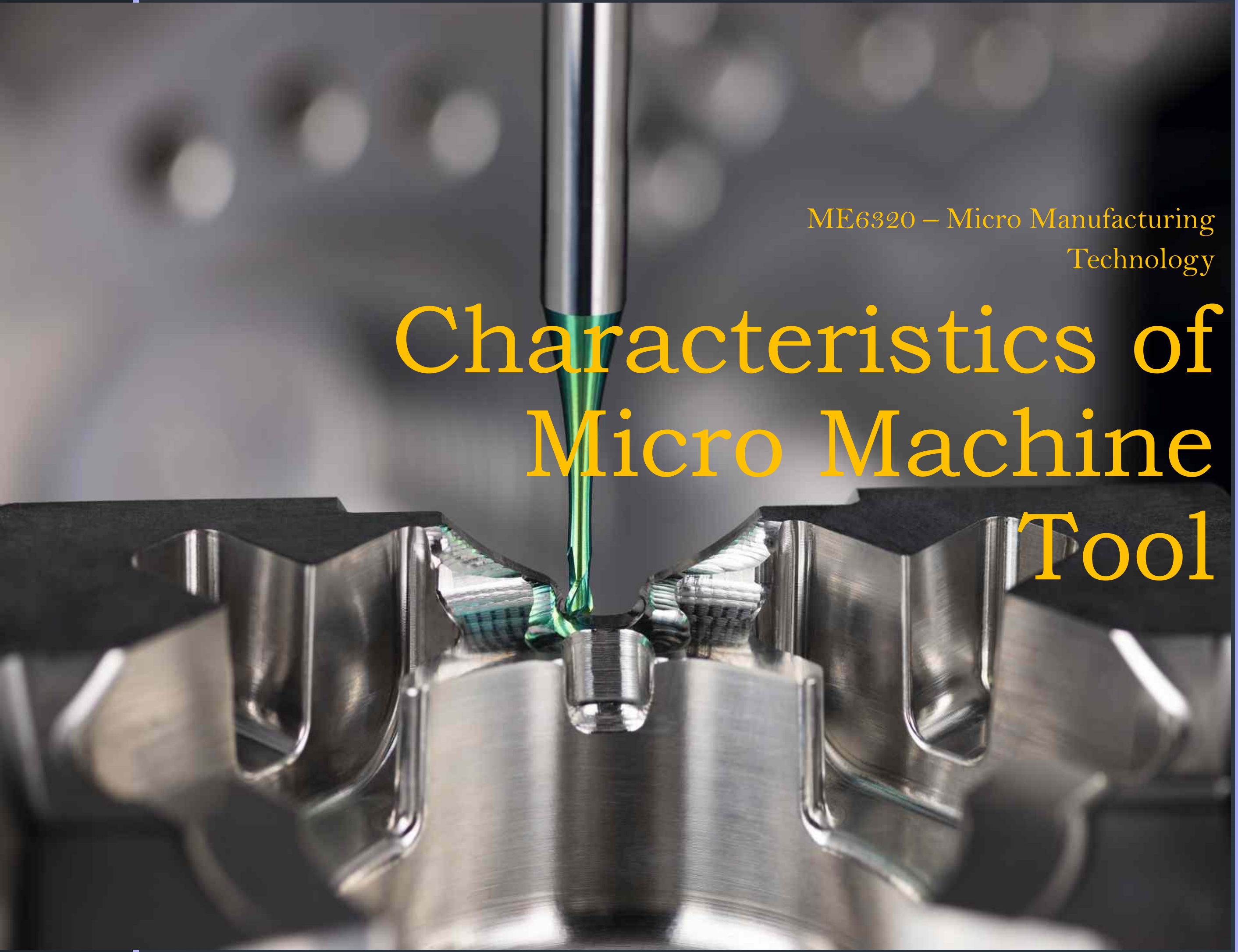
Components of mechanical micro-machine Tool

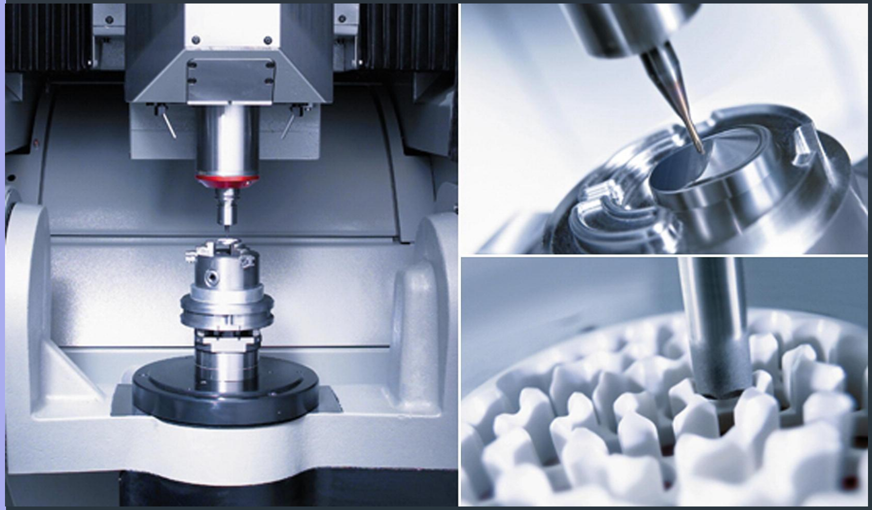
ME6320 – Micro Manufacturing Technology

Characteristics of Micro Machine Tool



General Machine Tool Characteristics

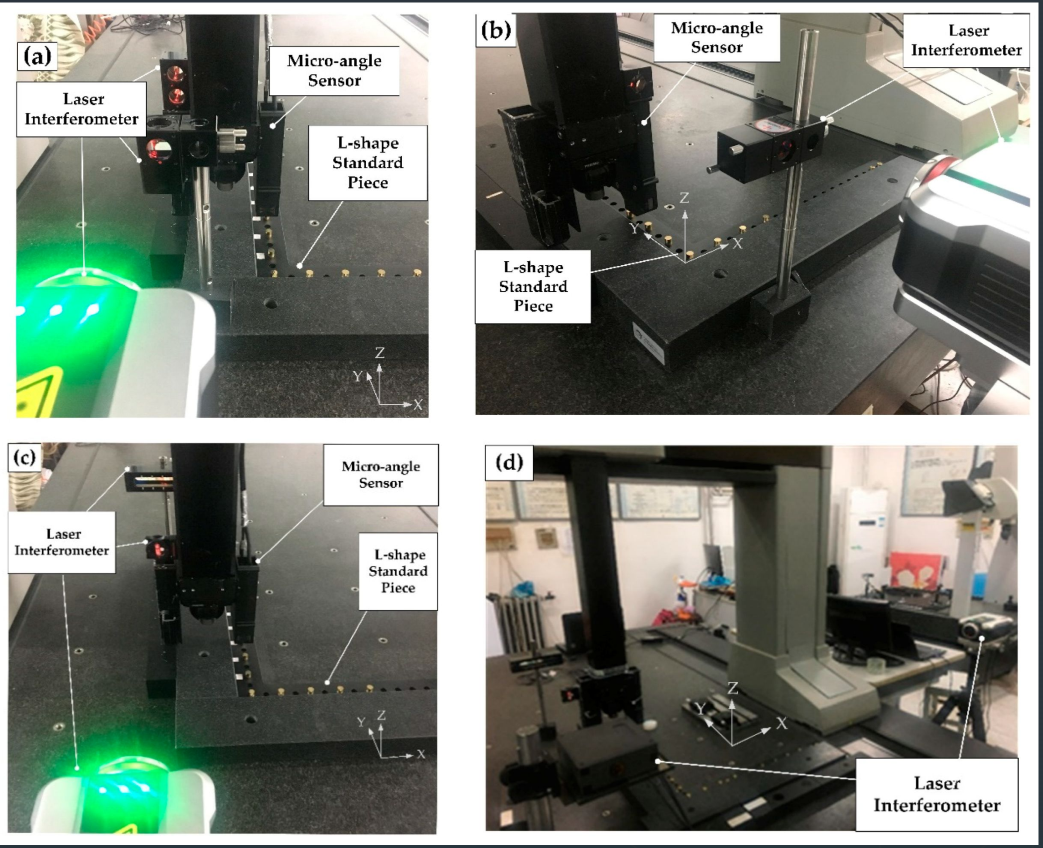
- Cutting tool characteristics were examined with respect to the effects of the machine controlled parameters and tool geometry on cutting phenomenon.



- Some research works concentrated on temperature generation usually without recourse to the combined effects of the machine controlled parameters and tool geometry.
- The cutting speed has a great influence on the forces and temperature and hence on tool life as well as the machining economics. The feed has similar but less influence on these quantities

Requirements of Micro Machine Tool

- Geometric Accuracy
- Static Stiffness
- Dynamic Stiffness
- Thermal Stability



- Spindle Error Analyzer
- Kinematic Accuracy
- Thermal Testing
- Vibration Testing
- Body Stiffness

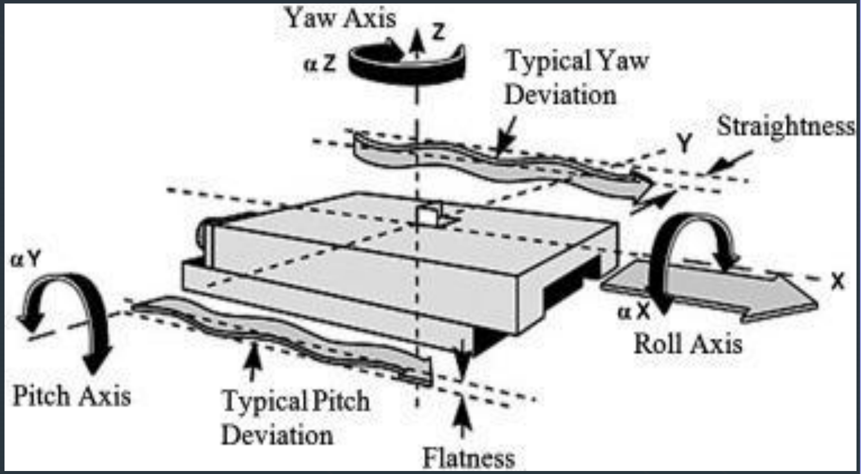
Geometric Accuracy of Machine Tool

- *Geometric accuracy* of the machine tool is related to the quality of the construction, the production of individual components and the assembly of the machine tool.

- Geometric Accuracy of Machine tool serves not only for the purpose of machine delivery to the customer or for demonstration of proper service intervention but also for assessment of improvements compared to the current state.

- The information on geometric accuracy of the machine is also used as a feedback to the machine development.

- Geometric accuracy is used to assess the future functionality of the machine. Geometric accuracy can be used to simply verify the correctness of the production of the individual parts, their assembly and the final adjustment of the machine.



Geometric Accuracy

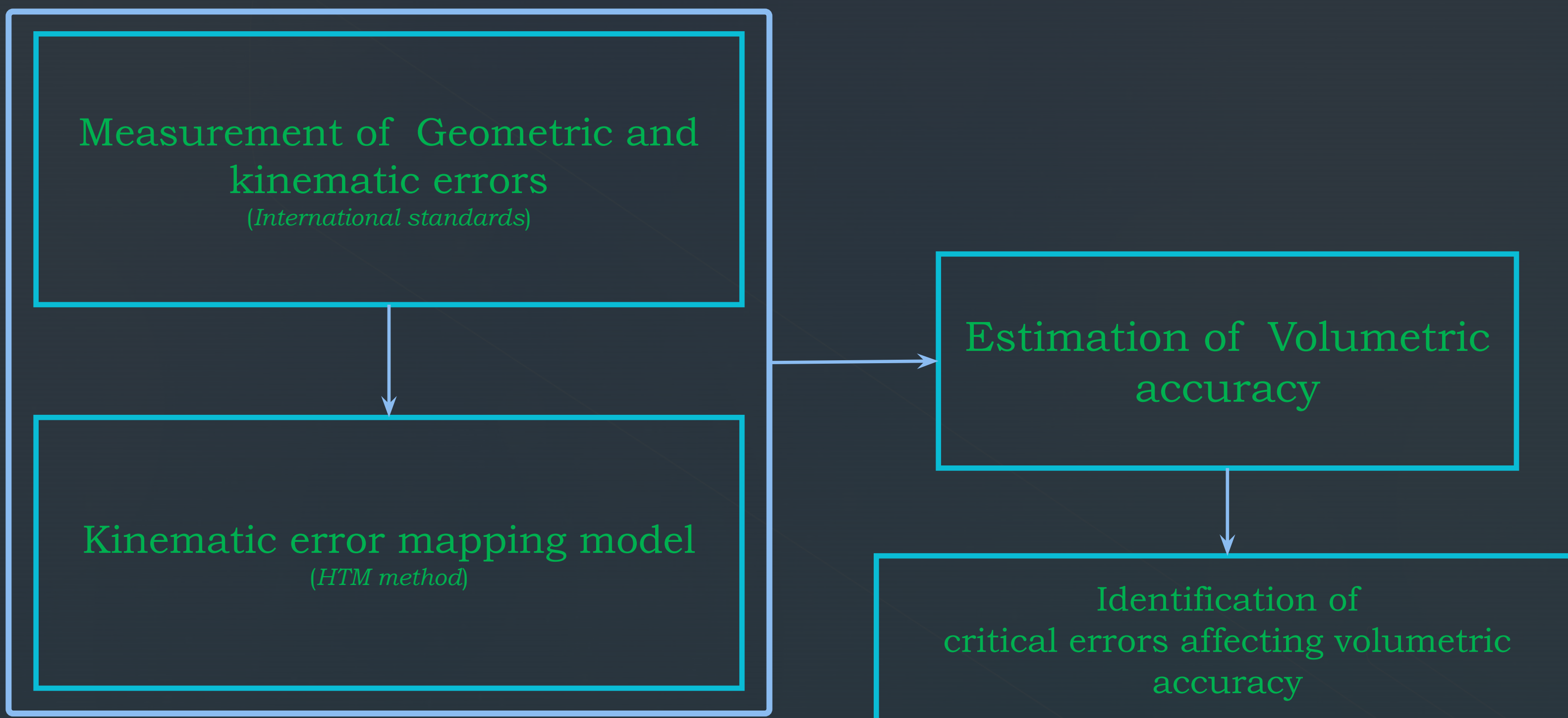
- Geometric accuracy is one of the parameters of machine tool that takes into account the quality of the machine production and assembly in the unloaded condition (no machining forces are considered).

- Under the geometric accuracy, we can imagine:
  - Deviations of the shape and position of fixing surfaces for workpieces and tools,
  - The relative position between the workpiece and the tool when defining the mutual adjustment of the individual parts of the machine which can be changed during the axis feed or when adjusting their positions.

