Research and Application of the Cutter Geometry On-Machine Measurement Using Laser Tool Setters

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ABSTRACT

Research and Application of On-Machine Measurement with Laser Tool Setter

Zixi Fang

This thesis mainly focuses on the study and application of the integration of Computer numerical control (CNC) machining and on-machine cutting tool measurement. According to the industry survey, in current aerospace industry, the usage of off-line tool setters is one of the most prevailing ways for cutting tools measurement. The following up manual tool data input is required so that the CNC machine will know the tool dimension and finish the assigned machining tasks. Off-line tool setters are often of high accuracy and the measurement results are reliable. However, due to its off-line characteristic, after the tool is used, its current dimension status cannot be known or updated. Thus the quality of the upcoming machined parts cannot be guaranteed. Moreover, the involvement of operators' manual data input in the traditional method inevitably introduces human error to machining from time to time.

To improve the process of part machining and eventually achieve produced parts that are within tolerance, a new approach is proposed in this thesis on the integration of machining and on-line tool measurement. The idea is to perform tool measurement without unloading the tool from the CNC machine, and update the tool dimension data in the machine control before the tool is used to machine the part. The key to this approach is the employment of a laser tool setter, an optoelectronic device that has the ability to communicate with the CNC control. Analysis on kinematics of this new type of device is conducted and its method of communication with CNC machine control is described.

Special software on CNC machine control level must be utilized to achieve the objective of on-machine measurement. Custom macros features of FANUC controls is used to suit the needs of parametric programming. The discussions on custom macros feature are carried out in this thesis. With the measurement method established, measurement uncertainty of the system will be discussed in depth. Considering the special attributes of the laser tool setter, the tool geometry and the machine control, an optimized measurement strategy is studied and proposed.

Finally, experiments are carried out to verify the accuracy and repeatability of the measurement system. Application on rejecting out-of-tolerance tool being used in machining is also discussed. The result of applications shows the measurement system is suitable for industry use.

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Table of Contents

List of Figures

List of Tables

CHAPTER 1 INTRODUCTION

1.1 Background

In modern manufacturing, Computer numerical control (CNC) machining occupies an important position due to its high accuracy and high efficiency. The rapid development of CNC machining technology pushes manufacturing industry toward mass production. The integration of machining and measuring providing a monitoring environment to guarantee the machined parts accuracy, has also become a mainstream in the modern manufacturing. Electronic sensors such as on-machine probe and tool setters can be installed and utilized to perform automatic gauging without unclamping the produced part or unloading the cutting tool, as opposed to tedious human measurement intervention. In this way, production cycle can be shortened while machine accuracy can be guaranteed and eventually the ability of manufacturing will be improved.

Due to its complexities and high quality requirement, parts for aerospace industries are the best suit for the implementation of on-machine measurement. For expensive aerospace parts, both quality and production efficiency play a very important role in the industry. The quality of produced parts directly affects the performance of the assembled products while the efficiency of production influences the overall manufacturing cycles. Meanwhile, as CNC machining has its unparalleled advantages in efficiency and accuracy, a broad adaption of CNC machining prevails in big aerospace companies, in order to suit the high requirement and demand market. These CNC machined parts have many features such as frames, walls, ribs, pockets, and holes etc. Besides, relatively larger in part size, these aerospace parts should be machined with longer time and multiple procedures. However, a high production quantity is also required by the industry. Machining a part with accuracy and efficiency is the most desirable condition in the aerospace industry. Hence, the requirements of aerospace parts highly demand the integration of on-machine measurement techniques while the CNC machining environment in the industry provides on-machine measurement a favorable and feasible practice environment.

This thesis describes an implementation of the on-machine measurement techniques, or what someone would called closed-door machining, with a laser tool setter. The method helps expedite the tool setup procedures, prevent initial manual input errors in tool data, update the tool data during production process, and report the tool excessive wear or breakage at a proper time.

1.2 On-machine Measurement Techniques

On-machine measurement integrated with traditional CNC machine procedures can also be called as closed door machining. It is a part-producing strategy using on-machine measurement devices to automate error adjustment as opposed to manual gauging intervention, with the aim of achieving within-tolerance parts. In terms of the device being used, on-machine measurement techniques can be divided into two categories: measure parts with touch probe and measure cutters with tool setter.

1.2.1 On-machine Measurement with Touch Probe

Throughout the years, many studies on the application of touching probes have been conducted in order to ensure the part accuracy on the CNC machine. These applications conduct the measurement on the machine so that procedures of unclamping the machine part and re-clamping it to the CMM machine can be avoid. They eliminate the often introduced errors such as: 1) unclamping/re-clamping error. 2) Deformation error due to multiple setups, especially for some large volume parts with thin walls.

1.2.2 On-machine Measurement with Tool Setter

The importance of applications of tool setters cannot be neglected. To machine a part accurately, the machine control should know the tool tip position relative to spindle reference point. The up-to-date cutter dimension information is crucial during the procedure of machining, as cutters wear after used and excessive wear will generate unqualified parts.

The tool setter installed on machine measures the tool data during the part producing process. The measured data can used in monitoring the current tool condition, ensuring the cutter's capability to perform the assigned tasks and thus reducing scrap. Software updates the tool registers in the machine control with the newest tool data automatically, automating the compensation of path procedure, improving the part accuracy while avoiding human error induced by manual offset updates.

In comparison to off-line tool setting, on-machine tool setting with laser tool setter takes the actual machining environment factors into account. Hence, it compensates the inability of the off-line tool setting system and yields a better measurement result. The main advantages can be summarized as the followings: 1) Errors caused by the spindle run-out, the tool holder and the tool itself can be eliminated as the tool setting procedure takes place while rotating; 2) Thermal factors and spindle "pull-up" can be take into account; 3) It can rapidly measure the on-machine tool length, simplifying setup procedure (no manual touch-off for every tool is required).

Tool setter also compensates the inability of part-probing measuring system by obtaining tool data. Even though the part-probing measuring system reports machined part dimension, due to the lack of information about the cutters condition, the reasons for some found errors in a machined part may not be identified.

1.2.3 Communication between Tool Setters and CNC Machine Controls

The on-machine measurement device like tool setter is an electronic sensor and its trigger signal should be recognized by the CNC control. An interface unit connecting the tool setter and CNC control is needed. It powers up the tool setter with the 12V output power source of the machine control. Meanwhile, it also works as a convertor, transforming the tool setter signals into voltage-free solid-state relay (SSR) outputs and sending to the machine control.

To serve the special requirements for the on-machine tool measuring, parametric programming with a high level CNC programming language is required. This kind of language is known as Custom *Macros, User Macros* or just *Macros* in Fanuc and various compatible controls such as Fadal and Okuma or *Flexible programming* in Siemens control. Custom macros offer the possibilities to perform logic, arithmetic and branching functions similar to other high-level computer languages like Visual C++, Visual Basic or Tool Command Language. Software with algorithm can be written with custom macros and installed in the machine control as any other NC programs. Then by using a certain NC command, such as G65 in FANUC control, the software will be called to perform its tasks from the machine control level and thereby realize the goal of on-machine measurement.

1.3 Literature Review

Over the years, a rapid growth of probing technology is seen and on-machine measurement systems have been put into practice in many fields. Studies have conducted to prove the accuracy of machining can be improved through on-machine inspection methods [1]. Hollingum and Jack [2] reported that with the help of touch probes, the continuous machining process can generate an error less than 6 μm. In the other technical papers, the device that can be used to perform on-machine cutting tool measurement tasks [3-9] are described and discussed. In 1997, Kurada and Bradley [3] made a summary about computer vision techniques used in tool condition monitoring. With a different approach involving the cutting tool touching the tool setter, RB Morrison and PK Hellier [4] purposed a touch-triggered type of tool position measuring device. Stimpson,Victor G [5] described a new type of tool position detecting device based on laser technology. After the implementation of laser technology in tool setters, British company Renishaw has gone further to perfect its measuring ability. Improving algorithms on processing the signal received from the laser tool setter had been discussed by Stimpson,Victor G [6] in 2005, Merrifield, Benjamin J [7] in 2007 and Egglestone, Edward Benjamin [8] in 2013. Meanwhile in 2004, Hyeon-Hwa Lee and Min-Yan Yang [9] described a three dimensional tool measurement system based on optical sensors, enabling a more detailed tool data measurement result.

With the tool setter technology available, it is important to apply it to the industry. M Lynch studied measurement error and calibration method for the workpiece probe and method to develop probing software using FANUC custom macro in his book [10]. These give significant insights for the later software development for tool setters. In 2001, Huang [11] carried out a study on the application of the touch-trigger tool setter based on FANUC custom macro. A different approach on facilitating the tool setter with NC machine was conducted in 2005 by Huang, Jiyong [12]. In his master thesis, a method based on PLC ladder diagram programming is proposed. Experiments comparing two types of laser tool setter had been carried out by Lee, Eung Suk & Sung Chung Kim [13] in 2008, demonstrating that the laser tool setter fits the requirement of industry.

To further understand the feature of measurement system, measurement error and measurement method must be addressed. Renishaw conducted surveys [14-15] on measurement uncertainty due to machine response time and measurement system geometry. These surveys give a preliminary understanding for the world about the tool probing technology. In order to further improve the performance of the measurement system, optimal measurement cycles are necessary. Although there is a lack of deep discussion on measurement strategy with laser tool setter, an optimal measurement strategy for workpiece probing has been addressed by Renishaw [16].

This thesis hence studies the measurement uncertainty and the optimized probing strategy for the laser tool setter.

1.4 Research Objective

The objectives of this thesis focus on proposing a better integration of laser tool setter and CNC machine and the work can be concluded by the following aspects:

- Components of on-machine measurement system and their intercommunication are studied.
- A high level CNC programming language that is key to the development of the measurement software is reviewed.
- To better understand laser tool setters and to develop an optimized probing strategy, measurement errors and measurement cycle time analysis are carried out.

Applications and experiments are also presented to prove the stability and reliability of the on-machine measurement system.

1.5 Thesis Outline

This thesis consists of six chapters. CHAPTER 1 gives a general introduction about the on-machine measurement system. Reviewed literatures on this topic are also presented. CHAPTER 2 dissects the components and technology used for the laser tool setter and its interface with CNC machine. Structure of CNC system is also described in details in order to establish a solid ground for the following up research. CHAPTER 3 focuses on the essence of the high level CNC programming language, FANUC custom macros, which are necessary for the measurement software development. CHAPTER 4 studies the communication between the laser tool setter and CNC machine. An in-depth examination is carried out on laser tool setter's characteristics and the measurement error that lead into the measurement results. In order to find out an optimized measurement strategy, measurement cycle time is also considered with CNC machine features. CHAPTER 5 presents the application of the integration of the laser tool setter and CNC machine to prove the reliability of the system. CHAPTER 6 concludes the work of the employment of on-machine measurement system and proposes the possible future work.

CHAPTER 2 ON-MACHINE MEASUREMENT SYSTEM WITH LASER TOOL SETTER

2.1 Introduction

Both hardware and software are required to support the on-machine tool measuring system. The system consists of a tool setter as the measuring device, an interface unit as the communication device and special NC programs as the software to drive the tool measuring movement.

This chapter describes the structure of the system. Hardware components of the on-machine tool setting system are also discussed in-depth. Software components are mentioned but not in depth as they employ algorithms depicted in the following chapters.

2.2 On-Machine Tool Measurement System Structure

The on-machine tool measurement system is constructed by three parts: a tool setter system, an interface unit and a CNC control, as can be seen from Fig 2.1.

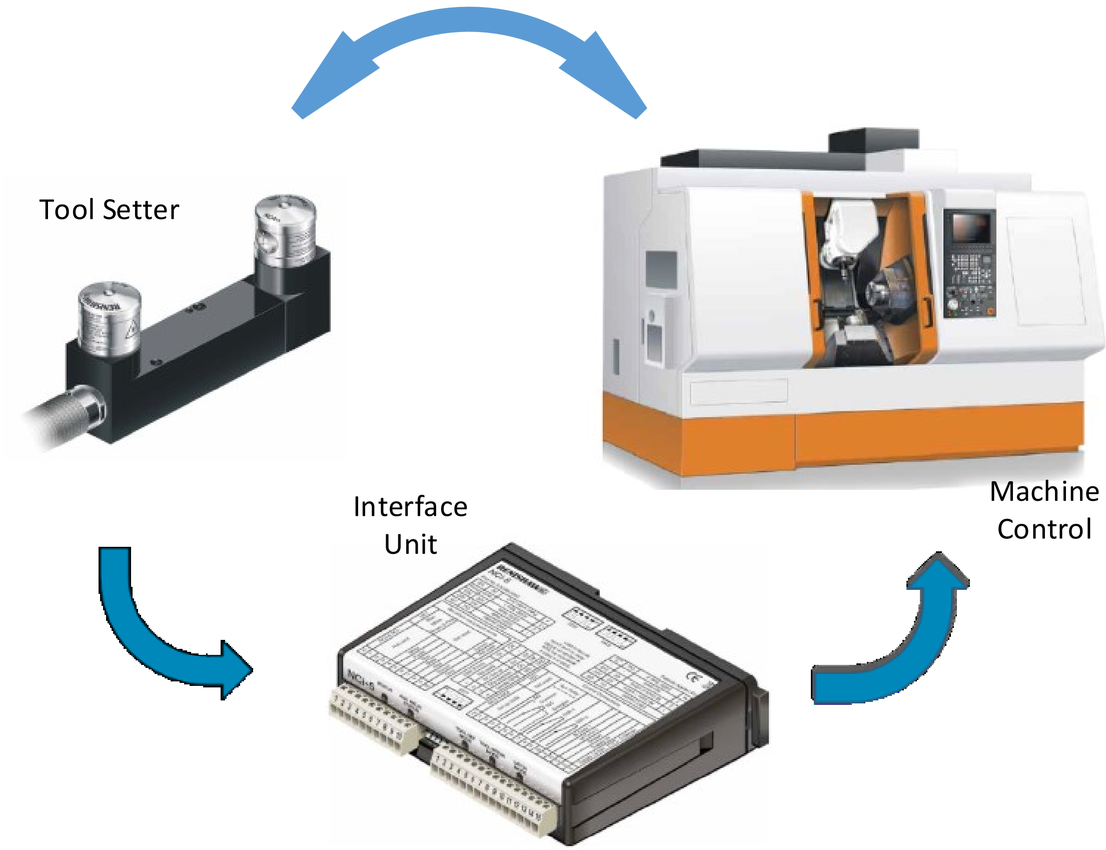


Fig 2.1 On-machine tool measuring system

Each component has its own functions: 1) Tool setter system is a mechatronic device equipped with sensors that transform the physical movement into digital signal; Circuits to preform pre-built algorithms functioning signal acquisition and signal processing is also included in tool setter; 2) Interface unit is a PLC that converts the receiving signal to solid state relays output for CNC control; 3) CNC control provides parametric programming environment for the development of the special tool setting software. The software is run according the commands given by the programmer. Machine tool is then controlled to perform measuring tasks, involving triggering the tool setter. With the received output signal passed by the interface unit, software also does the calculation and eventually updates the tool offsets or reports tool conditions. The working system proceeds as a close-loop system and the procedures are as shown in Fig 2.2 .

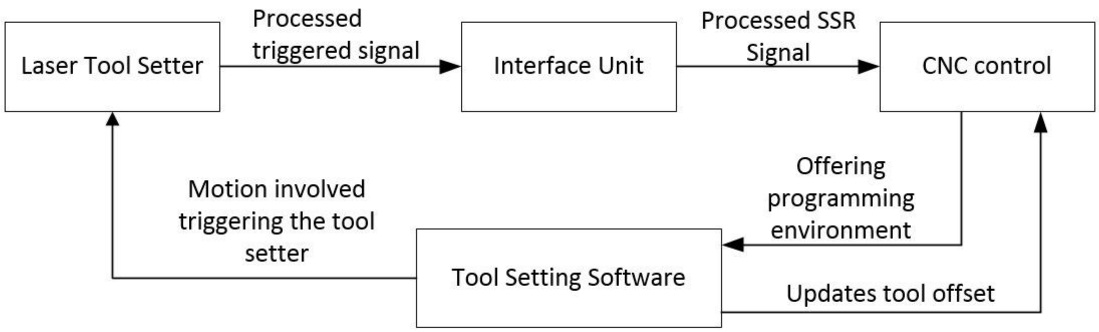


Fig 2.2 Measurement procedure

2.3 Tool Setter Device

2.3.1 Introduction to Tool Setter Device

Currently, methodology for on-machine measurement can be divided into two categories: touch-trigger measurement and non-contact measurement, or in common used terms, "contact" and "non-contact". Both methods are employed in the in-market tool setter. Contact-triggered is the signal-output method based on pressure-electronic sensors, which monitor the change in electrical resistance due to the displacement of the tool setter hardware. Contact-triggered method has high repeatability and accuracy and has been used for decades by the industry.

Whereas, non-contact triggered method is developed, based on modern optical science. Technology such as infrared wave, digital photos (machine vision), and laser have been applied to realize the purpose of goal of non-contact measuring. However, due to the instability of the vision system imaging quality and limitation of CCD camera resolution or image acquisition ability, vision based non-contact measuring system suffers from lower accuracy. Laser technology, on the other hand, overcomes the imperfection of vision based systems and is often applied with non-contact tool setters. Laser technology uses optical-electronic devices as the signal-output source. Tool setters integrated with laser technology equip advantages of having shorter response time while not losing accuracy. Compared to contact-trigger tool setters, its non-contact feature expedites the procedure of measurement as the tool can move toward the laser at a higher speed without damaging the tool setter. Therefore, the system discussed in this thesis is based on the use of non-contact laser tool setter.

2.3.2 Structure of Laser Tool Setter

Laser tool setter device works on the optoelectronic science basis. The main components consist of a laser transmitter and an optical receiver, as can be seen from Fig 2.3. When the cutter moves into the laser region, part of the laser is blocked and when the light reduction exceeds a certain level the tool setter will trigger.

