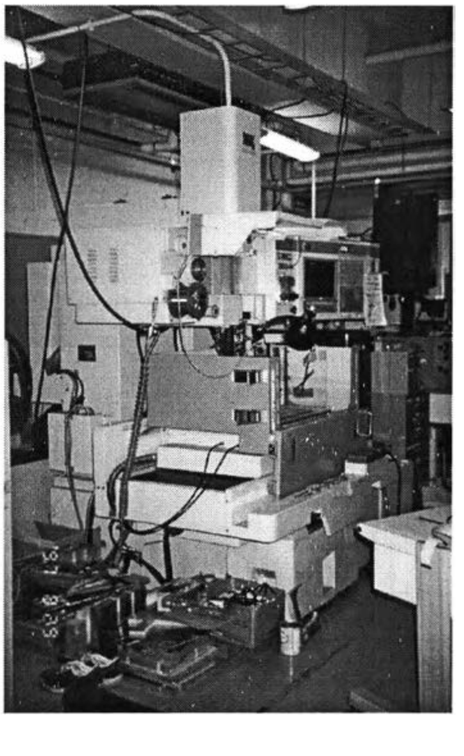

Figure 4.9 : A Wire-Cutting EDM

Figure 4.10 : A 3D Coordinate Measuring Machine (CMM)

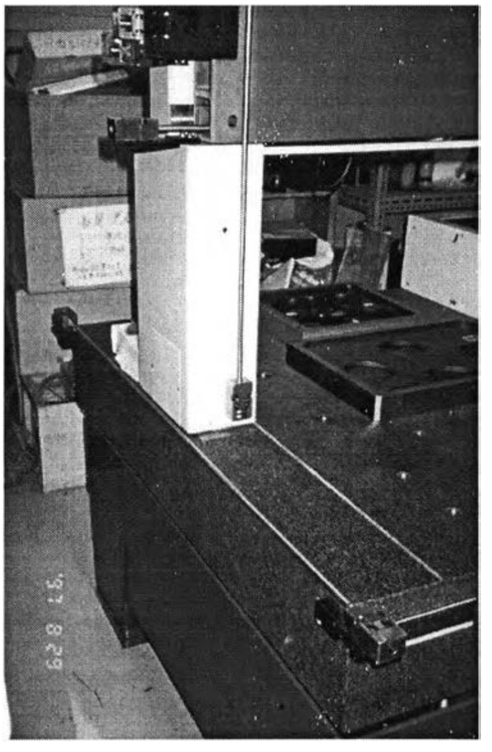

Figure 4.11 : A CMM equipped with Deformation Sensor

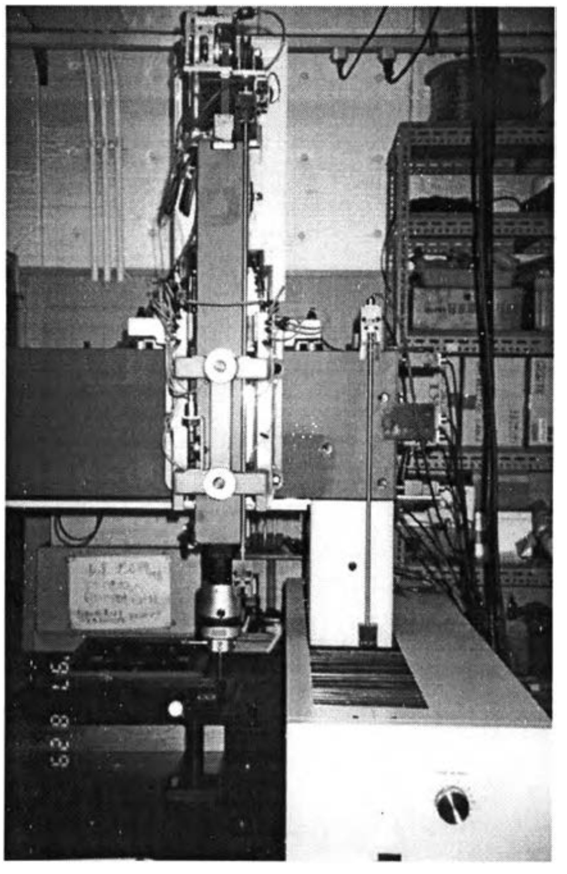

Figure 4.12 : A CMM equipped with Deformation Sensor

4.3 Principles of Designing the Intelligent Machine

To design an intelligent machine, Hatamura et al. [11],[13] propose a conceptual design process which compose of the main eight principles of machine design and six fundamental principles necessary for realizing the intelligent manufacturing as follow.

The main principles of machine design

Principle 1 **[Machine and Beauty]**

All machines and their component parts must satisfy balance, beauty, proportion, footing and position of the center of gravity. In the case where these are not satisfied, there must be very fatal flaws in the designed machine.

Principle 2 **[Machine and Force Flow]**

Forces flow in all machines. They are shown as force trajectories.

Principle 3 **[C-Circle of Force]**

The force trajectory in all manufacturing machines constructs a C-shaped circle where the tool is a starting point and workpiece is an ending point.

Principle 4 **[Working Error]**

The discrepancy between the starting point and the ending point in the "C-circle" generates working errors.

Principle 5 **[Deformation Causes of Machine]**

The main causes of the deformation of the "C-circle" are heat and force.

Principle 6 **[Breakage of Machine]**

In almost all cases, a machine deforms by bending, and then breaks when the surface strain reaches its allowable maximum strain. It is very unusual for a machine to fail in tension or shear across its full section.