- Geometric accuracy describes the geometric structure of the machine tool, based on which it is possible to evaluate the properties of the functional parts further influencing the working and production accuracy of the machine tool.

- Geometric accuracy tests are described in ISO 230 which states that the tests are carried out on the unloaded machine or under finishing conditions of machining.

Methods for estimating accuracy of Machine Tool

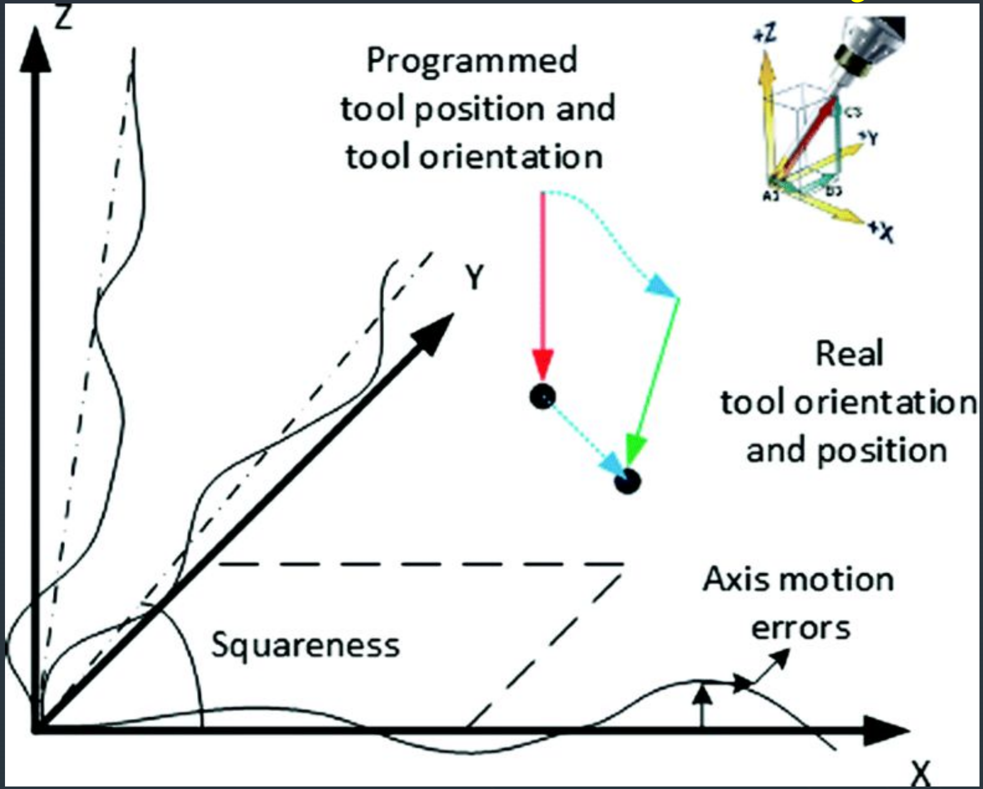


Estimation of Volumetric Accuracy

- The purpose of these advanced compensations is to minimize the deviation in the tool centre point (TCP) at any point of the measured machine space .

- This is the difference between the TCP programmed position and orientation and the real TCP position and orientation.

- For a three-axis machine, it is possible to describe 21 geometric errors of machine. This number is based on the number of degrees of freedom (DOF) of the axis in the space.



Interpretation of volumetric error in Cartesian coordinate system

Working Accuracy & Production Accuracy

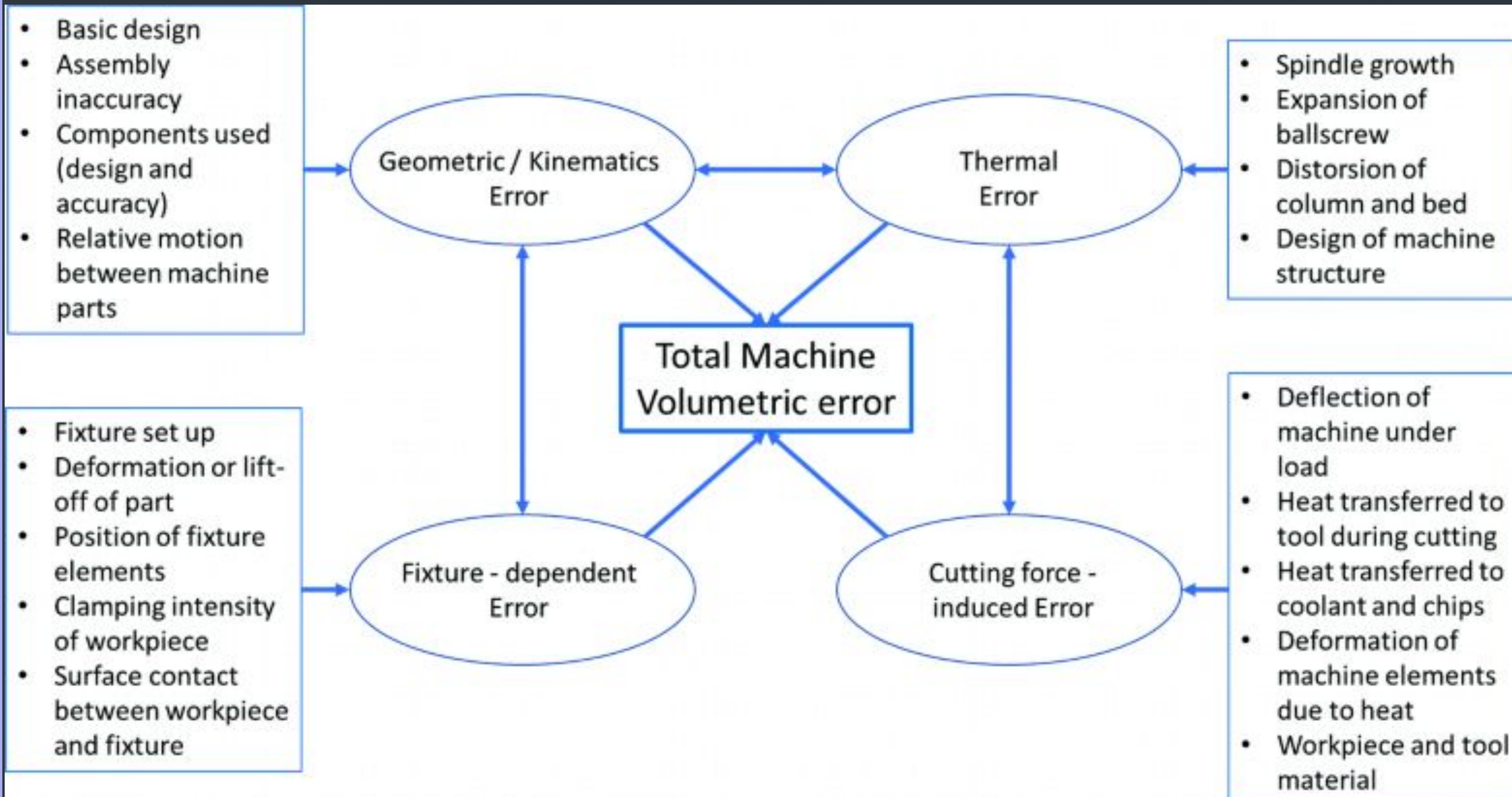
- Workpiece Accuracy is the property of the machine tool that expresses the quality and productivity of the workpiece manufacture.

- The working accuracy of the machine is affected by the accuracy of the relative tool path:
  - Geometric accuracy of the machine,
  - Accuracy of tool positioning relative to the workpiece (positioning accuracy),
  - Machine resistance to elastic deformations (caused by cutting forces, workpiece weight, etc.),
  - Machine resistance to thermal dilatations (“temperature stability”),
  - By selecting the cutting conditions, etc.

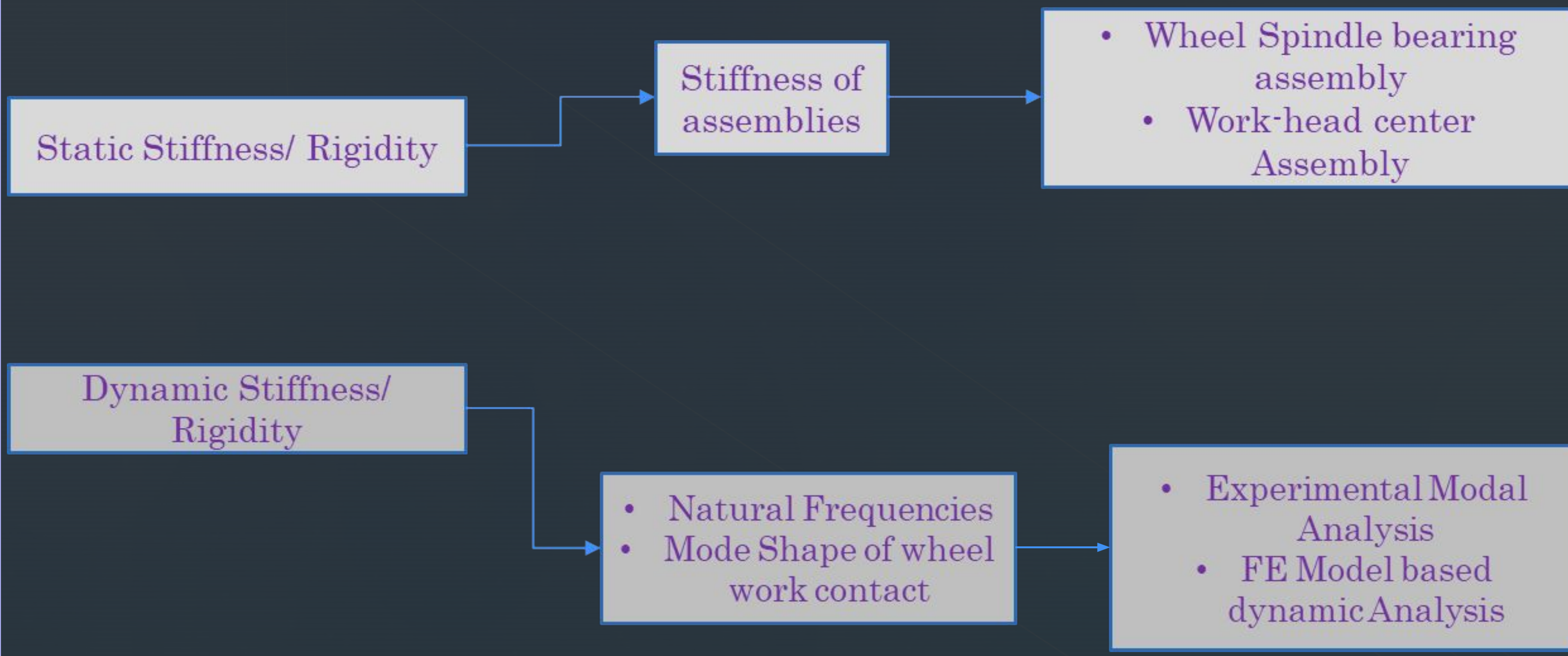
- Production accuracy is affected by geometric accuracy, positioning accuracy, working accuracy, errors caused by machine operators (poorly adjusted tool, poorly fixed workpiece) and by changes in environmental conditions.

- Direct information on the production accuracy is given by the fluctuations in the dimensions of the test workpieces during the production process.

Overview of the Error Budget in a Machine Tool

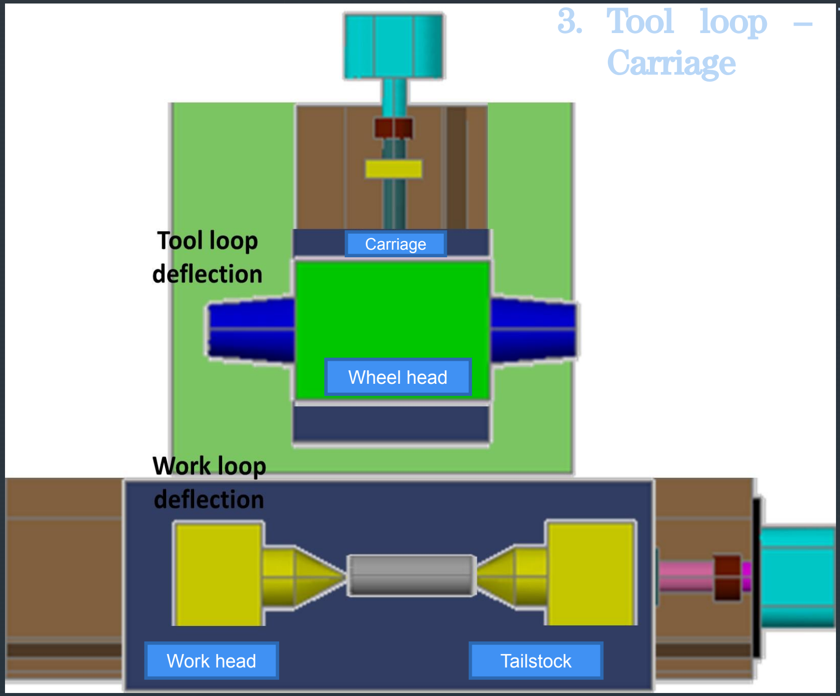


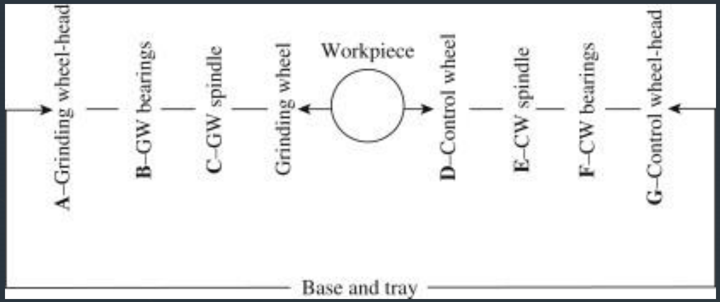
Static & Dynamic Stiffness of Micro Machine Tool



Static Rigidity

1. Deflection of the contact point
2. Work loop – Workhead, Tailstock assembly
3. Tool loop – Wheel spindle, Wheelhead assembly, Carriage





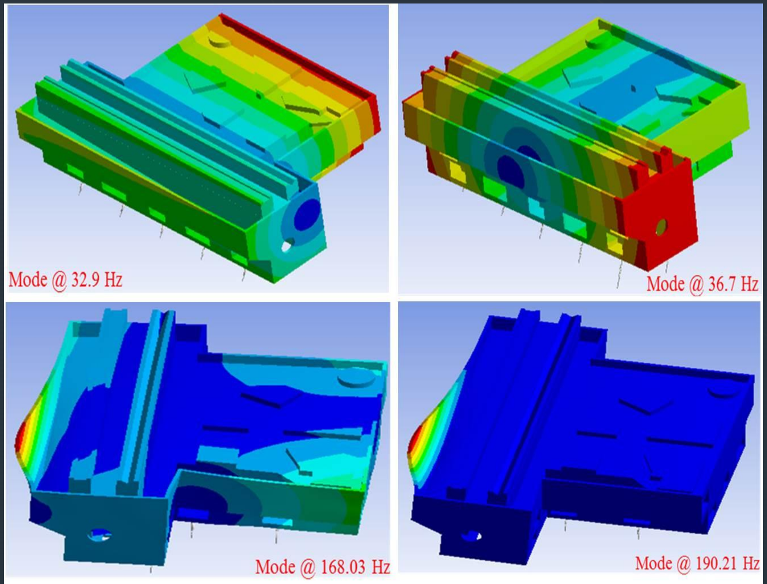
e.g. Elements comprising the force loop for centreless grinding

- Overall static stiffness of a machine depends on all elements acted on by the normal force.