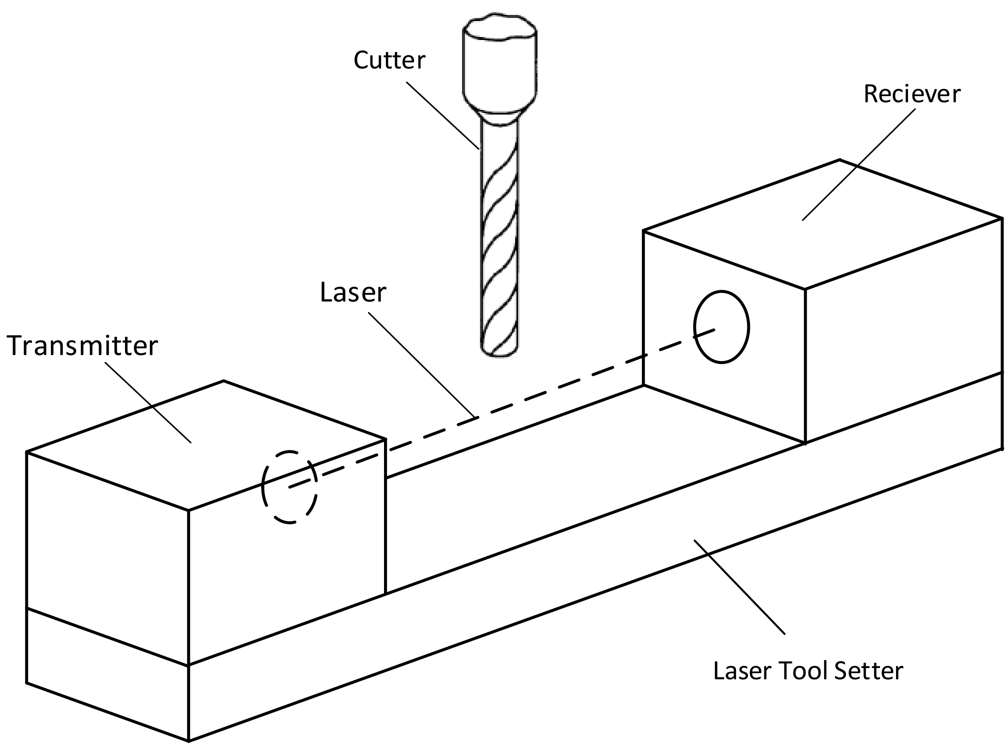


Fig 2.3 The main components of laser tool setter

2.3.3 Conical Laser Tool Setter

A conical laser tool setter uses conical-shaped laser beam to perform measuring task. It is the first generation of tool setter. A more detailed illustration of this type of tool setter can be seen from Fig 2.4. The laser diode in the transmitter emits the laser through the lens to form a conical set of laser which converges into a focus point between the transmitter and receiver.

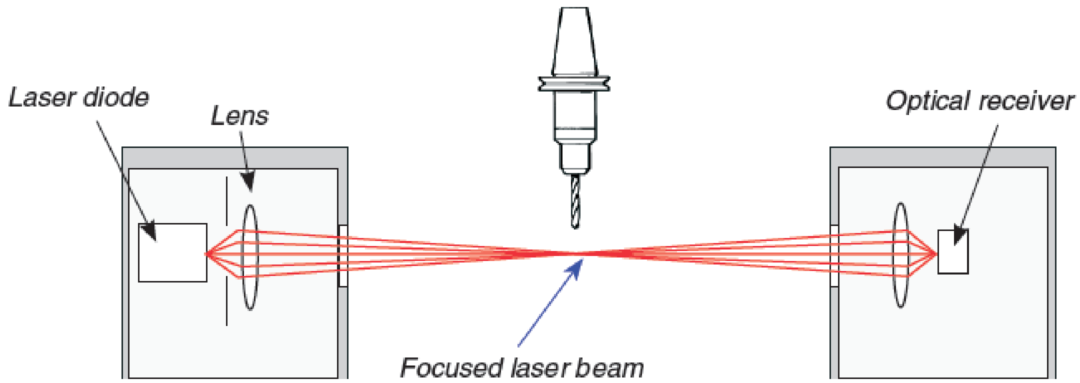


Fig 2.4 Tool setter with a focal point

On the focal point, the beam has narrowed to a small size that can be used to measure small tools, as can be seen from Fig 2.5.

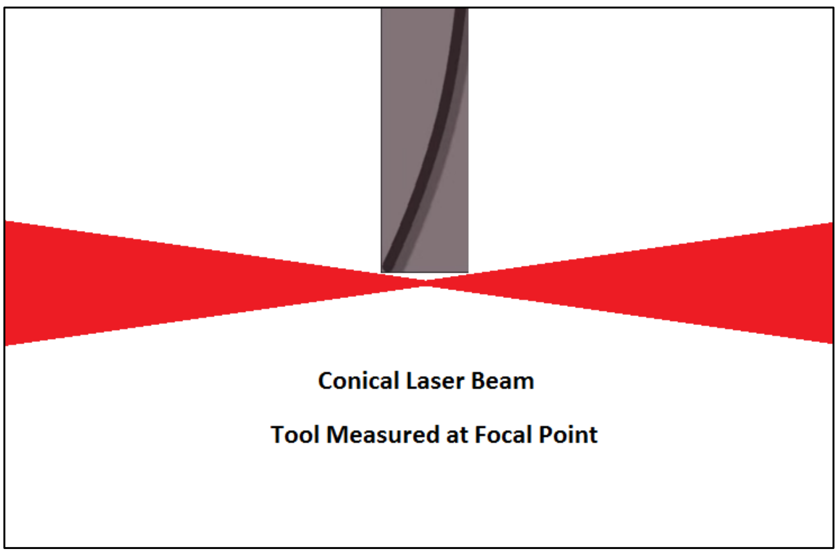


Fig 2.5 Tool setter with a focal point

The focal point for small tool measurement is crucial because the small tool may not be able to block sufficient laser elsewhere in the laser beam set to generate the trigger signal. However, this small tool measuring ability weakens as the separation of the transmitter and receiver grows. The farther the distance is, the less convergent the laser becomes. When measuring happens and in the same measuring position, the small tool does not block as much light in a less convergent situation as in a higher convergent situation. This yields the loss in sensitivity of the tool setter. Therefore, most of the conical laser tool setters are built with a compact design to ensure the measurement accuracy, which also limits the maximum measurable tool size. Conical laser tool setter also relies highly on alignment of the transmitter and the receiver, as the light gathered by the receiver will directly affect the measuring result.

2.3.4 Parallel Laser Tool Setter

To overcome the drawback of conical laser tool setters, the parallel laser is utilized. A more detailed illustration of this type of tool setters can be seen from Fig 2.6.

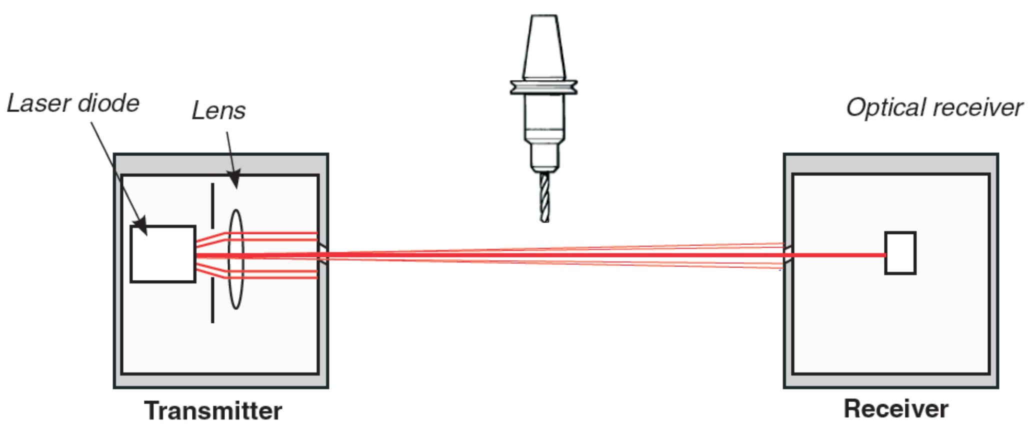


Fig 2.6 Tool setter with parallel laser

As illustrated by the figure above, the laser diode emits laser and the lens, which regulate the laser into a set of rather parallel laser. In addition, in order to diminish the effect of divergence of the laser beam, a set of two mini-pin holes are featured in proper positions, both on the transmitter and the receiver unit. The relatively parallel laser beam is further constrained by this set of small apertures. Therefore, only a small subset of the original, highly divergent laser is emerged but this subset is the strongest and most parallel set of laser. There, a set of strong, small shaped, highly parallel and slightly divergent laser is generated.

With the parallel laser beam, tool measurement can happen in anywhere along the beam between the transmitter unit and receiver unit (provided the tool does not collide with the tool setter), as shown in Fig 2.7.

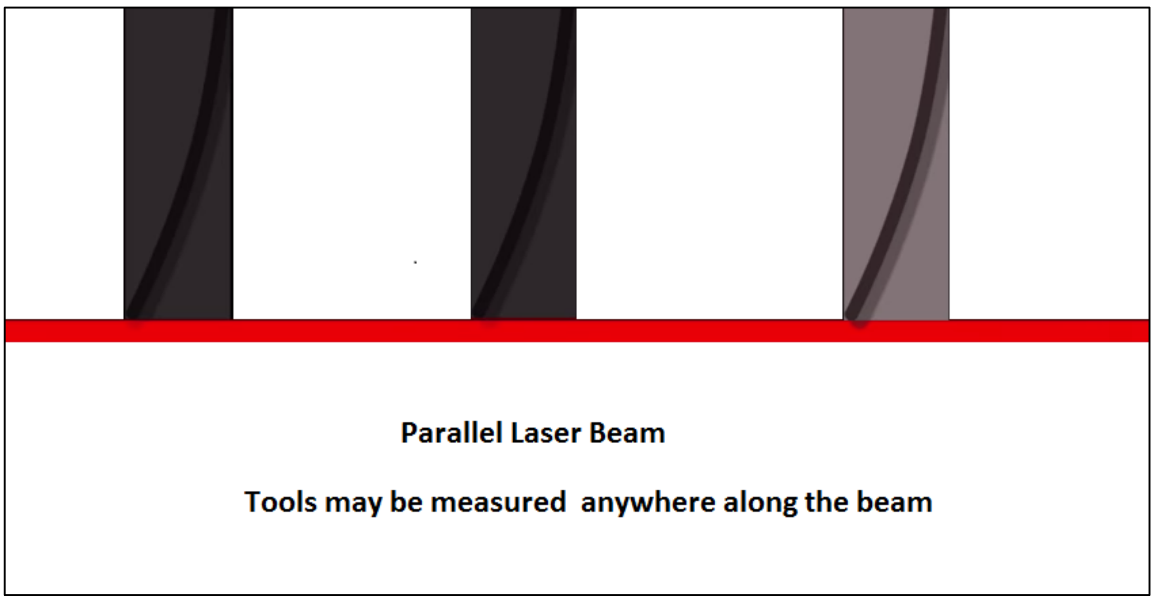


Fig 2.7 Tool measurement takes place anywhere along the beam

Since the parallel laser beam that comes out from the small aperture is highly convergent, strong and small in shape, when measuring a small tool, the small tool causes the same amount of light reduction. This equips the system with a better capability to measure small tools. In addition, as there is no longer the requirements of measuring a tool on laser focal point, the tool setter alignment also becomes easier which shortens setup cycle time.

2.3.5 Protection for the Tool Setter

Laser tool setter performs on-machine tool measurement and hence, it often works in unfavorable conditions. Coolant spraying off from the tool or any other dripping from the machine tool should never enter the tool setter unit. With the mini-pin holes featured on both transmitter and receiver unit, the tool setter is protected at a certain level. To further guarantee the tool setter protection, high pressure air is supplied within both the transmitter and receiver, as can be seen Fig 2.8.

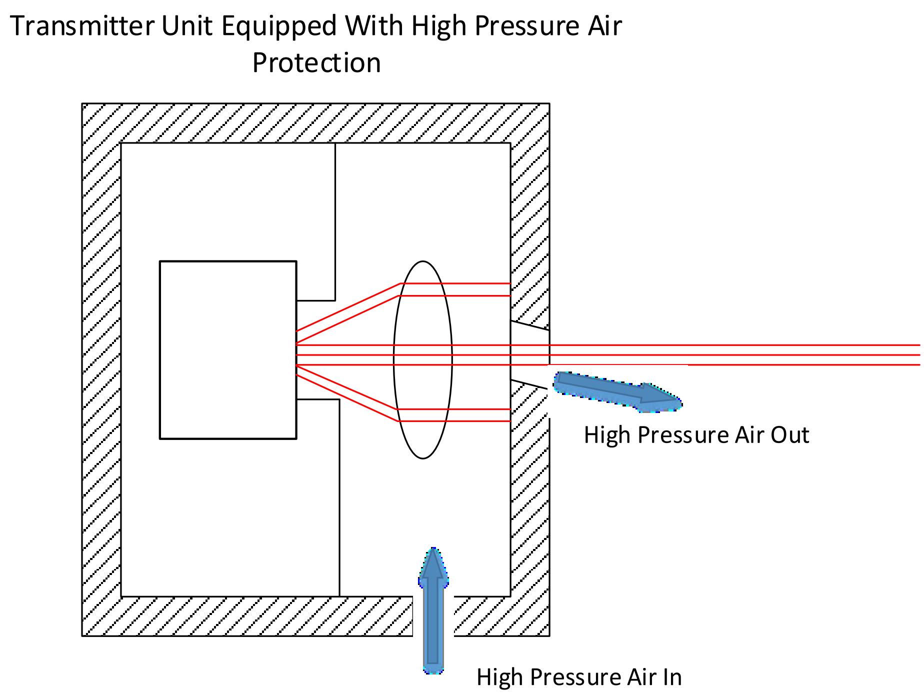


Fig 2.8 Tool setter protection mechanism

The figure above shows schematic for the tool setter protection mechanism. Continuous air stream is plumped into the transmitter and receiver unit to form positive pressure air steam so that the protection is available at all time. Meanwhile the mini-pin hole featured on the wall of transmitter unit also helps to guarantee the high air speed during its emergent process. Up to 250m/s can be reached for the air speed. With this feature, coolant mist near the transmitter or receiver will be blown away and thus it has no chance to condense or to block the laser.

What is worth noticing is that, the air flow may generate turbulence that will affect the laser beam condensation and consequently impinge the measurement results. In order to avoid this unfavorable situation, the mini-pin holes on the transmitter and receiver are setup with an angle. This way, the angled mini-pin holes will guide the air to a direction that is not parallel to the laser beam and thus the turbulence will not form in the direction of the laser beam, as shown in Fig 2.9.

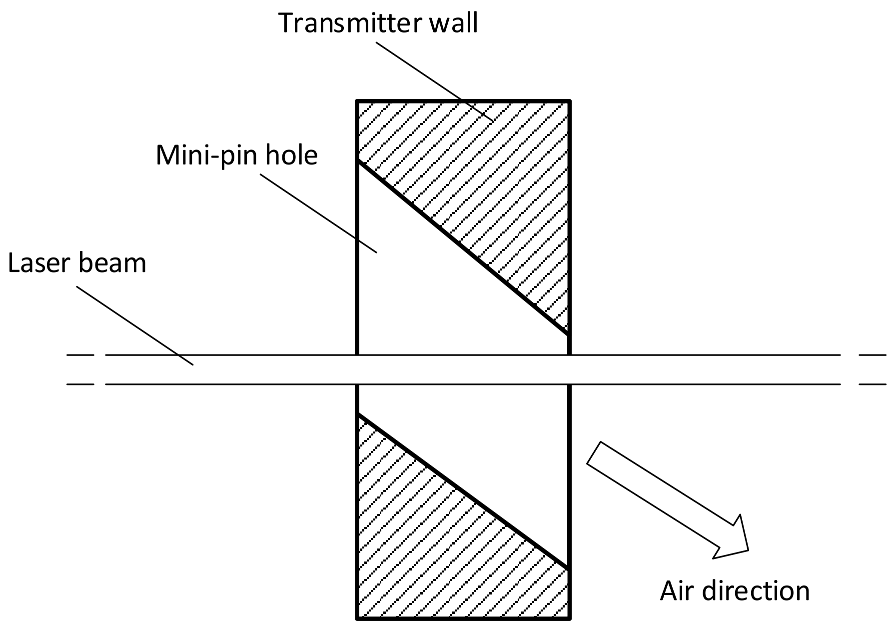


Fig 2.9 Mini-pin hole equipped on the walls

2.4 Interface Unit

Besides from the tool setter device above, a device working as the bridge connecting the tool setter side and machine control side is also needed. This device is called interface unit, as shown in Fig 2.10.

Fig 2.10 Interface unit

The interface unit converts trigger signal sent by the tool setter device into solid-state relay (SSR) output. Solid-state relay is an electronic switching device. Unlike the mechanical relays, which has actual mechanical action such as, turning coolant on/off, performing tool change etc., solid-state relay is voltage free and has no mechanical moving parts. This is the kind of relay signal that FANUC control and majority of controls use to communicate with external devices. The essence of this type of relay is semiconductor materials.

In addition, the interface also powers up the tool setter device by drawing power from the machine control side. Through the interface, the normal current and voltage 120mA at 12Vdc or 70mA at 24Vdc will be provided to the tool setter device.

2.5 CNC Systems

2.5.1 The Construction of CNC Systems

A CNC system comprises three units: NC unit which works as the “brain” of the CNC system by providing human-machine interface and carrying out position control, the motor unit, and the driver unit. In the scope of control, NC unit alone is referred to as the CNC control.

In the sense of different functions, the NC unit is composed by MMI (Man-machine interface), NCK (Numerical Control Kernel) and PLC. In the FANUC’s system, the NCK and PLC are referred to as CNC and PMC, respectively. Though difference can be seen in naming, they are referring to the same thing. MMI (man-machine interface) enables the communication between the end user and the CNC. It supports machine operation commands, current machine status display. Part programs input and editing are also done within this unit. CNC is the dedicated computer that interprets part programs, applies interpolation algorithm, position control and error compensation. Servo system of the CNC machine tool is controlled by CNC. It is the most important unit of CNC system. PLC (programmable logic control) performs overall machine control, such as tool change, spindle speed and in/out signal processing except for servo control.

Fig 2.11 Machine-Human interface of FANUC control

Fig 2.12 FANUC PMC

The architecture of the CNC system can be described by the schematic diagram below.

