Multi-objective Optimization for Error Compensation in Intelligent Micro-factory CPS

Azfar Khalid and Zeashan H. Khan

Abstract In the last decade, the demand of micro products and miniaturization has seen a wide spread growth. Currently, micro products and micro features are produced through conventional macro scale ultra-precision machines and MEMS manufacturing techniques. These technologies have limitations as conventional machining centers consume large energy and space. For mass production of micro components using non-silicon materials and real 3D shapes or free-form surfaces, mechanical micro manufacturing technology based machine tools are developed as an alternative method. The principle of "Small equipment for small parts" is gaining trend towards the investigation on micro-machine tools. One example of miniaturization of manufacturing equipment and systems is the Japanese micro-factory concept. Few micro-machines and associated handling micro grippers and transfer arms are developed to create micro-factory. The manufacturing processes are performed in a desktop factory environment. To explore the micro-factory idea, large number of micro machines can be installed in a small work-floor. The control of this micro factory concept for operation, maintenance and monitoring becomes a Cyber-physical system capable of producing micro-precision products in a fully-automated manner at low cost. Manufacturing processing data and condition monitoring of micro machine tools in a micro factory are the variables of interest to run a smooth process flow. Every machine out of hundreds of micro machines will have sensing equipment and the sensors data is being compiled at one place, ideally using wireless communication systems. One or two operators can run and monitor the whole micro-factory and access the machine if the fault alarms receive from any station. A variety of sensors will be employed for machine control, process control, metrology and calibration, condition monitoring

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of machine tools, assembly and integration technology at the micro-scale resulting in smooth operation of micro-factory. Single machine can be designed with a computer numerical control, but, flexible reconfigurable controllers are envisioned to control variety of processes that will lead to the development of open architecture controllers to operate micro-factory. Therefore, the control effort and algorithms have to utilize process models to improve the overall process and, ultimately, the product. Thus, we aim to introduce machine to machine (M2M) communication in the micro factory test bed. M2M communication enables micro actuator/sensor & controller devices to communicate with each other directly i.e., without human intervention, automating management, monitoring, and data collection between devices, as well as communicating with neighboring machines. All micro sensors communicate with a local short distance wireless network e.g. via Bluetooth piconet as well as with a centralized controller via WLAN 802.11 to exchange control/command from it. In this chapter, inherent issues are first highlighted where bulk micro-part manufacturing is carried out using large size machines. State-of-the-art micro machine tool systems designed and developed so far are discussed. With the help of precision engineering fundamentals and miniaturization scaling issues, a design strategy is formulated for a high precision 3-axis CNC micro machine tool as a model for micro-factory working. Based on this, a mathematical model is built that includes machine's design variables and its inherent errors. The volumetric error between tool/work-piece is evaluated from the machine's mathematical model and further used as an objective function to be minimized. Robust design optimization at micro machine development stage reveals the sensitivity analysis of each design variable. The optimization analysis employs different design of Experiment (DOE) techniques to make initial population that is governed by multi-objective genetic algorithm. Hence, the robust design is achieved for 3-axis micro machine tool using the essential knowledge base. The technique is used to remove the machine's repeatable scale errors via calibration and is known as error mapping. These errors are entered into the machine controller, which has the capability of compensating for the error. The machine does not need any extra hardware. Error mapping is a cost-effective tool in achieving volumetric accuracy in a micro manufacturing system.

Keywords Micro factory · Micro machines · Robotic cyber physical system · Machine to machine communication · Volumetric error · Error compensation

1 Introduction

In the last decade, the demand of micro products and miniaturization has seen a wide spread growth. The application areas for miniaturized products are micro-sensors, accelerometers, micro-mirrors, fiber optics connectors and micro and nano electronics components. Only the IT peripheral and biomedical industries have consumed micro products of worth US$80 billion in 2010. Currently, micro products and micro features are produced through conventional macro scale ultra-precision machines and MEMS manufacturing techniques. These technologies have limitations as conventional machining centers consume large energy and space. Some machine tool manufacturers equip machining centers with costly micro and nano scale machining accessories which caters meso and micro products manufacturing. On the other hand, MEMS is photolithography based fabrication technique. Although, it is an efficient technology for the mass production of micro parts but is limited in terms of variety of raw materials and 2D structures.

For mass production of micro components using non-silicon materials and real 3D shapes or free-form surfaces, mechanical micro manufacturing technology based machine tools are developed as an alternative method. The principle of "Small equipment for small parts" is gaining trend towards the investigation on micro-machine tools, such as, micro-lathe, micro-milling, micro-press and micro components holding, assembling and transfer devices. One example of miniaturization of manufacturing equipment and systems is the Japanese micro-factory concept. Few micro-machines and associated handling micro grippers and transfer arms are developed to create micro-factory. The manufacturing processes are performed in a desktop factory environment.

The meso scale lies between the molecular or atomistic scale (where it is convenient to describe molecules in terms of a collection of bonded atoms) and the continuum or macroscale (where it is convenient to describe systems as continuous). The idea of desktop machines was initiated for the concept of 'micro factories' in the previous decade. Presently, the meso scale parts are manufactured with various processes like electrolytic in-line dressing (ELID), Electro-chemical machining (ECM), die sinking electro discharge machining (EDM), wire cut electro discharge machining (WEDM), milling, turning etc. However, lithography based techniques are the most common for micro manufacturing. As the size of the products become increasingly smaller and market demand for meso scale parts are on the increase, the previous non-lithographic processes are required to be employed at the micro and meso scale. Many researchers in Japan have already developed micro machines that can be mounted on a table top.

This chapter first classifies the non-lithography based micro manufacturing on the basis of machine tool size. Several instances are provided for the use of both standard and desktop size machines in micro manufacturing. Several benefits are identified for the use of miniaturized machines in micro manufacturing processes. Challenges and foreseeable problems for the design and control of desktop size machines and micro-factories are discussed. A design strategy is proposed based on the robust design and optimization technique for a desktop machine tool. The technique can be extended to the design of a micro-factory.

1.1 Non-lithography Based Classical Micro-manufacturing

Non-lithography based meso scale parts are manufactured with different processes and from different size of machines ranging from small to large scale. Classification can be made in non-lithography based meso scale parts manufacturing, based on the size of machines employed for the purpose. Currently, two major groups exist for non-lithography based micro manufacturing; small scale machines often called desktop machines and the standard size machines. Size of machine is identified based on the total volume of the machine tool. Standard size machine tool developers have equipped standard machines for micro machining. Many researchers [1, 2] have also used standard machines for the fabrication of meso scale parts. Some commercial state of the art machine tools equipped with micro manufacturing modules are discussed below.

AGIE [3] **(Switzerland)**: This manufacturer is a leading supplier of ultra precision Wire Cut EDM and Die Sinking EDM. In addition to the different model series for WEDM like AGIECUT VERTEX, AGIECUT CLASSIC and for Die sinking EDM like AGIETRON SPIRIT and AGIETRON HYPERSPARK, it also offers EDM for micro and nano scale application. “Agietron Micro-Nano” is a die sinking machine that can perform micro drilling to machining of micro structures with the addition of nano module. Machine’s micro module has a travel range of 220/160/100 mm^3 (*X/Y/Z*), positioning accuracy of ± 1 μm, resolution, 0.1 μm and the surface roughness of work piece, Ra 0.1 μm. The nano module has a travel range of 6/6/4 mm^3 (*X/Y/Z*) and can fit on the same machine by replacing the rotary axis of the AGIETRON micro. The nano module uses voice coil linear motors and can achieve a positioning accuracy of ± 0.1 μm, resolution 0.02 μm and the surface roughness of work piece, Ra 0.05 μm. Nano module has used parallel kinematics for axes movements (See Fig. 1) .

PRIMACON [4] **(Germany)**: It has developed a 5-axis vertical machining centre (Model # PFM 4024-5D) for the manufacturing of small components. The machine has a travel range of 400/240/350 mm^3 (*X/Y/Z*) with a positioning accuracy, under 1 μm and a rotational repeatability of 1 s arc. The machine uses Heidenhain iTNC 530 controller for the CNC.

FANUC [5] **(Japan)**: The model of this company for micro manufacturing is ROBONANO α-0iB (See Fig. 2), 5 axis CNC precision machining centre. It is a multi-purpose machine used for milling, turning, grinding and shaping with a linear axes resolution of 1 nm. FANUC series 30i controller is applied for the CNC. Static air bearings are selected for the movement of slides, feed screws and direct drive motors. The machine has an overall size of 1500/1380/1500 mm^3 and the stroke length of 280×150 mm^2 in the horizontal direction and 40 mm in the vertical direction. Surface roughness of Ra 1 nm is achieved in the turning operation on aspherical lens core of material Ni–P plate.

Moore Nanotechnology Systems [6] (USA): The company manufactures many medium size lathe machine models like Nanotech 250UPL, 350UPL and 450UPL whereas Nanotech 350FG and 500FG are 3-axis micro milling and 5-axis grinding

Fig. 1 AGIETRON MICRO NANO, nano module (Courtesy of Agiecharmilles)

Fig. 2 ROBONANO developed by Fanuc, Japan

machines respectively. 350UPL is a 4 axis lathe using oil hydrostatic slide ways. Delta Tau PC based CNC motion controller is applied. Linear feed drives use frameless, brushless DC motors having a resolution of 1 nm. Surface roughness of a cubic phase plate of Zinc sulphide material as machined on the Nanotech 350UPL is 4.112 nm Ra.

Meso and micro scale manufacturing form a middle-scale stepping stone by which the benefits of nanotechnology may be accessed. In the past 5–10 years, these meso and micro scale parts have seen increased use in medical applications, consumer products, defense applications and several other areas. A generalized approach is required for the robust miniaturization of standard size machines and manufacturing processes. Miniaturization of conventional machine tools has become a potential research area due to the high demand of the meso scale components.

1.2 Micro-manufacturing Through Micro-machines

There are many miniaturized machine tools developed so far by different research groups and institutions in different parts of the world. In Japan, micro machines are being developed as a part of a big project ‘Development of a Micro-factory’ [7]. Micro machines were first developed to utilize with the robotic arms in the micro factories. Micro factories are envisaged to save space and energy as they consume much less resources as compared to the existing size of machines and factories. Lu et al. [8] have developed a micro lathe turning system and tested a work material 0.3 mm in diameter that was cut to a minimum of 10 μm in diameter with a rotation speed up to 15,000 rpm. They have investigated the cutting forces and the possibility of reduction of cutting forces, thereby improving the working accuracy.

Rahman et al. [1] have assessed the machinability of micro parts by force analysis, chip analysis and tool wear criterion. They have experimented by using brass, aluminium alloy and stainless steel as a work material and carried out the experiments by varying the depth of cut, feed rate and spindle speed. One parameter was varied while the other two were kept constant in order to identify the best combination of cutting parameters. The machine tool has dimensions of 560 × 600 × 660 mm (W × D × H), and the maximum travel range is 210 × 110 × 110 mm ($X \times Y \times Z$).

Ito et al. [9] have developed a small CNC micro turning system and achieved a circularity of 50 nm and a surface roughness of 60 nm by turning a stainless steel cylinder. Kussul et al. [10] have developed micromachining centres in two stages. They call first stage to be the first sequential generation of micro equipment that is manufactured from the standard size machine tools. The second generation with smaller size than the first generation may be manufactured by using the first generation micro machines. The first generation prototype size is 130 × 160 × 85 mm^3. Some developments in the last decade in micro machines are summarized below in Table 1.