Dynamic Rigidity

1. Operating frequency closer to natural frequency of elements

1. Modal characteristics of assemblies



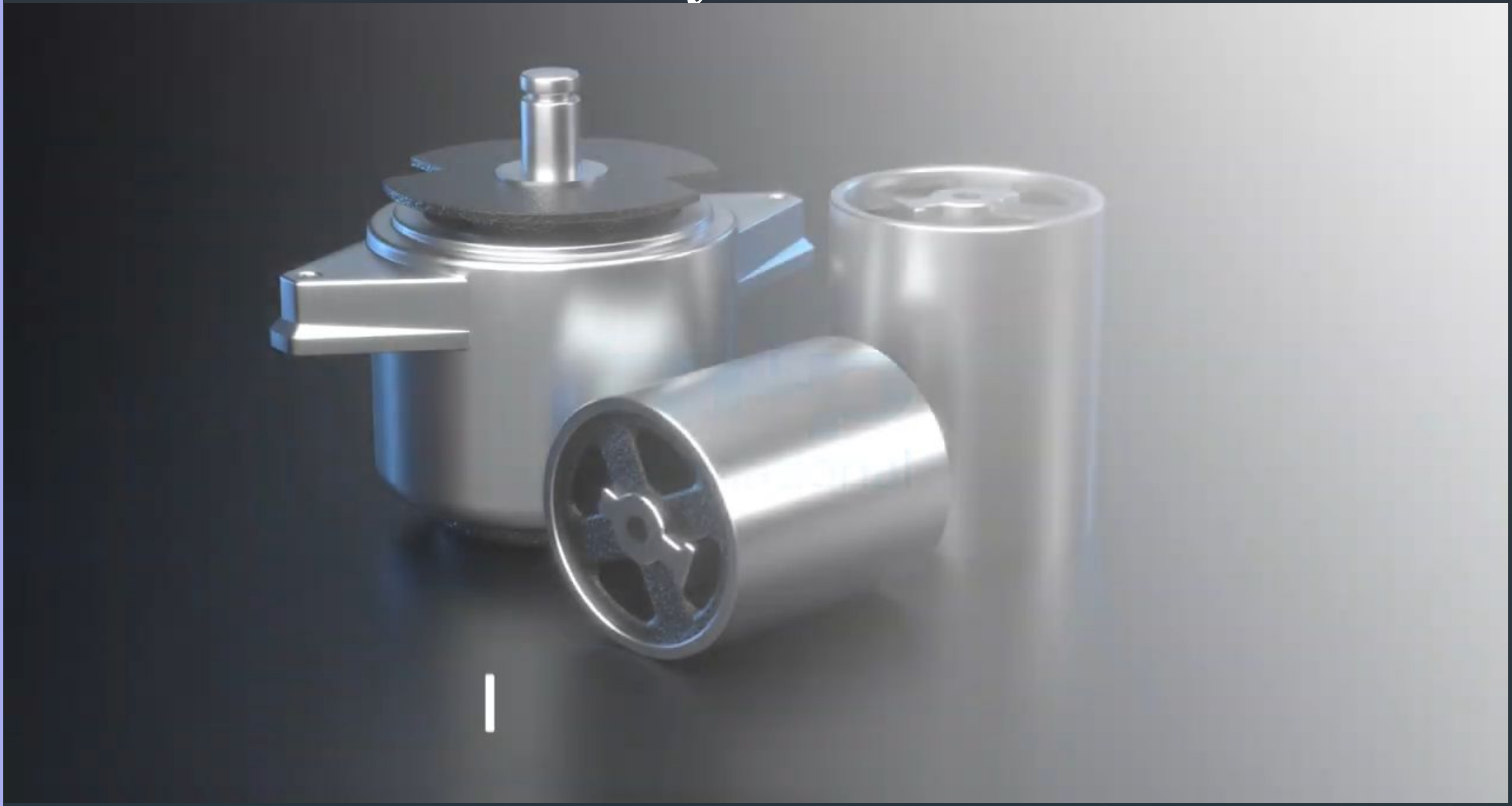
- The accuracy of the work produced on a machine tool is determined by the deviations at the cutting point from the required relative motion between the tool and the workpiece.

- These deviations are caused in addition to geometric and kinematic errors by static and dynamic forces present in the machine tool

- Dynamic stiffness (frequency dependent flexibility) is used to assess a machine's dynamic behaviour.

- For an existing machine tool, experimental procedures called 'acceptance tests' are developed to obtain the required metrics.

Dynamic Stiffness

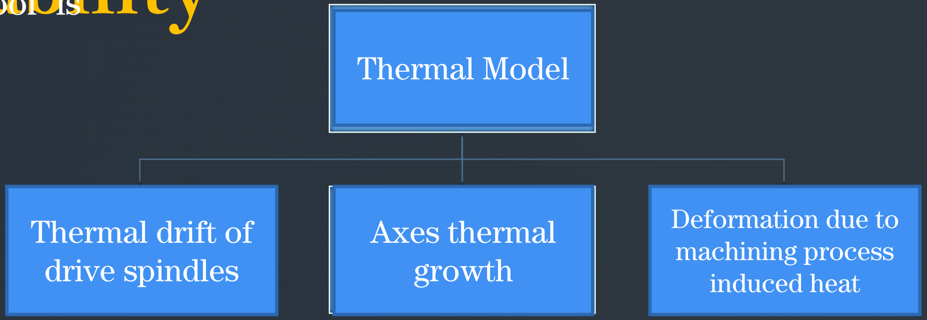


video link

Thermal Stability

- Thermal mapping of the machine tool is done using a thermal imaging camera.

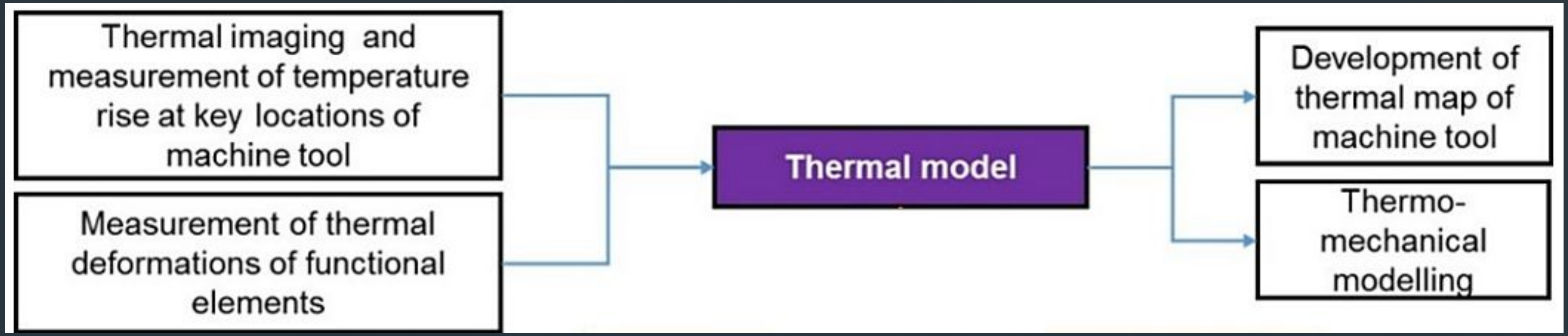
- Computing the thermal errors of machine tools include both, temperature distribution and displacements.



- Sources of thermal influences on a machine tool:
  - The cutting process itself and the heat generated in it
  - Heat generated by different heat sources inside the machine
  - Thermal influences provided by heating or cooling systems
  - Environmental conditions
  - The effect of people
  - Thermal memory of previous environment

Thermal Stability

- Thermal issues in machine tools includes measurement of temperatures and displacements, especially displacements at the tool centre point, computations of thermal errors of machine tools, and reduction of thermal errors.
- Thermal errors are computed with various numerical algorithms and a movement to compensate for the thermally-induced errors is generated by a controlled actuator.
- The material properties of the chosen fluid primarily influence the design and energy efficiency of the cooling system. Temperature rise in machine tools is always provoked by components with energy loss and further power expenditure is required to reduce errors induced by this loss.



Thermal Compensation of Machine Tool

video link

Accuracy on Modern

video link

Requirements of a Micro machine Tools

1. Geometry Accuracy
2. Static Stiffness
3. Dynamic Stiffness
4. Thermal Stability.

Spindle Tests:

Spindle Error Analyzer.

Spindle Speed & Stroke

Kinematic accuracy

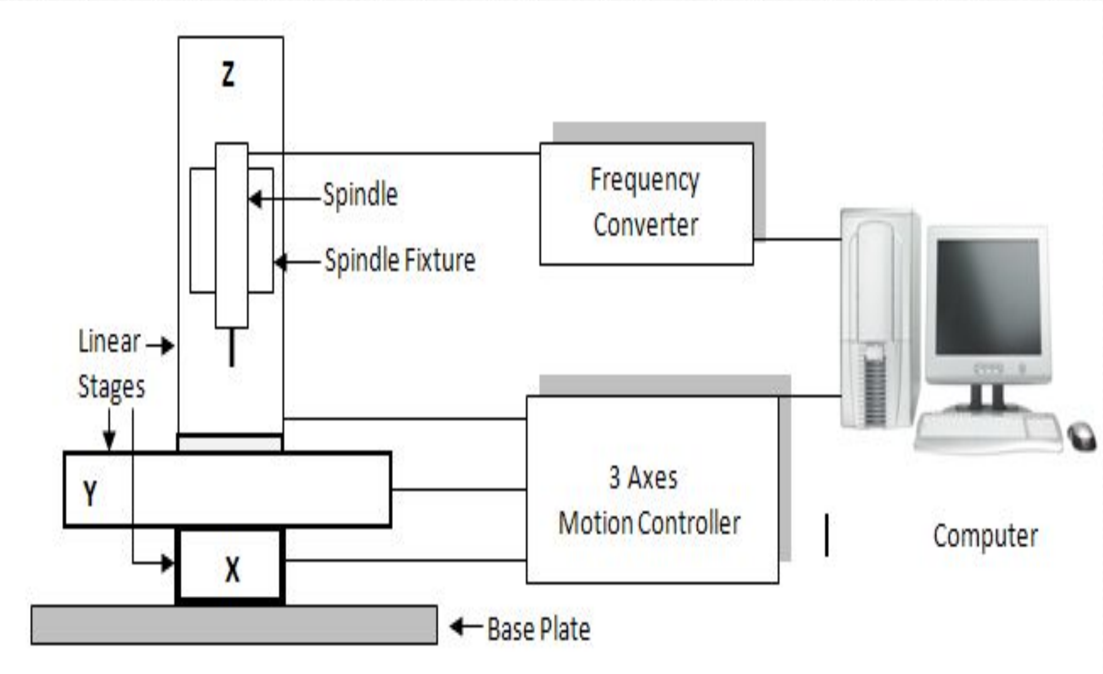
Body Stiffness

- No Load Testing
- Load Testing
- Thermal Testing
- Vibration Testing.

Process capability

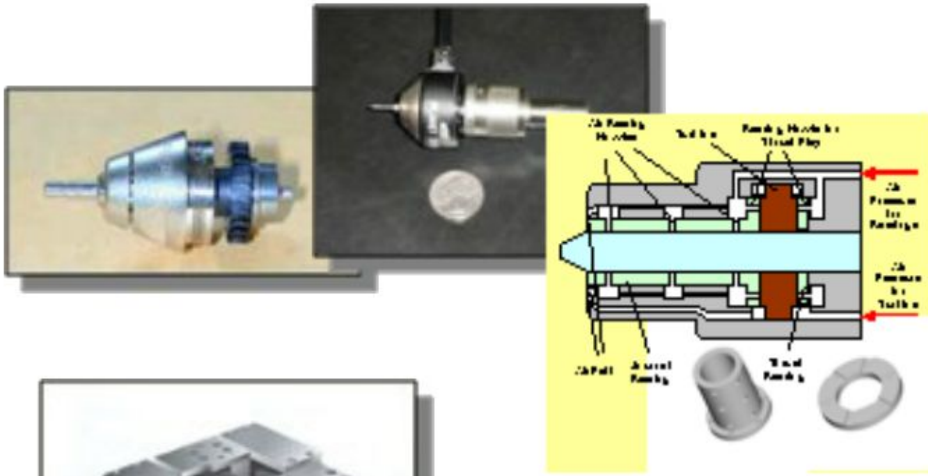
Diagonal Test – Laser Interferometer

Main Components of a Micro Machine Tool

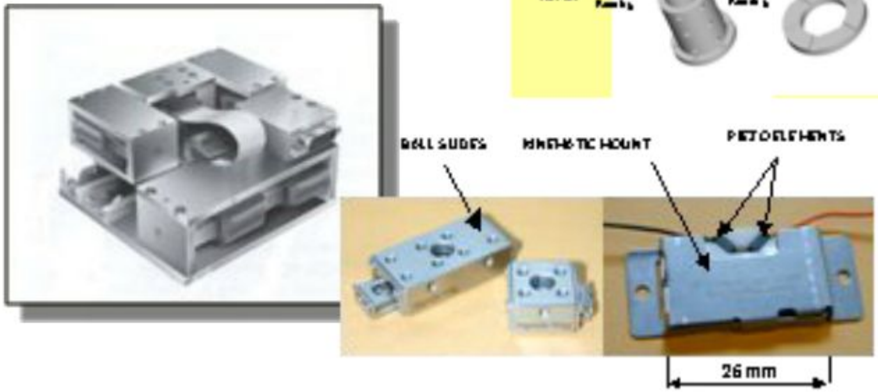


Development of Component Systems

- **Spindle**
  - *Increased spindle speeds*
  - *Runout reduction*
  - *Reduced spindle size*