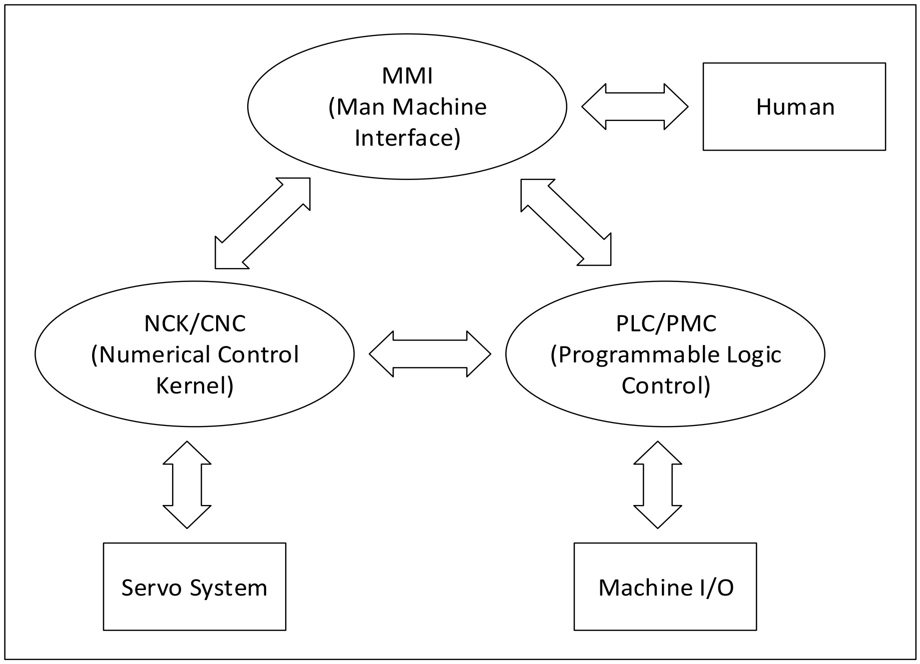


Fig 2.13 CNC system architecture

Information is input by user through MMI. These information will be scanned, and executed either by CNC or PMC. Feedback from CNC and PMC of their current status will be available and sent back to MMI for display. Meanwhile, CNC and PMC exchange their status information. Communication between CNC and PMC is very necessary, for example, when the part program requires general machine operations such as tool change, spindle rotation and coolant on/off etc. These operations will be executed by PMC and when the operations have completed, PMC sends signals to prompt the CNC to start executing the next command of the part program.

2.5.2 MMI Function

The MMI unit in CNC machine usually consists of two parts, control panel and operation panel. Control panel consists display screen and soft keys, selection keys, address and numeric keyboard, and reset key etc. Fig 2.14 shows the layout of a typical control panel. Operation panel consists main buttons and switches, status indicator lights, ON/OFF switches (option stop on/off, single block on/off, coolant function on/off, etc.), Rotary switches (Select mode, feedrate override, spindle override, etc.), setup handle, etc. Fig 2.15 shows the layout of a typical operation panel.

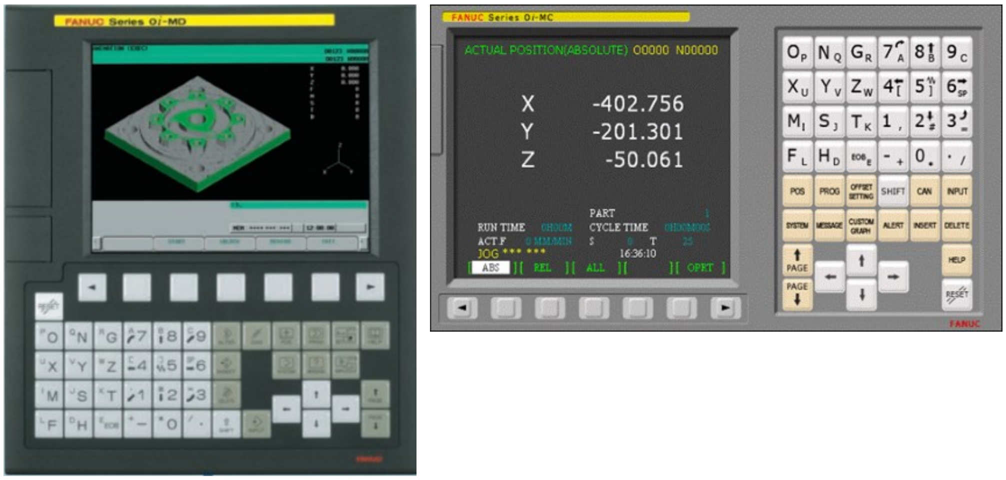


Fig 2.14 Fanuc control panel

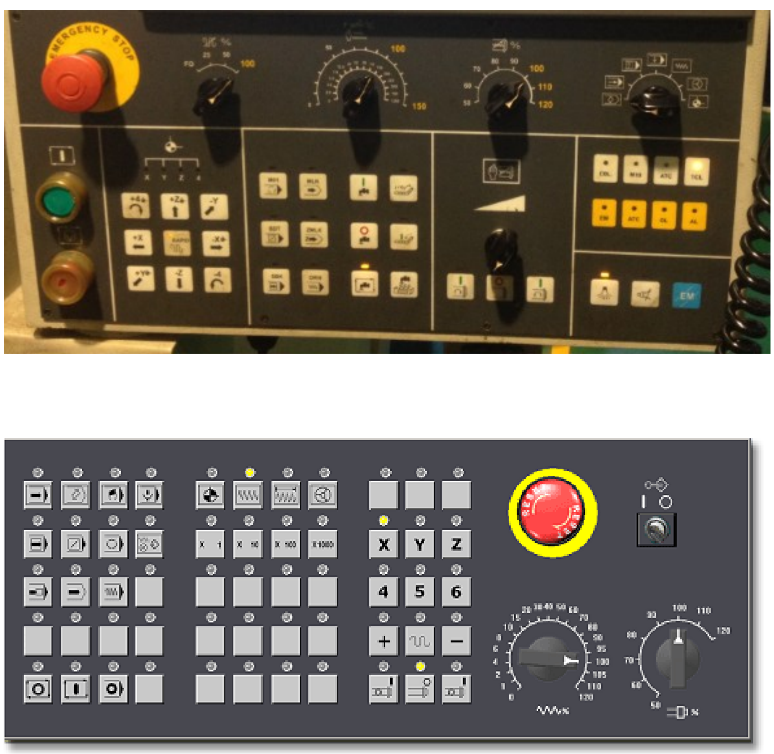


Fig 2.15 Fanuc operation panel

Control and operation panels provide the availability for user to realize the following functions:

- Operation functions, such as feed override, spindle override, MDI…
- System parameter-setting
- Program-editing
- Machine status monitoring and alarm message display

2.5.3 CNC Function

CNC interprets part programs and performs position calculation. Its main components include interpreter, interpolator, acceleration/deceleration controller and position controller [18]

Interpreter reads the part program and stores data in internal memory. With the help of buffer, this can be proceeded very quickly. Interpolator calculates the position and velocity for the machine by using the interpreted data. Position controller uses the interpolated data to control the servo and motor in order to drive the machine to a certain position. Acceleration/deceleration controller is introduced to calculate the acceleration/deceleration for the machine to reach a certain speed in order to prevent vibration and shock.

2.5.4 PMC Function

PMC is responsible for general machine control, except for the axis positioning. PMC system possesses abilities to perform logic, sequencing, timing, counting or arithmetic calculation. PMC system in CNC machine is a software-based control system so it has advantages in flexibility and economic efficiency and due to its programmable characteristic, some advanced control tasks can be accomplished. Pre-written sequence programmed are compiled and stored in PMC. The program executes from the beginning of the ladder diagram to the end and then the procedure repeats. The execution time from the beginning to the end is called a scan. This scan time can be set through a system parameter. The default setting for a FANUC 0i-MC control is 8 msec.

PMC has the following functions when applied to CNC machine tool:

- Sends operation status from MMI to CNC and displays CNC status to user via MMI
- Information of the change of operation mode (e.g. MDI, Reference, Edit) made by operator through operation panel is sent to CNC by PMC
- JOG, cycle start, feedhold, emergency stop are done through PMC
- Though the communication with CNC, PMC helps with the part program execution by executes M-, T-, S- codes.
- Receives and in some cases, processes input signals from external equipment.

2.5.5 Communication between CNC and PMC

In CNC control system, communication between CNC and PMC is of great importance. In FANUC control, four designated addresses are used to signify the input/output signal for PMC side and CNC side. These two way communication between machine tool and PMC; PMC and CNC are described [17] by Fig 2.16.

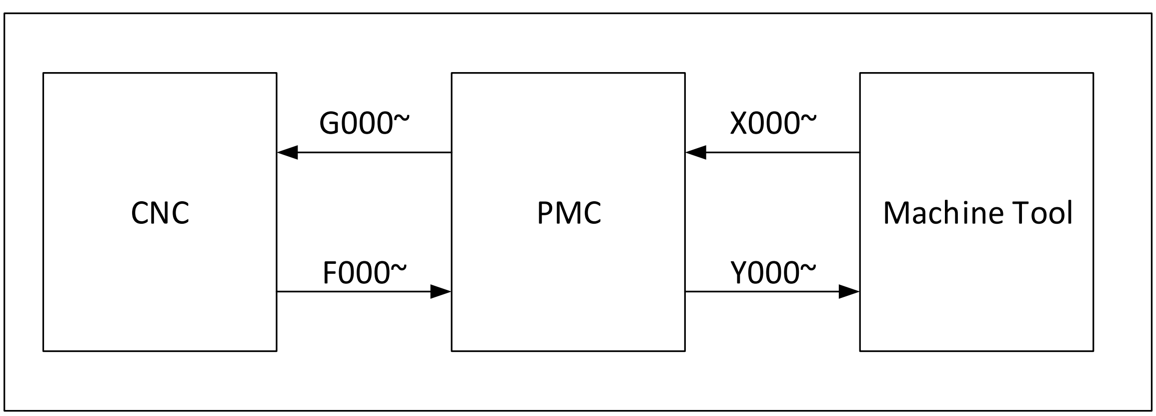


Fig 2.16 Communication between CNC, PMC and machine tool

CNC does not communicate with external devices connected to the machine tool directly. PMC is the medium between CNC and external devices.

Between the PMC and CNC, F- signal is used for input signal from CNC to PMC while G-signal is used for PMC output to CNC. Between the PMC and machine tool side, X- signal is used for input signal from external devices to PMC while Y- signal is used for PMC output to external devices.

2.6 Compatible Measurement Software

Compatible software written in Custom Macros should be used to practise on-machine measurement with laser tool setter. In fact, due to the sophistication and difference in tool geometry data, it would be impossible to program just by using low level G-code language. Nowadays, some of the newest controls (Sinumerik 840d or some Haas controls) offer measuring can-cycles (manufacturer-developed measuring software) to perform the measuring task. However, for the most prevailing FANUC 0i control, these measuring can-cycles are not available. Therefore, development of these NC programs is required. The following chapter will be concentrating on Fanuc Custom Macro Programming.

CHAPTER 3 FANUC MACRO PROGRAMMING

3.1 Introduction

To achieve the goal of on-machine programming, compatible software should be developed and installed on the machine control level. High-level CNC programming technique, typically known as Custom Macros in Fanuc control is essential for this type of software development. This chapter is dedicated to discussing this type of programming technique and its application.

3.2 Macro Programming in a Nutshell

Although over the years, formidable improvement in capability and flexibility of the CNC machine tools and their controls have been seen, macro programming techniques have not yet drawn much attention. The reasons for it to be under-publicized could be: 1) in the age where CAM software prevails and automates the programming process, most of complicated machining tasks can be accomplished by the only utilization of low-level language such as G-code, M-code… 2) originally, macro programming instructions are not intended for the CNC users rather, for the machine tool builders to interface the machine control to accessory device [19]. Therefore, reference materials are rather rare.

However, these high-level instructions featured in CNC control possess the powerful arithmetic abilities and high flexibility resembling to high-level programming languages such as Visual C++, Basic or PASCAL in computer programming and should not in any extent be under-addressed. Custom macros make the parametric programming on machine control level possible. In addition, by using custom macros, internal information of the CNC control can be attained and thus the back-staged communication between NC program and CNC control can be accessed and as a result, program development is granted with more information.

For tool setting software development, the ability to parametrically program and the knowledge of the system internal information such as current part zero offset, current machine position etc. are of extreme importance. There is no command in low-level G-code language being able to perform tasks, for example, to attain the current position in Z-axis once the tool setter is triggered or calculate the difference in X-axis between two positions.

In all, custom macros are a special set of high-level CNC control instructions, mainly used for realizing special requirements. They possess features resemble to computer programming languages while also integrate CNC machine related features.

3.3 Macro Programming Structure

A macro is similar to a subprogram but more sophisticated. It can be thought as the equivalent to "function" in BASIC or C++.

3.3.1 Macro Definition

A macro should be defined before used. A program number should be assigned to a macro program. Later by using this program number, the corresponding macro can be called, resembling calling a function by its name in BASIC or C++. These program number must be integer following a capital letter "O" and must be within the acceptable range of FANUC control. Table 3.1 shows the program number range [20] for FANUC 0i control. Note that the numbers have been categorized into four groups based on their conventional usage.

Table 3.1 Program number range

Program Number Range	Description
O0001 to O7999	Standard program numbers, mostly used for main programs
O8000 to O8999	Group 1 Macro program numbers
O9000 to O9049	Group 2 Macro program numbers with special function

	(Can use G,M,S and T function to call the macro, instead of using a program number)
O9050 to O9999	Group 2 Macro program numbers

3.3.2 Macro Call and Return

A specific command should be used to call the macro. Once the main program encounters this command, it will go into the corresponding macro and execute the program until a return command is reached. Then the program returns to the same point in the main program, from which it diverts to the macro program, and continues executing the following program blocks, as Fig 3.1 shows. Table 3.2 shows the designated commands for macro call and macro return [20].

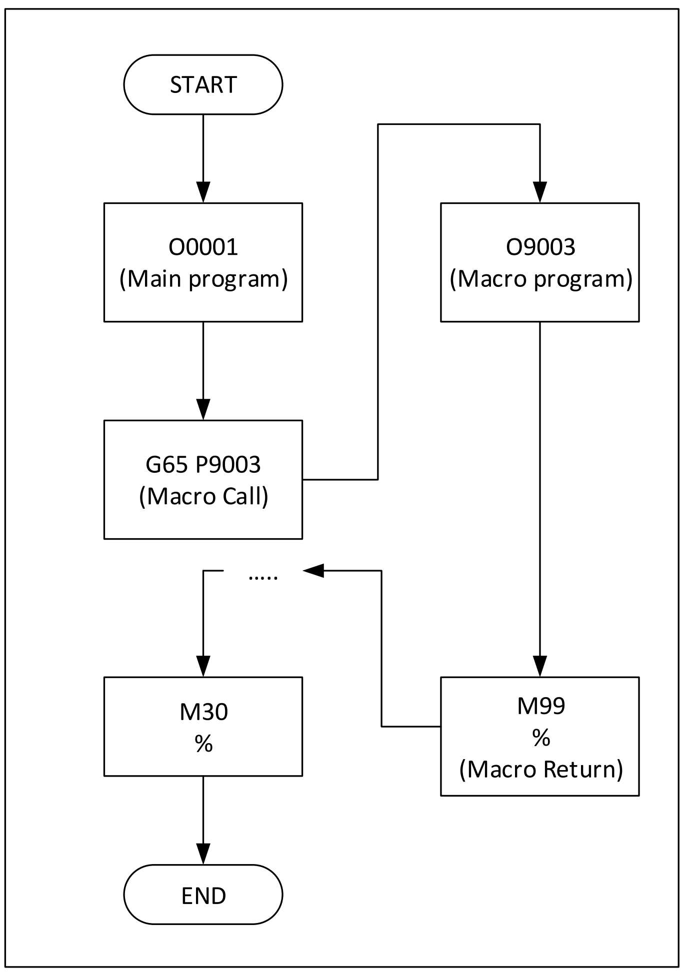


Fig 3.1 Embedded macro program

Table 3.2 Command for macro call and macro return

Command Syntax	Description
G65 P----	Macro call command. After the address “P” follows the program number for the macro (“O” in the program number is not needed).
M99	Macro return command. This command resides in the macro program. Every macro program should end with M99

3.3.3 Macro Input

Data can be input to the macro program as the values on which the macro program calculation is based. This type of data is called macro arguments. They are defined with macro call command. Syntax is shown in the following table.

Table 3.3 Macro call with arguments

Command Syntax	Description
G65 P---- <Arguments>	Macro call command with arguments.

Arguments are input to the macro program by writing the desired values following special capital letters. For example, the following syntax defines 10.5, 9 and 5 as the values for argument A, B and C.

$$G65\ P8003\ A10.5\ B9\ C5$$

These values are then passed into the macro body. Inside the macro body, a special set of symbols, known as local variables, are utilized to reference the input argument values. Local variables and the capital letters are used in a corresponding way. Table 3.4 shows the relationship between the local variables and input arguments [20].

Table 3.4 Relationship between local variables and arguments

Argument Address	Local Variable	Argument Address	Local Variable
A	#1	Q	#17
B	#2	R	#18
C	#3	S	#19
D	#7	T	#20
E	#8	U	#21
F	#9	V	#22
H	#11	W	#23
I	#4	X	#24
J	#5	Y	#25
K	#6	Z	#26
M	#13		

For example, the following syntax is used to call the macro program.

$$G65\ P8006\ T14\ W10.5$$

According to Table 3.4, in the macro program O8006, values stored in local variable #20 and #23 will be assigned with 14 and 10.5. Note that, only the addresses given by Table 3.4 can be used to pass values as input to macro program.

3.3.4 Macro Body

Three types of components make a complete body of a macro program: Variables, Functions and Logics. Details on these three types of components will be discussed in the following section.

3.3.5 Macro Nesting

Nesting feature is also available in macro programs, like other computer programming languages. Nesting means one macro program is called within another macro program. Up to 4-

level of nesting is allowed by FANUC control. Fig 3.2 shows the visual representation of the macro nesting.