Table 1 shows the comparison of the capabilities and design aspects of existing micro machines. There are 3 micro lathes and 4 micro milling machines presented in the comparison. Out of the four milling machines, micro milling made by the AIST, Japan has less weight and size whereas Robonano machining centre has the highest resolution achieved as compared to other machines. Robonano has also achieved the highest work piece quality with a surface roughness of 1 nm. MMT from KERN, Germany has the highest spindle rotation speed of 1,60,000 rpm. In the micro lathes, MTS3 has achieved better work piece surface roughness as compared to its counterparts. However, micro lathe made by AIST, Japan is the smallest in size and the micro lathe developed by Kanazawa University, Japan, has much higher resolution than the other micro lathe machines. Figure 3 shows some machines covered in comparison.

Okazaki et al. [7] have provided a brief development history of Japanese micro factory and the benefits of utilizing it in the industry. As a first stepping stone, a micro-lathe was developed in 1996. The lathe has a size of 32 × 25 × 30.5 mm^3

Table 1 Comparison of micro machines: Features and capabilities

Machine characteristics	MTS3 (Micro Lathe)	MTS5/MTS6 (Micro milling)	Micro Lathe	Micro milling	Micro Lathe	ROBONANO α-0iB	MMT
Country of origin/make	Nano Corporation, Japan [11]	Nano Corporation, Japan [11]	AIST, Japan [7]	AIST, Japan [7]	Kanazawa University, Japan [8]	FANUC, Japan	KERN Germany
Overall size dimensions $l \times w \times h$ (mm)	400 × 300 × 150 Bed size: 300 × 200	260 × 324 × 370 Bed size: 260 × 320	32 × 25 × 30.5	119 × 119 × 102	200 × 200 × 200	Length of stroke 280 × 150 × 40	2000 × 1200 × 2550 XYZ Travel (160 × 100 × 200)
Weight (kg)	25	43	0.1	0.7	10	–	500
Carried out processes	Turning of SS, boring and drilling with brass	Milling operations	Turning	Surface cutting and drilling	Facing, turning and taper turning	Milling, turning, grinding and shaping	Milling and drilling
Resolution (µm)	0.1	0.1	0.05	0.05	0.004	0.001	0.1
Maximum spindle speed (rpm)	3,000	20,000	10,000	20,000	15,000	70,000	1,60,000
Maximum work piece dimensions	Ø10 mm	50 × 50 × 16 mm^3	Ø2 mm	4 × 4 mm^2	Ø0.3 mm	–	350 × 230 mm^2 Max. workpiece weight = 30 kg
Positioning accuracy (µm)	0.5	1	0.5	0.5	–	–	± 1
Maximum work piece accuracy achieved	Circularity: 50 nm surface roughness: 60 nm	–	Surface roughness: 1.5 µm roundness: 2.5 µm	–	Surface roughness: 1 µm	Surface roughness: Ra 1 nm is achieved while turning aspherical lens core	± 2.5 µm

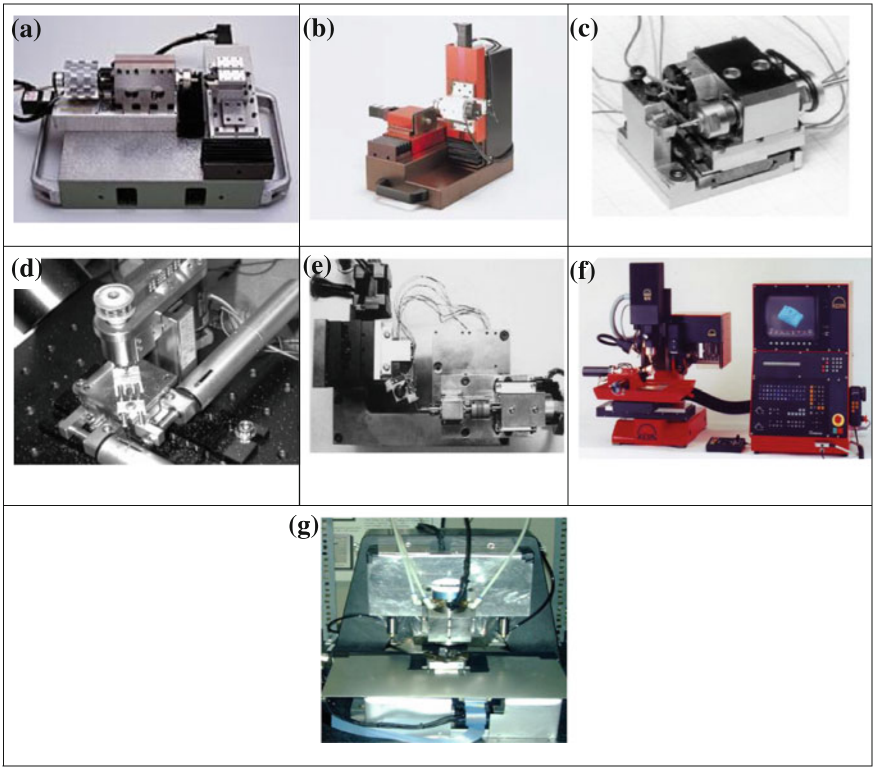


Fig. 3 **a** MTS3 [11]. **b** MTS5/MTS6 [11] (Courtesy of Nanowave, Japan). **c** AIST Micro Lathe [7]. **d** AIST Micro milling machine [7]. **e** Micro Lathe developed by Lu and Yoneyama [8]. **f** Micro machine Table top model (MMT) developed by KERN, Germany (Courtesy of KERN-microtechnic) [12], Micro milling developed in University of Manchester, UK [13]

and weighs only 0.1 kg. The machine has a feed drive resolution of 0.05 μm, positioning accuracy of 0.5 μm and can hold a maximum workpiece diameter of 2 mm. It comprises of an X–Y driving unit driven by laminated piezoactuators, a main shaft device driven by a micro motor that incorporates ball bearings with rotating accuracy of less than 1 μm. The machine has achieved a surface roughness of 1.5 μm and roundness of 2.5 μm in the workpiece turning operation of a brass rod.

Lu and Yoneyama [8] have built a micro lathe turning system of overall size $200 \times 200 \times 200$ mm^3 and weighs about 10 kg. The machine consists of X–Y and Z driving tables with an axis resolution of 4 nm. A work material of brass, Ø 0.3 mm is cut to a minimum diameter of 10 μm achieving a surface roughness under 1 μm. Kussul et al. [10] have developed micro machine tool of overall size $130 \times 160 \times 85$ mm^3 and a travel range of $20 \times 35 \times 20$ mm^3 with a resolution of 1.87 μm. Test pieces manufactured with this machine have dimensions from 50 μm to 5 mm with a tolerance range of 20 μm.

KERN [12] (Germany): KERN offers a 5-axis table top version (KERN MMT) of a large machining centre with the smallest travel range option of 160/100/200 mm^3 (X/Y/Z). Heidenhain TNC controller is applied and a feed drive resolution of 0.1 μm, positioning accuracy of ± 1 μm and the work piece accuracy of ± 2.5 μm is achieved.

NANOWAVE [11] (Japan): Many desktop models are offered by this company. MTS2, MTS3 and MTS4 are the CNC precision micro lathe systems with cross roller slide ways arranged in a 'T' configuration. MTS3 has the base size of $200 \times 300\ mm^2$, feed drive positioning accuracy of 0.5 μm and a work piece surface roughness, Ra 0.02 μm achieved by turning brass C3604. MTS5 is a small CNC precision milling machine having a bed size of $320 \times 260\ mm^2$. Table for each axis is supported by a set of crossed roller ways and drives through a lead screw. Machine uses a G8 controller and the positioning accuracy of feed drive is 1 μm.

2 Micro-factory as a Concept

Overall, there are plenty of benefits in miniaturization of machine tools where as there are some hidden challenges to overcome as well. To augment the desktop factory idea, large number of micro machines can be installed in a small work-floor. Manufacturing processing data and condition monitoring of micro machine tools in a micro factory are the variables of interest to run a smooth process flow. Every machine out of hundreds of micro machines will have sensing equipment and the sensors data is being compiled at one place, ideally using wireless communication systems. One or two operators can run and monitor the whole micro-factory and access the machine if the fault alarms receive from any station. The control of this micro factory concept for operation, maintenance and monitoring becomes a Cyber-physical system capable of producing micro-precision products in a fully-automated manner at low cost.

2.1 Benefits of Miniaturization

1. Miniature machines will bring economical space utilization and energy saving. Individual micro machines in the Japanese micro factory take 1/50 of the space that the standard size machine tool, occupy on the shop floor. In watch manufacturing, the amount of energy consumption may be reduced to approximately 30 percent of the conventional factory by the half-miniaturization of the production systems [14].
2. Vibration amplitude will be minimized due to the reduction in mass of the moving components. Large natural frequencies will be obtained for the micro system.
3. Cutting forces will also be reduced in micro manufacturing processes that may increase the achievable accuracy of machine tool.

4. Thermal drifts that are generated by the machining process causing deformations that effect directly the accuracy of standard machines. These effects are reduced in micro machines due to the miniature nature of the components, and can often be regarded as negligible.
5. Small machines will be capable of providing high acceleration. The next generation of machine tools, will require axes to have acceleration capabilities in excess of 1 g.
6. Micro machine tool's accuracy will improve by the inherent reductions of machine component's inertia, negligible thermal drift and larger eigenfrequencies [15].
7. Consumption of raw material will be dramatically reduced in micro manufacturing. Due to the low consumption of raw material, costly materials can be utilized. Even machining of non-conventional materials like ceramics may also be possible.
8. No new research is required for the materials to be specifically used for micro manufacturing. Almost all the efforts carried out so far in micro manufacturing have made use of the same materials that are used in the macro manufacturing machines and processes.

2.2 Challenges of Miniaturization

1. The dominant hurdle for the development of micro manufacturing machines capable of machining with a very high accuracy is the identification and evaluation of the micro physical phenomena. At the micro scale, the laws of macro scale physics, no longer prevails. As different forces behave differently at the macro, micro and nano-scales, some of them are more influential at a particular scale. For example, surface forces become very important at the micro scale but their influence is negligible at the macro scale.
2. Another important issue is the assembly of the micro parts. Micro scale and multi scale products may have different challenging issues for assembling and packaging. Even the micro and meso-scale parts which will be manufactured with micro machines will have their unique requirements for fabrication and assembling. Human handling of micro parts is certainly impossible and special robotic manipulators are essentially required. All the micro machine tool developers have addressed this issue by developing micro manipulators like transfer arm and a two-fingered hand in the case of Japanese micro factory. With micro-scale components, interactive forces (e.g. van der Waals, surface tension, electrostatic) will exist between components, which instigate difficulties in manipulation and control. To overcome these problems, contact type manipulators such as ultrasonic travelling waves, or mechanical grippers; or non-contact type manipulators for example magnetic fields, aerostatic levitation, or optical trapping could be used in place of the conventional solutions [16].