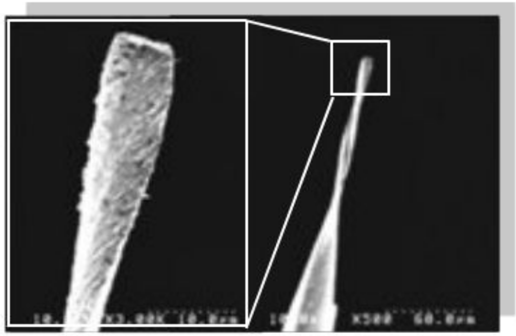


- **Feed Drive**
  - *High positioning/motion accuracy*
  - *High stiffness*
  - *Compact (or monolithic) topology*



Motion controllers

- *Increased control of geometric features*



10μm Endmill

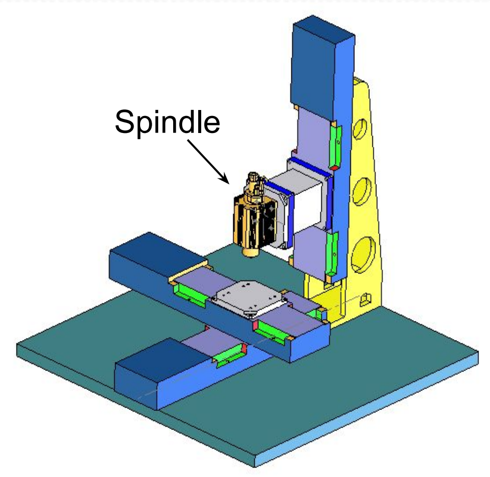
Main Components of a Micro Machine Tool

Sl.No	Components Name	Manufactures.
1	Micro Motor Spindle & Spindle bracket	Alfred Jager GmbH, Germany.
2	Frequency converter	BMR GMBH, Germany.
3	Linear stages	Newport Corporation, USA
4	Right-angle brackets	Newport Corporation, USA
5	Motion controller/driver	Newport Corporation, USA
6	Miniature Tools micro drills micro end mills	Guhring, Titex & Prototyp. Germany. Axis Tools

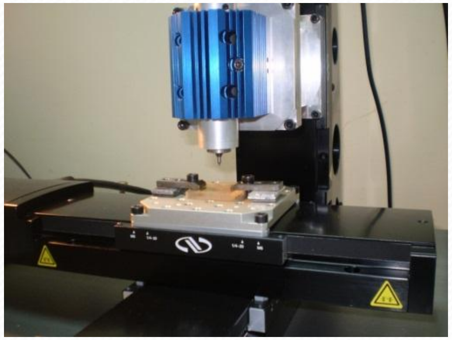
Importance of spindle and its rotational accuracy in Micro-Machines

- Spindle is an important component of a micro machine – “the heart of a machine tool*”
- Spindle speed are very high *(10,000 to 150,000 rpm)*
- Micro feature size itself in micrometers – the order of spindle error will have large influence geometry, form and finish of the micro components

- **4th International Workshop on Microfactories,** October 15-17, 2004, Shanghai, China, Dr. Yuichi Okazaki, **The National Institute of Advanced Industrial Science and Technology, Japan** presenting a paper titled “Development of a Desk-top Milling Machine with a 300 Krpm Spindle and a Linear Motor Stage” mentioned that “the most difficult task in development of micro machine tools is measurement and control of spindle motion”



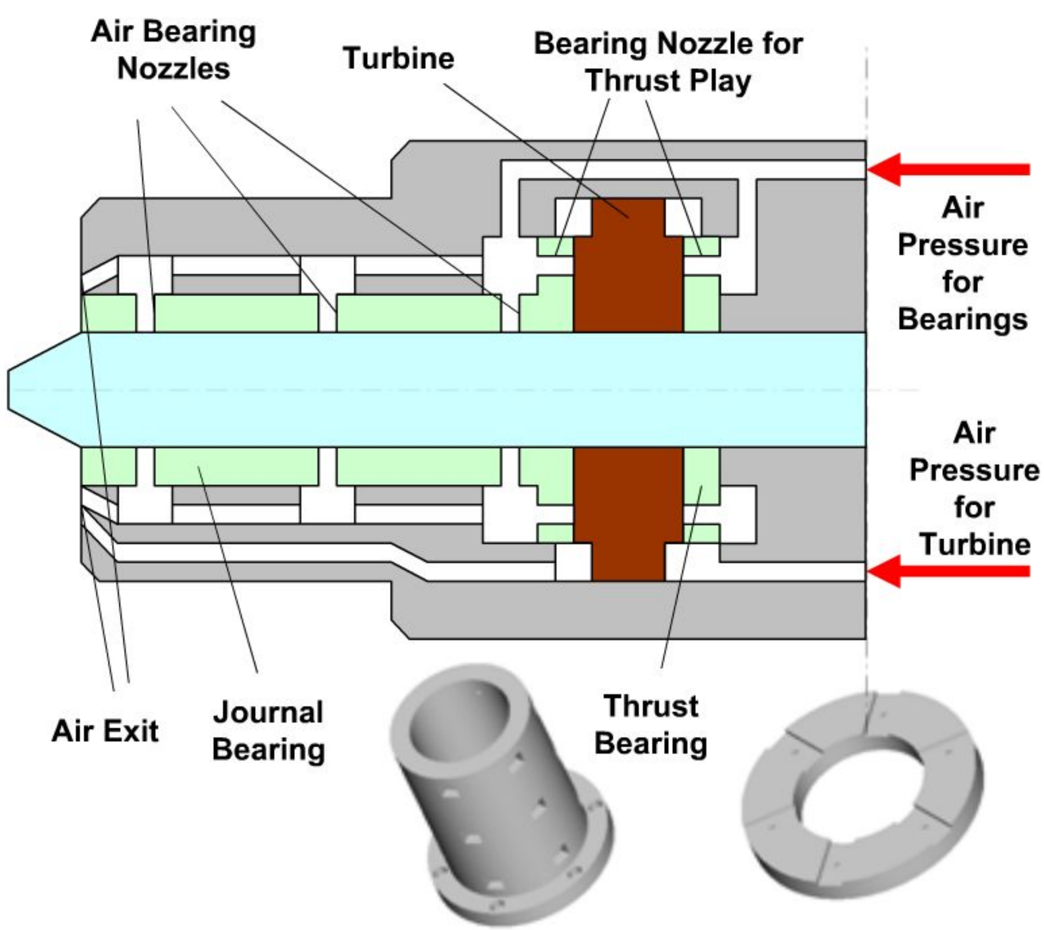
Miniaturized Machine Tool



High Speed Spindle

* *www.blaessinger.com/products/assembly/main-spindle.html*

High Speed Air Bearing Spindle



TARGET FEATURES

- **System size**: *13* × *17* mm
- **Rotational speed***:*
  300,000~600,000 RPM
- **Relative accuracy***: 10^{-3}~10^{-4}* μm
- **Run-out***: less than 0.5* μm

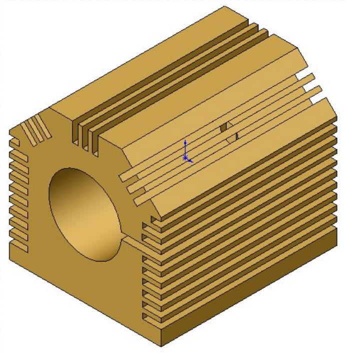
High Speed Spindle

Technical specifications:

Sl. No	Specifications	Data
1	Make	Alfred Jager GmbH, Germany
2	Rotation speed max.	100,000 rpm
3	Clamping range	up to 3 mm
4	Spindle run out	1 ~ 3 μm
5	Frequency max.	1666,6 Hz
6	Weight apporx :	0.5 kg
7	Type of cooling	Non Cooling:
8	Bearing Type	High precision hybrid ceramic ball bearing
9	Lubrication and Maintanance	lifetime lubricated, maintenance free

High Speed Spindle

1.Micro motor spindle & spindle bracket



Spindle bracket

Spindle

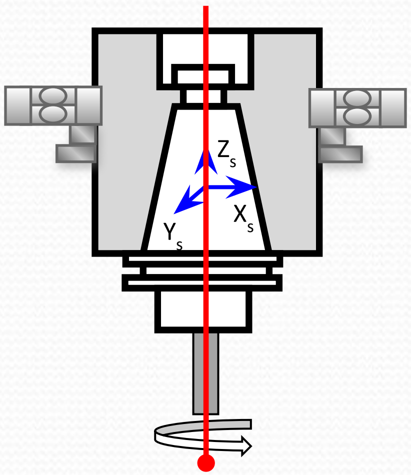
2.Frequency Converter – Spindle Drive

Features

- Convert the fixed 50 Hz network into a 3-phase network with variable frequency and voltage.
- Create, store and modify up to 16 spindle characteristics.
- Digital display of the spindle speed.
- Manual & Control through the software .
- All parameters, such as current, voltage and frequency, are captured in real time, and adjusted by implementing via the Vector Control according to loading.

Frequency Converter

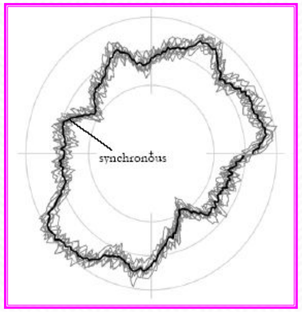
Spindle Errors



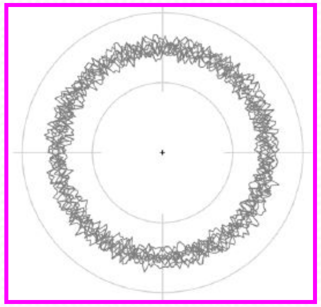
Axis of rotation

Spindle errors

- **Radial error** **(δ_x, δ_y)**
- Axial error (δ_y)
- Tilt error (α,β)



Synchronous error
(Repeatable)



Asynchronous error
(Non repeatable)

Spindle Errors:

1. Obtaining spindle data using appropriate method
2. Analysis of measurement data

Form error separation methods

1. Donaldson Reversal Method

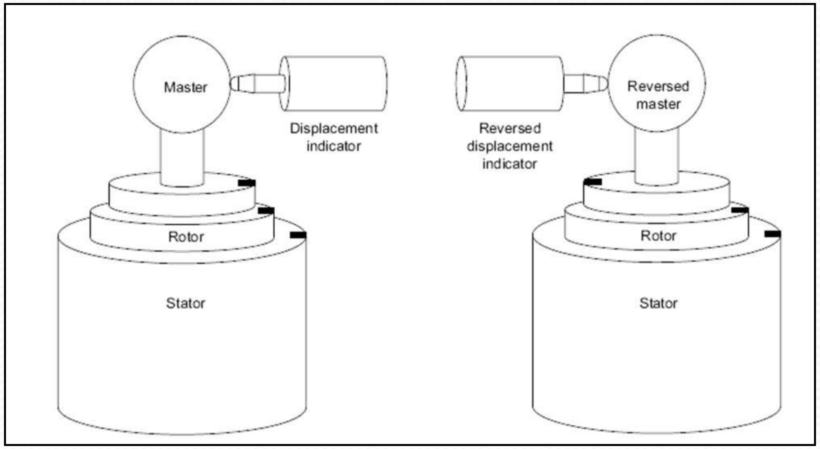
1. Three point method

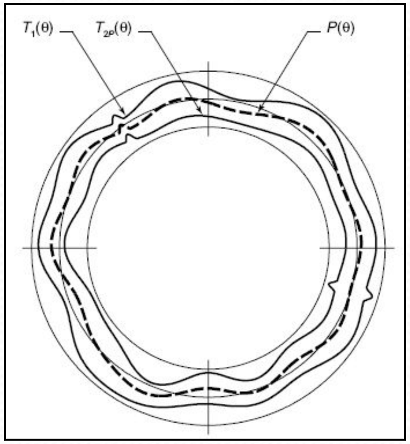
1. Double probe, Double orientation method

1. Multistep method

Form error separation methods

1. Donaldson Reversal Method (1972)





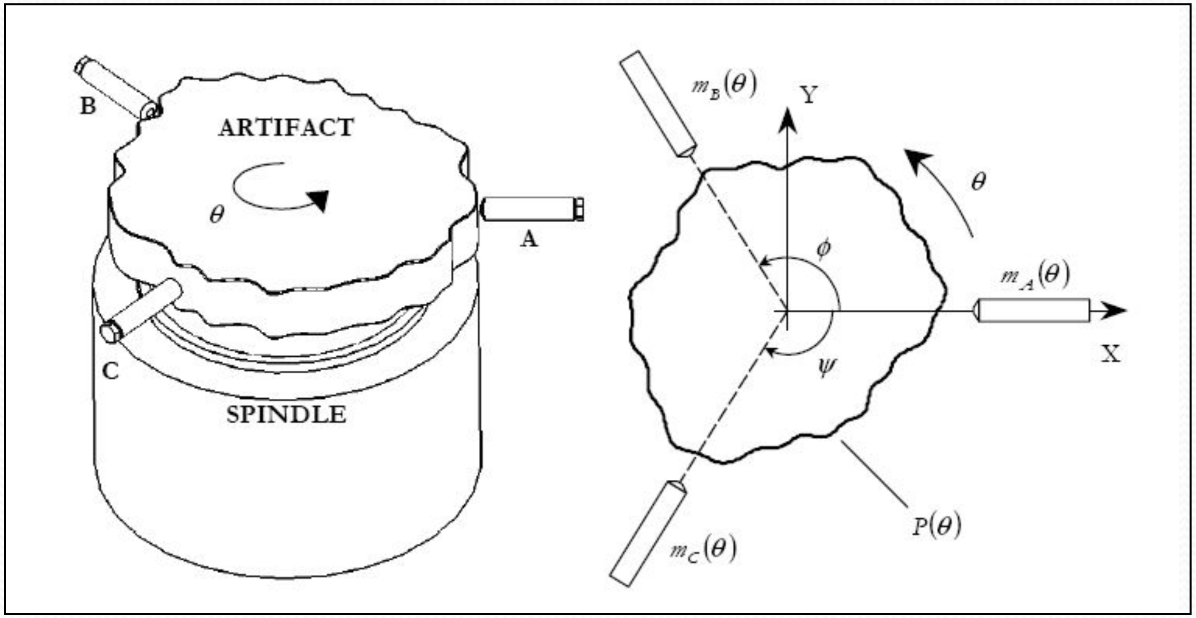
$$T_1(\theta) = P(\theta) + S(\theta) \quad T_{2P}(\theta) = P(\theta) - S(\theta)$$

Limitations:

- Requires repeatability of spindle (forward and reverse)
- Repositioning of master and sensor

Form error separation methods in Literature….