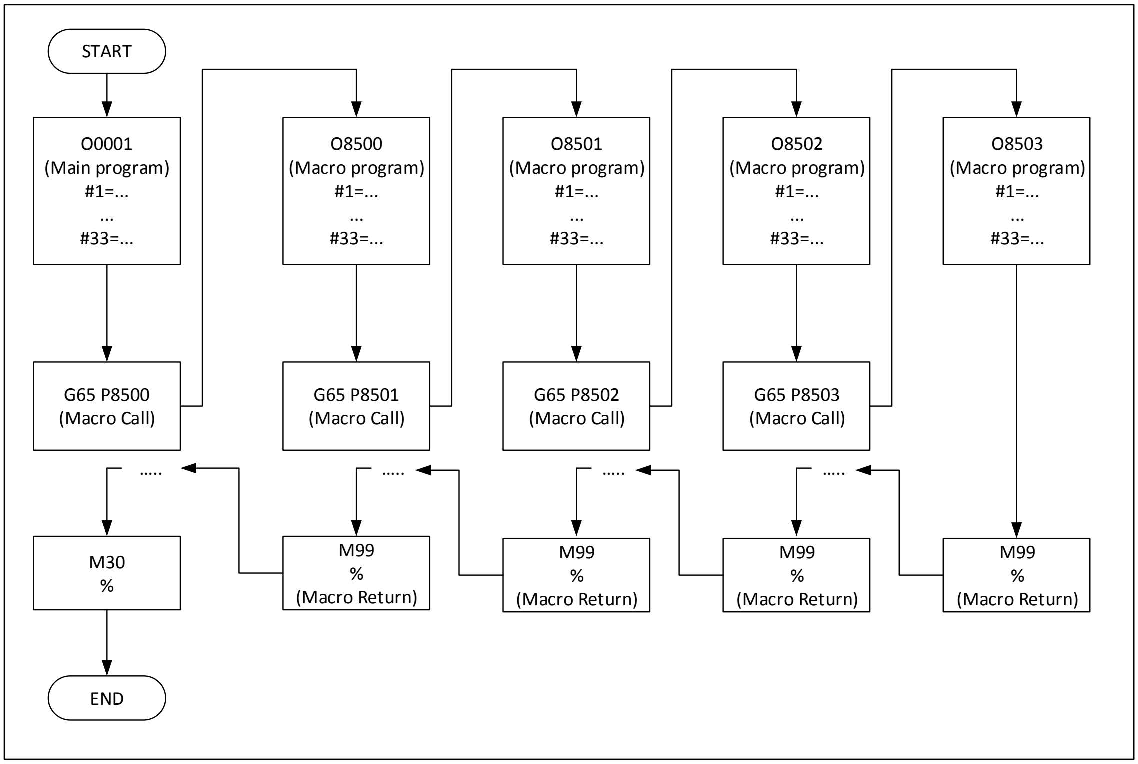


Fig 3.2 Macro nesting and local variables

Local variables would not be passed from one macro to another, as the figure above shows. Every macro has its own set of local variable #1~#33. Further description on local variables is given in the following sections.

3.4 Features of Macro Programming

Macro programming has features just like any other computer programing languages and employment of these features comprises the macro body.

3.4.1 Variables

Variables are the most distinct feature in macros. Macro programming can also be thought as parametric programming in CNC programming. The NC program is developed with combination of G-codes and macro statements. For example, the program may be created to tell the machine carry the tool to a certain position. The position the machine is about to go to is not directly programmed to movement command (G00 for instance), but is programmed as a variable which receives input from the user later. It can also be said that variables are storage units for changing data. Values can be stored in these storage units and be used during execution of the program.

1) Variable Type

Variables supported by FANUC controls can be subdivided into four categories, namely, null variables, local variables, common variables and system variables. FANUC assigns certain ranges of integer number following the # symbol to its variables. Different ranges of integer number represents different categories of variable. Table 3.5 sums up the link between variable categories and integer ranges. The scopes of each type of variables are also given in Table 3.5. [20].

Table 3.5 Variable scopes

<table>
<tr><th colspan="2">Number range</th><th rowspan="2">Type</th><th rowspan="2">Description</th></tr>
<tr><th>From</th><th>To</th></tr>
<tr><td colspan="2">#0</td><td>Null variable</td><td>A variable with no value/ A vacant variable</td></tr>
<tr><td>#1</td><td>#33</td><td>Local variables</td><td>These are temporary variables are used in a macro body and cleared when macro exits</td></tr>
<tr><td>#100
#500</td><td>#149
#999</td><td>Common variables
Global variables</td><td>Common variables are still valid when macros exit but cleared when the machine resets
Global variables are not cleared even when the machine resets</td></tr>
<tr><td>#1000</td><td>… and up</td><td>System variables</td><td>System variable can read and write CNC internal data such as tool registers data, current work offset, etc.</td></tr>
</table>

2) Variable Declaration and Usage

Just like any other computer programming languages, variables should be declared before used. The way to declare variables in FANUC macros is by assigning the # symbol before certain integer, as has been roughly described in the earlier text:

$$\#i = assigned\ value$$

Table 3.6 gives some examples of declaring variables:

Table 3.6 Variable declaration

Expression	Description
$\#10 = 1000$	Defines a local variable #10 and assigns value 1000 to it.
$\#103 = 50$	Defines a common variable #103, which will retain when macro exits but will be reset when machine resets. Assigns value 50 to it.
$\#560 = 90$	Defines a global variable #560, which will retain when macro exits and machine resets. Assigns value 90 to it
$\#5221 = 70$	Assigns value 70 to a predefined system variable #5221

Once a variable has been declared, it can be used as an actual number. For example, a command for the machine rapidly moving to a position (30, 40, 50),

$$\boldsymbol{G00\ X30.\ Y40.\ Z50.\ .}$$

It is equivalent to the following command:

$$\#5 = 30.$$
$$\#6 = 40.$$
$$\#7 = 50.$$

$$\boldsymbol{G00\ X\#5\ Y\#6\ Z\#7}$$

Variables in custom macros play a role that is analogous to variables in other computer language. Many of their applications are similar. In custom macros programming, the following are the main applications for variables:

- serving as input entries for arguments in parametric programs,
- working as temporary storage location,

- working as step counter used in looping,
- providing the ability of setting flags,
- serving as constants which values keep unchanged,
- editing CNC control internal data, and
- changing CNC control settings.

3.4.2 Functions

Types of different functions are supported by FANUC custom macros. These functions offer options to process the variables in various ways. Four groups of functions can be divided according to their difference in use:

- Arithmetic functions
- Trigonometric functions
- Logical operations
- Miscellaneous functions

1) Arithmetic functions

Mathematical calculations are available in macro programming. Table 3.7 shows the symbols that are used in macro programming language as arithmetic functions.

Table 3.7 Arithmetic functions summary

Function	Symbol
Addition	+
Subtraction	-
Multiplication	*
Division	/
Nesting	[ ]

Examples for the use of arithmetic functions are used as shown in the follow table.

Table 3.8 Examples of the use of arithmetic functions

Expression	Results
#10 = 5 + 8	Returns 13 as the value of variable #10
#11= #10*2	Returns 26 as the value of variable #11
#12=#11 / [#10*4]	Returns 0.5 as the value of variable #12

2) Trigonometric functions

FANUC Macro supports the employment of trigonometric functions. Table 3.9 shows the summary of the trigonometric functions available in FANUC macros.

Table 3.9 Trigonometric functions summary

Function	Symbol	Example
Sine	SIN	#1=SIN[30]
Cosine	COS	#1=COS[30]
Tangent	TAN	#1=TAN[30]
Arc Tangent	ATAN	#1=ATAN[2]/[6]

Note that the inputs for SIN, COS and TAN are of the type of angle.

3) Logical operations

Boolean and binary logical operators are also available in FANUC macros. Table 3.10 shows the summary of the logical operations in FANUC macros.

Table 3.10 Logical operation summary

Function	Symbol
Equal To	EQ
Not Equal To	NE
Less Than	LT

Greater Than	GT
Less Than Or Equal To	LE
Greater Than Or Equal To	GE
And	AND
Or	OR
Exclusive Or	NOR

The given result of the operations above would be either 0 (False) or 1 (True). Examples for the use of logical operations are used as shown in Table 3.11.

Given the following variables with values:

#1= 5 **#2=10** **#3=5** **#4=20**

Table 3.11 Examples of the use of logic operators

Expression	Results
#10 = #1 GE #2	Returns 0 as the value of variable #10
#11= #3 EQ #1	Returns 1 as the value of variable #11
#12=[#2LT#1]OR [#4GT#3]	Returns 1 as the value of variable #12

4) Miscellaneous functions

Other functions are also supported by FANUC macros. These functions help to facilitate the programming process and grant programmers a higher level of flexibility. Table 3.12 shows the summary of the logical operations in FANUC macros.

Table 3.12 Logical operations summary

Function	Symbol	Example	Results
Rounding	ROUND	#1=ROUND[1.2] #2=ROUND[1.7]	#1=1.0 #1=2.0
Round Down	FIX	#3=FIX[0.85]	#3=0.0
Round Up	FUP	#4=FUP[0.2]	#4=1.0
Absolute Value	ABS	#5=ABS[-3.5]	#5=3.5

Square root	SQRT	#6=SQRT[9]	#6=3

3.4.3 Program Control

With logic operators, decisions can be made within the macro body. To execute the decision, program control methods such as loop, jump and break are required. These methods are available in FANUC macros. Table 3.13 shows the summary of the program control commands in FANUC macros.

Table 3.13 Program control summary

Function	Symbol
Statement Label	N word
Unconditional Jump	GOTO n
Conditional Jump	IF…GOTO n
Looping	WHILE…DO m END m

Where,

n is an integer. GOTO statement will branch the program to the position labeled by the N word with the integer n;

m is an integer. DO statement will branch the program to the position where END statement

3.5 Custom Macro and CNC Internal Information

FANUC control provides support for the communication between macro programs and CNC through system variables, which have been briefly described before. System variables empower macros in a great extent. The CNC internal data now can be edited or obtained, just by writing and reading system variables. Internal data refers to those information saved in the registers of the control memory. For example, information saved in tool offsets registers can be read and edited through macro program. Similarly, information about the current machine position, work coordinate systems, alarms, modal codes and many other CNC internal data can be accessed.

As described previously, system variables carry numbers greater than #1000 (four digits or five digits). Unlike other types of variables that can be displayed on the control screen, the display of system variables cannot be achieved directly. Value transfer will be needed. For example, to display the system variable #10001, the system variable should first pass to a variable that is not system variable:

$$\#20 = \#10001$$

The display of #20 can be seen on the control screen and it contains the value of #10001.

There are different sections in numbering for system variables, each reflecting their functions. The most used group of system variables are described in the following text.

3.5.1 Work Offset

In FANUC 0i control, six work offsets (from G54 to G59) and one external work offset are available. Their information are stored in the work offset register on the machine control. For a typical 3-axis milling machine, the work offsets registers are shown in Fig 3.3. Different system variables are assigned accordingly to these registers and make these information accessible through a macro program. The corresponding relationship between system variables and work offset registers are shown in Fig 3.4 [20].

	EXT
X	0.000
Y	0.000
Z	0.000

	G54
X	0.000
Y	0.000
Z	0.000

	G55
X	0.000
Y	0.000
Z	0.000

	G56
X	0.000
Y	0.000
Z	0.000

	G57
X	0.000
Y	0.000
Z	0.000

	G58
X	0.000
Y	0.000
Z	0.000

	G59
X	0.000
Y	0.000
Z	0.000

Fig 3.3 Work offset registers of a 3-axis milling machine

	EXT
X	#2500
Y	#2600
Z	#2700

	G54
X	#2501
Y	#2601
Z	#2701

	G55
X	#2502
Y	#2602
Z	#2702

	G56
X	#2503
Y	#2603
Z	#2703

	G57
X	#2504
Y	#2604
Z	#2704

	G58
X	#2505
Y	#2605
Z	#2705

	G59
X	#2506
Y	#2606
Z	#2706

Fig 3.4 System variables corresponding to work offset

3.5.2 Tool Offset Memory

In FANUC 0i, the Type C tool offset memory is implemented. Type C tool offset memory is the type of tool offset memory with highest flexibility. Registers for information on tool length geometry, tool length wear, tool radius geometry and tool radius wear are available for this type of the tool offset memory. For a typical 3-axis milling machine, the tool offset registers are shown in Table 3.14. The corresponding relationship between system variables and tool offset registers are shown in Table 3.15.

Table 3.14 Tool offset registers

Offset No.	H-Offset		D-Offset	
	Geometry	Wear	Geometry	Wear
1	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000
…	…	…	…	…
400	0.000	0.000	0.000	0.000

Note: H-Offset in the table above refers to tool length information.

D-Offset refers to tool radius information

Table 3.15 System variables corresponding to tool offset registers

Offset No.	H-Offset		D-Offset	
	Geometry	Wear	Geometry	Wear
1	#10001	#11001	#12001	#13001
2	#10002	#11002	#12002	#13002
3	#10003	#11003	#12003	#13003
…	…	…	…	…
400	#10400	#11400	#12400	#13400

Note: H-Offset in the table above refers to tool length information.

D-Offset refers to tool radius information

3.5.3 Axis Position

An NC program controls the movement of the machine, and the control system records and displays the current axis position related to the tool data. These position values change constantly during the movement but keep unchanged when the movement task is completed. By accessing system variables, axis position information can be obtained. There are four types of position data that can be accessed from system variables: programmed endpoint coordinate; machine position; absolute position relative to part zero; position stored due to the trigger of SKIP signal. Table 3.16 below shows the summery of these positions and their relating system variables for a 3-axis milling machine. Position information on each axis is stored on one system variable and from X to Z, the last digits in the corresponding variable numbers are 1, 2 and 3 respectively.

Table 3.16 System variables on axis position data

Variable Number		Position Description	Coordinate System
From	To		
#5001	#5003	Previous block endpoint	Workpiece coordinate (e.g. G54)
#5021	#5023	Current axis position	Machine coordinate
#5041	#5043	Current axis position	Workpiece coordinate (e.g. G54)
#5061	#5063	Skip signal stored position	Workpiece coordinate (e.g. G54)

3.5.4 Other CNC Functions Associating with System Variable

Other CNC functions such as alarm generation, timer, feedhold switch control and modal function information are controllable through macro programs by using system variables.

Different control has different functions available for control. Table 3.17 below shows the most common used functions and their relating variables.

Table 3.17 Other functions and system variables

System Variable Number	Description
#4107	Current cutter radius offset number
#4109	Current feedrate
#4111	Current tool length offset number
#4119	Current spindle speed
#4120	Current tool number
#3000	Alarm generation
#3001	Timer
#3004	Feedhold switch control

CHAPTER 4 MEASUREMENT UNCERTAINTY AND PROBING STRATEGY STUDY

4.1 Introduction

This chapter focuses on the measuring algorithm based on the characteristics of on-machine tool setter system described in chapter 2. Measurement support function in CNC will be further discussed. Measurement strategy will be addressed. Under the current measurement strategy, measurement error will be analyzed and conditions which fail the measurement process will also be study.

4.2 Measurement Support Function

FANUC control supports measurement functions on both hardware and software side. On hardware side, tool setter trigger signal is recognized by either PMC or CNC. On the software side, G codes such as G31, G31.1…are available for measurement.

4.2.1 Interface Signals and SKIP Signal

Interface signals are needed for communication between external devices and CNC machine. Tool setter is like any other external devices. Its trigger signal should be detected by CNC so that measurement data can be acquired. Three types of interface signals can be used for the CNC to respond on tool setter trigger signal.

1) Standard interface signal

As mentioned in Chapter 2, section 2.5.4, external devices are generally connected to PMC. When a tool setter is connected to PMC like other external devices, its trigger signal is considered as any other standard interface signal to PMC.

PMC continuously loops to scan input signals from the beginning to the end within a certain period of time in order to execute its built-in program. This period of time is called scan time. In many cases, the scan time can last up to 8 msec. In this case, from the tool setter trigger signal becomes available to CNC recognizes the trigger signal, the delay in response can be up to 8 msec.

2) SKIP signal

In order to shorten the response delay, a new type of interface signal is equipped in FANUC controls. This type of signal is call SKIP input (PMC signal X004.7) [18]. Tool setter can be connected to the pin on PMC where SKIP signal will be read by CNC directly. When the tool setter is triggered, PMC will no longer process the trigger signal, instead CNC directly reads the signal. This way, the delay in response is on the CNC side instead of on the PMC side and this time period is no more than 2 msec [22].

3) High speed skip signal (HSS)

To further cut the responding time, a special signal is also made available in FANUC 0i control. This is called high speed skip signal. Unlike most of the interface signal, this signal is connected directly to CNC.

In Fanuc 0i MD control, the PMC signal number F122.7 [18] reflects the status of high speed skip signal. As mentioned before, in section 2.5.5, F- signal is used as input for PMC from CNC. Since high speed skip signal (HSS) is input directly to the CNC from external device, to check its status, information on HSS should be input from the CNC to PMC and PMC shows the information through MMI.

The high-speed skip signal improves the CNC response delay to 0.1 msec or less [22]. Thus it provides possibility to perform high precision measurement.

Table 4.1 shows the comparison between three types of interface signals. As can be seen, SKIP signal or high speed skip signal reacts in a shorter response delay. Thus SKIP or high speed skip signal is more favorable for measurement.