Principle 7 **[Nap of Central Part]**

The central portion of a machine structure is taking a nap. This portion can be converted to a cavity, because it is not contributing to bending stress. Moreover it is the most suitable space for a transmission route of information and energy.

Principle 8 **[Conceptual Operation]**

Conceptual operations are very effective in machine design. For example, in machine design, it is almost always possible to convert mutually between a passive component and an active component. By using this principle alone, many kinds of new ideas can be generated almost automatically.

Fundamental principles necessary for realizing the IMS

In order to make an intelligent machining center which can realize high accuracy without requiring a constant temperature environment and specific high rigidity, the following principles have been adopted.

Principle 1 **[Working and Information Emission]**

All phenomena in manufacturing emit information in various forms such as through force, heat, sound, strain deformation, vibration, and light.

Principle 2 **[Working and Model]**

The relationship between the information and phenomena in manufacturing, and the mutual relation between any two factors in the information are pre-determined. The relation particular to the manufacturing systems are described by models and the general relation among working phenomena are described by knowledge.

Principle 3 **[Control of Phenomena]**

Required phenomena in manufacturing can be realized by using the relations discussed above.

Principle 4 **[Conversion from Passive to Active Countermeasure]**

In traditional machine design, high rigidity and constant temperature environment are used to minimize deformation caused by force and heat respectively. Both of these are passive countermeasure. In an intelligent machine, completely different countermeasure are adopted, where passive measure are converted to active measures.

Principle 5 **[Fundamental Elements for IMS]**

In order to realize intelligent manufacturing, three fundamental elements : sensors which extract information from the phenomena, knowledge which describes the mutual relationships of information, and actuators which change phenomena according to the information produced, are indispensable. In addition, a deformation element, which is the forth element, is also indispensable in order to construct a concrete system.

Principle 6 **[Conceptual Method for Intelligentization]**

Conceptual operation is effective in realizing the desired performance and mechanisms of intelligent manufacturing systems. In particular, the two issues of the information emission from the C-circle of force and the mutual conversion between passive and active elements are critical. For example, with regard to the latter issue, the following design principles can be developed. If one wants to reduce deformation, he/she should actively generate the correct deformation to cancel the effects of any naturally produced deformations. A structure, which is a typical passive element, can be converted to an actuator, which is an active element. It is possible to convert mutually between a sensor and an actuator, or a tension spring and a compression spring.

4.4 Design of an Intelligent Machining Center

To design an intelligent machining center, four main functions (functional requirements, FRs) : detection of deformation, calculation of compensation values, implementation of compensation and countermeasures to excess force are essential.

Each function is decomposed to lower level elements. The mechanism elements are determined corresponding to each functional requirement. This determination made by mapping process as described by Suh [38] in chapter 3.

At the lower level, they are realized as a deformation sensor, six-axis force sensing table, torque-thrust sensor, a neural network system, thermal actuators and a hydraulic fail-safe system, fail-safe table, etc.

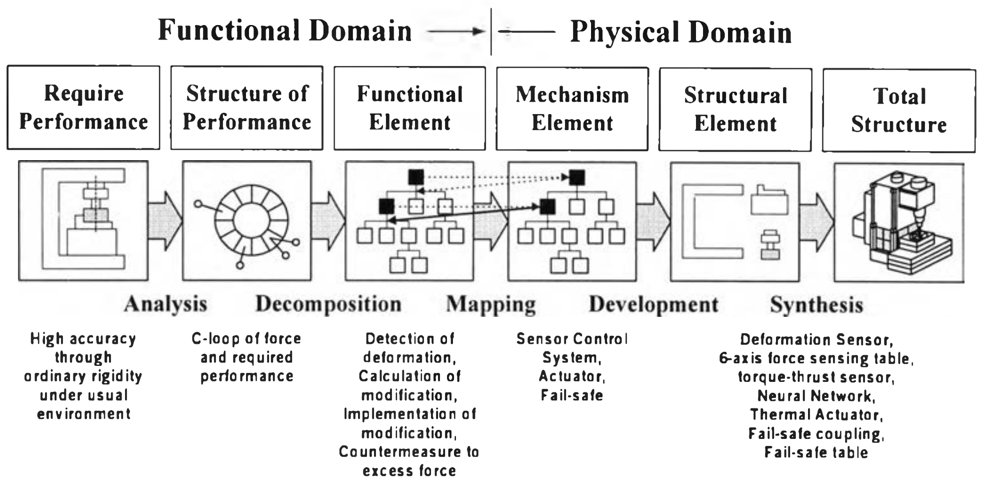

Figure 4.13 : Conceptual Designing Process of an Intelligent Machining Center

Consequently, the detail and concrete characteristics such as dimensions and material of each mechanism element are added and developed into a structural element.

Finally, all structural elements are synthesized to one machine satisfying the various constraint conditions. The conceptual development process in the design of an intelligent machining center is illustrated in Figure 4.13.

For the intelligent machining center, there are three important elements needed, in addition to the usual mechanisms, **sensors elements**, **actuator elements**, and **deformable elements**. [12]

Sensor elements are served for gathering information, such as a force sensor for detecting the cutting force and deformation sensors for detecting the deformation of the machine structure.

Actuator elements are served for deforming the machine tool structure in response to the sensed distortions.

Deformable elements are served as fail safe mechanisms to protect the system by retracting and stopping the feed motion when an unexpected excess force appears during working.