2. Three point method (Mitsui,1987)

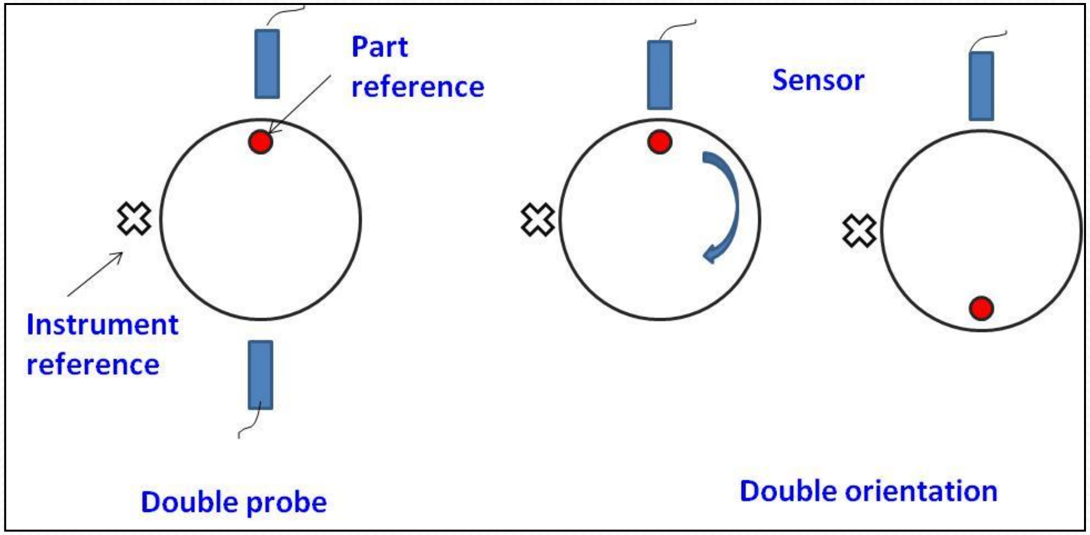


Limitations:

- Requires accurate knowledge on angular position of sensor
- Sensors with similar sensitivity

Form error separation methods in Literature….

3. Double probe, Double orientation method (Whitehouse, 1976)

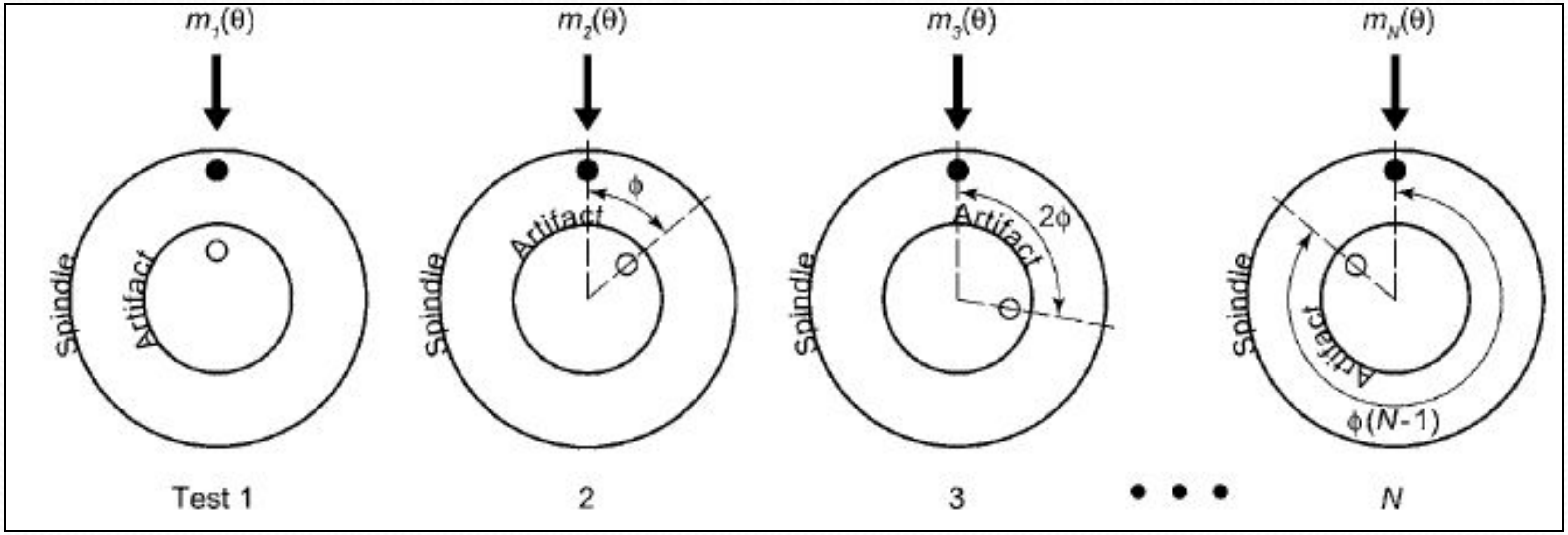


Limitations:

- Requires multiple measurements
- Can remove only second harmonic and its multiples
- Repeated movement of master

Form error separation methods in Literature….

4. Multistep method (Chetwynd and Siddal,1976)

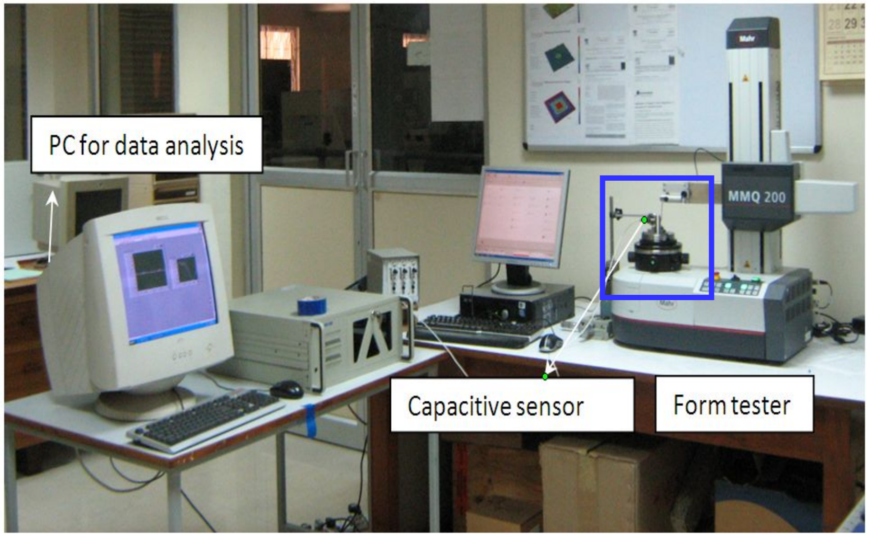


Limitations:

- Requires multiple measurements
- Repeated movement of master

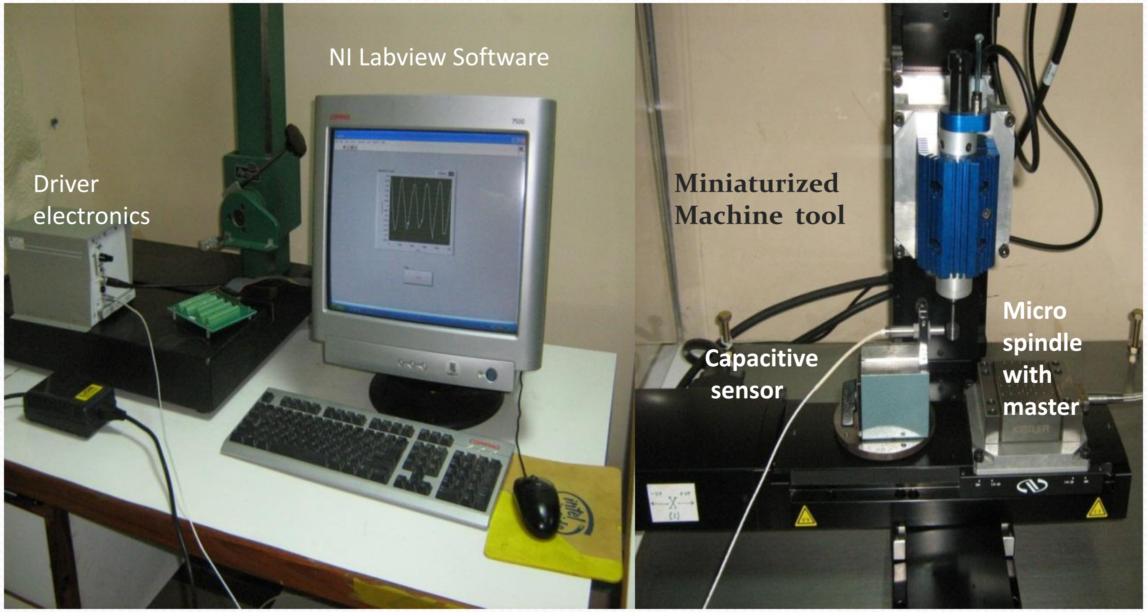
Present method for separation of Form Error

Separation method based on Harmonics in the form profile

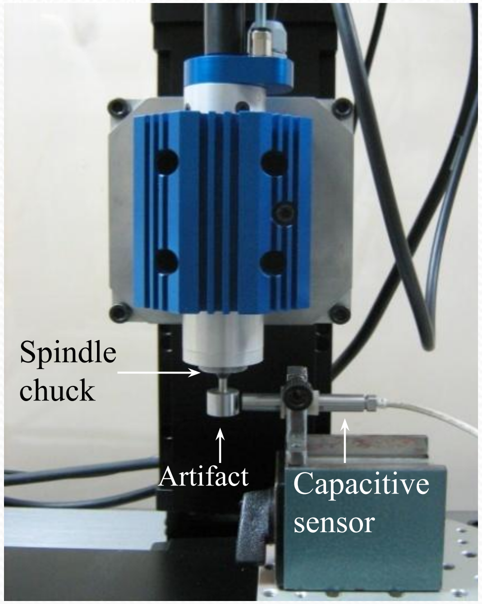


Experimental arrangement for measurement of form error using capacitance sensor and roundness tester

Capacitance sensor based set-up for measuring spindle errors

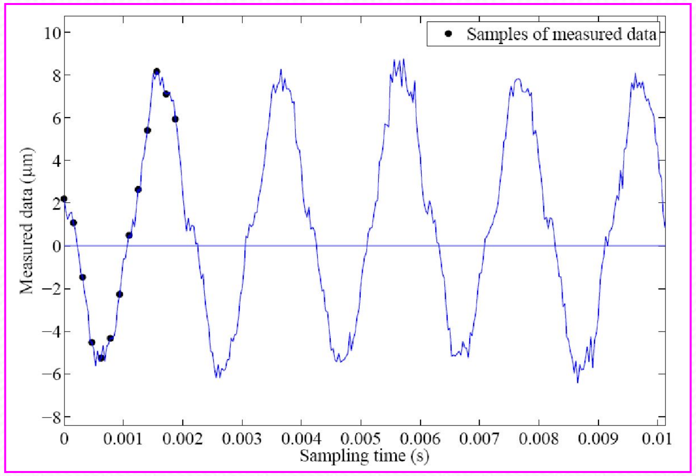


Experimental setup

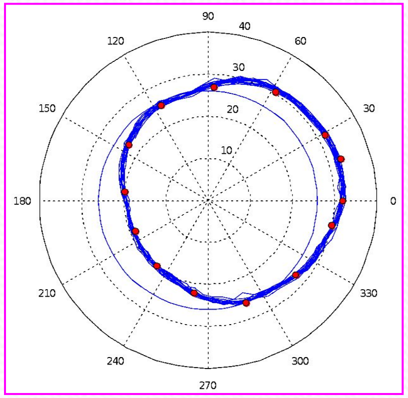


Close-up view

Samples of spindle data obtained at 30,000 rpm



Spindle data obtained in time domain

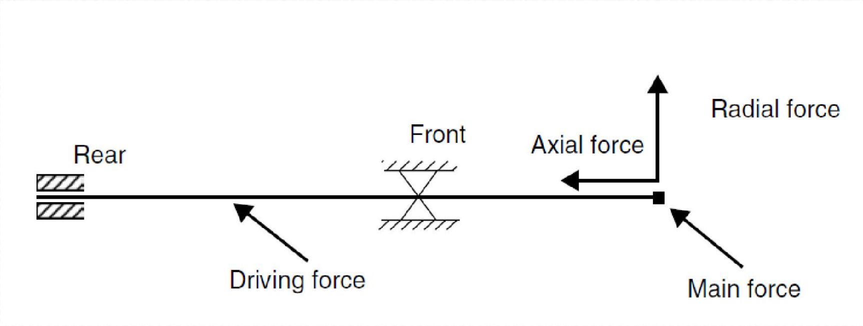


Polar plot of the data with 25 µm base circle radius

Sample Spindle data at 30,000 rpm

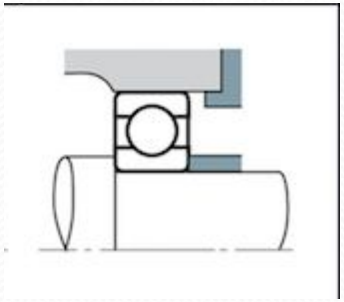
Sl. No	Sampling time (µs)	Angular position (degrees)	Magnitude of spindle data (µm)
1	0.000	33.84	2.2017
2	0.188	67.50	0.7610
3	0.375	101.34	-2.6379
4	0.563	135.00	-4.9264
5	0.750	168.84	-4.5801
6	0.938	202.50	-2.2718
7	1.125	236.34	0.3988
8	1.313	270.00	3.9409
9	1.500	303.84	8.0761
10	1.688	33.84	7.2283

Spindle for micro machine tools



Top view of Spindle

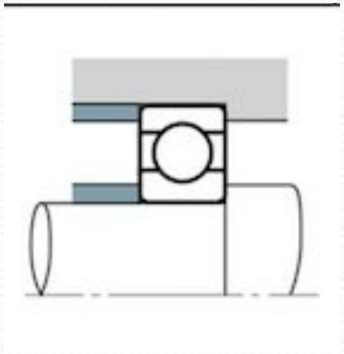
Main force – cutting force which can be resolved into 2 components (axial and radial)
Driving force acts in between the spindle bearings



Floating bearing (Rear)