Table 4.1 Three types of interface signals

Signal type	Connection	Does PMC process signal?	Maximum delay
Standard interface signal	To PMC	Yes	8 ms
SKIP	To PMC	No	2 ms
High speed SKIP	To CNC	No	0.1 ms

4.2.2 SKIP Function Command (G31)

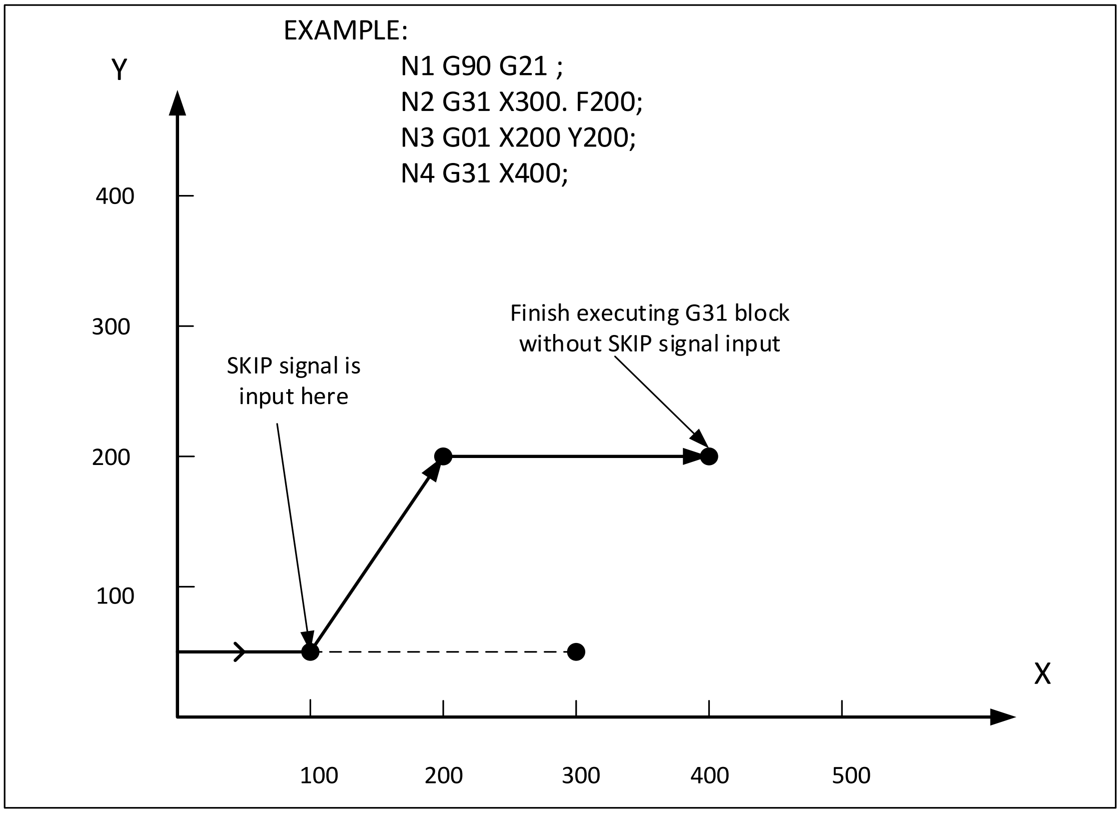
Machine commands should be available for the user to use the skip signal as measurement signal. FANUC provides G31 command for this purpose.

G31 command behaves the same as linear interpolation command G01. However, when an external SKIP signal is input during the execution of the block containing G31 command, the control will stop executing the current block and the next block is executed.

Programming format for G31 is same to G01, end-point coordinates should be specified. If SKIP signal is not input during the execution of G31 block, end-point coordinates will be reached. G31 motion uses value specified by the latest F- command as feedrate. In addition, G31 is non-modal G code, which means that it is effective only in the block where it is specified. The programming syntax is as follow [20].

$$\boldsymbol{G31\,X_{\dots}Y_{\dots}Z_{\dots}F_{\dots}}$$

The following is the example illustrating how G31 works:



As can be seen, in block N2, end-coordinate is given as (300, 50) for G31 execution. However, while the motion is under proceeding, SKIP signal is input. CNC stops the rest movement of block N2 and executes block N3. In block N4, end-coordinate is also given for G31 execution. This time during the whole G31 motion, SKIP signal is not input. Therefore, the machine arrives at the end-coordinate as programmed.

Another very important feature of G31 is that it allows users to access the machine position information where the SKIP signal is input. Coordinates in workpiece coordinate system when the skip signal is detected by the CNC are stored in system variables (#5061 ~ #5063). The stored values of these variables can be accessed through custom macros, as discussed before in chapter 3. For a standard 3-axis milling machine, the system variables number and their corresponding axis values are shown in Table 4.2.

Table 4.2 System variable and machine axis values for SKIP

System variable	Machine axis values
#5061	X-axis
#5062	Y-axis
#5063	Z-axis

4.2.3 Application of CNC Measurement Support Functions with Laser Tool Setter

CNC measurement support functions make on-machine measurement system available. The following are the steps necessary for the tool setter to perform on-machine tool measurement.

1) Laser tool setter is connected to SKIP input pin of PMC through interface unit, as described in chapter 2. Therefore, laser tool setter trigger signal is recognized by CNC as SKIP signal.

2) A tool is loaded into the spindle and G31 command is programmed to drive the tool to the laser zone of the laser tool setter. As the tool approaching the laser, receiver unit of the laser tool setter will sense the reduction of laser receiving. When the threshold value is reached, tool setter trigger signal is generated and CNC stops the machine from moving further, as shown in Fig 4.1.

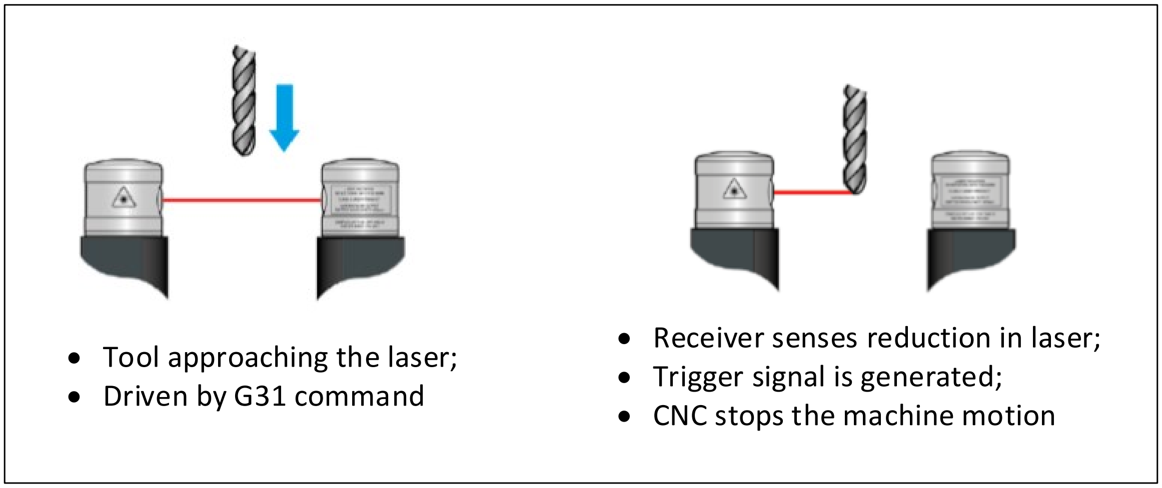


Fig 4.1 Measurement schematics

3) Coordinates of the machine tool when triggered signal is detected by the CNC is captured and stored in system variable #5061 to #5063. Calculations performing on the stored values with the aide of custom macro will yield the result of tool length, tool radius or other tool data.

4.3 Measurement Uncertainty

Acquiring an accurate and reliable measurement result is of great importance. Factors inducing measurement uncertainty will be analyzed in the following text. There are many factors that can affect the measurement results significantly. However, the most noteworthy factors relating to reliability of measurement results are residual coolant drops and swarf, alignment errors, and machine response delay.

4.3.1 Residual Coolant

Incoherent measurement results may be obtained due to the coolant applied on the tool during most of the CNC machining procedure. Residual coolant can be a very challenging problem for performing measurement task with laser tool setter. This is because the laser tool setter is based on non-contact triggered method, trigger signal is not generated by contacting the hard surface as contact triggered method.

Measurement task will fail if the laser tool setter cannot recognize the falsely triggered signal generated by coolant drops at any unpredictable moment. Moreover, residual coolant tends to accumulate on the tip of the tool due to gravity. Thus, if diameter measurement takes place too close to tool tip, the accumulated coolant will be considered as part of the tool and error in measurement results will be generated.

To overcome the disadvantages due to the coolant, a high speed could be applied to the spindle prior to measuring to dislodge the coolant. Air blast can also be used to remove the residual coolant. To avoid disadvantage of the accumulated coolant near tool tip, measurement task should take place higher up the tool tip position.

4.3.2 Alignment Error

Measurement error will result, if a laser tool setter unit is poorly aligned. For a VMC, the alignment in X or Y axis affects the radius/diameter measurement results while the alignment in Z-axis affects the results of tool length measurement. Consider the laser beam should be parallel to Y-axis of VMC. Fig 4.2 shows the measurement error in radius measurement due to poor alignment of laser tool setter in Y axis.

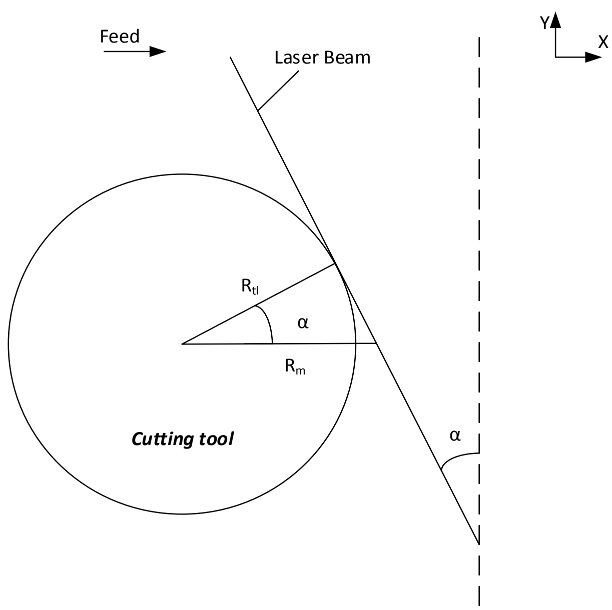


Fig 4.2 Misalignment in Y-axis direction

The measurement error due to misalignment in Y-axis direction can be calculated as:

$$\varepsilon_y = |R_{tl} - R_m| = |R_{tl} - R_{tl}/\cos\alpha| \quad \text{Eq.4.1}$$

,where R_{tl} is the actual tool radius; R_m is the measured tool radius; α is the laser beam misalignment angle along Y-axis.

Fig 4.3 shows the measurement error due to poor alignment of laser tool setter in Z-axis:

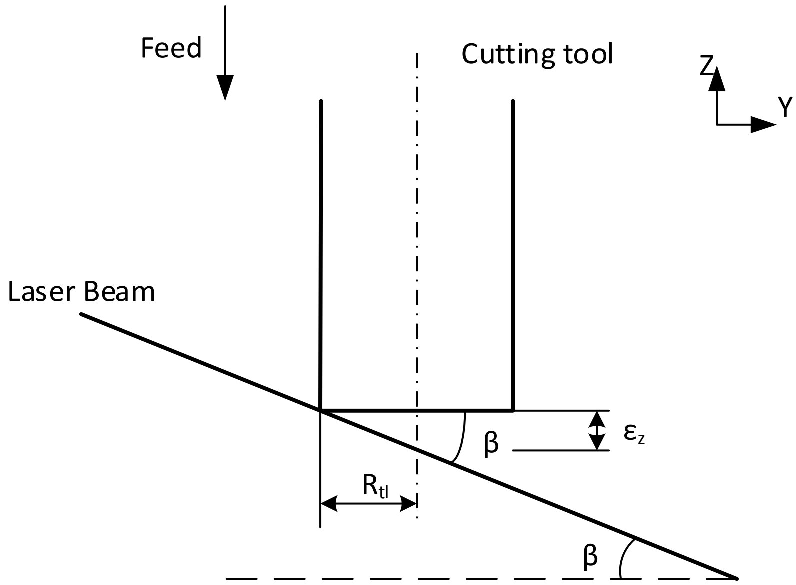


Fig 4.3 Misalignment in Z-axis direction

The measurement error due to misalignment in Z-axis direction can be calculated as:

$$\varepsilon_z = |R_{tl} \cdot \tan\beta|,$$

Eq.4.2

where R_{tl} is the actual tool radius; β is the laser beam misalignment angle along Z-axis.

The signal response time for the laser tool setter is finite. Hence, in some cases, for example if the lowest point of the tool does not locate on the tool center line and the teeth of the tool is too small to break the laser beam and to trigger the tool setter, a off-center distance must be applied before the tool length measurement. Fig 4.4 shows the situation where a boring bar is measured.

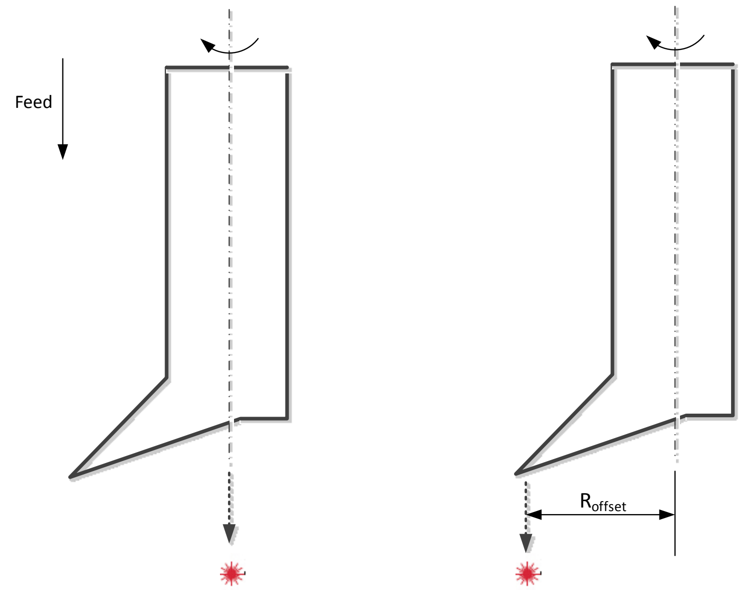


Fig 4.4 Tool length measurement with radius offset applied

A radius offset R_{offset} is applied prior the measurement of tool length to make sure the tooth of the boring bar blocks enough laser beam. In this case, measurement error due to the misalignment in Z-axis can be described by Fig 4.5.

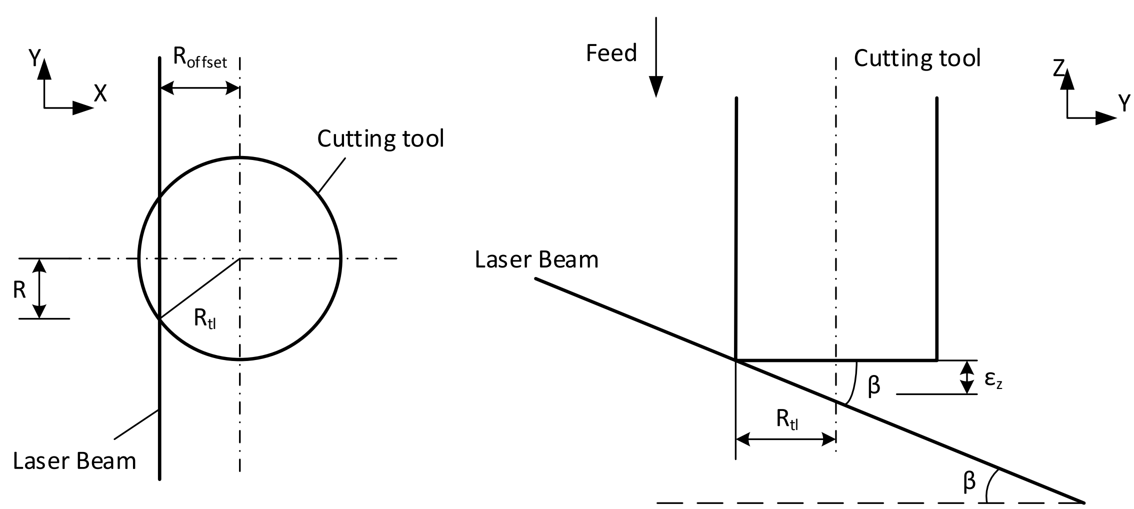


Fig 4.5 Measurement error due to Z-axis misalignment 2

The measurement error due to misalignment in Z-axis direction can be calculated as:

$$\varepsilon_z = |R \cdot \tan\beta| = \left|\sqrt{R_{tl}^2 - R_{\text{offset}}^2} \cdot \tan\beta\right|.$$

Eq.4.3

As can be seen from Eq.4.3, the error ε_z tends to zero as R_{offset} tends to R_{tl}. Therefore, when it is possible, it is favorable to apply radius offset to length measurement. The radius offset can be set to be slightly inside tool tip radius. This value should be no larger than the tool wear tolerance, otherwise tool length measurement may fail after the tool wears.

If Y-axis alignment is better than 1mm per 100mm, for the tool with 100 mm in diameter, according to Eq.4.1, the error would be:

$$\varepsilon_y = |R_{tl} - R_{tl}/\cos\alpha| = 2.5\ \mu m$$

If Z-axis alignment is better than 10 μm per 100 mm, for the tool with 100 mm in diameter, according to Eq.4.2, the error would be:

$$\varepsilon_z = |R_{tl} \cdot \tan\beta| = 5\ \mu m$$

The errors in real measurement tasks would not reach value mentioned above as the errors will be calculated relative to the calibration tool.

4.3.3 Trigger Signal Response Delay

Trigger signal response delay is another significant factor that influences the measuring system. The time sequence of measurement movement, including a tool triggering the tool setter, CNC obtaining position information and machine tool decelerating is shown in Fig 4.6. Consider the situation where SKIP signal is used as the tool setter input signal.