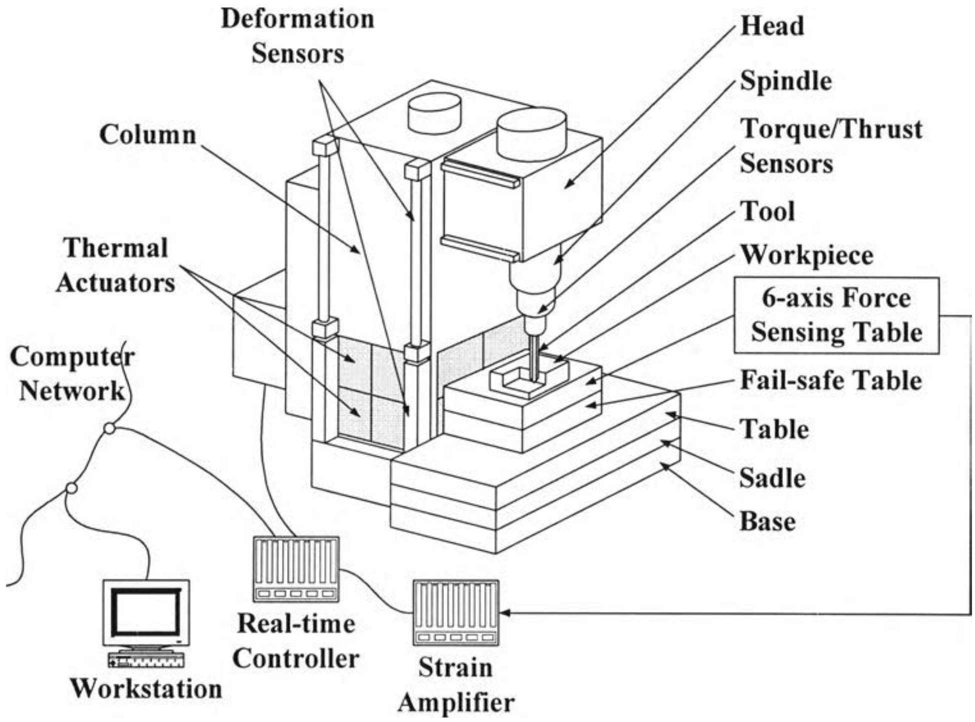

Figure 4.14 : Structure of an Intelligent Machining Center

Figure 4.14 illustrates the structure of an intelligent machining center which equipped with Thermal Actuator, Deformation Sensors, Torque/Thrust Sensors, 6-axis Force Sensing Table, and Fail-safe Table. The output signal from the force sensing table is amplified by a strain amplifier and sent to the real-time controller. The real-time controller, the database and the CAD system are connected and integrated with each other through a computer network.

Figures 4.15, 4.16, 4.17, 4.18, and 4.19 show an intelligent machining center, spindle head with a deformation sensor, connection of the machining center with a strain amplifier and a real-time controller, a strain amplifier, and a real-time controller, respectively.