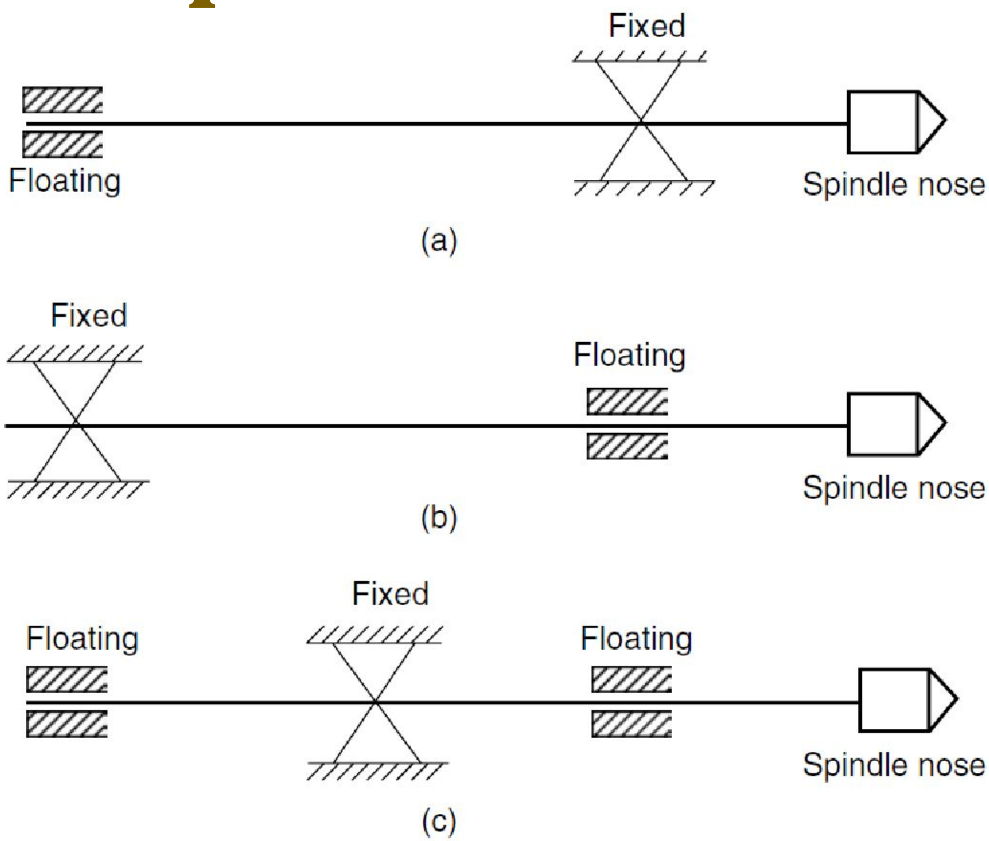
Floating bearing provides only a radial support and provides axial displacement due to differential thermal expansion of the spindle shaft and the housing

Fixed bearing (front)

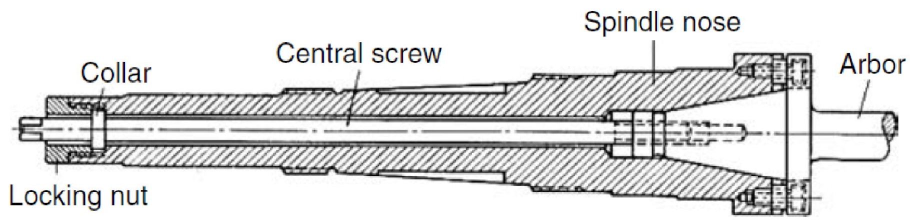


Fixed bearing does not allow axial movement of spindle under the effect of the cutting and driving forces

Spindle for micro machine tools



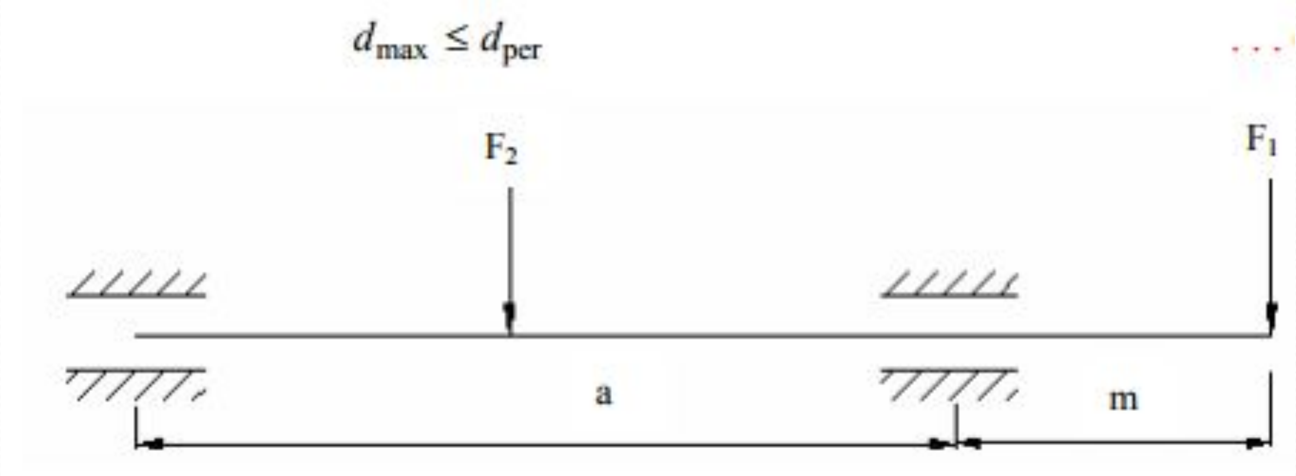
Fixed and floating bearing arrangements:
(a) fixed front,
(b) fixed rear,
(c) fixed middle



Typical milling machine Spindle

Design of spindle

(a) length ‘a’ which is acted upon by driving force F2, and
(b) cantilever of length ‘m’ acted upon by external force F1.



$$d_{max} = d1 + d2 + d3$$

The spindle is basically designed for bending stiffness which requires that maximum deflection of spindle nose should not exceed a pre specified value,

Forces:

(Forces in N-mN)

- External force, F1
- Drive force, F2

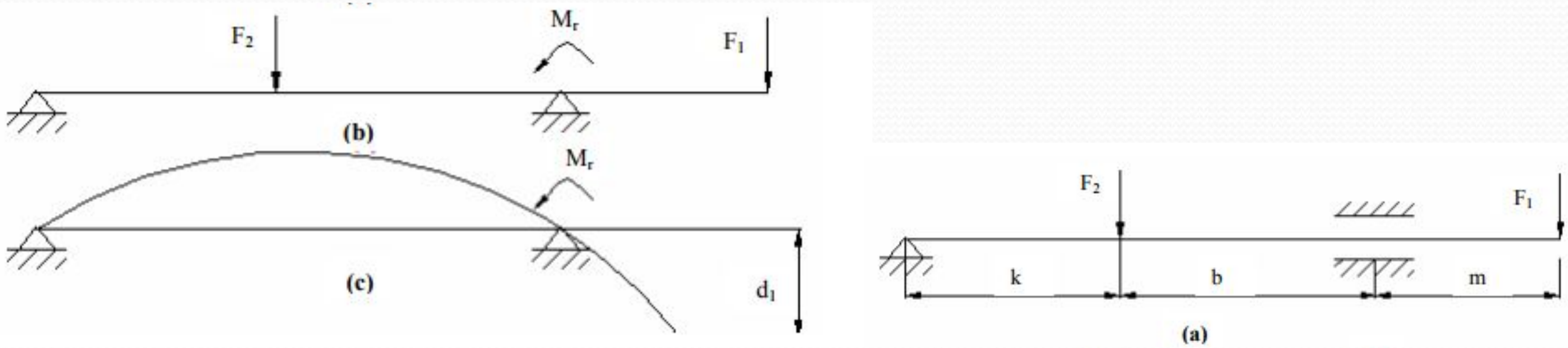
Deflection:

- d1 – bending due to F1 and F2
- d2- compliance of spindle support
- d3- compliance of tapered nose

Source : Advances in Tool Engg and Management

Design of spindle- Deflection of spindle

- Consider spindle as a beam



$$d_1 = \frac{1}{3EI_a}\left[F_1 m^2 (a+m) - 0.5 F_2 k b m \left(1 - \frac{k}{a}\right) - M_r a m\right]$$

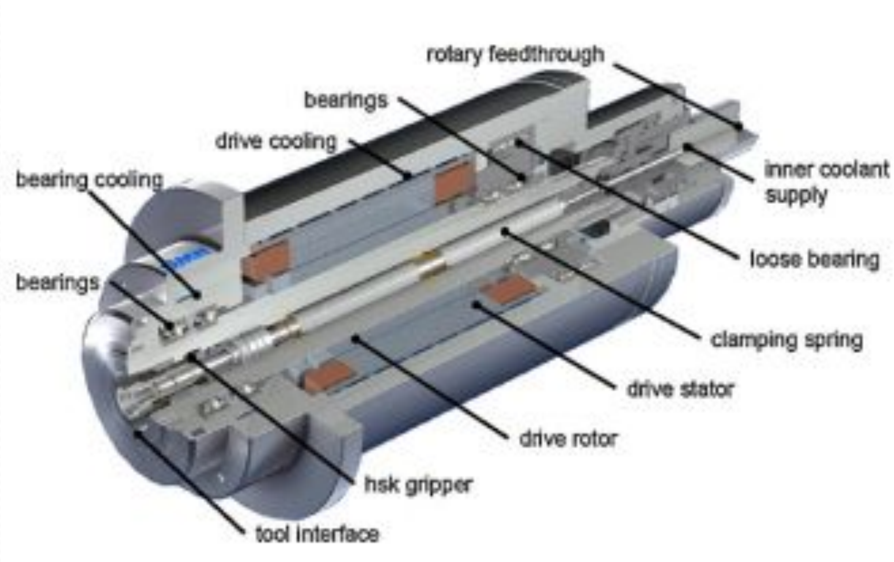
where E is Young's modulus of the spindle material.

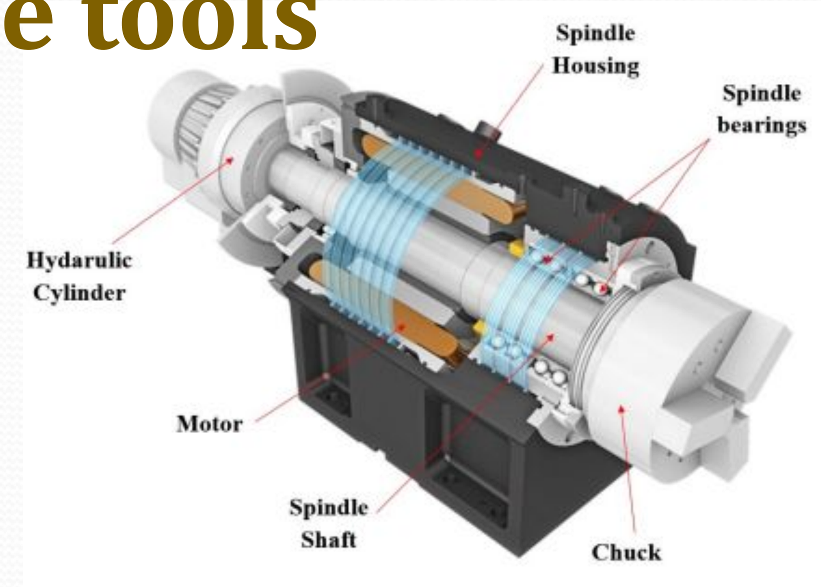
I_a is average moment of inertia of the spindle section.

Mr= Const.x M

Source : Advances in Tool Engg and Management

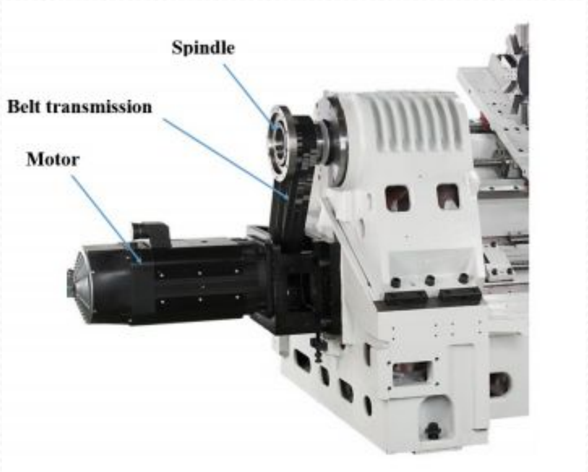
Spindle for machine tools





-Hydraulic driven

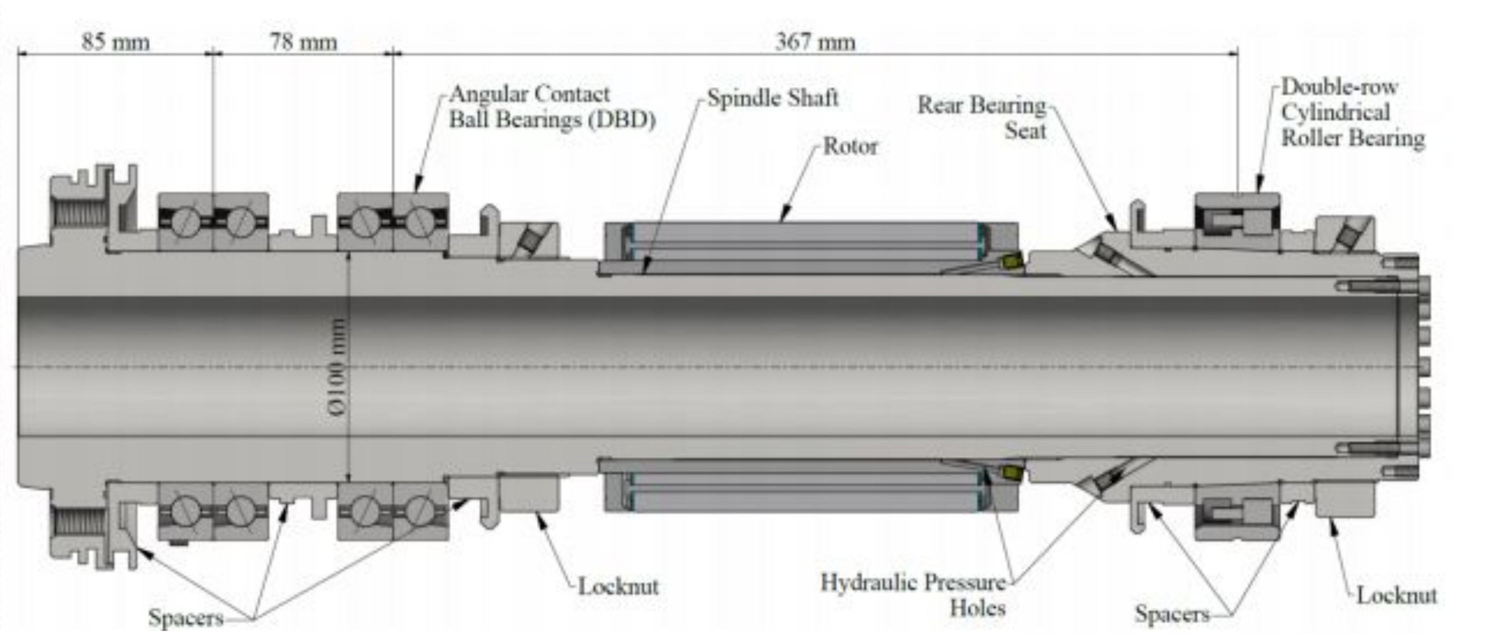
-Motor driven

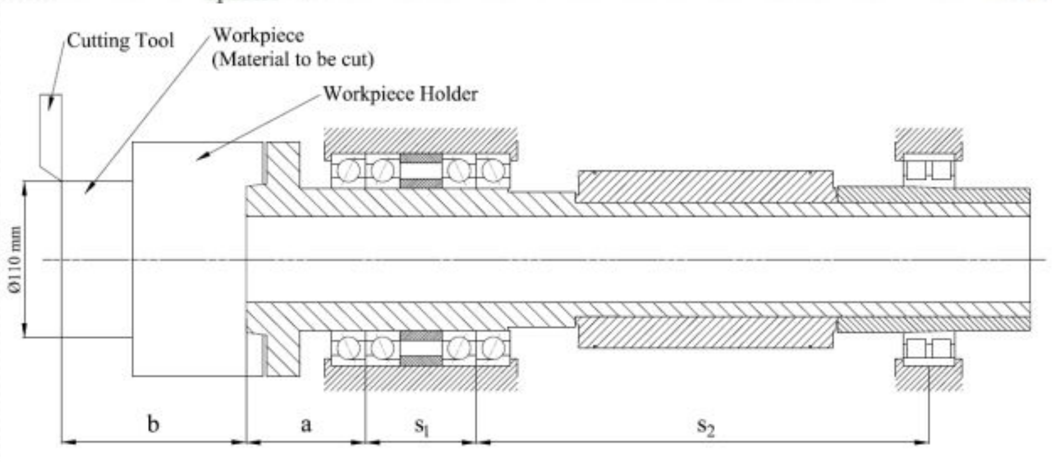


-Direct belt driven

Source : Machining technology : machine tools and operations / Helmi A. Youssef, Hassan El-Hofy.