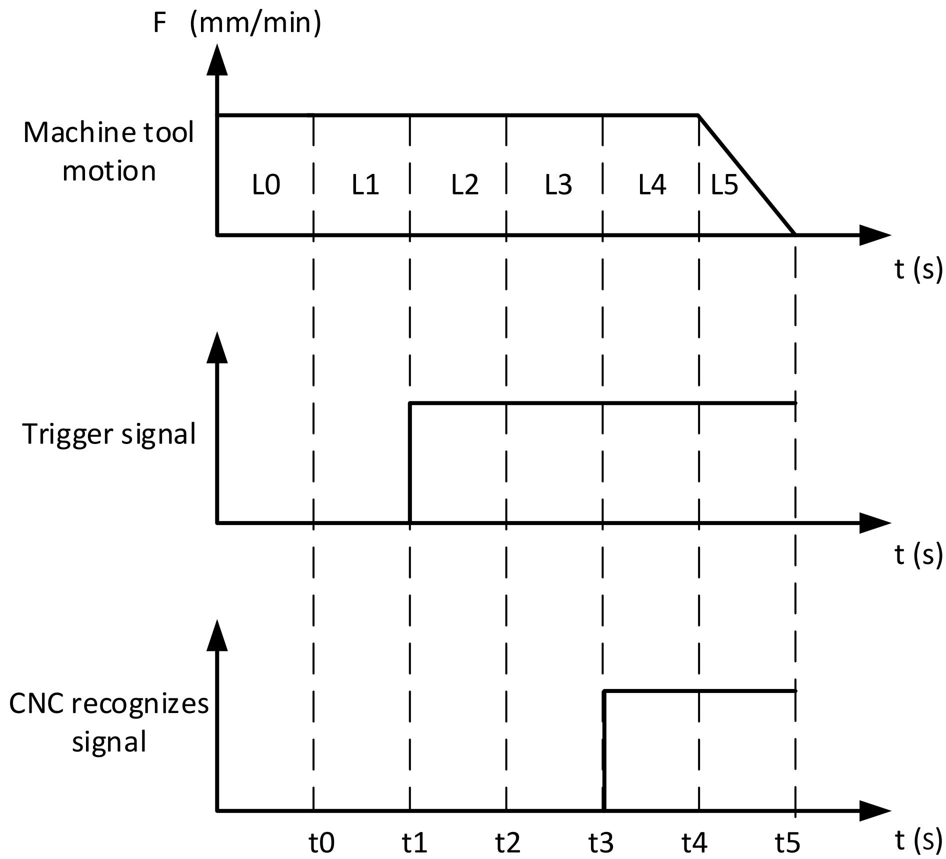


Fig 4.6 Time sequence for a tool to trigger the tool setter

- Machine tool pre-travels to trigger the tool setter (from t_0 to t_1).

The machine advances by the distance of L_1 during this period. It is the distance that the tool travels from the instant it enters the laser beam to the instant it blocks 50% of the laser beam and triggers the tool setter. The machine travels with the programmed feedrate during this period.

- Machine tool travels due to signal transferring delay (from t_1 to t_2).

The machine advances by the distance of L_2 during this period, due to the delay or variation of the receiver and interface unit of the tool setter. The machine travels with the programmed feedrate during this period. L_2 is introduced to measurement results.

- Machine tool travels due to CNC response delay (from t_2 to t_3).

The machine advances by the distance of L_3 during this period, due to the time needed for the CNC to process the SKIP signal and to capture the current position. The machine travels with the programmed feedrate during this period. L_3 is introduced to the measurement results.

- Machine tool travels due to PMC scan delay [22] (from t_3 to t_4).

The machine advances by the distance of L_4 during this period. Before machine tool starts to decelerate, PMC must finish one scan and confirm SKIP signal is valid. The machine travels with the programmed feedrate during this period. However, the distance due to this type of delay does not affect the measurement results.

- Machine tool decelerates (from t_4 to t_5).

The machine advances by the distance of L_5 during this period before reaching a full stop. The distance L_5 the machine tool travels during this period does not affect the measurement results.

From the discussion above, the measurement error due to various signal response delay can be calculated as,

$$\delta_{delay} = L_1 + L_2 + L_3 = \frac{F_v}{60} \times (t_3 - t_0)$$

Eq.4.4

Furthermore, for the same laser tool setter equipped with the same interface unit, the measurement error cause by pre-travel and interface response is consistent and thus can be calibrated out. However, CNC response time, which varies from 0 msec to 2 msec (with SKIP signal), is unpredictable. Eq.4.4 can be written as:

$$\delta_{delay} = \frac{F_v}{60} \times (t_2 - t_0) + \frac{F_v}{60} \times (t_3 - t_2)$$

Eq.4.5

The first term on the right hand side of Eq.4.5 is the measurement error that can be compensated, while the second term will result uncertainty ε in calculation readout,

$$\varepsilon = \pm \frac{F_v}{60} \times (t_3 - t_2)$$

Eq.4.6

For example, if the response time for the CNC to capture the machine position is 2 msec, the measurement readout error due to feedrates can be described in Fig 4.7.

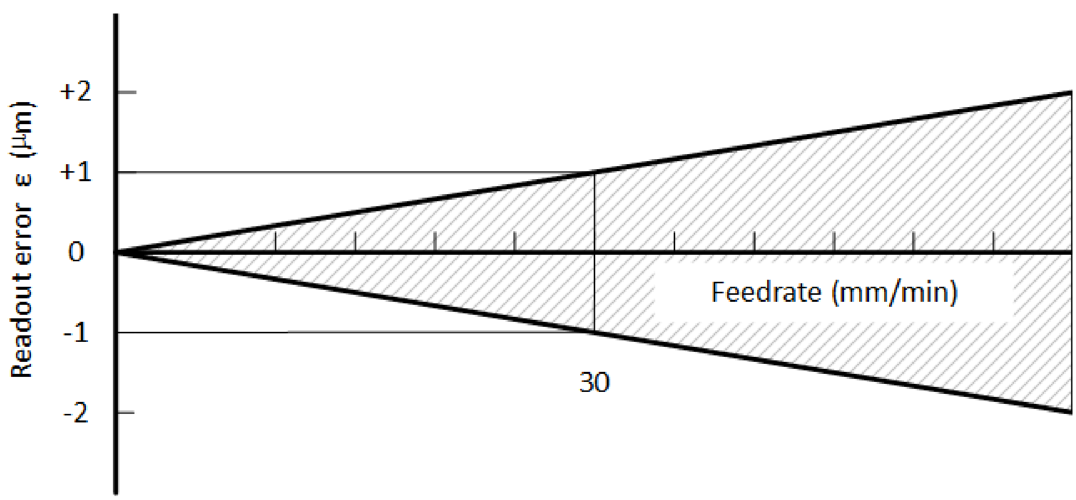


Fig 4.7 Relationship between readout error and feedrate

If readout error should be within the range of $\pm 1\ \mu m$, the programmed measurement feedrate cannot be greater than 30 mm/min, as can be seen from Fig 4.7. It is also noted that a slower feedrate is more favorable for measuring as the readout error will be minimized.

4.3.4 Compensation Method

As established, signal transferring delay can be considered as a consistent system error whilst CNC delay is the uncertainty. Thus, only the former delay can be reliably compensated and variation will always exist in CNC delay. The following method is used to compensate the delay that affects the measurement results.

Drive the tool to trigger the tool setter at two different speed F_{c1} and F_{c2}. Consider the signal transferring delay to be t_s, CNC delay for the two triggers to be t_{cnc1} and t_{cnc2}. The recorded positions for two triggers L_{c1} and L_{c2} can be calculated as:

$$L_{c1} = F_{c1} \cdot t_s + F_{c1} \cdot t_{cnc1}$$

Eq.4.7

$$L_{c2} = F_{c2} \cdot t_s + F_{c2} \cdot t_{cnc2}$$

Eq.4.8

Subtracting Eq.4.8 from Eq.4.7 yields,

$$L_{c1} - L_{c2} = (F_{c1} - F_{c2}) \cdot t_s + F_{c1} \cdot t_{cnc1} - F_{c2} \cdot t_{cnc2}$$

Dividing $F_{c1} - F_{c2}$ from both sides yields,

$$\frac{L_{c1} - L_{c2}}{F_{c1} - F_{c2}} = t_s + \frac{F_{c1} \cdot t_{cnc1} - F_{c2} \cdot t_{cnc2}}{F_{c1} - F_{c2}}$$

Eq.4.9

Take the left hand side of Eq.4.9 as measurement delay Δt. As can be seen, signal transferring delay can be fully compensated. However, the method cannot calibrate out CNC delay.

4.4 Measurement Strategy

To perform the measurement task, it is always favorable if the results can be obtain as quick as possible and as accurate as possible. Certain strategy on measuring the tool should be employed.

4.4.1 Multi-touch Measurement Strategy

The discussion in section 4.3.3 established that the CNC response time delay introduces uncertainty into the measurement results. The single triggered measurement strategy is clearly with a lot of drawbacks, since a high probing feedrate generates large measurement uncertainty while a small feedrate increases cycle time.

It is more favorable to use multi-touch measurement strategy to perform measurement tasks. First, the high feedrate is used to drive the tool to trigger the tool setter and then retracts in a high feedrate. A smaller probing feedrate is used to perform the second triggering from a relatively closer position to the beam and a high feedrate is still employed to retract the tool. At last, the tool approaches the tool setter at a very small feedrate from a very close position to the laser beam to perform the final measurement. To further eliminate the measurement uncertainty, repeat the last measurement procedure three times and take the average from the results.

Fig 4.8 shows the motion sequence of a multi-touch measurement cycle.

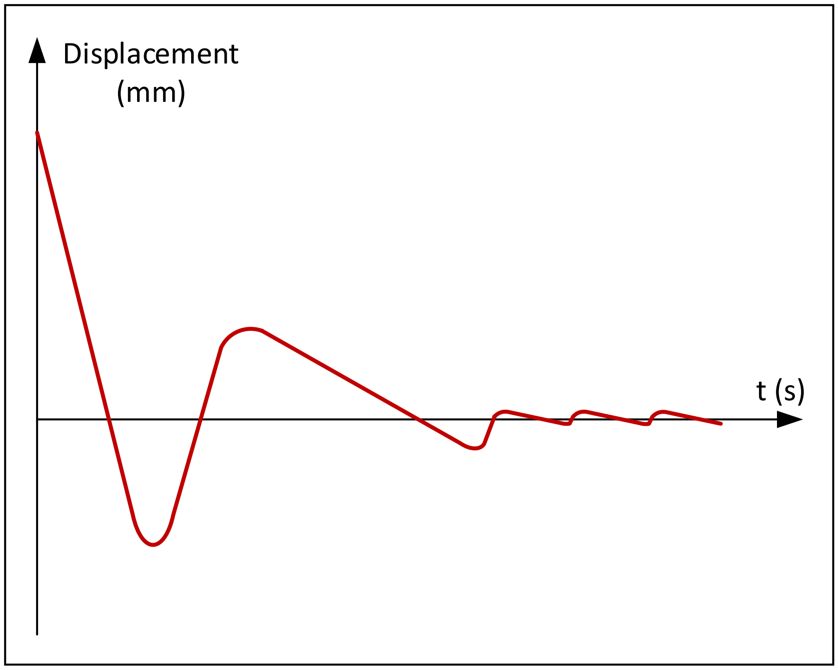


Fig 4.8 Motion sequence of a multi-touch measurement cycle

4.4.2 Measurement Cycle Time Calculation

In measurement tasks, the tool is rapidly brought to a position that is close to the laser beam trigger position. In this position, the distance between the tool and laser beam is called clearance distance. For example, in radius/diameter measurement, the tool is rapidly brought to the radius clearance position, as it is shown in the following figure.

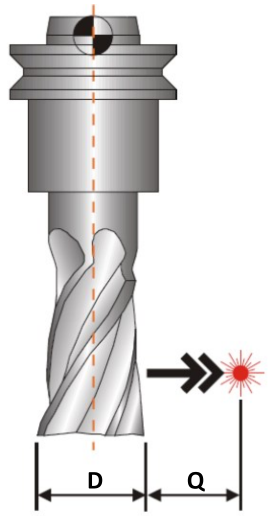


Fig 4.9 Radius clearance position

In the above figure, Q is the radius clearance distance while D is the diameter of the cutter. The clearance distance Q ensures the tool does not break the beam and triggers the tool setter during the rapid positioning. After this rapid positioning, the tool advances toward the laser beam and start the measurement cycle.

In detail, the distance a tool travels during one measurement motion, comprises four major parts: clearance distance and pre-travel distance, overtravel due to CNC response delay, overshoot and back-off travel distance.

1) Clearance distance and pre-travel distance P_1.

For a standard pin with a known diameter, by travelling clearance distance Q , it should trigger the tool setter. In this case, $P_1 = Q$. The time it takes for the pin to cover this distance can be calculated as,

$$t_1 = P_1/F_v$$

Eq.4.10

2) Overtravel P_2 due to signal transferring and CNC response delay.

As described previously, it takes time for the trigger signal to reach CNC and for the CNC to react on the signal. The distance the tool travels during this period of time t_2 can be calculated as,

$$P_2 = F_v \cdot t_2$$

Eq.4.11

3) Overshoot

After the CNC finishes processing the trigger signal, the current position coordinates will be captured into system variables. If the next block contains no further motion, the machine tool will decelerate and eventually stop. Therefore, the final position of the machine is not identical to the captured position. The difference in distance between final position and the captured position is called overshoot. Overshoot calculation is more complicated than other the measurement motion distance calculation. Time spent on overshoot distance consists of two parts: PMC preparation time t_{31} and deceleration time t_{32}, as discussed previously.

- PMC preparation time t_{31}.

As described before, using SKIP signal as tool setter trigger signal, CNC reads the SKIP signal directly and PMC does not process the SKIP signal. During the time CNC takes to process the SKIP signal (which is t_2), PMC continues to scan all its input signals, including SKIP input. Unless PMC successfully scans the valid SKIP signal, the feed would not stop, even if CNC finishes processing the SKIP signal and decides to skip to the next block. Hence, it takes time t_{31} for the PMC to confirm the SKIP signal and t_{31} varies from 0 msec to 8 msec (one PMC scanning period). During this time, machine tool moves at the programmed feedrate and the distance it travels can be calculated as:

$$P_{31} = F_v \cdot t_{31}$$

Eq.4.12

- Deceleration time t_{32}

The time for deceleration consists of two parts. For one part, the machine tool decelerates in a designated time called time constant t_c [21] set by a system parameter (No.1622) [23]. Another part of the deceleration period is the time for servo delay.

Considering a linear deceleration profile for a programmed feedrate, the deceleration Dec for the machine to reach a full stop, is calculated based on the time constant $t_c$and the programmed feedrate F_v:

$$Dec = F_v/t_c$$

Eq.4.13

Within the time period $t_{321} = t_c$, the machine performs purely linear deceleration motion. However, tasks such as position check and other servo related actions must also be performed in the process of deceleration and a delay t_{322} is introduced. The motion of deceleration can be described in

Fig 4.10:

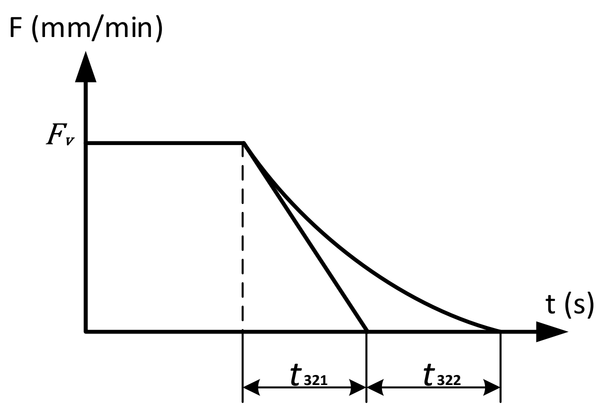


Fig 4.10 Deceleration

While the distance the machine tool travels due to linear deceleration P_{321} can be calculated as

$$P_{321} = \frac{1}{2} F_v \cdot t_{321},$$

the calculation of the distance the machine tool travels due to servo delay P_{322} is not trivial. The overshoot due to deceleration is calculated as

$$P_{32} = P_{321} + P_{322}$$

and the total deceleration time is

$$t_{32} = t_{321} + t_{322}$$

If consider the servo delay time is small enough to ignore, P_{32} and t_{32} reduce into:

$$P_{32} = P_{321} = \frac{1}{2} F_v \cdot t_{321}$$

$$t_{32} = t_{321} = t_c$$

The overall overshoot distance can be calculated as

$$P_3 = P_{31} + P_{32} = F_v \cdot (t_{31} + \frac{1}{2} t_c)$$

Eq.4.14

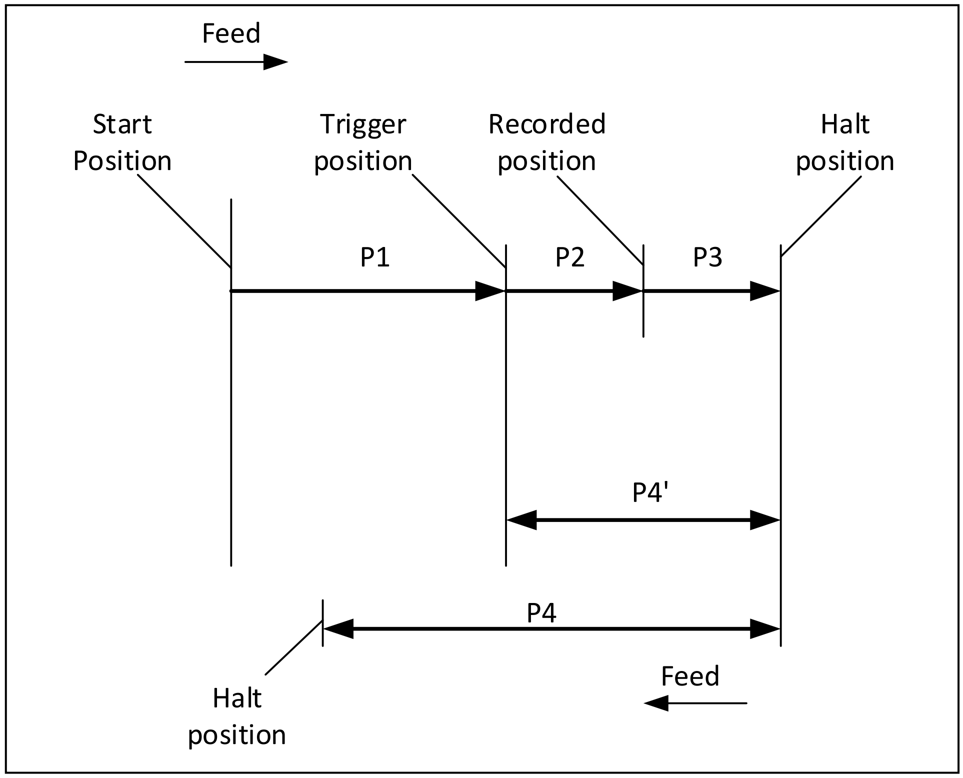
Overall overshoot delay can be calculated as

$$t_3 = t_{31} + t_c$$

Eq.4.15

4) Back-off travel distance P_4

After the tool triggers the tool setter and stops, it should withdraw to a position that is enough to reset the tool setter status back to un-triggered. Back off distance P_4 is defined from the point where the tool halts, as shows in Fig 4.11.