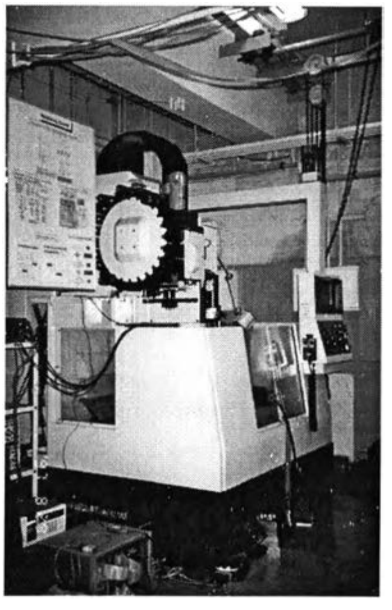

Figure 4.15 : An Intelligent Machining Center

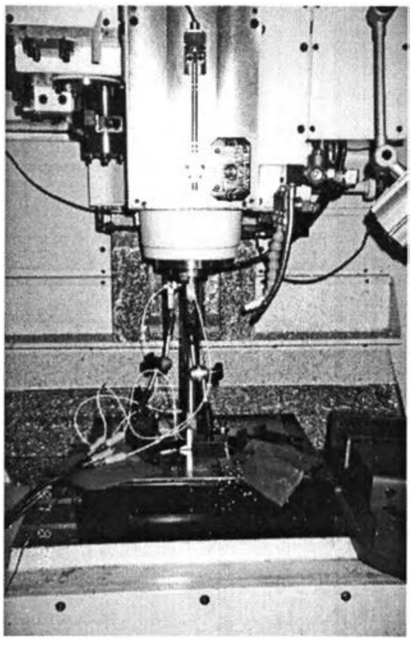

Figure 4.16 : Spindle with a deformation sensor and six-axes force sensing table

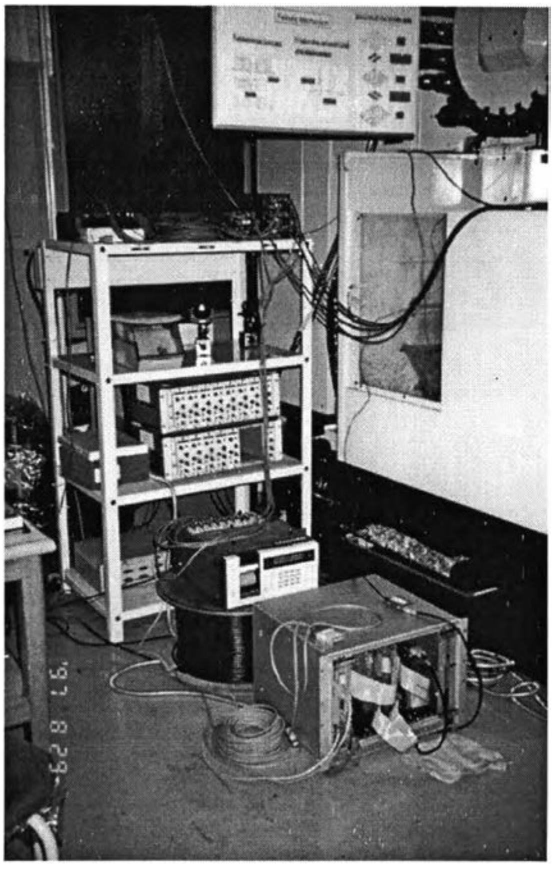

Figure 4.17 : Machining center with a strain amplifier and a real-time controller