3. When multi-scale parts may assemble together, the multi scale physics will play its role in design, packaging and assembly of the products. Normal design and modelling tools are not capable of handling multi scale physics and modelling. The need to interface and integrate micro scale parts with parts of a different scale may require multi-scale modelling tools to predict system-level behaviour. These implications point to a need for a departure from traditional macro scale design models and simulation tools.
4. In the micro-turning process, the rigidity or strength of the shaft decreases as the diameter of the shaft reduces. There will be a restriction of achievable minimum diameter of the shaft which can withstand the magnitude of the cutting forces for the acceptable deflection in the shaft. Lu and Yoneyama [8] have measured the deflection of work piece shaft, 50 μm in length with its reducing diameter in the micro turning operation (See Fig. 4).
5. There are many design techniques available in the literature and in practice as well for the macro scale parts. But these design techniques will not work for the micro scale parts unless the dominant physical phenomena will be addressed fully and incorporated at the design stage. Modelling tools will also be required to acquire multi scale physics. Micro manufacturing standards have not been established so far and no work is done for micro metrology and inspection of micro and meso scale parts. Being the nascent stage of this technology, there is a need to limit the gap of the state of the art micro manufacturing technology and the required knowledge. At this stage, uncertainty and risk of utilizing micro manufacturing technology for the commercial manufacturing of meso scale parts is higher. Due to the lack of modelling tools and standards for micro manufacturing and micro metrology, researchers are using their own means of modelling and simulation tools to design meso scale parts.

2.3 Micro-machine Tool Components

Following are some of the important tool components of micro machine.

Carriages and Guideways: The carriages or stages of a machine tool are components which provide movement between a probe or tool and a work piece. Carriages are railed through the guide ways in the free direction of movement. Carriages are constrained by guide ways which limit motion in any direction other than a specified linear or angular path of travel. Accurate movement of feed units is dependent on the positional accuracy determined by the encoders thereby limiting the accuracies of the traditional machine tools. Carriages are also bound to the inaccuracies present in the straightness and parallelism of the guide ways. Highly precise carriages are being designed in the industry with a positioning accuracy in nano-meters. Japanese micro machine tools have been specifically developed to be used in the microfactory concept. Linear micro stages shown in Fig. 5 were designed with piezo-actuators. Slocum et al. [17] has made a precise linear motion

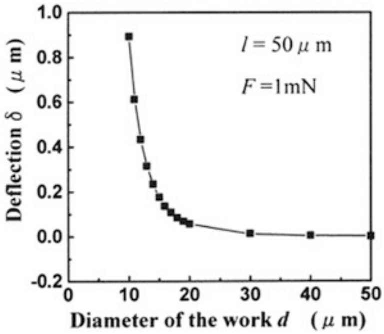


Fig. 4 Deflection estimation of work piece under cutting force [8]

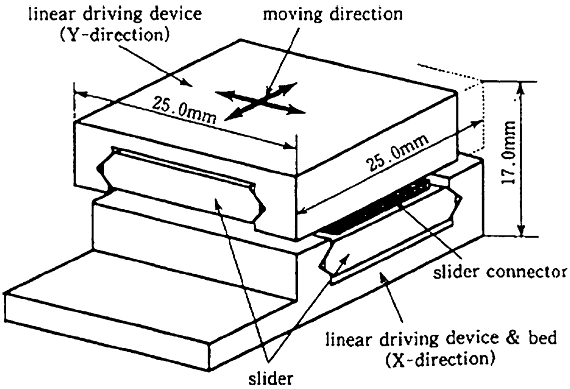


Fig. 5 X-Y Feed drives of micro machine tool [7]

carriage on which a preload is applied through the attractive force of a linear motor. The 330 mm long carriage can bear a load of more than 20 kg with a pitch error of an arc second and is supported by the six rigidly attached porous carbon air bearings (See Fig. 6). The rail is designed to be employed for standard size machine tools and macro scale applications. Mekid [18] has designed a short stroke linear high precision carriage with a 16 nm positioning accuracy. Very high axis stiffness is claimed to be achieved with a steel slide of mass 100 kg and the working motion length of 220 mm that is fully floated by three hydrostatic bearings. Yang et al. [19] have presented the design and characterization of a single-axis, low profile, piezodriven, vertical motion micro positioning stage with a travel range of 200 μm and a vertical stiffness of 6 N/μm. Mekid and Bonis [20] has presented the design of an optical delay line with a long stroke of 3 m and a 16 nm resolution. Gao et al. [21] have presented the design and characterization of a piezodriven precision micro positioning stage utilizing flexure hinges.

Bearings: A bearing is a component that allows for relative motion between two parts. There are two major classes of bearings: Contact bearings and non-contact bearings. Bearings contacts induce friction due to rolling elements, i.e., balls or rollers. Non-contact bearings are aerostatic, magnetic and hydrodynamic.

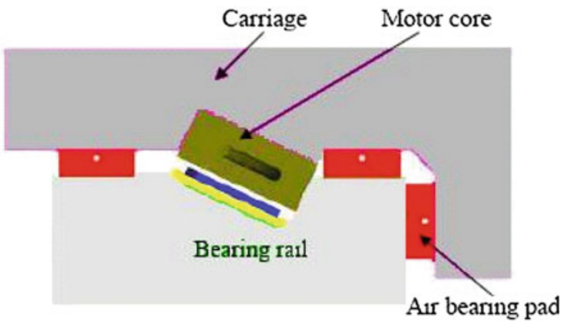


Fig. 6 Use of Aerostatic Bearings in linear motion carriage design [17]

Both classes of bearings are used in high precision machines. The industrial revolution was made possible by rotating shafts that were supported by a thin film of lubricant induced by hydrodynamic shear. Aerostatic and hydrostatic bearings rely on an external pressure source to supply gas or liquid through an inlet restrictor to a bearing pad [22]. Figure 6 shows the use of aerostatic bearing pads to bear the preload and weight of the carriage. Magnetic bearings are also been used as a non-contact type, as they have no mechanical contact with the supported component.

Spindle: Spindle unit is used to hold the tool holder in the machine tools. Spindle rotates generally up to 30,000 rpm in the modern day high speed machine tools. Influence of cutting forces is largely reduced in high speed machining. This fact may go in favour of designing ultra-precise, high speed, light weight micro spindle for machine tool. Figure 7 shows the micro spindle and the micro chuck gripping the work material 0.3 mm in diameter at a speed of 15,000 rpm.

2.4 Sensors and Actuators Used in Micro-machines and Micro-factory

Servo control should be able to handle the complete process control in a single machine. The success of machine servo control depends on the type of control applied and the interaction agility between sub-systems. Process control is extremely important for such machines to fit machine kinematics with machining process. An intelligent controller can be applied for micro-factory to control the machining process of multiple machines through CAM (Computer aided machining). CAM will include complete process planning and NC programming that can be integrated with the PC-based control system. The CAD/CAM system is directly linked to computer-aided process planning (CAPP) software tool, hence the manufacturing process can become totally automatic thus improving efficiency.

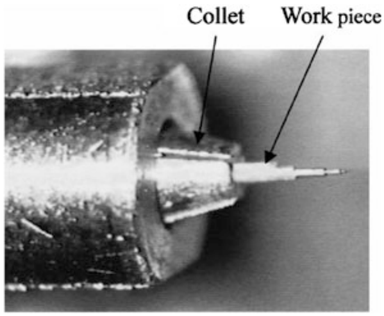


Fig. 7 Micro spindle and Chuck [8]

Modern CNC approaches employ PC-based solutions to incorporate extensive functionality in order to combine high quality and flexibility, with reduced processing time. One must also consider the processing power of the controller hardware, as too great a modularity can result in deterioration in the real-time performance of the system. Sensors and actuators employed in individual micro-machine and in the micro-factory are enlisted. This list includes the machine's inherent sensors which measure actuator's working in closed loop. These sensors and actuators are used in basic machine operation and metrology. Extra metrology sensors are also listed that will serve in micro-factory for a group of machines.

(a) **Machine operation**: (4–5 sensors per machine) Linear (bandwidth to beyond 500 kHz) or rotary encoders (High-speed rotary magnetic encoders with resolutions to 13-bit, 8192 positions per revolution) are used. Three linear encoders will work for three machine tool axis (x, y, z). One rotary encoder will measure the spindle rpm. For a three axis machine tool, these 4 sensors are enough for machine normal operation. However, the extra two rotary encoders can be employed for building up the 5-axis complete machining centre (MC). In 5-axis MC, two rotary axes are added to get maximum machining flexibility. A control model can be built for a three axis machine tool using 4 sensors. An optional study can be made using the total of six sensors for a 5 axis MC.

(b) **Machine tool Metrology**: Single machine metrology frame contains a scanning white light interferometer with CCD (Optical sensor) for calibration. Its controller sends serial data at the rate of 30 MHz for a system of resolution 6 nm and a speed of nearly 200 mm/s. Some extra positioning sensors like LVDT (Linear-voltage Differential Transformers) normally designed with sampling rate of 250 Hz output bandwidth may be employed for circularity or cylindricity measurements. Visible (normal CCD) and IR spectrum cameras for a group of machines may also be employed for operator visual aid. These cameras can be wall mounted for better visualization. Normal working of cameras is 25 frames per second.

(c) **Condition Monitoring and in-process inspection**: Capacitive micro and nano-sensing is a non-contact position measuring system and can be used for condition monitoring of machine tools especially structural and metrology frame deformation over time. Worked on an average bandwidth of up to 5 kHz and DSP 32-bit floating point, 8.3 μsec sampling rate servo controller may be implemented. As an additional condition monitoring sensor, temperature sensor like thermocouple may also employed with sampling rate of 100–1,000 Hz. In-process inspection sensors may be added in the advanced control model but not required in the basic model. In-process inspection sensors are a new concept to be used while machine operation. It can be based on laser interferometer with the sampling rate of 30 MHz

(d) **Actuators**: Some basic actuation system includes three linear motors employed for three stages. Two rotary axis may be added in case of five axis machining centre. Spindle motor needs high linearity or co-axiality and no backlash. Every stage actuator needs high stiffness in the active axis, low disturbance, availability of reverse motion and fast time response to active control. Both linear and rotary encoders explained above can be used for the actuation system. Appropriate actuation in real time is necessary. Sometimes, piezo actuators are used in micro machine tool design. Piezo-actuators work on bandwidth of up to 10 kHz.

3 Machine to Machine (M2M) Control Design in Micro-factory

An important aspect to be considered is the control system for micro manufacturing, which is increasingly being required to perform a wide variety of complicated tasks under varying operating conditions and in different environments, while at the same time achieving higher levels of precision, accuracy, repeatability and reliability [23]. In the general case of machine tools, these control techniques are commercially available into two distinct groups, i.e., open and closed architecture control. Conventional approach uses closed architecture control, however, the machine tool controller designers are turning towards more open architecture systems to address system re-configurability inventions.

The other benefit comes with multiple variety of manufacturing processes to run by the same machine. Open architecture controller may also provide the facility of programming process control at the micro factory level with re-configurable machines and CAM operations of a single machine tool simultaneously. The classical control architecture for micro machines operation in micro factory is shown in Fig. 8. However, with the advent of sensor networks and communication technologies, a micro factory CPS can be shown in Fig. 9. The disturbance shown at the input of plant can be regarded due to vibration which is compensated via active vibration control in the actuation of each axis in micro machines.