P_4' in the figure above is the back off distance by definition. However, since measurement error exists in information on P_2 and P_3, a larger back of distance P_4 is defined. P_4 can be calculated as:

$$P_4 = P_2 + P_3 + \Delta l$$

Eq.4.16

, where Δl is the extra distance added to back off distance to ensure the tool setter reset.

When considering no servo delay, the machine will travel the distance P_4 with either of the following velocity profiles.

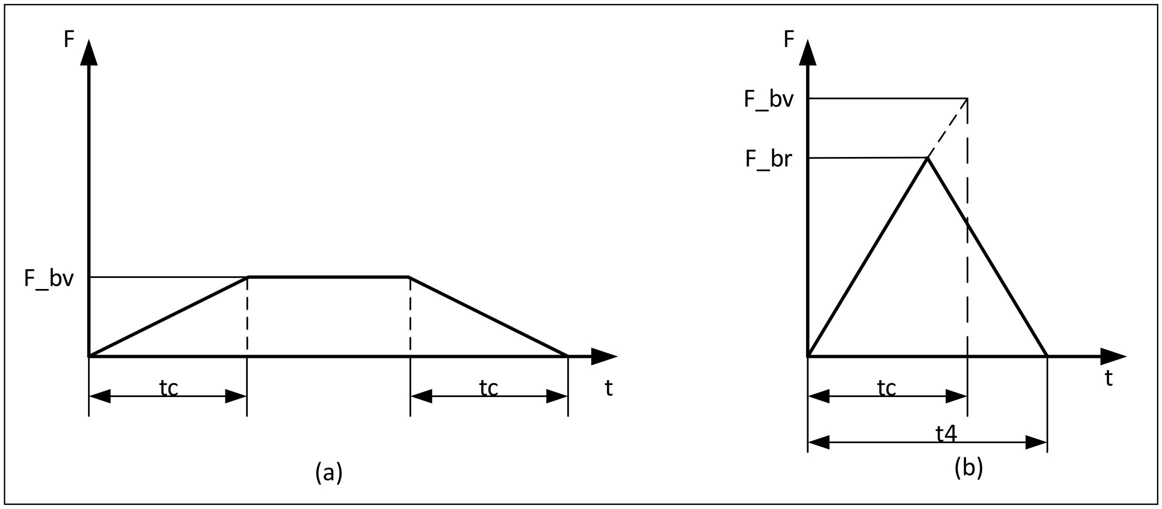


Fig 4.12 Velocity profile

In the case of Profile (a), the machine fully accelerates to the programmed back off feedrate F_{bv}. The acceleration period will take up one time constant t_c. And since the machine also needs to decelerate to a full stop, another time constant t_c is necessary. This type of profile takes up at least 2 time constants. In the case of Profile (b), due to the limited travel distance, the high programmed feedrate cannot be reached. CNC will set an equal time period $t_4/2$ for acceleration and deceleration and the maximum feedrate can only go up to F_{br}. As can be seen, profile (b) requires less time to cover the same travelling distance.

For profile (a), total time spent on back-off motion can be calculated as:

$$t_4 = (P_4 - F_{bv} \cdot t_c)/F_{bv} + 2t_c$$

For profile (b), total time spent on back-off motion can be calculated as:

$$t_4 = \sqrt{P_4 \cdot t_c / F_{bv}}$$

These can also be written as:

$$t_4 = \begin{cases} \dfrac{P_4 - F_{bv} \cdot t_c}{F_{bv}} + 2t_c & , P_4 > \ F_{bv} \cdot t_c \\ 2 \times \sqrt{P_4 \cdot t_c / F_{bv}} & , F_{bv} \cdot t_c \gg P_4 > 0 \end{cases}$$

Eq.4.17

According to the analysis above, the measurement cycle time t can be calculated as:

$$t = t_1 + t_2 + t_3 + t_4$$

Eq.4.18

Substituting Eq.4.10, Eq.4.11, Eq.4.14, Eq.4.15, Eq.4.16 and Eq.4.17 into Eq.4.18, yields

$$t = \begin{cases} \frac{P_1}{F_v} + t_2 + t_{31} + t_c + \left[\frac{F_v\left(t_2 + t_{31} + \frac{1}{2}t_c\right) + \Delta l}{F_{bv}} + t_c \right] & , F_v\left(t_2 + t_{31} + \frac{1}{2}t_c\right) + \Delta l > F_{bv} \cdot t_c \\ \frac{P_1}{F_v} + t_2 + t_{31} + t_c + 2 \times \sqrt{\left[F_v\left(t_2 + t_{31} + \frac{1}{2}t_c\right) + \Delta l\right] \cdot t_c / F_{bv}} & , F_{bv} \cdot t_C \gg F_v\left(t_2 + t_{31} + \frac{1}{2}t_c\right) + \Delta l > 0 \end{cases}$$

Eq.4.19

where,

P_1 is clearance distance and pre-travel distance;

F_v is the programmed probing feedrate;

t_2 is signal transferring and CNC response delay;

t_{31} is PMC preparation time;

t_c is the time constant for CNC machine;

F_{bv} is the programmed back-off movement feedrate;

Δl is the extra travel distance for back-off movement that ensures the tool setter to be reset.

In addition, since the second and final touch are performed at relatively smaller feedrates, the uncertainty of the measured position is less significant. Therefore, back-off distance can be set less conservatively. A smaller back-off distance not only helps to shorten back-off movement time but also reduces the distance for the next triggering movement at a smaller feedrate. The extra back-off distance Δl can be used to control the back-off distance.

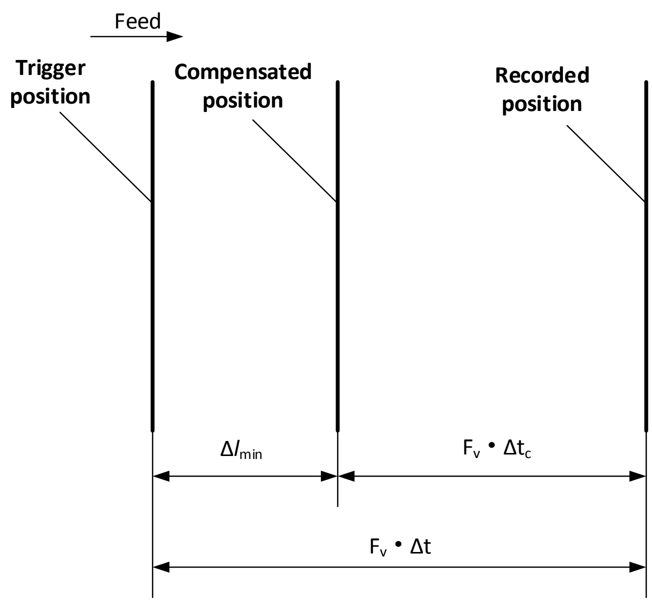


Fig 4.13 Back-off distance and compensated position

In Fig 4.13, Δt is the measurement delay; Δt_c is the calibrated measurement delay; F_v is the probing feedrate. To ensure the reset of the tool setter, the minimum extra back-off distance

$$\Delta l_{min} = F_v\ (\Delta t - \Delta t_c)$$

It is proportional to the probing feedrate.

For the second touch, the probing feedrate F_{v2} reduces to $1/n$ of the initial feedrate. Its extra back-off distance Δl_2 should also reduce to $1/n$ of Δl_1. Note that Δl_1 and Δl_2 are the clearance and pre-travel distances for the second touch and final touch. The time t_{23} it takes for the probe triggering the tool setter in second touch and final touch can be calculated as

$$t_{12} = \frac{\Delta l_1}{F_{v2}} = \Delta l_1 \cdot n/F_{v1}$$

$$t_{13} = \frac{\Delta l_2}{F_{v3}} = \frac{\Delta l_1}{n \cdot F_{v3}}$$

$$t_{23} = t_{12} + t_{13} = \Delta l_1 \cdot \frac{n}{F_{v1}} + \frac{\Delta l_1}{n \cdot F_{v3}}$$

Eq.4.20

The following set of parameters is the typical value for a measurement task.

Table 4.3 Parameters for measurement cycle time

Parameter's Name	Symbol	Value	Unit
Initial clearance distance & pre-travel distance	P_{11}	5	mm
Initial Probing feedrate	F_{v1}	3000	mm/min
Final touch probing feedrate	F_{v3}	6	mm/min
Signal transferring and CNC response delay	t_2	0.0013	s
PMC preparation time	t_{31}	0.004	s
Time constant for CNC machine	t_c	0.06	s
Back-off motion feedrate	F_{bv}	3000	mm/min
First extra travel distance for back-off motion	Δl_1	1.2	mm

Eq.4.20 has a minimum at $n = 22.36$. Take $n = 22$, the measurement cycle time can be calculated to be $t = 13.106\ s$.

4.5 Measurement Error Analysis

4.5.1 Flute Trajectories

During diameter measurement task, the tool spins and advances at a constant speed towards the laser beam and eventually triggered the tool setter. In other words, the flutes move in circular path while they also move forward with a feedrate perpendicular to laser beam simultaneously. An n-flute cutter, the flutes under the motion of diameter measurement form n sets of trochoidal trajectories with phase differences. Moreover, for any given tool, there is always a cutting edge that extends farther from the center line than the other cutting edges, as shown in Fig 4.15. The flutes will form trajectories with different radii.

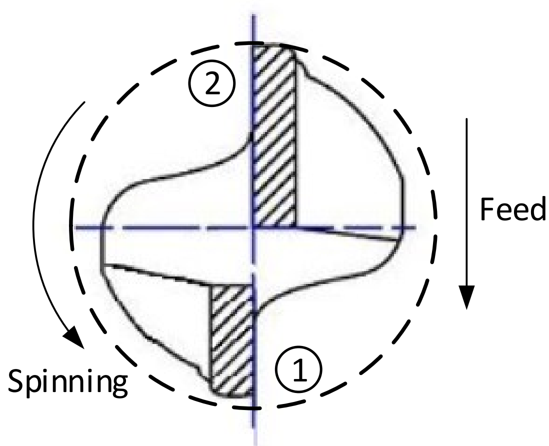


Fig 4.15 An end mill with 2 flutes

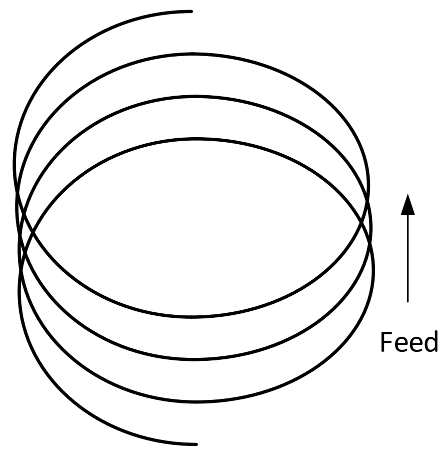


Fig 4.14 Trochoidal trajectory

The flutes of an end mill spinning clockwise at a speed of $s\ RPM$ and moving perpendicular to laser beam at a velocity of $F\ mm/min$ generate a set of trochoidal trajectories. Suppose the end mill has n flutes with the same pitch angle for each flute. Their pitch angle can be calculated as follow:

$$\emptyset_p = 2\pi/n$$

Eq.4.21

Their trajectories can be represented by a set of parametric equations with time t as variable:

$$\begin{cases} x_1 = x_s + F \cdot t/60 + r_1 \cdot \cos(-\omega t + \varphi) \\ y_1 = y_s + r_1 \cdot \sin(-\omega t + \varphi) \end{cases},$$

$$\begin{cases} x_2 = x_s + F \cdot t/60 + r_2 \cdot \cos\left(-\omega t + \emptyset_p + \varphi\right) \\ y_2 = y_s + r_2 \cdot \sin\left(-\omega t + \emptyset_p + \varphi\right) \end{cases},$$

$$\dots$$

$$\begin{cases} x_i = x_s + F \cdot t/60 + r_i \cdot \cos\left[-\omega t + (i-1) \cdot \emptyset_p + \varphi\right] \\ y_i = y_s + r_i \cdot \sin\left[-\omega t + (i-1) \cdot \emptyset_p + \varphi\right] \end{cases},$$

$$\dots$$

$$\begin{cases} x_n = x_s + F \cdot t/60 + r_n \cdot \cos\left[-\omega t + (n-1) \cdot \emptyset_p + \varphi\right] \\ y_n = y_s + r_n \cdot \sin\left[-\omega t + (n-1) \cdot \emptyset_p + \varphi\right] \end{cases},$$

Eq.4.22

where ω (radius per second) represents the angular velocity the tool spinning speed and can be calculated as:

$$\omega = 2 \cdot \pi \cdot s/60,$$

Eq.4.23

r_1 ,r_2, r_i...r_n are the distances each flute extends from the center point respectively, φ is the starting phase and (x_s, y_s) is the starting position of the end mill.

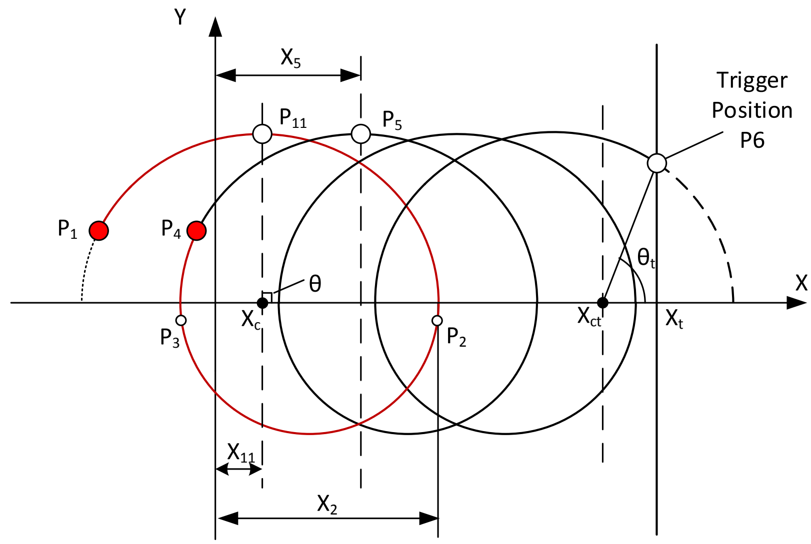


Fig 4.16 Flute trajectory for one flute

Fig 4.16 shows the trajectory that a flute circumscribes during the diameter measurement task. The trajectory is a trochoidal curve made of repeating patterns. The pattern starts at P_1 and ends at P_4, marked in Fig 4.16. This pattern repeats itself in the next period of time T until the flute reaches trigger position P_6. During each period, a point in a pattern advances by the distance of:

$$\Delta l = F/s$$

Eq.4.24

If the trigger position of the tool setter is x_t, when the ith flute arrives at the trigger position, we have

$$x_t - x_i = 0.$$

Eq.4.25

When the flute triggers the tool setter at P_6, the tool center point X_{ct} subtends an angle θ_t to the positive x-axis.

4.5.2 Condition for the Correct Trigger Status

When the tool is spun clockwise and is moved towards the laser beam from the left side of the laser beam, the only correct trigger status is that when the flute triggers the tool setter, the tool center should not pass the beam and should locate at the right side of the beam. Based on this condition, the range for angle θ_t for the tool to trigger the tool setter correctly can be derived.

Consider tool center position is $(0,0)$ at $t = 0$. The parametric equation for tool center point can be written as:

$$\begin{cases} x_c = x_s + F \cdot t/60 = F \cdot t/60 \\ y_c = y_s = 0 \end{cases} .$$

Eq.4.26

When a flute triggers the tool setter with an angle θ_t, the parametric equation for a flute can be written as

$$\begin{cases} x_f = F \cdot t/60 + r \cdot \cos(\theta_t) \\ y_f = r \cdot \sin(\theta_t) \end{cases} .$$

Eq.4.27

If the time it takes for the flute to trigger the tool setter is t_t, the tool center position in x direction is

$$x_c = F \cdot t_t/60.$$

Eq.4.28

The flute position at trigger position in x direction is

$$x_f = F \cdot t_t/60 + r \cdot \cos(\theta_t) = x_t.$$

Eq.4.29

Since at trigger position, the tool center must locate on the left of the laser beam,

$$x_c < x_t.$$

Eq.4.30

Substitutes Eq.4.28 and Eq.4.29 in to inequality Eq.4.30, we have

$$F \cdot t_t/60 < F \cdot t_t/60 + r \cdot \cos(\theta_t)$$

Therefore, we have:

$$\theta_t \in (-\pi/2, \pi/2).$$

This is the necessary and sufficient condition for the tool to trigger the tool setter correctly.

4.5.3 Relation between Feedrate, Spindle Speed and Flute Radius

To guarantee the flute to trigger the tool setter correctly, namely $\theta_t \in (-\pi/2, \pi/2)$, the form of the flute trajectory must satisfy certain requirements. Since different feedrate, spindle speed and flute radius can result in different trajectory profiles, by finding out the trajectory form in critical condition resulting by these parameters, the relation between feedrate, spindle speed and flute radius can be derived.

The following experiments have been conducted to visualize the combination of spindle speed and feedrate at critical condition for one-flute tools with different radii. Six experiments have been done with the flute lengths r ranging from 1mm to 6mm. When the spindle speed ranges from 800 rmp to 3000 rmp, the corresponding feedrate under critical condition for different flute length is plot in Fig 4.17.