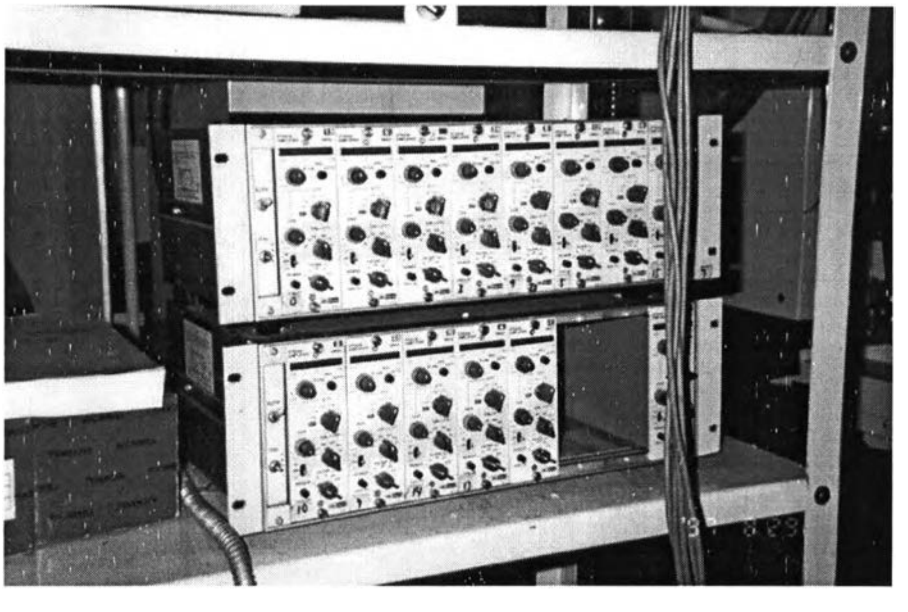

Figure 4.18 : A strain amplifier

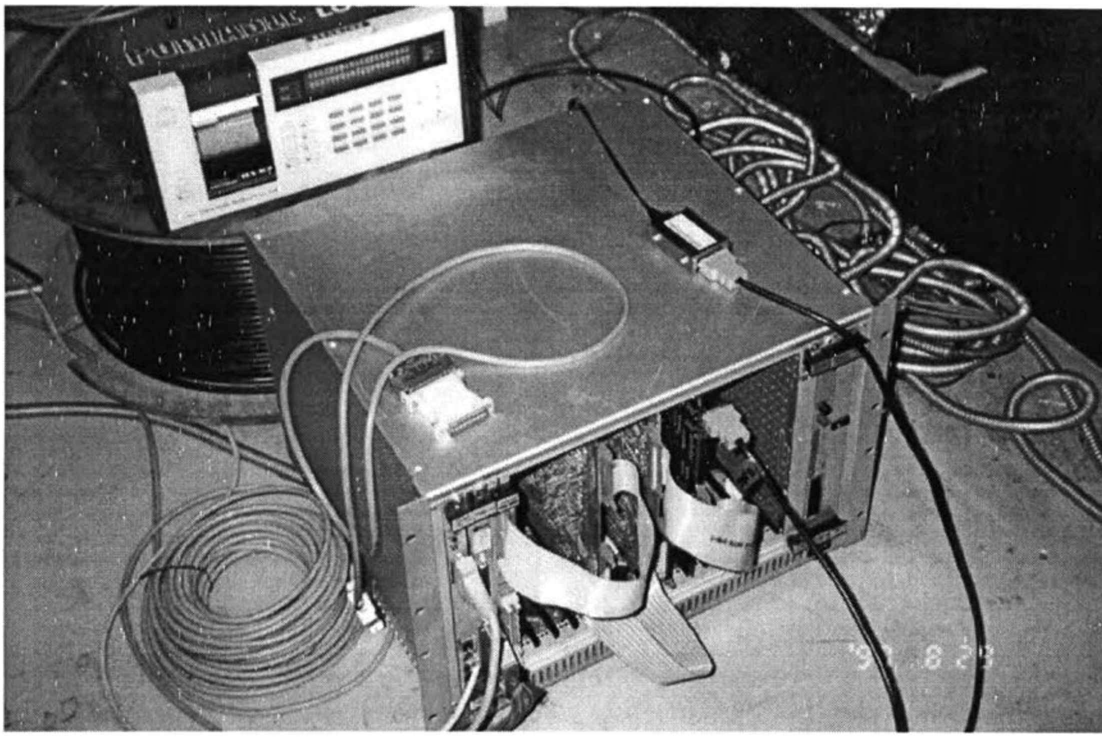

Figure 4.19(a) : A real-time controller

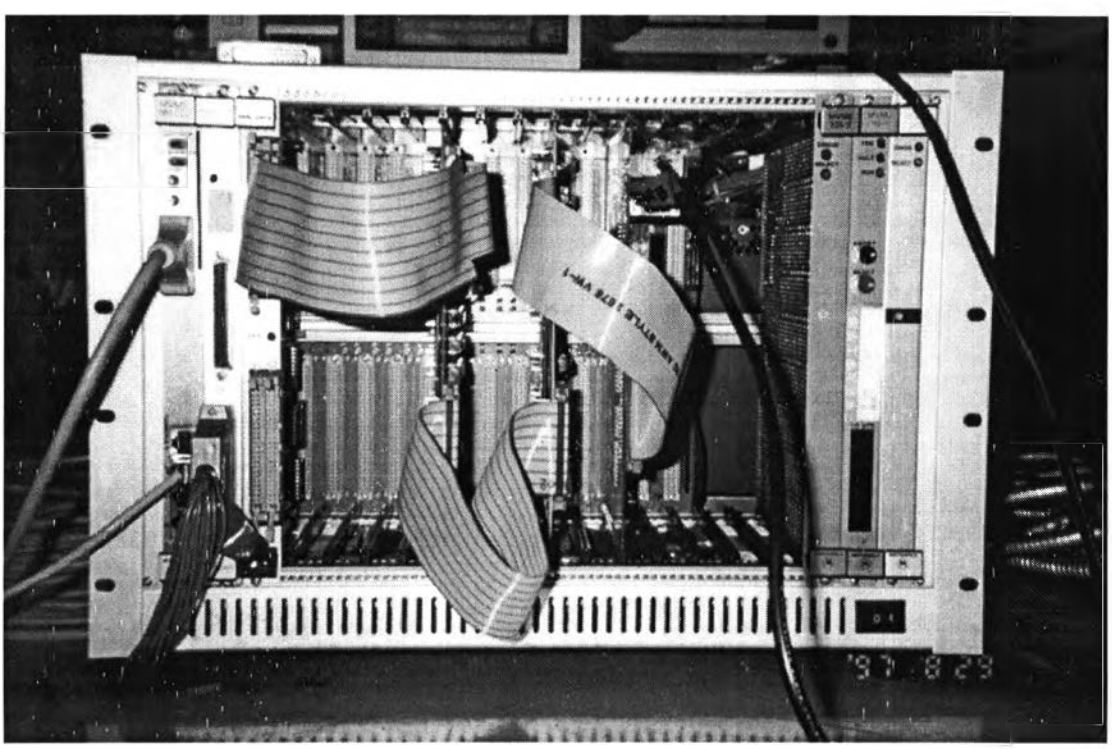

Figure 4.19(b) : A real-time controller

The real-time controller is a VME bus platform computer which is equipped with a UNIX base real-time operating system (RTOS), VxWork from Wind River Systems.

This real-time computer is powered by a Motorola microprocessor, MC68040, on an MVME 162-222 mainboard. It is equipped with a PVME-301 card which is an analog to digital (AD) converter and an AVME 342 AVAL DATA card which is a parallel I/O.

In addition, there is an additional FANUC board attached to this real-time controller. This additional board is functioned for sending commands from the real-time controller to the NC controller through an optical fiber which is attached to the I/O unit of the machining center.