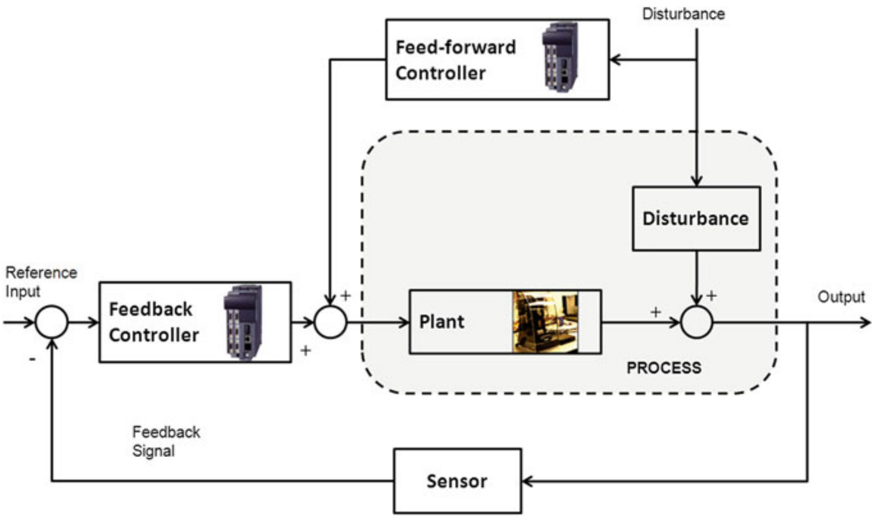


Fig. 8 Classical Control architecture of a single micro-machine

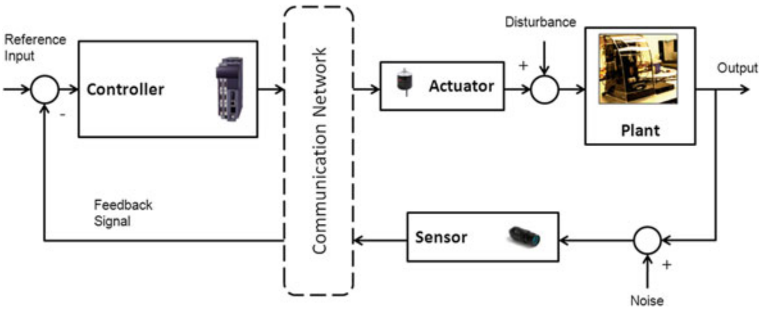


Fig. 9 Embedded Network incorporated in Control architecture

In micro factory, where multiple machines work in parallel, variety of sensors are employed for machine control, process control, metrology and calibration, condition monitoring of machine tools, assembly and integration technology at the micro-scale resulting in smooth operation of micro-factory. Single machine can be designed with a computer numerical control, but, flexible reconfigurable controllers are envisioned to control variety of processes that will lead to the development of open architecture controllers to operate micro-factory. Therefore, the control effort and algorithms have to utilize process models to improve the overall process and, ultimately, the product. Thus, we aim to introduce machine to machine (M2M) communication in the classical micro factory manufacturing test bed.

M2M communication enables micro actuator/sensor and controller devices to communicate with each other directly and without human intervention, automating management, monitoring and data collection between devices, as well as communicating with neighboring machines. All micro-sensors communicate with a local short distance wireless network e.g. via Bluetooth piconet as well as with a centralized controller via WLAN 802.11 to exchange control/command from it.

3.1 System Controllers

In order to control the machine tool position and speed, two distinct groups of open and closed architecture exist as on today. Closed architecture controllers being more popular, have established the norm in the machine tool manufacturers market. Two popular ones are the Fanuc 15i Controller and the Mitsubishi CNC 700 series controller (See Fig. 10). Both of these controllers have high-speed reduced instruction set computing (RISC) based processors, having the ability of controlling a wide variety of systems. The CNC 700 series of Mitsubishi implements nano-control technology with RISC based processor and high-speed optical servo communication network for high-speed and high-precision real time control in 5-axis. These systems are closed architecture in nature, and the designers/manufacturers of the closed architecture controls do not anticipate moving to a more open architecture [24].

In Europe, two German companies, Bosch and Siemens are flag holders of open architecture controllers. The Bosch Rexroth IndraMotion MTX is used for controlling high-precision grinding and machining applications. While, the Siemens 840 series CNC controllers also belongs to open architecture controller group. Both of these controller designers plan to permit more advanced process control in addition to the standard servo position control. Delta Tau, D-Space, and National Instruments are some of the other open architecture systems developers actively participating in related research and development. To remain compatible with the industrial standards, the data processing for these controllers is preferably done with a combination of LabVIEW and MATLAB tools. Control of micro-machine tools requires high speed controllers, position counters having higher resolution capabilities and spline interpolation.

In order to efficiently control high bandwidth processes at micro level, increased controller speed is mandatory due to several reasons. The foremost of them is because the higher speed allows for smoother interpolation. Secondly, servoing at ultra-high resolution (on the order of 1 nm) requires that the controller is capable of tracking commands at very high rates. For example, if a machine has 1 nm resolution and is traveling at feed rate of just 1 mm/s, the controller must track an encoder pulse at a rate of 1 pulse/μs, resulting in a 1 MHz clock requirement. However, if the system is traveling at feed rate of 1 m/s, an encoder pulse is generated every ns which requires a 1 GHz clock. If this same machine has a one-meter range, the controller must be able to track a billion encoder counts, requiring a 30-bit (minimum) counter [24]. This theoretical curve for encoder speed vs. range of the encoder counts is quite significant and outside of most standard controller specifications.

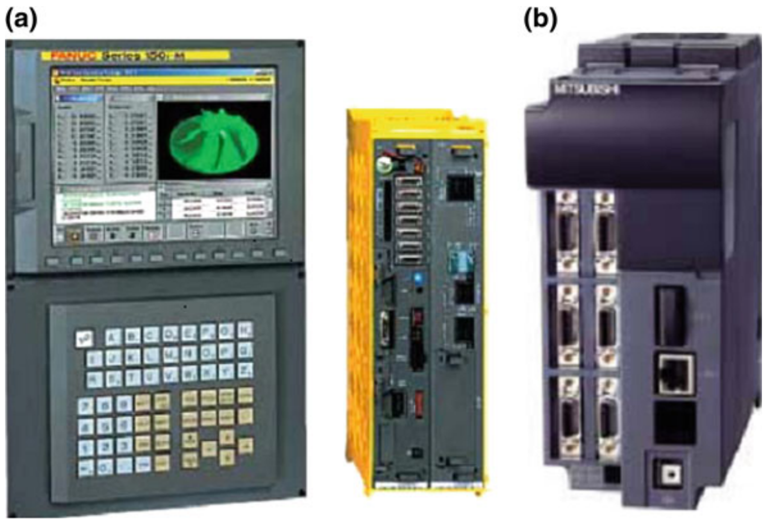


Fig. 10 **a** FANUC 15i controller (Courtesy of FANUC Inc.), **b** Mitsubishi CNC 700 controller (Courtesy of Mitsubishi Inc.) [24]

3.2 Open Architecture Controls/Control Flexibility

There is a clear dichotomy regarding the utilization of open architecture controls in the micro-manufacturing area. In application specific embedded systems and industrial solutions, closed architecture controllers are used. While in R&D centers, an open architecture and flexible platforms are specifically preferred as per research needs. PC based controllers that are operated in real-time, single-board motion controllers (SBMC) and field programmable gate arrays (FPGA) provide flexibility of processing. However, from an industry/implementation perspective, closed architecture controllers using hardware based on application specific integrated circuit (ASIC) systems are employed as the process specific hardware design has already been finalized.

There are some designs with the “closed architecture” controls such as the FANUC or Mitsubishi controllers, where a single controller can run multiple types of machines. For example, ROBOnano can be configured for milling, turning, shaping and several other operations using FANUC 15i controller. These controllers are flexible enough but with closed architecture. Some designers prefer to stick with their policies e.g. the mainstream control companies in Japan such as FANUC and Mitsubishi seems to continue producing controllers only with closed loop architecture. On the other side, German control companies such as Siemens and Bosch appear to provide a more open architecture platform but still not as open as the DSP and FPGA based controllers [24].

4 Micro-factory Cyber Physical System Architecture

Machine to machine (M2M) refers to communication technologies that allow wireless and/or wired systems to communicate with other devices of the same type [25–27]. M2M is a generalized title which does not pinpoint specific wireless or wired networking, information and communications technology. The application areas for M2M include industrial instrumentation where sensor measurements can be relayed through a network (wireless, wired or hybrid) to a supervisor application that translates the captured event into meaningful information and records in the data base. Such communication was originally accomplished by having a remote network of machines relay information back to a central hub for analysis, which would then be rerouted into a system. M2M is also visualized as a combination of automation, network and SCADA. Figure 11 shows a sensor and actuator network installed within a micro factory for control and command tracking. Position and speed sensors send information to controller which commands the actuators to nullify the error.

We are aiming to introduce machine to machine, machine to man and man to machine communication integration within micro factory CPS which will enable the flow of data between micro-machines and ultimately to micro-factory supervisor. Generally, the information flows from a machine over a network, and then through a gateway to a system where it can be reviewed and acted on. Within that basic framework, there are many different choices to make such as how a micro-machine is connected to its neighboring machine in micro-factory to perform the manufacturing tasks in a collaborative manner, what type of embedded as well as long range communication protocol is used, and how the data is interpreted. Machine to machine conversation will take most of the process planning and execution control from the human intervention. Thus making the system intelligent enough to plan and execute the tasks by itself. Human supervisor role will only be maintenance specific. Even though it can be complex, once a designer knows what it wants to do with the data (whether allow more liberty to embedded computing and decision making or to include human in the loop for critical tasks), the options for setting up the application are usually straightforward. There are four basic stages that may be shortlisted in our micro-factory CPS application. Those components are sensor data acquisition and embedded control, data transmission through a communication network, data logging and Man-In-the-loop operation.

4.1 Collection of Data and Embedded Control

The first stage for error compensation in desired manufacturing dimensions is to sense these measurements. The intelligence of microfactory CPS can be enhanced just by installing multiple sensors e.g. force sensors and accelerometers, linear and rotary encoders for position sensing, temperature sensor, visual sensing using an industrial computer system with a Modbus communication port.

Fig. 11 Description of a stand-alone micro factory

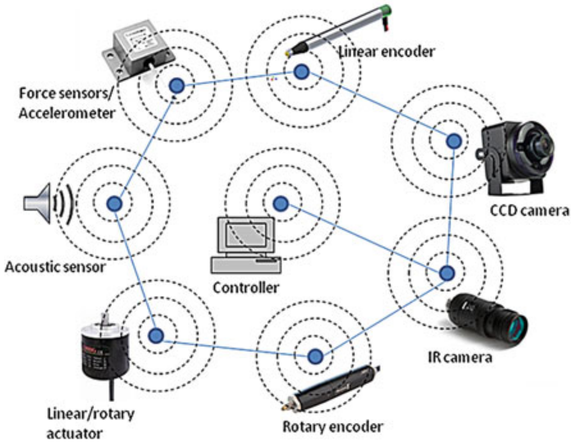


Table 2 Comparison of WPAN and WLAN protocols

Type	Protocol	Frequency band	Data rate (Mbps)	Bandwidth efficiency (bps/Hz)	QoS	Range (m)
WPAN	Bluetooth v2.0	2.4–2.4835	2.1	2.1	No	10
	UWB	4.8–10	480	0.96	No	10
	ZigBee	2.4–2.484	250 Kbps	0.125	Yes	50
	6loWPAN	2.4–2.484	250 Kbps	0.125	Yes	50
	Wireless HART	2.4–2.4835	250 Kbps	0.125	Yes	50
WLAN	802.11a	5	6–48	2.7	Yes	70–100
	802.11b	2.4–2.484	11	0.55	Yes	35–100
	802.11g	2.4–2.484	6–54	2.7	Yes	100

The process of M2M communication in microfactory CPS begins with taking data out of a machine so that it can be analyzed and sent over a network. The controller node performs the intelligent control part for precise command following as desired. A list of WPAN and WLAN protocols is shown in Table 2. The choice of a suitable protocol depends upon the data rate, secure communication and range. Bluetooth piconet is preferred when communicating in close proximity while ZigBee or wireless HART based 802.15.4 protocol is preferred for medium range communication. In wireless HART, a time division protocol is utilized for real time communication over wireless. Also, it uses channel blacklisting to avoid interference. The availability of quality of service option can be used to give preference to certain communicating node for time/resource sharing as compared to others.