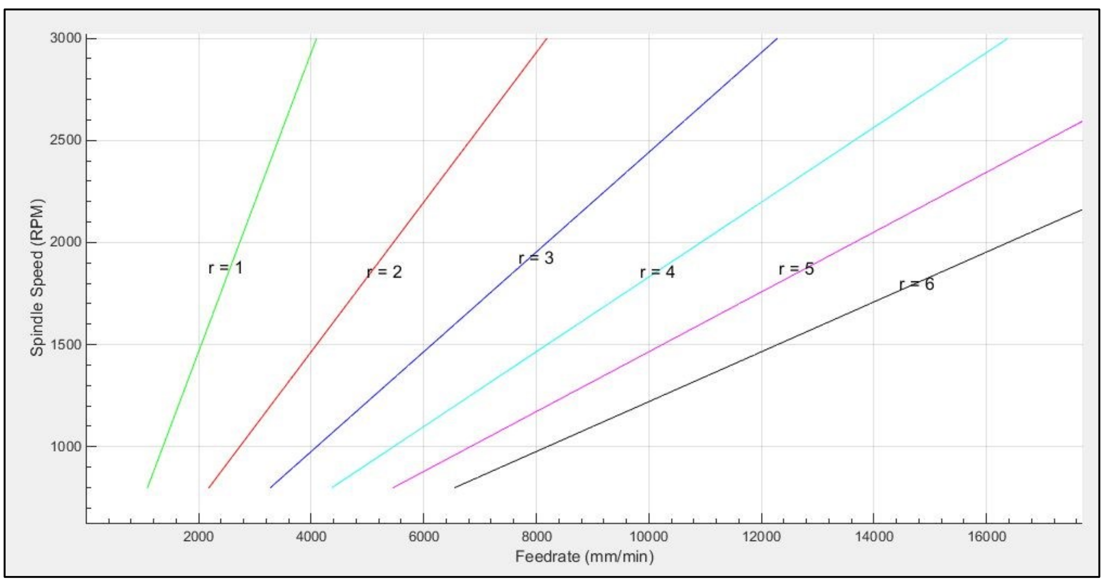


Fig 4.17 Relationship between spindle speed and feedrate

As can be seen from Fig 4.17, each flute length corresponds to a curve. Only spindle speed and feedrate combinations on the left upper side area of the curve are available for selection in order to gain correct measurement results. For example, when measuring a $r = 3mm$ one-flute tool with a spindle speed $s = 1000\ RPM$, the maximum feedrate cannot exceed $4000\ mm/min$; when measuring a $r4$ one-flute tool with a spindle speed $s = 800\ RPM$, the maximum feedrate cannot exceed $4400\ mm/min$. Otherwise, the boring tool will not trigger the tool setter correctly.

It can also be seen that for the same flute length, the lower spindle speed is used, the lower the maximum feedrate is available for selection. In addition, the larger the flute radius is, the curve tends to locate farther to the right, meaning that with the same spindle speed, the larger the flute length is, the larger the maximum feedrate can be.

4.5.4 Application of the Relation between Spindle Speed, Feedrate and Radius

The choice of combination of spindle speed and feedrate determines validity of the measurement task. The choice should be made according to the Fig 4.17. Choosing the valid combination of spindle speed and feedrate according to flute length, is extremely important in boring bar measurement. Because the tooth of a boring bar can miss the laser beam and trigger the tool setter with an incorrect status, when feedrate is too large, spindle speed is too small or flute length is too small.

Normally, there are two forms of boring bar: 1) A boring bar with the farthest extended point also as the lowest point of the cutter, as shown in Fig 4.18; 2) A boring bar with the farthest extended point not as the lowest point of the cutter, as shown in Fig 4.19.

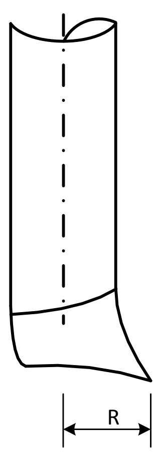


Fig 4.18 Type 1 boring tool

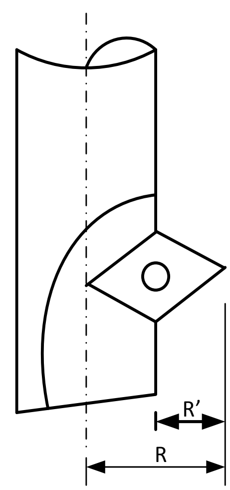


Fig 4.19 Type 2 boring tool

For a boring bar with a form shown in Fig 4.18, to accurately measure the tool radius, it is important to measure the lowest point of the boring bar. Therefore, during measurement, the tool should locate at a position as shown in the following figure.

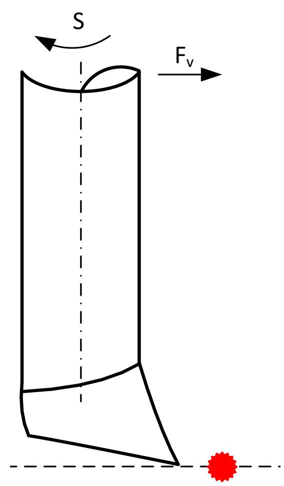


Fig 4.20 Beam position

Because the farthest extended point is the lowest point of the boring bar, if with a poorly chosen spindle speed and feedrate combination, the undesired trigger status, where the flute triggers the tool setter with $\theta_t \notin [-\pi/2, \pi/2]$, may occur. For example, if a $\emptyset 8$ boring bar is spun at $s = 800\ RMP$, the feedrate $F_v = 5000\ mm/min$ is chosen. According to Fig 4.17, this combination lies on the lower right area of the curve for $r = 4mm$. When the tool triggers the tool setter, its center may locate on the right side of the beam, as shown in the following figures. In consequence, a wrong tool radius will be calculated.

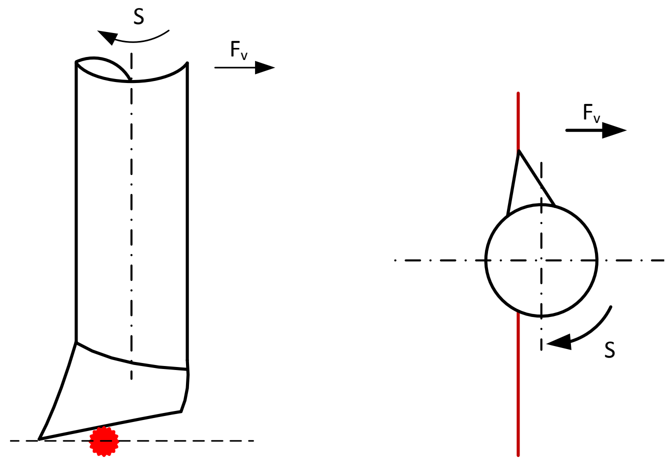


Fig 4.21 Unfavorable trigger condition for type 1 boring bar

For a boring bar with the other form shown in Fig 4.19, to measure the tool radius, the position of the boring bar should locate as Fig 4.22 shown.

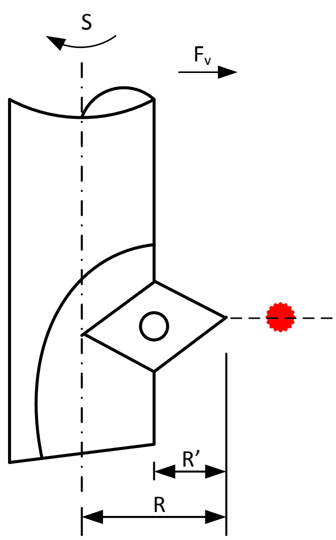


Fig 4.22 Beam position for type 2 boring bar

A boring bar with this form, a poorly chosen spindle speed and feedrate combination, the undesired trigger status, where the flute rigger the tool setter with $\theta_t \notin [-\pi/2, \pi/2]$, may occur too. For example, if a Ø8 boring bar is spun at $s = 800\ RMP$, the feedrate $F_v = 5000\ mm/min$ is chosen. According to Fig 4.17, this combination lies on the right side of the curve for $r = 4mm$. When the tool triggers the laser beam, the tool center will not be on the right side of the laser beam. A trigger situation, where it is the wrench instead of the flute that triggers the tool setter, may occur, as Fig 4.23 shown. In consequence, a wrong tool radius will be calculated.

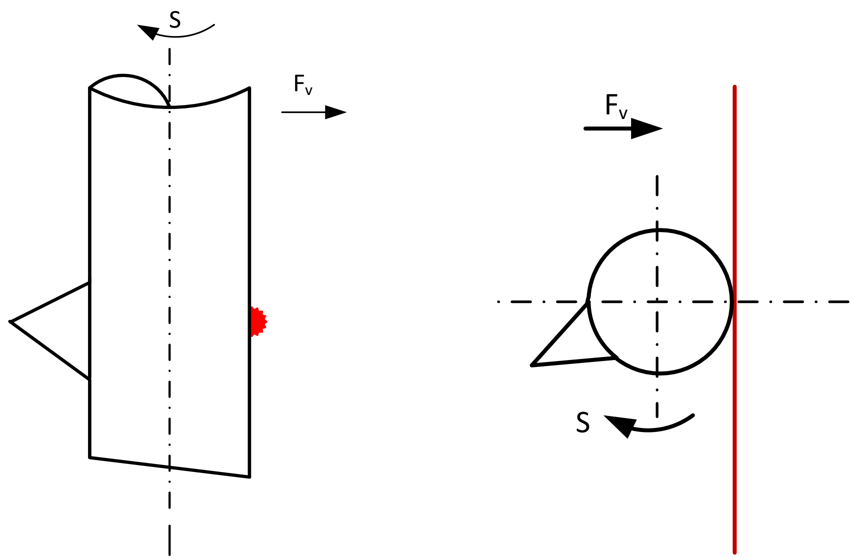


Fig 4.23 Unfavorable trigger condition for type 2 boring bar

CHAPTER 5 APPLICATION

5.1 Introduction

In this chapter, application of on-machine measurement system with laser tool setter will be described. The effect of the application on improving stability of manufacturing is also discussed.

5.2 Experiment

Experiments are carried out on a BridgePort/Hardinge VMC1500P 3-axis vertical mill equipped with FANUC 0i-MC control. Calibration and measurement cycles are programmed in FANUC Custom Macros and installed to the machine control through RS232 serial interface. NC-4/NCi-5 unit produced by Renishaw is selected as laser tool setter and interface unit. To better eliminate the measurement uncertainty, high speed SKIP signal is used for tool setter trigger signal.

Calibration cycles are run prior any measurement task is performed. These cycles are intended to “tell” the machine where the laser tool setter locates and to compensate the consistent system error. Measurement cycles are embedded into part programs, automating the tool measurement tasks. For example, measurement cycles are added after tool change so that every time the machine finishes changing the tool, it will measure the current tool data. The results of radius measurements of three different two-flute milling tools are shown in Table 5.1.

Table 5.1 Radius measurement results (units: mm)

Tool Number	Manual radius measurement result	Tool setter radius measurement result 1	Tool setter radius measurement result 2	Tool setter radius measurement result 3
1	9.958	10.008	10.007	10.007
2	5.901	5.924	5.924	5.925
3	3.375	3.508	3.508	3.508

The radius measurement experiments conducted above are under the conditions of final probing feedrate $F_v = 2\ mm/min$ and the tool spinning at $S = 1000\ rev/min$. Measurement uncertainty is no more than 0.001 mm. The repeatability of measurement results from the table above shows reliability. Also it is worth mentioning that, the measurement results gained from tool setter are larger than manual radius measurement results. This is because while measuring with tool setter, the tool rotates and thus spindle run out is added into the measuring results.

On the other hand, since high speed SKIP is used as trigger signal, the CNC response delay is no more than 0.1 msec. Thus the hardware delay compensation method described in section 4.3.3 has a very good result. Therefore, the repeatability and accuracy of the measurement system is acceptable for industry use. Fig 5.1 shows the tool is being measured by the tool setter.

Fig 5.1 Measurement with laser tool setter

5.3 Application with Out-Of-Tolerance Warning Feature

Further application can be made in order to prevent the situation where an out-of-tolerance tool is used to perform the machining task. The purpose can be achieved through editing measurement cycles macros. The following two parameters are introduced: The maximum initial input radius wear R_{w1} and the maximum radius wear compared to the initial radius value R_{w2}. The edited cycle performs the following tasks:

- Checks if the radius wear input to the control registry is larger than R_{w1} , if the input is initial; If yes, an out-of-tolerance warning is issued.
- Checks if the difference between the current input radius wear and the initial radius wear is larger than R_{w2} ; if yes, an out-of-tolerance warning is issued.

In the case of manual input radius wear information, mistakes always happen when it is required to input decimal. For example, the correct radius wear is -0.043 mm but the value to the control registry is mistakenly input to be -0.43mm. A 10-time difference is added. The application described in this section prevents situations like these.

Consider the maximum difference between actual tool radius and nominal tool radius cannot be larger than 1.1 mm and a newly mounted tool should not have the radius wear that exceeds $R_{w1} = 0.6\,mm$. Therefore, $R_{w2} = 1.1 - R_{w1} = 0.5\,mm$. Fig 5.2 describes acceptable range of input.

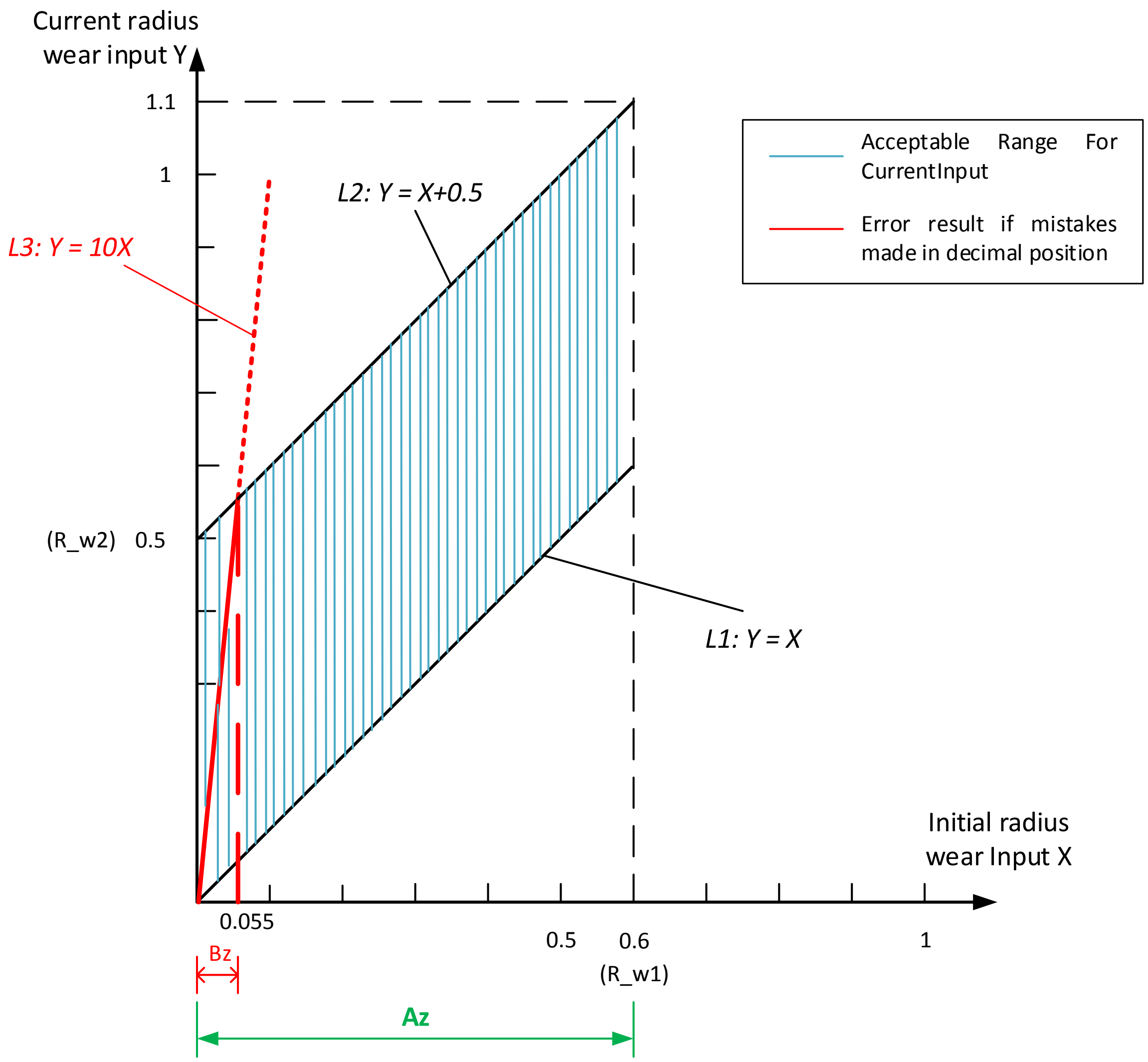


Fig 5.2 Acceptable range of radius wear input

For the initial radius wear input, the input value must fall into the range of A_z, as shown in Fig 5.2. In the case of the updated radius wear input, the input value must fall into the region specified by the blue lines. Consider the manual input error is misreading the decimal position, which yields a 10-time difference in value. The mistaken values follow the line 3 depicted with red color in the figure above. At $X = 0.5555\ mm$, line 3 intersects with line 2. This means that, in the range of B_z ,from 0 to 0.555 mm, the program cannot warn about the input error due to misread decimal position. However, outside of the range of B_z, this type of human error can be fully prevented.

CHAPTER 6 CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

In this work, a method to performed on-machine tool measurement tasks is proposed with the help of laser based tool setter. Analysis has been carried out on the laser tool setters' hardware structure and the components of the CNC system structure. To further pinpoint the measurement uncertainty, the effects on measurement results due to residual coolant, geometry effect and CNC response delay are studied. The maximum deviation in measurement results are derived according to a more accurate mathematical model and compensation method is explained. These give a better understanding on the measurement system ability. To perform the measurement tasks, a dedicated software (measurement cycles) must be installed in the CNC control. This software is written with the aid of FANUC custom macros, which is described in detail in Chapter 3. The major concerns of any measurement are how to gain a result as accurate as possible and as fast as possible. To accomplish these, examination on measurement cycle time is carried out and a multi-touch method with an optimized probing feedrate is proposed.

The result of the applications prove that the repeatability and reliability of the measurement method. By employing out-of-tolerance check, situations where tools of excessive wear are still used for machining can be avoided.

6.2 Future work

For further research, the following topics can be considered to expand the present work:

To obtain the more detailed compensation data, such as machine error and temperature difference.

CAM software can be developed. According to the machine position of the tool setter and workpiece, the software can simulate the on-machine measurement tasks to avoid collision in actual working environment. In addition, parameters of the tool can be taken into consideration in order to choose the best set of input for measurement cycle.

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