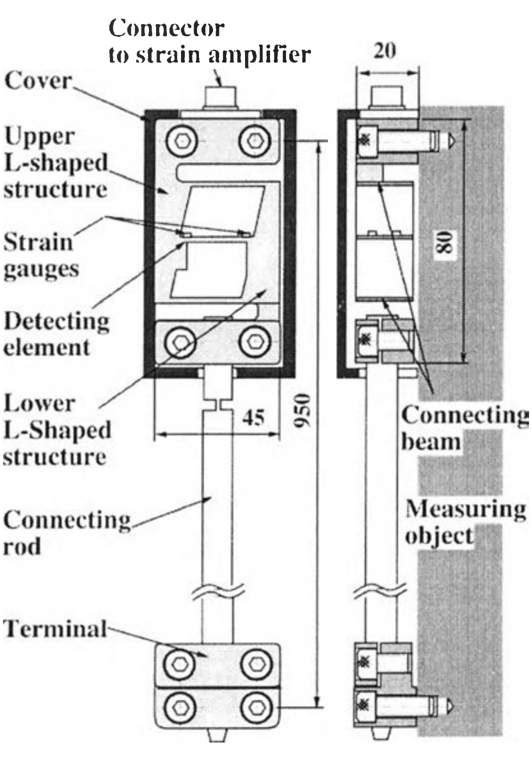

Figure 4.15 (a) : Structure of the Deformation Sensor

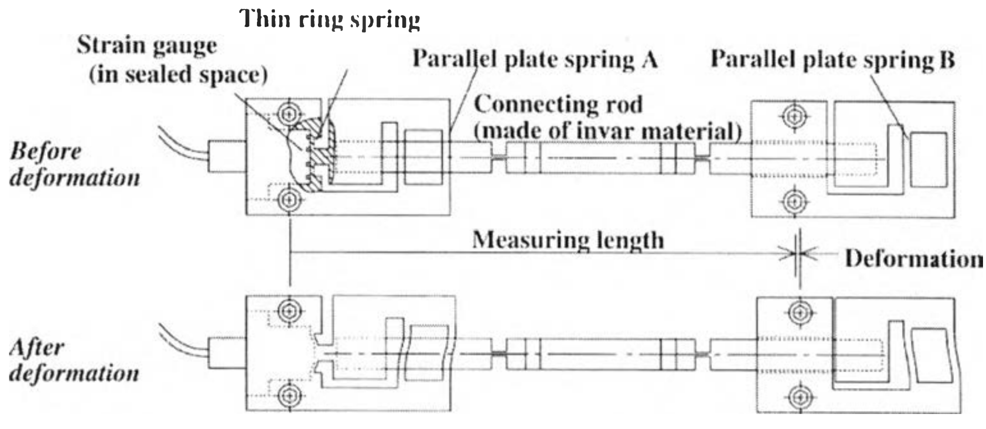

Figure 4.15 (b) : Structure of the Deformation Sensor

Since the main causes of the distortion of a machine tool are heat and force, the control and compensation for the distortion by heat are considered by the thermal actuation.

Traditionally, the spindle location is monitor externally by using a laser interferometer, and NC commands are sent to shift the position of the workpiece relative to the spindle in accordance with the measured deformation. For the implementation at The University of Tokyo, changes in the machine tool position and orientation are detected through an internal monitoring method using the deformation sensors which are attached to the machine structure, and corrections are made by deforming the machine structure by thermal expansion and contraction [22],[24].

The deformation sensor consists of a strain gauge type detecting block and a connecting rod as shown in Figure 4.15. The deformation between the both fixing points is concentrated in the deformation of three thin beams located in the center of the detector. Thus, small changes in the long distance between the two measuring points can be detected with high precision and stability. As the deformation sensor is made of super-invar metal with very low thermal expansion, only the thermal distortion of the machine itself is measured without influence of the thermal changes in the environment or in the machine structure.

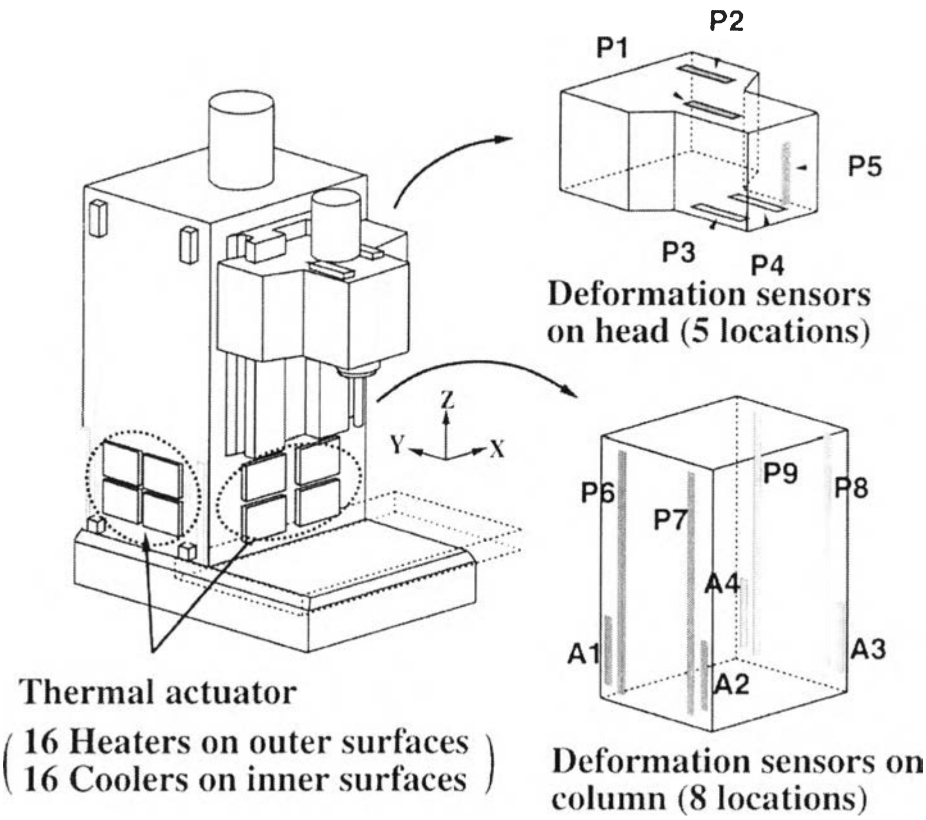

Figure 4.16 : Location of Thermal Actuators and Deformation Sensors

To measure the deformation of a vertical type machining center, 4 deformation sensors are attached to the head. and 4 and 8 deformation sensors are attached to the upper and lower parts of the column as shown in Figure 4.16.

The fundamental concept of thermal distortion is shown in Figure 4.17. If the amount of deformation is detected by a suitable sensor and if the configuration of the machine is controlled by suitable actuators on the machine structure, the location and orientation of the top of the spindle can be maintained constant.