In a high end application where man in the loop supervisory control is available, it may be necessary to send a constant stream of real time data describing the machine or process. But in many cases, this is not necessary or worth the cost. In these cases, the M2M local controller should minimize the amount of data to be sent by constantly reviewing the data, comparing it against programmable alarm limits or safety set points, and then transmitting only those real time information when a measurement is out-of-limit. For example, in micro-assembly, it is a common issue of releasing micro parts once gripped by a micro-gripper due to highly influential surface tension forces. Such information or alarm of not releasing the micro-part must reach the supervisor to go for an alternate method. In addition, the application will typically be programmed to send complete data updates on a time scheduled basis or anytime upon request from the web server for supervisory control only. This reduces the bandwidth and data rate demand for the long range communication segment.

4.2 Transmission of Data Through a Communication Network

Once the data is gathered and useful data set is picked, the next step is to transmit the data to the remote supervisor through a communication network. There are several options for transporting data from the micro-factory CPS to the network operation center. The cellular network, telephone lines, and communication satellites are all common solutions. The telephone may be the best choice if a line is already installed. Its disadvantage is usually the ongoing monthly cost and sometimes the cost and difficulty of installation beside disconnection issues. Satellite may be the most expensive solution, but is often the most reliable and the only solution for monitoring equipment remotely. The advantage of cellular networks is the ability to send large amounts of data frequently at a cheap price.

As shown in Fig. 12, a gateway is used to connect the micro-factory with the cellular or satellite network. Data security features such as authentication and access control can be managed by the gateway and the application software. The gateway can also support IP communication for an end-to-end IP network flow. Specially, when the flow of data is from supervisor to the micro-factory for supervisory control, the gateway not only converts the protocol but also transforms high-bandwidth Internet protocols to low-bandwidth wireless protocols so that the minimum data is sent over a cellular or satellite network.

4.3 Data Logging and Record Keeping

Data from the micro-factories is logged on the controller as well as to the supervisor via a long distance network. Data logging and record keeping is an essential feature of M2M communication. It is worth mentioning that the data records are matched with the historical data for performance indication and fault detection in the machine calibration. Later, these observations are used in maintenance cycle.

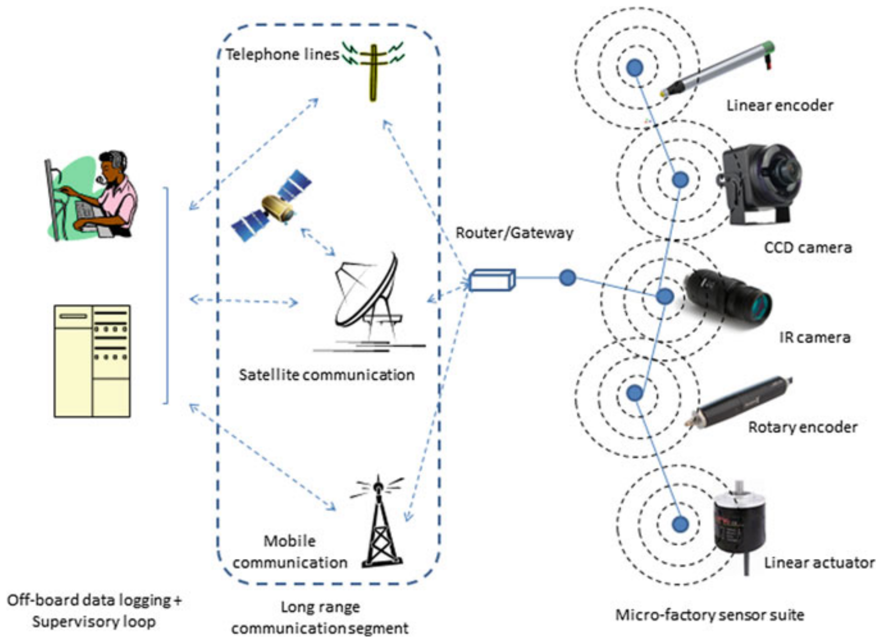


Fig. 12 Micro-factory test-bed and Supervisory control

4.4 Man-in-the-Loop Operation

In micro-factory CPS, the optimal performance can be achieved by taking into account the embedded control solution. However, if need arises, man-in-the-loop operation can be used to remotely access the system. However, despite the existence of QoS support on various long range protocols, it is very difficult to obtain real time performance. Hence, the stabilization loop in the micro-factory must incorporate embedded control loop and only few commands can be operated remotely to avoid malfunction due to time delay.

5 Design Tentative

The comparison of existing micro-machine tools shows a picture about the state of the art technology. But the designs are nascent and need considerable time in future for commercialization. Machining centers are also developed for the multipurpose applications of milling, drilling, turning and grinding. Before starting the work for the design strategy of this type of micro machining centre to be used in a micro-factory concept, familiarity with the components used in the construction and assembly of modern micro machines is discussed above.

5.1 Physical Phenomena of Scaling

Design strategy is developed with the aim of getting a very high accuracy in micro machining. The difference in this design strategy from the strategy of standard size machine lies in the introduction of second order phenomena that includes the micro physics involved between the components of the micro machine tool. As evident from the comparison of existing micro machines developed so far, the accuracies obtained from them are not improved in comparison to the standard machines. Micro machines should be developed with the aim that down scaling of machine dimensions will give more accuracies than the standard machines. But to get higher accuracies, certain design strategies have to be developed and the miniaturization issues are to be addressed. These issues deal with the magnitude of the cutting forces, thermal drift, reduced masses and inertia and down scaling of physical forces.

The common example of scaling implies that while gravitational force may be a significant phenomenon between two large bodies, surface tension forces which are not important between two large bodies become significant in the case of small/micro objects. If the scale factor *'s'* is used to describe how the physical phenomena change. All the lengths will scale by the factor *'s'*, but the volume scales differently:

$$V = L \times W \times H \tag{1}$$

$$V = S^3(L \times W \times H) \tag{2}$$

If our mechanical system scale down by a factor of 10, then volume will scale as (1/10)3, or 1/1,000. Different forces and parameters scale differently. For example, the mass scales as s^3. As mentioned, Trimmer [28] has tried to make use of the scaling of electromagnetic and electrostatic forces to build micro motors that can be used in micro machine and MEMS applications.

Micro-motors based on electrostatic force are theoretically a potential candidate, as electrostatic force scales to s0 (See Table 3). But MEMS micro motors experience demonstrate that in the micrometric range, the electrostatic motors cannot have sufficient power to be used in micro machining and especially in high speed machining. In this sense, they cannot compete with micro motors based, for example, on piezoelectric forces. However, these small motors have plenty of small applications like the microcomb drive motor [29] is being used in automobiles as an airbag sensor. The miniaturization process has some inherent problems that must be highlighted. The matter is not only size reduction but the effect of new physical phenomena on micro machining has to be identified. As mentioned, the behavior of forces changes in the micro domain as compared to the standard scale. This implies that the micro-machining cannot be handled as standard scale machining. There is a difference between the two and it needs to be verified experimentally that the theoretical downscaling results presented in Table 3 holds true. There is also a possibility of making use of these scaling results in order to enhance the micro machine's accuracy.

Table 3 Influence of physical forces at miniature level

Type of force	Formula	scaling factor	Symbols explained
Gravitational force	Gm_1m_2/r^2	s^4	G—Gravitational constant, m_i—interacting masses
Elastic force	$EA\Delta L/L$	s^2	E—Young's Modulus, A—Cross-section Area
Inertial force	$M\partial^2 x/\partial t^2$	s^4	$\delta^2 x/\delta t^2$—Acceleration, M—moving mass
Electrostatic force	$\varepsilon AV^2/2d^2$	s^0	ε—Permittivity, V—Voltage applied, d—Gap between electrodes
Surface tension force	γL	s^1	γ—Surface tension constant
Electromagnetic force	$BA/2\mu$	s^4, if B is constant s^2, if heat sink is used	B—Magnetic field density, μ—Permeability, A—Surface area
Thermal expansion force	$EA\Delta L(T)/L$	s^2	E—Young's Modulus, T—Temperature
Piezoelectric force	$EA\Delta L(E)/L$	s^2	E—Young's Modulus, L—Piezo length
Centrifugal force	$m\omega^2 r$	s^4	ω—Constant rpm, r—Radius of gyration
Hydraulic force	ΔPA	s^2	ΔP—Pressure difference on the piston
Capillary force	$\sigma\pi d$	s^1	σ—Surface tension force, d—Capillary diameter
Van der wall force	E/r	s^{-1}	r—Atomic centre dist., E—Atom bonding energy
Viscosity force	$\frac{cA\partial x}{L\partial t}$	s^2	c—Viscosity co-efficient, L—Characteristics length
Frictional force	μmg	s^3	μ—Frictional constant, g—gravity constant

5.2 Precision Engineering Fundamentals

Machine tools performance is always measured by their capabilities in terms of accuracy, resolution and repeatability. These metrological terms are defined according to the 'International vocabulary of basic and general terms in metrology'.

Accuracy: Closeness of the agreement between the actual value resulting from an operation and a target value of the quantity. Accuracy is a qualitative description.

Uncertainty: Parameter associated with the result of an operation that characterizes the dispersion of the values that could reasonably be attributed to the quantity.

Resolution: Smallest difference between indications of displaying device that can be meaningfully distinguished.

Repeatability: Closeness of the agreement between the results of successive operations of the same quantity carried out under the same conditions.

Reproducibility: Closeness of the agreement between the results of operations of the same quantity carried out under changed conditions.

5.3 Design Strategy

The strategy started with the problem definition or the specifications of the micro machine tool. i.e., the design features and objectives. This is followed by the generation of basic conceptual ideas of the micro machine tools. The concepts are based on the precision design principles. All the initial concepts are compared according to the selection criteria. The criterion is defined on the basis of machine's static and dynamic design factors. The concept analysis will result into a final model that will be further refined and analyzed. The detailed model will be further used for the mathematical modeling of the system. The Homogenous Transformation matrices are applied to the machine tool detail design. The HTM model is then used for the optimization analysis. Objective function is defined based on the machine's relative volumetric error. From the optimization analysis, tolerances budget can be evaluated for the machine's components. The sub-systems will include machine's carriages, guide ways, bearings and spindle system etc. The modeling of micro physical phenomena or commonly called 'the second order phenomena' can also be modeled with the theoretical model of machine tool. Finite Element Analysis based static, dynamic and thermal models can be integrated with the optimization model for this purpose.

For control design, there are two different philosophies opted in precision machine design to achieve high precision as follows.

1. Design of precise mechanical structures with most of the phenomena considered as second order error sources addressed. An adjusted servo-controller will animate the system to satisfy the specifications.
2. Design of a mechanical structure with an overall satisfaction with the implementation of an expert dedicated servo controller to compensate for all errors [22].

If the robust design analysis is conducted with the complex mechanical second order phenomena addressed, the first philosophy can be applied with an adjusted servo controller. Servo control will also handle the complete process control. An intelligent controller will be applied to control the machining process through CAM (Computer aided machining). CAM will include complete process planning, and NC programming. In the case of un-modeled errors, specific controllers will be applied for an eventual compensation. Finally, the success of the machine servo control depends on the type of control applied and the interaction agility between sub-systems.