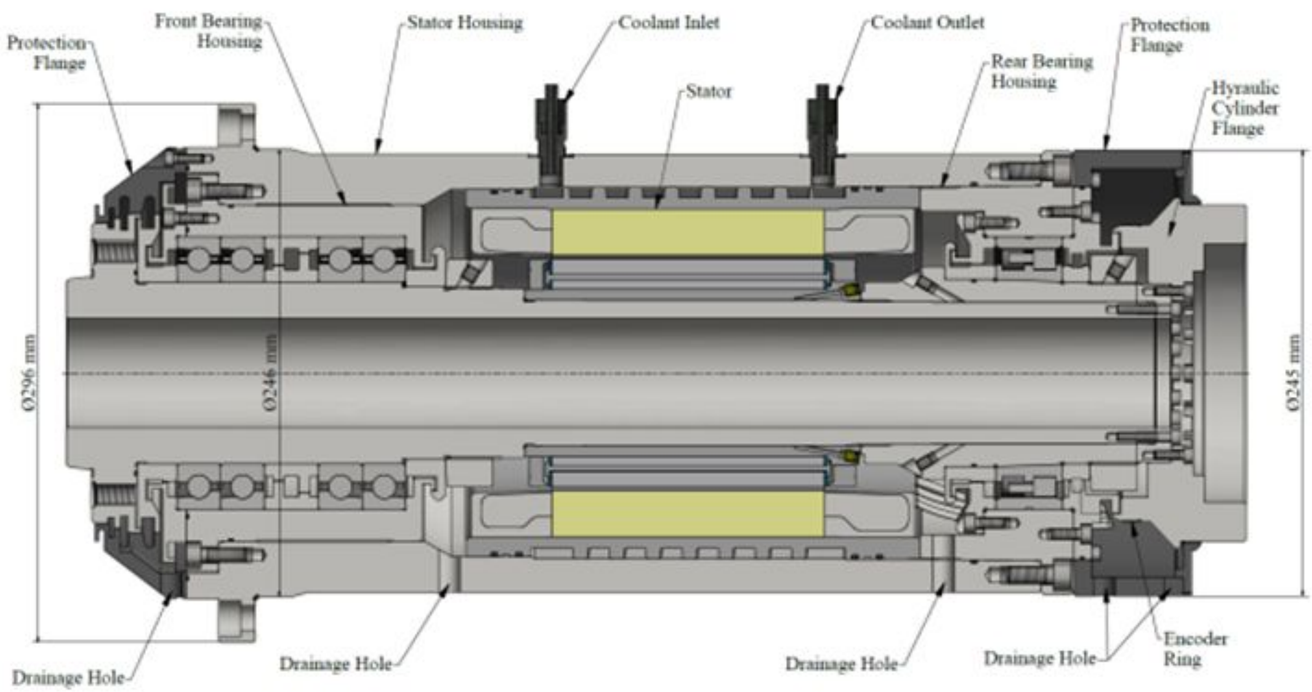
Spindle configuration of motor driven





Source : Machining technology : machine tools and operations / Helmi A. Youssef, Hassan El-Hofy.

Spindle typical configuration



Spindle with motor housing and coolant holes

3.Linear Stage

Features

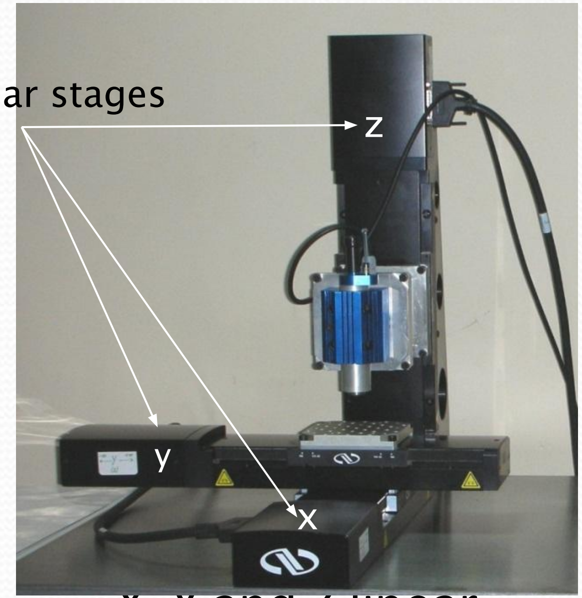
- Base Material : Extruded Aluminum
- Total travel Range 150 mm
- **Resolution 0.1 μm**
- **Maximum Speed 100 mm/s**
- On Axis Accuracy 2 μm
- Uni-directional Repeatability 0.2 μm
- Reversal Value (Hysteresis) 0.1 μm
- Weight 4.8 kg
- Optical limit switches

Linear Stage

X, Y and Z linear stages

Technical specifications:

Sl. No	Specifications	Data
1	Make	Newport Corporation, USA
2	Total travel Range	150 mm (X and Y) 100 mm (Z)
3	**Resolution**	**0.1 µm**
4	**Maximum Speed**	**100 mm/s**
5	On Axis Accuracy	2 µm
6	Uni-directional Repeatability	0.2 µm
7	Reversal Value (Hysteresis)	0.1 µm
8	Weight	4.8 kg



X, Y and Z linear stages

Alignment of Different Axes:

Right Angle Bracket

Features

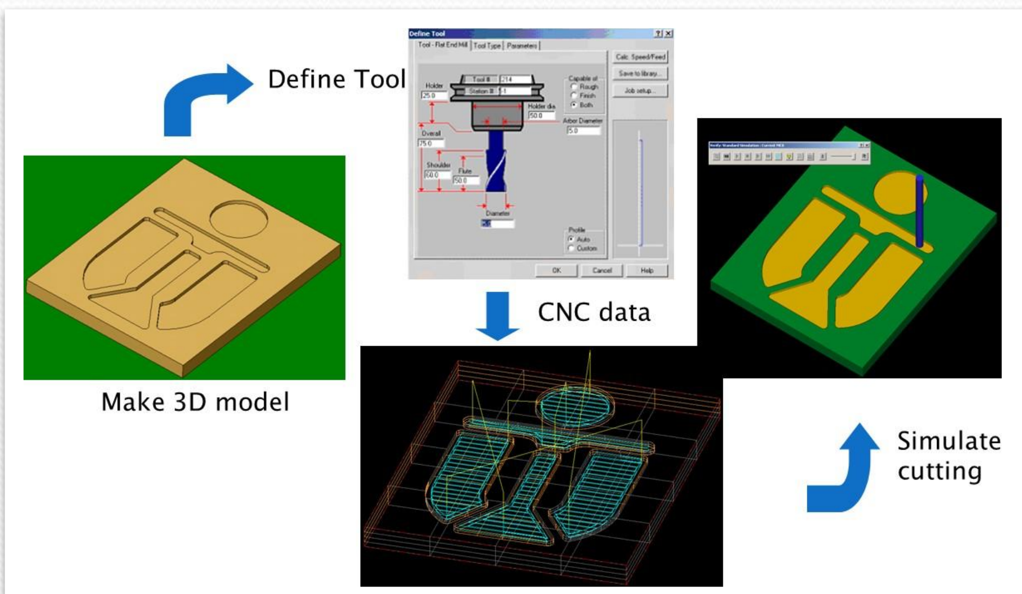
- Made of anodized aluminum
- Extra light and stiff design
- Adjustable Vertical arm for perfect alignment

Right Angle Bracket

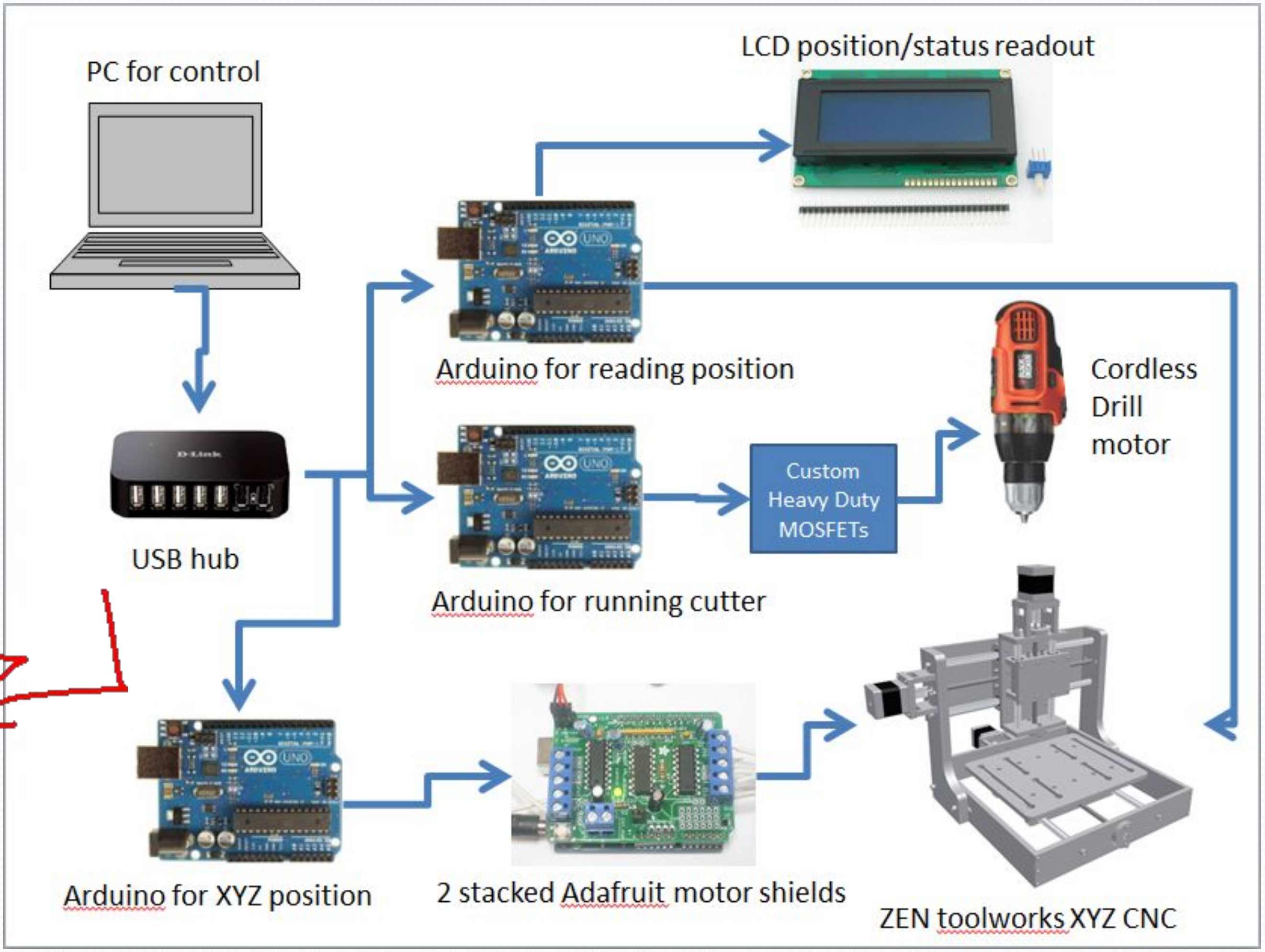
CNC Motion Controllers

Software programs can automatically generate of CNC tool path data

- CNC or Computer Numerical Controls are the operating system or brain of a CNC system.
- A controller completes the all important link between a computer system and the mechanical components of a CNC machine.
- The controller's primary task is to receive conditioned signals from a computer or indexer and interpret those signals into mechanical motion through motor output.