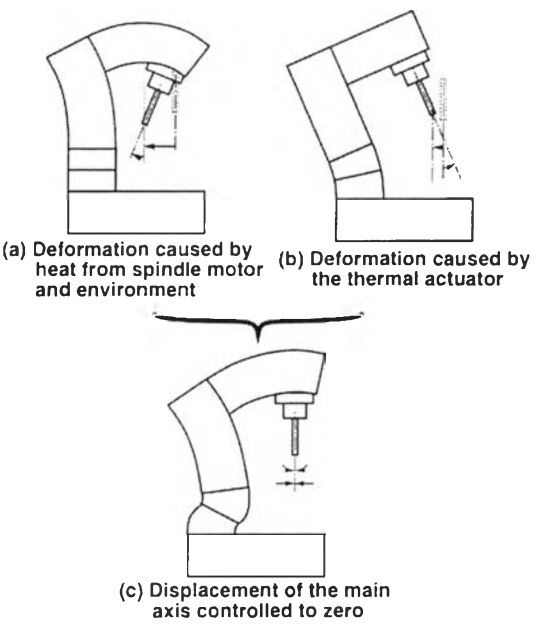

Figure 4.17 : Fundamental Concept of Thermal Distortion Control

The detailed structure of the thermal actuator is shown in Figure 4.18. Sixteen electrical heaters are installed on the outer surface of the column and sixteen corresponding cooling jackets are attached on the inner surface of the column. The expansion and contraction of the corners of the column are monitors by the eight deformation sensors. The heating and cooling pads are controlled by the thermal distortion controller on the basis of the outputs from the deformation sensors. Three tiers of thermal insulation have been installed to thermally isolate the machine structure and to prevent interference between upper and lower thermal actuators.

By selecting suitable combinations of the sixteen couples of heater and coolers, six-axis movement, including translations in the x, y and z directions and rotations about the x, y and z axes can be generated as shown in Figure 4.19.

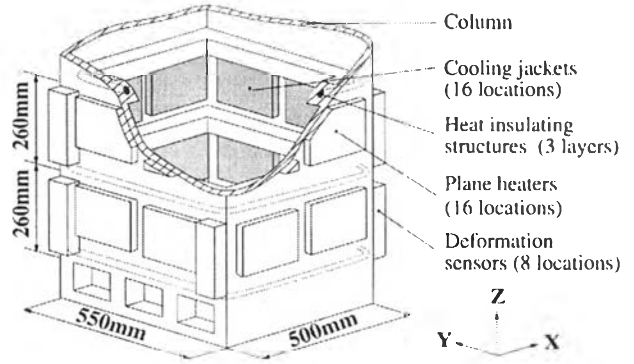

Figure 4.18 : Structure of the Thermal Actuator

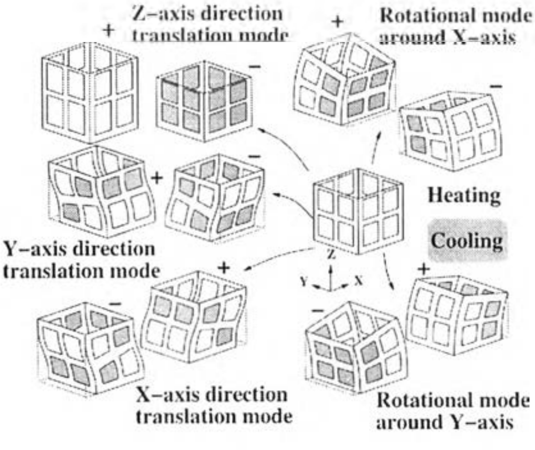

Figure 4.19 : Fundamental Deformation Mode of Thermal Actuator

In order to realize an unmanned operation, where the failure caused by various unexpected faults as shown in Figure 4.20 can be detected and automatically recovered, the fail-safe system was developed for this purpose.

The system performs an automatic reaction, moving the workpiece or the tool backward slightly when the force level exceeds a pre-determined threshold value.

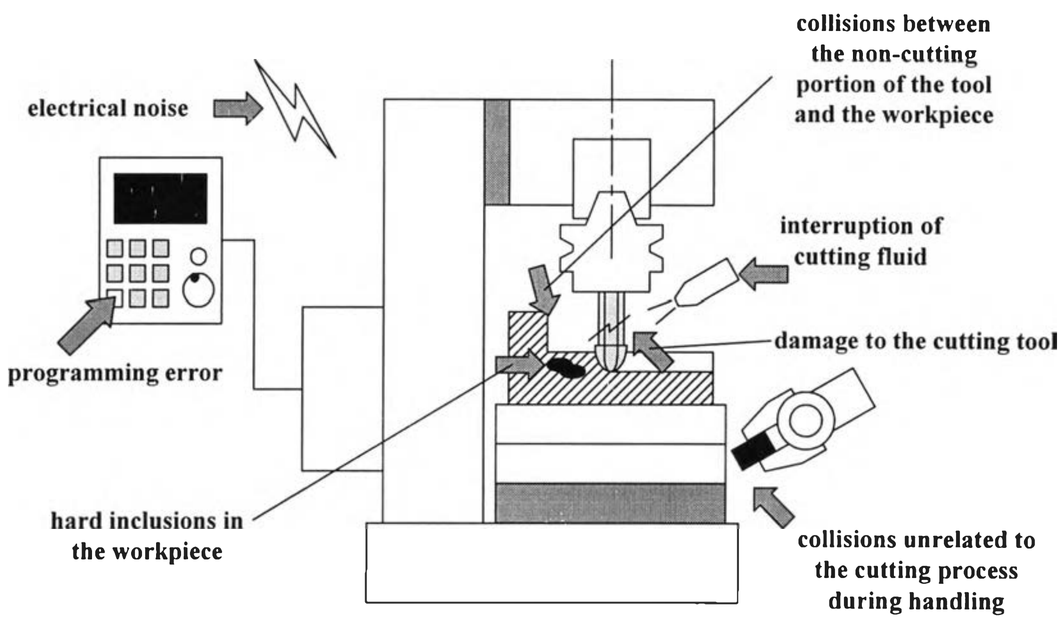

Figure 4.20 : Unexpected Faults in Machine Tool

The fail-safe system must not significantly reduce the stiffness of the machine tool system. Accuracy can not be maintained unless the machine tool has sufficient rigidity, and in some cases of low rigidity, chatter conditions may prevent the successful completion of the desired cut.