A conceptual example of a 5-axis micro milling machine with 3 translational (x, y, z) and 2 rotational stages, shown in Fig. 13. The machine comprised of a

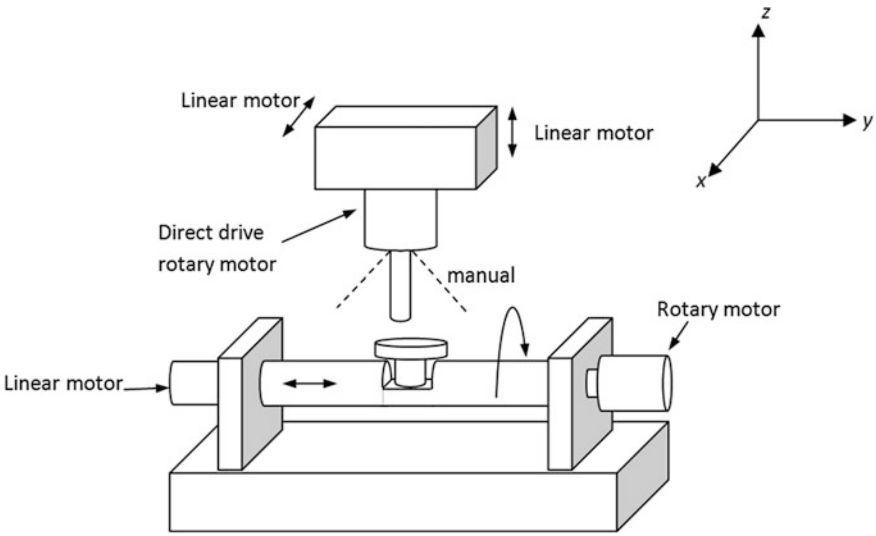


Fig. 13 5-axis micro machining center concept

central shaft that can translate in the Y axis and rotate around the same axis. This Hybrid Axis is used to mount the work piece. The axis will be mounted on air bearings on both sides for high precision.

5.4 Error Model

A robust design with an optimization method considering the volumetric error as the objective function is applied to characterize some of the key-design parameters of the machine. The method is presented with few dimensional results. A serial micro milling machine (See Table 4) with X–Y linear stages and the vertical Z slide has its overall error modeled through homogeneous transformation matrices (HTM). The motion transformation matrices from reference to work piece and from reference to the tool are shown in Eqs. (3) and (4).

$$ {}^{R}T_{Work} = {}^{R}T_{Y}.{}^{Y}T_{X}.{}^{X}T_{Work} \tag{3} $$

$$ {}^{R}T_{Tool} = {}^{R}T_{Z}.{}^{Z}T_{Tool} \tag{4} $$

where,

$$ {}^{R}T_{Y} = \begin{bmatrix} 1 & -\varepsilon_{zy} & \varepsilon_{yy} & \delta_{xy} + a_1 + S_{xy}.Y \\ \varepsilon_{zy} & 1 & -\varepsilon_{xy} & \delta_{yy} + Y + b_1 \\ -\varepsilon_{yy} & \varepsilon_{xy} & 1 & \delta_{zy} + c_1 + S_{zy}.Y \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5} $$

Table 4 Detailed selected concept with nominal dimensions

	Overall machine dimensions/Specs (mm)	Initial nominal dimensions (mm)
	Base size: $300 \times 200 \times 50$ Y Carriage: $l_y \times 120 \times l_{thy}$ X Carriage: $100 \times 100 \times l_{thx}$ Work piece : $20 \times 20 \times 20$ Column : $200 \times 70 \times 210$ Z slide thickness: 40 Spindle: $l_s \times Ø50$ Tool height : $l_t \times Ø14$ Machine working volume $= 150 \times 80 \times 20\ mm^3$	l_s—Spindle thickness—20 $l_{th} = l_{thx} = l_{thy}$—*X* and *Y* Feed unit thickness—20 l_y—*Y* Carriage length—250 l_d—Spindle column distance—90 l_t—Tool length—20

and a_1, b_1 and c_1 are constant offsets defined on the basis of machine design variables. δ_{xy} and δ_{zy} are straightness errors. S_{xy} and S_{zy} are the squareness angles between the respective axis and Y is the position of Y axis where these angles are amplified to yield an Abbé error in Y-direction [30].

Similar transformations are defined for Y to X and reference to Z carriages.

$$
{}^{Y}T_{X} = \begin{bmatrix} 1 & -\varepsilon_{zx} & \varepsilon_{yx} & \delta_{xx} + a_2 + X \\ \varepsilon_{zx} & 1 & -\varepsilon_{xx} & \delta_{yx} + b_2 + S_{xy}.X \\ -\varepsilon_{yx} & \varepsilon_{xx} & 1 & \delta_{zx} + c_2 + S_{zx}.X \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}
$$

$$
{}^{R}T_{Z} = \begin{bmatrix} 1 & -\varepsilon_{zz} & \varepsilon_{yz} & \delta_{xz} + a_3 + S_{zx}.Z \\ \varepsilon_{zz} & 1 & -\varepsilon_{xz} & \delta_{yz} + b_3 + S_{zy}.Z \\ -\varepsilon_{yz} & \varepsilon_{xz} & 1 & \delta_{zz} + Z + c_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}
$$

For the work piece and the tool, the position vector is given as:

$$
{}^{X}T_{Work} = \begin{bmatrix} W_x \\ W_y \\ W_z \\ 1 \end{bmatrix} \tag{8}
$$

$$
{}^{z}T_{Tool} = \begin{bmatrix} T_x \\ T_y \\ T_z \\ 1 \end{bmatrix} \tag{9}
$$

For the ideal situation without errors, we take:

$$
{}^{R}T_{Work} = {}^{R}T_{Tool} \tag{10}
$$

$$
{}^{R}T_{Y}.{}^{Y}T_{X}.{}^{X}T_{Work} = {}^{R}T_{Z}.{}^{Z}T_{Tool} \tag{11}
$$

Hence,

$$
{}^{X}T_{Work} = \begin{bmatrix} W_x \\ W_y \\ W_z \\ 1 \end{bmatrix}_{ideal} = \left[{}^{R}T_{Y}.{}^{Y}T_{X}\right]^{-1}\left[{}^{R}T_{Z}.{}^{Z}T_{Tool}\right] \tag{12}
$$

$$
{}^{X}T_{Work} = \begin{bmatrix} -a_1 - a_2 + a_3 - X + T_x \\ -b_1 - b_2 + b_3 - Y + T_y \\ -c_1 - c_2 + c_3 + Z + T_z \\ 1 \end{bmatrix} \tag{13}
$$

By putting the ideal ${}^{X}T_{Work}$ in Eq. (3) and assuming that the work piece mounted on the x-axis stage is error free, the final vector for the tool and work piece respectively are given as follows:

$$ {}^{R}T_{Tool} = \begin{bmatrix} a_3 + \delta_{xz} + T_x - T_y \varepsilon_{zz} + T_z \varepsilon_{yz} + S_{zx}.Z \\ b_3 + \delta_{yz} + T_y + T_x \varepsilon_{zz} - T_z \varepsilon_{xz} + S_{zy}.Z \\ c_3 + Z + \delta_{zz} + T_z - T_x \varepsilon_{yz} + T_y \varepsilon_{xz} \\ 1 \end{bmatrix} \tag{14} $$

Equation (14) shows three dimensional error between global reference and tool (${}^{R}T_{Tool}$) and Eq. (15) is showing error between global reference and work piece (${}^{R}T_{Work}$). The difference of the two will give the three dimensional volumetric error.

$$ {}^{R}T_{Work} = \begin{bmatrix} a_1 + a_2 + X + \delta_{xx} + \delta_{xy} \\ + \left[\left(-a_1 - a_2 + a_3 - X + T_x \right) \left(1 - \varepsilon_{zy}\varepsilon_{zx} - \varepsilon_{yy}\varepsilon_{yx} \right) \right] \\ + \left[\left(-b_1 - b_2 + b_3 - Y + T_y \right) \left(-\varepsilon_{zx} - \varepsilon_{zy} + \varepsilon_{yy}\varepsilon_{xx} \right) \right] \\ + \left[\left(-c_1 - c_2 + c_3 + Z + T_z \right) \left(\varepsilon_{yx} + \varepsilon_{yy} + \varepsilon_{zy}\varepsilon_{xx} \right) \right] \\ - \varepsilon_{zy} \left(\delta_{yx} + b_2 + S_{xy}.X \right) + \varepsilon_{yy} \left(\delta_{zx} + c_2 + S_{zx}.X \right) \\ + S_{xy}.Y \\ \\ b_1 + b_2 + Y + \delta_{yy} + \delta_{yx} \\ + \left[\left(-a_1 - a_2 + a_3 + T_x - X \right) \left(\varepsilon_{zx} + \varepsilon_{zy} + \varepsilon_{xy}\varepsilon_{yx} \right) \right] \\ + \left[\left(-b_1 - b_2 + b_3 - Y + T_y \right) \left(1 - \varepsilon_{zy}\varepsilon_{zx} - \varepsilon_{xy}\varepsilon_{xx} \right) \right] \\ + \left[\left(-c_1 - c_2 + c_3 + Z + T_z \right) \left(\varepsilon_{zy}\varepsilon_{yx} - \varepsilon_{xx} - \varepsilon_{xy} \right) \right] \\ + \varepsilon_{zy} \left(a_2 + X + \delta_{xx} \right) - \varepsilon_{xy} \left(c_2 + \delta_{zx} + S_{zx}.X \right) \\ + S_{xy}.X \\ \\ c_1 + c_2 + \delta_{zx} + \delta_{zy} \\ + \left[\left(-a_1 - a_2 + a_3 - X + T_x \right) \left(-\varepsilon_{yx} - \varepsilon_{yy} + \varepsilon_{xy}\varepsilon_{zx} \right) \right] \\ + \left[\left(-b_1 - b_2 + b_3 - Y + T_y \right) \left(\varepsilon_{xy} + \varepsilon_{xx} + \varepsilon_{yy}\varepsilon_{zx} \right) \right] \\ + \left[\left(-c_1 - c_2 + c_3 + Z + T_z \right) \left(1 - \varepsilon_{yy}\varepsilon_{yx} - \varepsilon_{xx}\varepsilon_{xy} \right) \right] \\ - \varepsilon_{yy} \left(a_2 + X + \delta_{xx} \right) + \varepsilon_{xy} \left(\delta_{yx} + b_2 + S_{xy}.X \right) \\ + S_{zx}.X + S_{zy}.Y \end{bmatrix} \tag{15} $$

The total error vector is found in Eq. (16) and the individual equations of its components P_x, P_y and P_z are given by Eqs. (17–19) (Fig. 14).

$$P_e = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = {}^{R}T_{Tool} - {}^{R}T_{Work} \tag{16}$$

$$\begin{aligned} P_x = & - a_1 - a_2 + a_3 + T_x - X - \delta_{xy} - \delta_{xx} + \delta_{xz} \\ & - (c_2 + \delta_{zx} + S_{zx}.X)\varepsilon_{yy} + T_z\varepsilon_{yz} + \left(b_2 + \delta_{yx} + S_{xy}.X\right)\varepsilon_{zy} \\ & - (-c_1 - c_2 + c_3 + T_z + Z)\left(\varepsilon_{yy} + \varepsilon_{yx} + \varepsilon_{xx}\varepsilon_{zy}\right) \\ & - \left(-b_1 - b_2 + b_3 + T_y - Y\right)\left(\varepsilon_{xx}\varepsilon_{yy} - \varepsilon_{zy} - \varepsilon_{zx}\right) \\ & - T_y\varepsilon_{zz} - (-a_1 - a_2 + a_3 + T_x - X)\left(1 - \varepsilon_{yy}\varepsilon_{yx} - \varepsilon_{zy}\varepsilon_{zx}\right) \\ & + S_{zx}.Z - S_{xy}.Y \end{aligned} \tag{17}$$

$$\begin{aligned} P_y = & - b_1 - b_2 + b_3 + T_y - Y - \delta_{yy} - \delta_{yx} + \delta_{yz} \\ & + (\delta_{zx} + c_2 + S_{zx}.X)\varepsilon_{xy} - T_z\varepsilon_{xz} - (a_2 + X + \delta_{xx})\varepsilon_{zy} \\ & - (-c_1 - c_2 + c_3 + T_z + Z)\left(-\varepsilon_{xy} - \varepsilon_{xx} + \varepsilon_{yx}\varepsilon_{zy}\right) \\ & - (-a_1 - a_2 + a_3 + T_x - X)\left(\varepsilon_{xy}\varepsilon_{yx} + \varepsilon_{zy} + \varepsilon_{zx}\right) \\ & + T_x\varepsilon_{zz} - \left(-b_1 - b_2 + b_3 + T_y - Y\right)\left(1 - \varepsilon_{xy}\varepsilon_{xx} - \varepsilon_{zy}\varepsilon_{zx}\right) \\ & + S_{zy}.Z - S_{xy}.X \end{aligned} \tag{18}$$

$$\begin{aligned} P_z = & - c_1 - c_2 + c_3 + T_z + Z - \delta_{zy} - \delta_{zx} + \delta_{zz} \\ & - \varepsilon_{xy}\left(\delta_{yx} + b_2 + S_{xy}.X\right) + T_y\varepsilon_{xz} + (a_2 + X + \delta_{xx})\varepsilon_{yy} \\ & - (-c_1 - c_2 + c_3 + T_z + Z)\left(1 - \varepsilon_{xy}\varepsilon_{xx} - \varepsilon_{yy}\varepsilon_{yx}\right) - T_x\varepsilon_{yz} \\ & - (-a_1 - a_2 + a_3 + T_x - X)\left(-\varepsilon_{yy} - \varepsilon_{yx} + \varepsilon_{xy}\varepsilon_{zx}\right) \\ & - \left(-b_1 - b_2 + b_3 + T_y - Y\right)\left(\varepsilon_{xy} + \varepsilon_{xx} + \varepsilon_{yy}\varepsilon_{zx}\right) \\ & - S_{zx}.X - S_{zy}.Y \end{aligned} \tag{19}$$

6 Robust Design Optimization

Robust Design is defined as a process of making a product insensitive to the effects of variability without actually removing the sources of disturbance. Robust design analysis has to reach a trade-off point to ensure the best compromise between different conflicting objectives. Optimization is defined as the setting of design variables such that the design is least sensitive to the effects of external variations or noise [31]. Optimization at the early design stage gives the designer a precise prediction of the outcome of the design process. A general optimization problem can be written as follows:

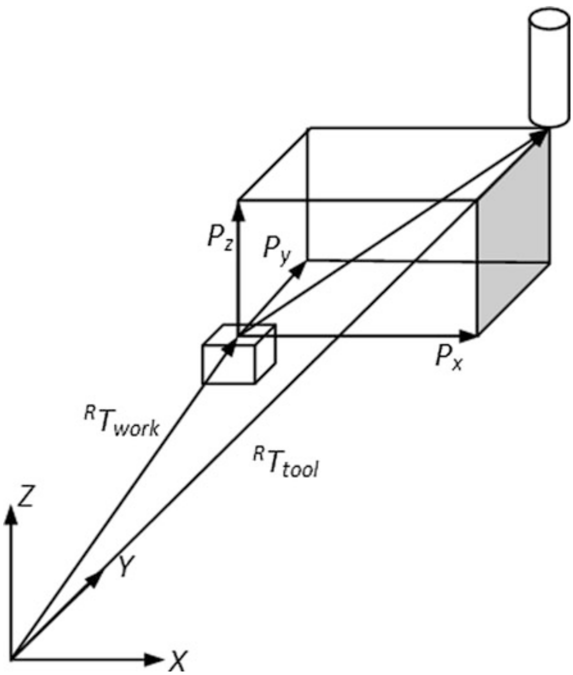


Fig. 14 Description of volumetric error

$$\min f_i(x)$$
$$\text{subject to} \begin{cases} g_i(x) \geq 0 \\ x_{iU} \geq x_i \geq x_{iL} \end{cases} \quad (20)$$

where, x_i is the vector of variables which may be continuous, discrete or integer with upper and lower limits, $f_i(x)$ are objectives and $g_i(x)$ are the inequality constraints. Design of Experiments (DOE) are defined as a process for generating data that utilizes a mathematically derived matrix to methodically gather and evaluate the effect of numerous parameters on a response variable [31]. Mishima [32] have modeled a miniaturized lathe through HTM and performed a tolerance analysis with the help of Taguchi Design of experiments technique.

Optimization algorithms treat the initial design of experiments data and start the search for the optimum point. 'Multi-Objective Genetic Algorithm' (MOGA) is selected as the optimization Algorithm. It has the ability of multi-objective search with fast convergence and continuous objective function penalization. Any type of variables including continuous, discrete or integers can be used. In this study, initial data is tabulated using different DOE techniques such as Taguchi, Random sequence and reduced factorial. These techniques are employed with the Multi-objective Genetic Algorithm to find out the optimum design variables for micro milling machine.

Various mechanical concepts were considered according to the functional requirements of the proposed micro machine. The concept presented in Table 4

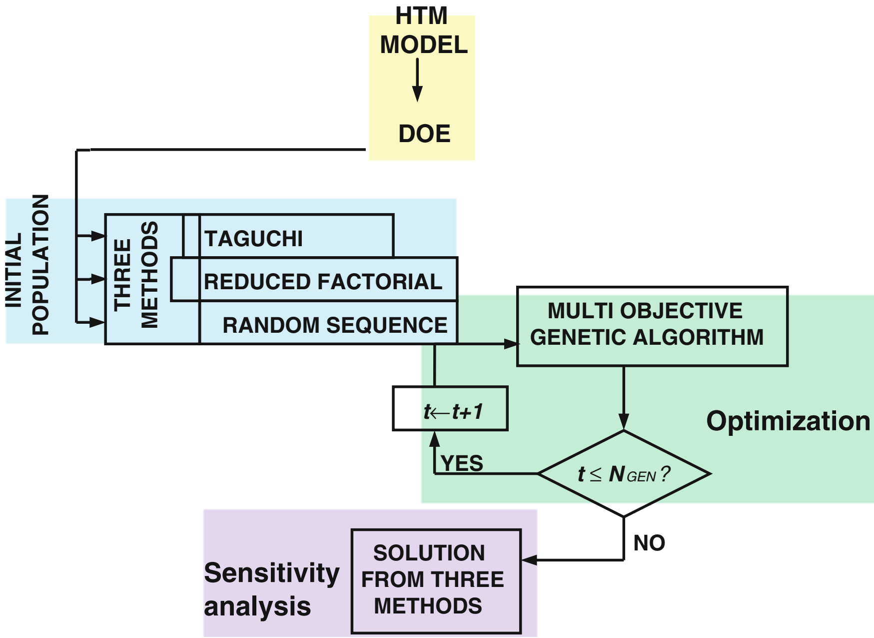


Fig. 15 Multi_objective Genetic Algorithm based optimization algorithm

was selected due to the simplicity in design and static and dynamic specifications. Dynamic characteristics become important when the tool is in contact with work piece generating cutting forces. The overall geometric errors of this concept are modeled using Homogenous Transformation Matrices (HTM) and the objective function is defined as:

$$\delta_{error} = \left(P_x^2 + P_y^2 + P_z^2\right)^{1/2} \tag{21}$$

where Px, Py and Pz are the overall volumetric errors in x, y and z directions respectively defined in Eqs. (17–19). There are five design variables chosen as an example, for the system of interest (See Table 4), three axis positions and 21 geometric errors associated with three axis of machine tool. The five design variables are evolved from the offset lengths a1, b1, c1, a2, b2, c2, a3, b3, c3, Tx, Ty and Tz. Nominal values of design variables are searched using pre-selected ranges in the optimization process (See Table 4). The procedure of calculation is shown in Fig. 15. The sensitivity analysis is carried out using the results found in the case of Taguchi method. The sensitivity of each design variable on the objective function is shown in Fig. 17; each variable is varied over a range while the other ones are kept fixed. The tolerance could be drawn from those ranges after a careful analysis. Objective function defined in Eq. (21) is used by the optimizer to minimize it for error convergence, i.e.,

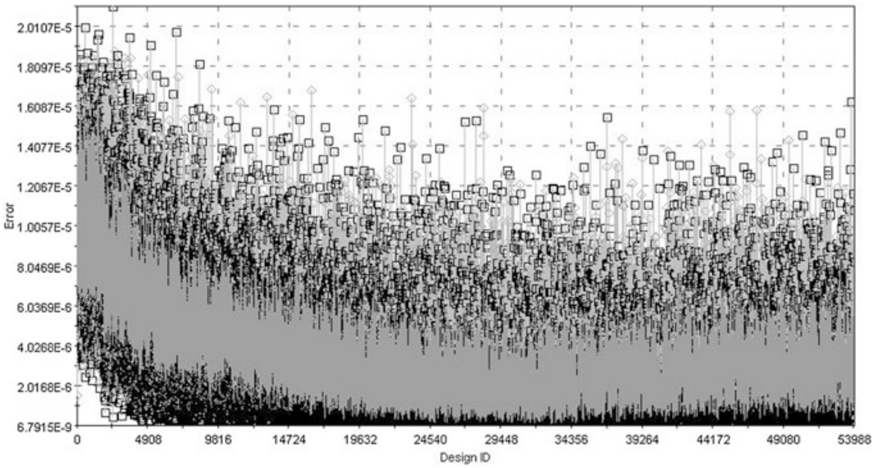


Fig. 16 History chart

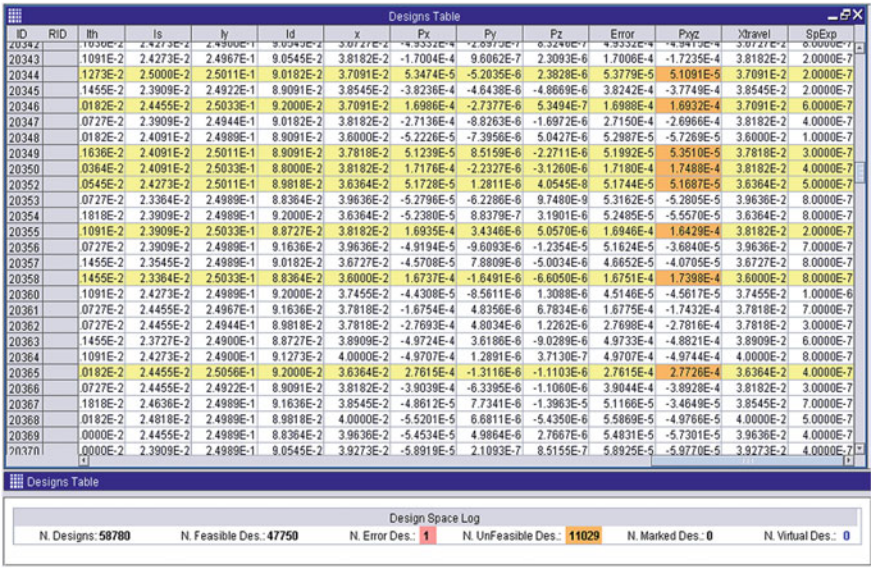
Table 5 Three results with three different DOE techniques

Design variables	Initial values (mm)	Pre-selected range set	Convergence step		
			Taguchi	Reduced factorial	Random sequence
l_s	20	18–30	19	18	27.9
l_{th}	20	17–25	18	21	18
l_y	250	220–280	251	227	254
l_d	90	75–105	105	75	98
l_t	20	15–25	19	20	16
δ_{error}	–	–	6.79 nm	14.63 nm	6.93 nm

$$\delta_{error} \to 0 \tag{22}$$

Three sets of solutions are obtained by the three methods depicted in Fig. 15. An analysis of the results according to requirements will help in choosing the most adequate solution. All the three solutions have reached almost the same minimum objective value for their respective particular position (X, Y, Z) belonging to the machine workspace. Multi Objective Genetic Algorithm is used to run the model as optimizer. It is selected for its ability of fast convergence, directional cross-over and objective function penalization. Figure 16 shows the optimizer convergence towards the minimum objective function and the history of the designs.