Therefore, the fail-safe system must have high rigidity during normal processing, performing its retraction function only under fault conditions. Figure 4.21 shows the fail-safe table designed and developed to be used as the fail-safe system of the intelligent machining center at the University of Tokyo [9], [12].

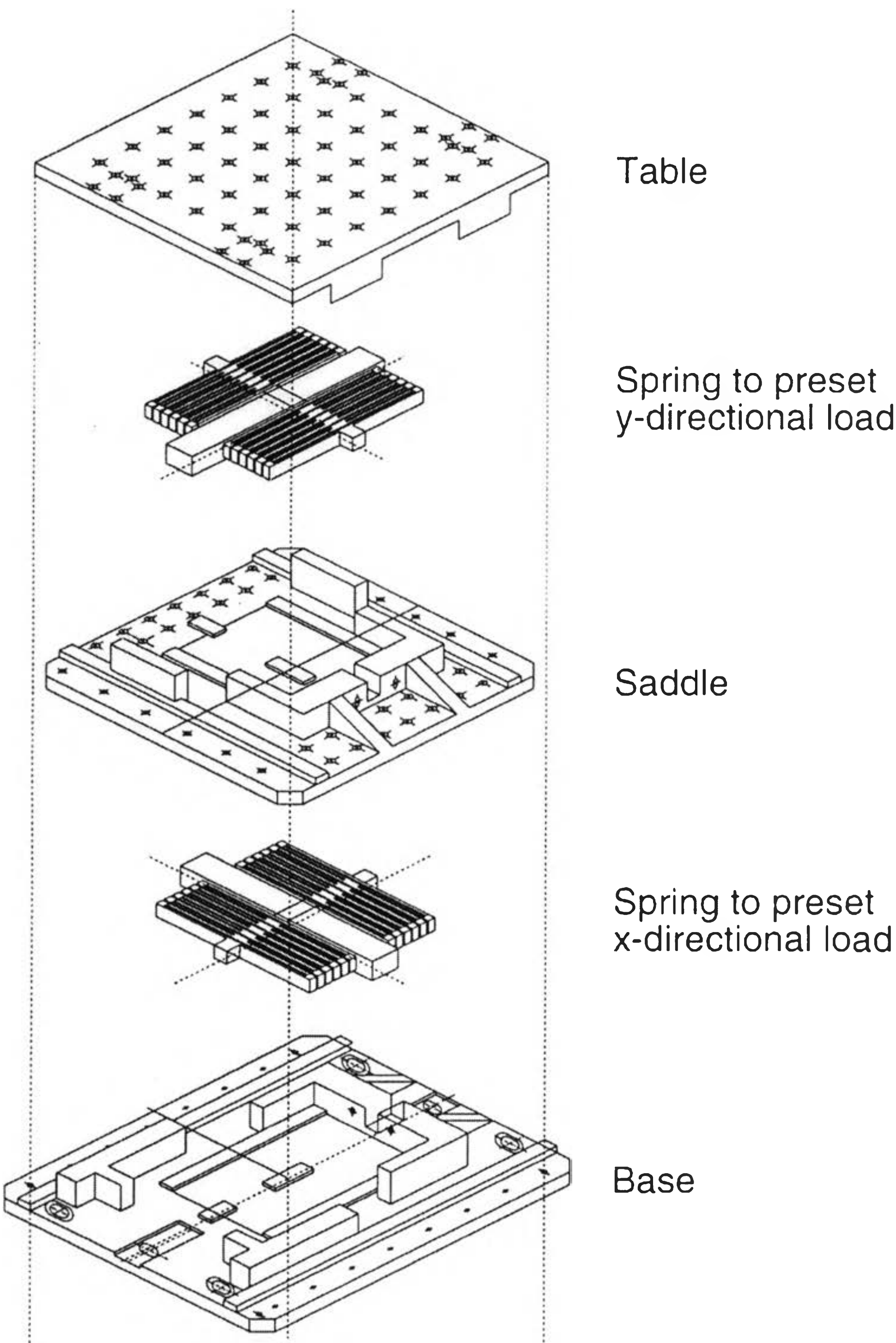

Figure 4.21 : Structure of the Fail-Safe Table

With the fail-safe system, as long as the cutting force stays in the normal region, almost no displacement of the fail-safe system occurs and the high rigidity of the cutting system is maintained. When the cutting force exceeds the threshold level, the fail-safe controller produces an emergency stop signal, which is transmitted to the highest hierarchical level of the NC controller, stopping the whole machine, and an automatic retraction is initiated. The system will be stopped without any damage to the components. In contrast, without the fail-safe system, the force will increase and damage will occur at the point when the force reaches the breaking load.

In the future, fail-safe performance will become a common and necessary feature in completely unmanned factory automation systems and also in the IMS, where a machine has its own intelligence and automatically makes the required movements to prevent the failure occurred to the system.

4.5 Conclusion

This chapter has provided a perspective picture of the IMS implemented at The University of Tokyo, Japan. The original system consists of an intelligent machining center, an intelligent lathe, an NC precision face grinding machine, an EDM, a Wire-Cutting EDM, and a 3D CMM. All of these machines are modified to be information-oriented which connected to the computer network and each exchanges information with a real-time controller and a workstation implementing adaptive control.