Figure 18 shows the values of the design parameters after the convergence solution step is completed. Output parameters P_x, P_y and P_z are constrained to 1 μm individually. Designs with higher value than 1 μm of any one of them result in violation of the objective function. Data in Fig. 17 highlight different color coding for the invalid designs.



Designs Table

ID	RID	Ith	Is	Iy	Id	x	Px	Py	Pz	Error	Pxyz	Xtravel	SpExp
20343		.1091E-2	2.4273E-2	2.4967E-1	9.0545E-2	3.8182E-2	-1.7004E-4	9.6062E-7	2.3093E-6	1.7006E-4	-1.7235E-4	3.8182E-2	2.0000E-7
20344		.1273E-2	2.5000E-2	2.5011E-1	9.0182E-2	3.7091E-2	5.3474E-5	-5.2035E-6	2.3828E-6	5.3779E-5	5.1091E-5	3.7091E-2	2.0000E-7
20345		.1455E-2	2.3909E-2	2.4922E-1	8.9091E-2	3.8545E-2	-3.8236E-4	-4.6438E-6	-4.8669E-6	3.8242E-4	-3.7749E-4	3.8545E-2	2.0000E-7
20346		.0182E-2	2.4455E-2	2.5033E-1	9.2000E-2	3.7091E-2	1.6986E-4	-2.7377E-6	5.3494E-7	1.6988E-4	1.6932E-4	3.7091E-2	6.0000E-7
20347		.0727E-2	2.3909E-2	2.4944E-1	9.0182E-2	3.8182E-2	-2.7136E-4	-8.8263E-6	-1.6972E-6	2.7150E-4	-2.6966E-4	3.8182E-2	4.0000E-7
20348		.0182E-2	2.4091E-2	2.4989E-1	8.9091E-2	3.6000E-2	-5.2226E-5	-7.3956E-6	5.0427E-6	5.2987E-5	-5.7269E-5	3.6000E-2	1.0000E-7
20349		.1636E-2	2.4091E-2	2.5011E-1	8.9091E-2	3.7818E-2	5.1239E-5	8.5159E-6	-2.2711E-6	5.1992E-5	5.3510E-5	3.7818E-2	3.0000E-7
20350		.0364E-2	2.4091E-2	2.5033E-1	8.8000E-2	3.8182E-2	1.7176E-4	-2.2327E-6	-3.1260E-6	1.7180E-4	1.7488E-4	3.8182E-2	4.0000E-7
20352		.0545E-2	2.4273E-2	2.5011E-1	8.9818E-2	3.6364E-2	5.1728E-5	1.2811E-6	4.0545E-8	5.1744E-5	5.1687E-5	3.6364E-2	5.0000E-7
20353		.0727E-2	2.3364E-2	2.4989E-1	8.8364E-2	3.9636E-2	-5.2796E-5	-6.2286E-6	9.7480E-9	5.3162E-5	-5.2805E-5	3.9636E-2	8.0000E-7
20354		.1818E-2	2.3909E-2	2.4989E-1	9.2000E-2	3.6364E-2	-5.2380E-5	8.8379E-7	3.1901E-6	5.2485E-5	-5.5570E-5	3.6364E-2	8.0000E-7
20355		.1091E-2	2.3909E-2	2.5033E-1	8.8727E-2	3.8182E-2	1.6935E-4	3.4346E-6	5.0570E-6	1.6946E-4	1.6429E-4	3.8182E-2	2.0000E-7
20356		.0727E-2	2.3909E-2	2.4989E-1	9.1636E-2	3.9636E-2	-4.9194E-5	-9.6093E-6	-1.2354E-5	5.1624E-5	-3.6840E-5	3.9636E-2	7.0000E-7
20357		.1455E-2	2.3545E-2	2.4989E-1	9.0182E-2	3.6727E-2	-4.5708E-5	7.8809E-6	-5.0034E-6	4.6652E-5	-4.0705E-5	3.6727E-2	8.0000E-7
20358		.1455E-2	2.3364E-2	2.5033E-1	8.8364E-2	3.6000E-2	1.6737E-4	-1.6491E-6	-6.6050E-6	1.6751E-4	1.7398E-4	3.6000E-2	8.0000E-7
20360		.1091E-2	2.4273E-2	2.4989E-1	9.2000E-2	3.7455E-2	-4.4308E-5	-8.5611E-6	1.3088E-6	4.5146E-5	-4.5617E-5	3.7455E-2	1.0000E-6
20361		.0727E-2	2.4455E-2	2.4967E-1	9.1636E-2	3.7818E-2	-1.6754E-4	4.8356E-6	6.7834E-6	1.6775E-4	-1.7432E-4	3.7818E-2	7.0000E-7
20362		.0727E-2	2.4455E-2	2.4944E-1	8.9818E-2	3.7818E-2	-2.7693E-4	4.8034E-6	1.2262E-6	2.7698E-4	-2.7816E-4	3.7818E-2	3.0000E-7
20363		.1455E-2	2.3727E-2	2.4900E-1	8.8727E-2	3.8909E-2	-4.9724E-4	3.6186E-6	-9.0289E-6	4.9733E-4	-4.8821E-4	3.8909E-2	6.0000E-7
20364		.1091E-2	2.4273E-2	2.4900E-1	9.1273E-2	4.0000E-2	-4.9707E-4	1.2891E-6	3.7130E-7	4.9707E-4	-4.9744E-4	4.0000E-2	8.0000E-7
20365		.0182E-2	2.4455E-2	2.5056E-1	9.2000E-2	3.6364E-2	2.7615E-4	-1.3116E-6	-1.1103E-6	2.7615E-4	2.7726E-4	3.6364E-2	4.0000E-7
20366		.0727E-2	2.4455E-2	2.4922E-1	8.9091E-2	3.8182E-2	-3.9039E-4	-6.3395E-6	-1.1060E-6	3.9044E-4	-3.8928E-4	3.8182E-2	3.0000E-7
20367		.1818E-2	2.4636E-2	2.4989E-1	9.1636E-2	3.8545E-2	-4.8612E-5	7.7341E-6	-1.3963E-5	5.1166E-5	-3.4649E-5	3.8545E-2	7.0000E-7
20368		.0182E-2	2.4818E-2	2.4989E-1	8.9818E-2	4.0000E-2	-5.5201E-5	6.6811E-6	-5.4350E-6	5.5869E-5	-4.9766E-5	4.0000E-2	5.0000E-7
20369		.0000E-2	2.4455E-2	2.4989E-1	8.8364E-2	3.9636E-2	-5.4534E-5	4.9864E-6	2.7667E-6	5.4831E-5	-5.7301E-5	3.9636E-2	4.0000E-7
20370		.0000E-2	2.3909E-2	2.4989E-1	9.0545E-2	3.9273E-2	-5.8919E-5	2.1093E-7	8.5155E-7	5.8925E-5	-5.9770E-5	3.9273E-2	4.0000E-7

Designs Table

Design Space Log

N. Designs: 58780 N. Feasible Des.: 47750 N. Error Des.: 1 N. UnFeasible Des.: 11029 N. Marked Des.: 0 N. Virtual Des.: 0

Fig. 17 Example of color coding for feasible and unfeasible designs

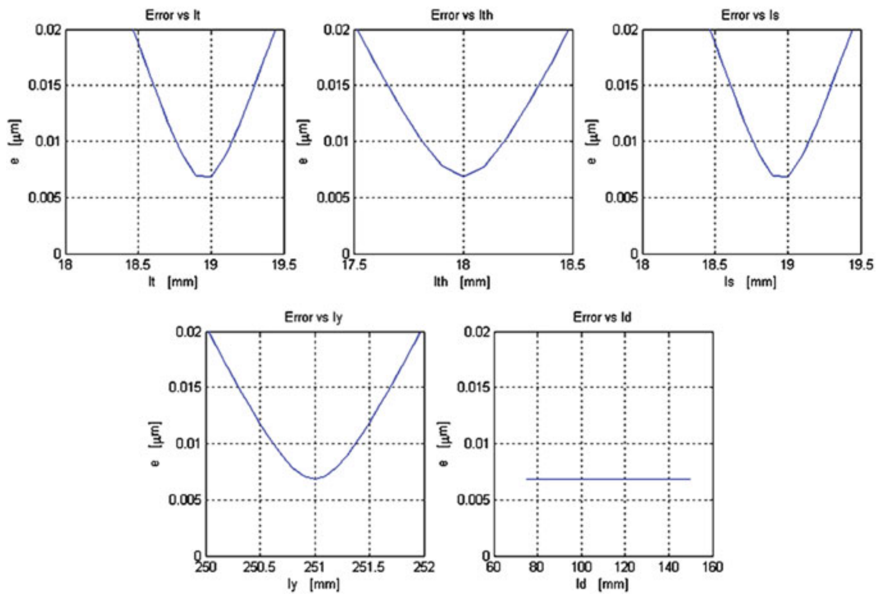


Fig. 18 Sensitivity analysis of design variables (Volumetric error vs. design parameter tolerance range)

The parameters 'l_t', 'l_{th}' and 'l_s' are found to be more sensitive design parameters than the others as shown in Fig. 18. Their tolerance band is about 1 mm for the maximum objective value of 0.02 μm. 'l_d' has been an insensitive parameter in this first analysis, as the spindle-column distance of machine tool has a specific stiffness, e.g. cantilever and will only be fully designed with dynamic analysis. Table 5 is showing the optimized design parameters using three different design of experiments techniques and the calculated objection function value in each case.

7 Conclusion

Development of high precision micro-machines is an important area where bulk micro parts can be manufactured at a high rate. Many small micro-machines that can be installed in a micro-factory environment cannot work in isolation and all the re-configurable micro-machines needs certain intelligence to work with flexibility and in an optimized fashion. For that matter, M2M communication is envisioned to run the smart micro-factory and selected parameter's data flow for the supervisory control and reporting. M2M communication is envisaged with wireless Bluetooth technology having appropriate data rates to accommodate the required operational and condition monitoring data of micro machines. A cellular network as a gateway is suggested to be used to connect the micro-factory with the remote supervisor. Data security features such as authentication and access control can be managed by the gateway through IP communication for an end-to-end IP network flow. This work also presents a robust design method of an example micro-machine tool in a micro-factory CPS using volumetric error optimization. This volumetric error is found to be critical for getting high precision to be embedded as an error compensation tool. Furthermore, three methods were used to generate the initial population of weak non-linear equations formed from the HTM model. The sensitivity investigation of the design variables of a three axis micro-machine tool reveals respective tolerance bands for the design parameters.

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