CNC Motion Controller Architecture



5.Motion Controller (ESP300)

Features

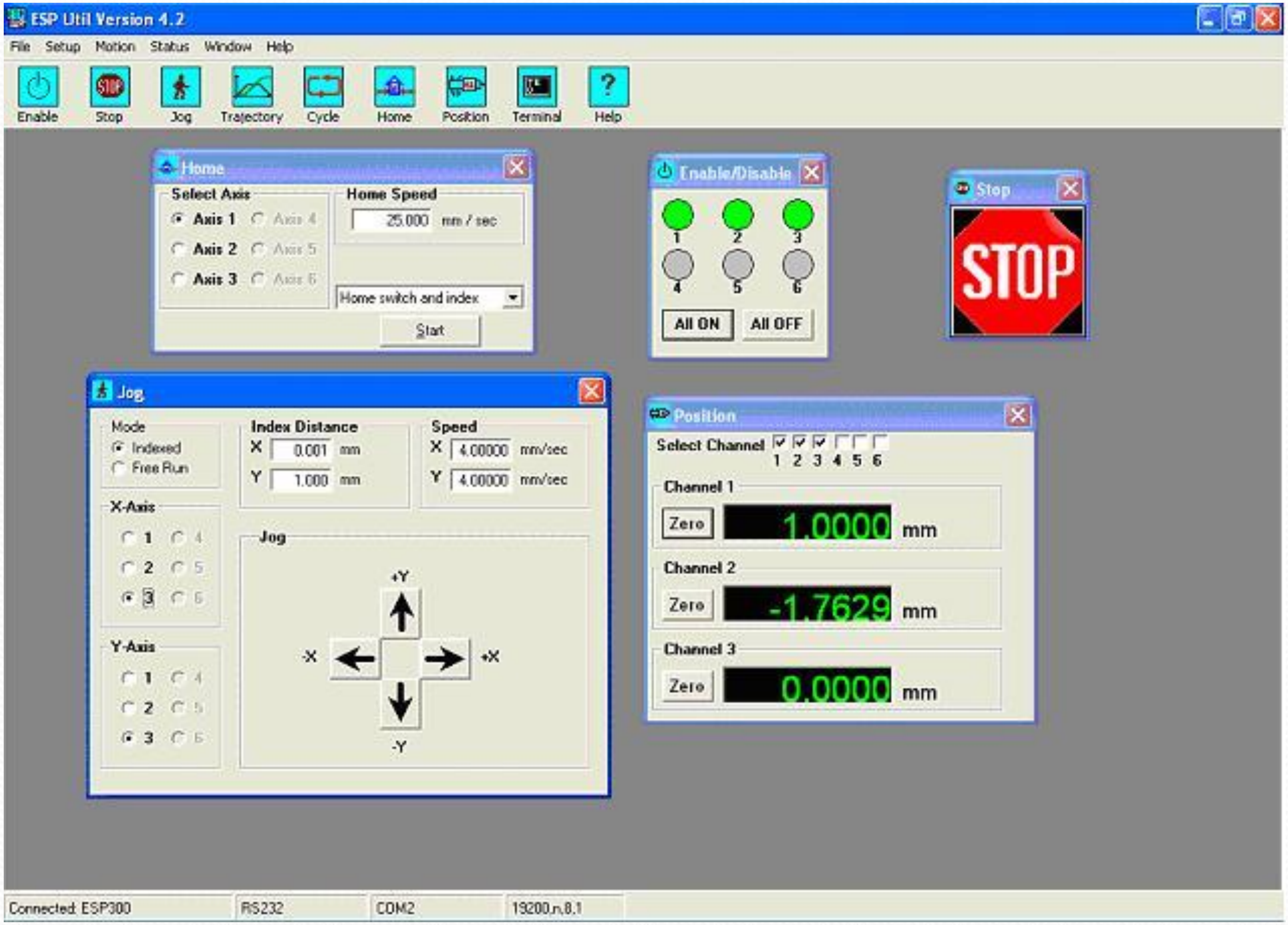
- Drive and control up to three axes of motion.
- Programmable micro-step resolution 1000x for ultra smooth low speed steeper positioning
- Synchronized circular/ linear interpolation & Continuous path contouring for complex motion profiling.
- RS232-C communications link for easy computer interfacing

Motion Controller

0.01 um

0.00000001

Motion Controller Software- Front Panel



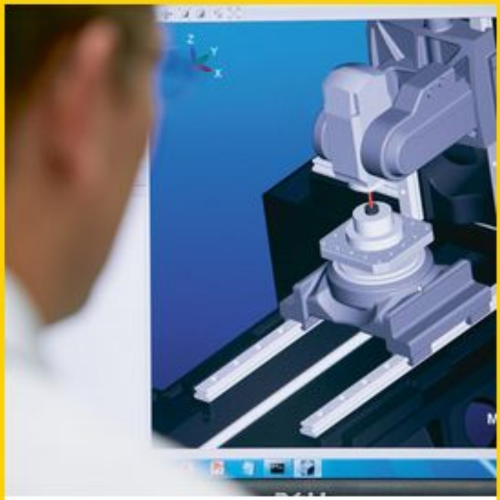
SIEMENS

Modular and scalable
In addition to a scalable NCU performance, the SINUMERIK also provides excellent modularity of the operator components.

Benchmark in Open Architecture
The open system architecture of the SINUMERIK is unique.
For example, the CNC can be optimally adjusted to the machine technology and shows a high degree of freedom in production automation.

Communicative at all levels
SINUMERIK is perfectly integrated in Totally Integrated Automation (TIA) – from the field level to the production level through to the manufacturing execution level.

FANUC



Configure your CNC system

Each FANUC CNC model can be equipped with a wide range of optional panels and screen solutions to give you a rich variety of configuration options and the ability to fully live out your machine design concepts and ideas.

Versatile field bus systems

- FANUC I/O Link *i*
- PROFINET IO
- EtherNet/IP
- FL-net
- PROFIBUS DP
- Modbus TCP
- DeviceNet

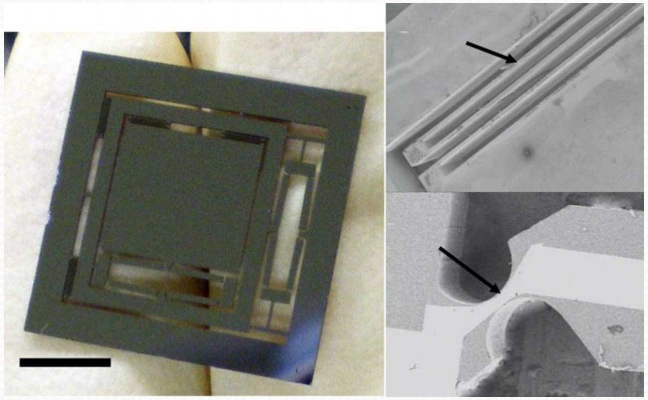
Built in PMC/PLC

Easy to learn, the integrated Programmable Machine Control (PMC) includes everything you need to operate the machine as well as external devices in up to 5 PMC pathes.

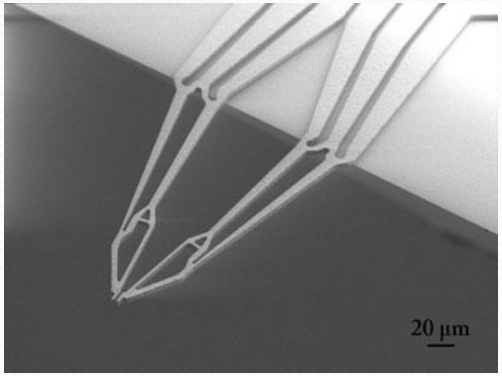
TNC -**Terminal Node Controller**

Micro Positioning and Assembly systems

- Micro/nano multi-degree freedom positioning systems
- Micro grippers and assembly devices for handling micro components.

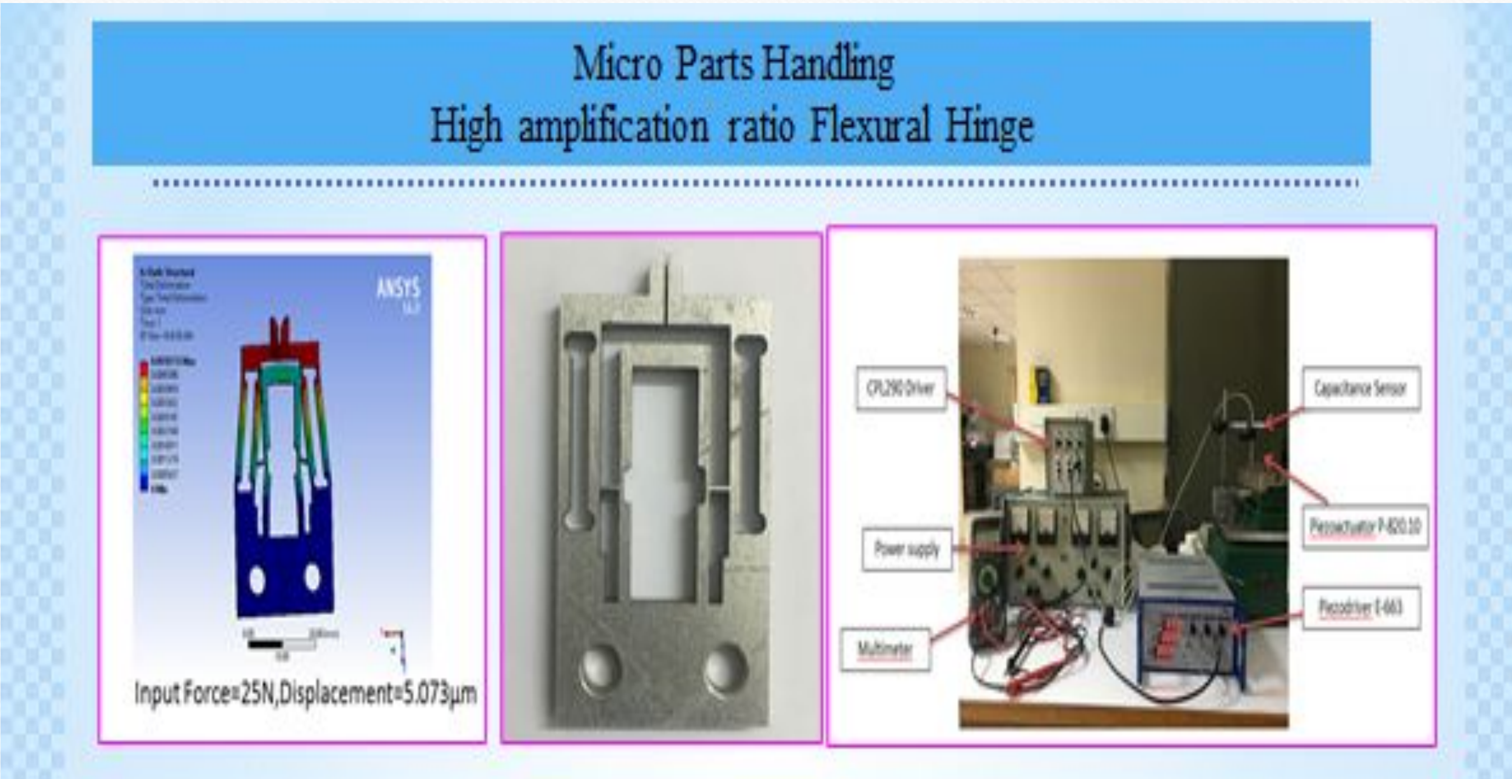


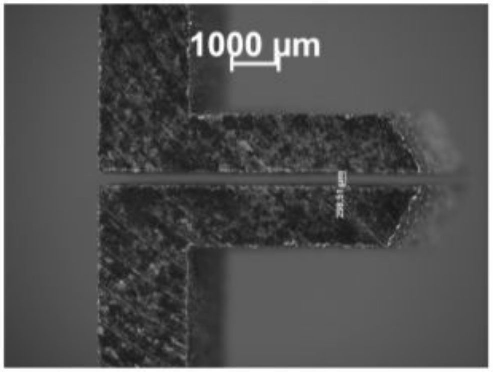
Micro Positioning System

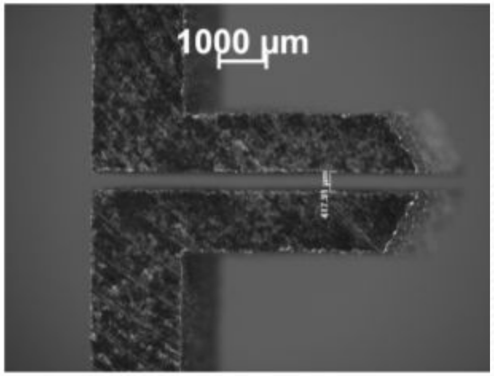


Micro Handling System

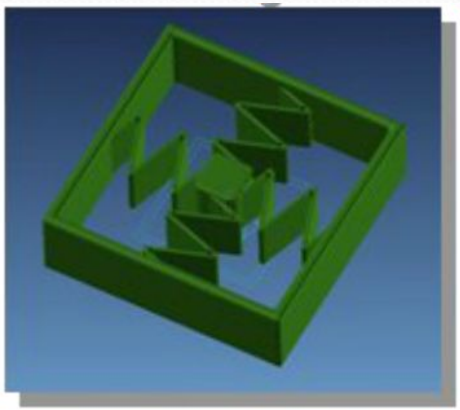
Micro Gripper

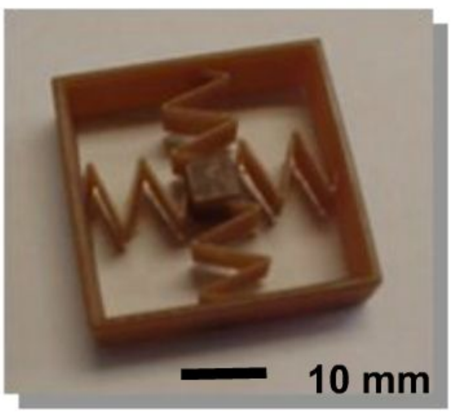




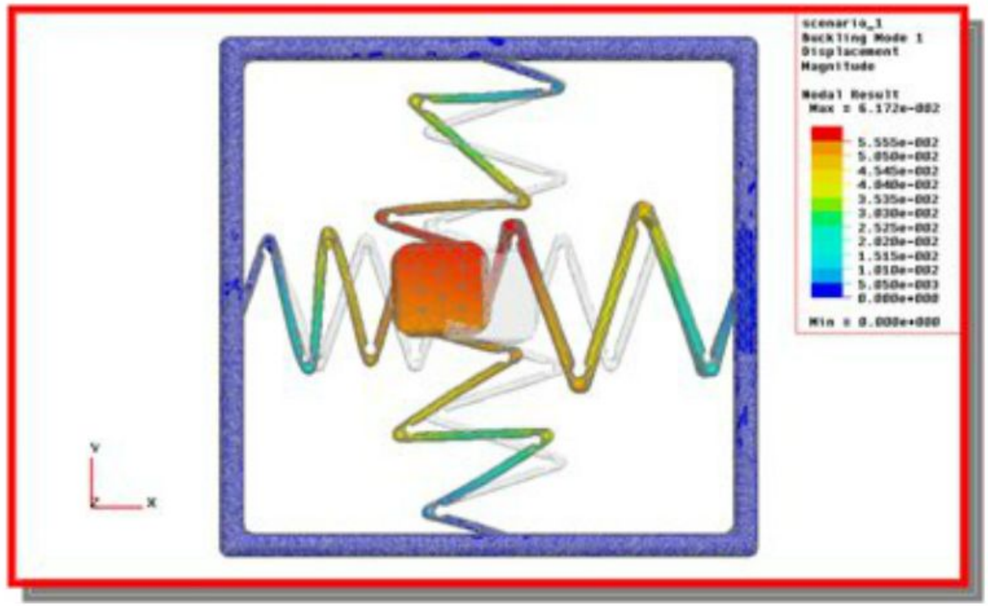


Micro/Nano Positioning Systems





Wax 3-D Prototype of SMA XY- linear stage

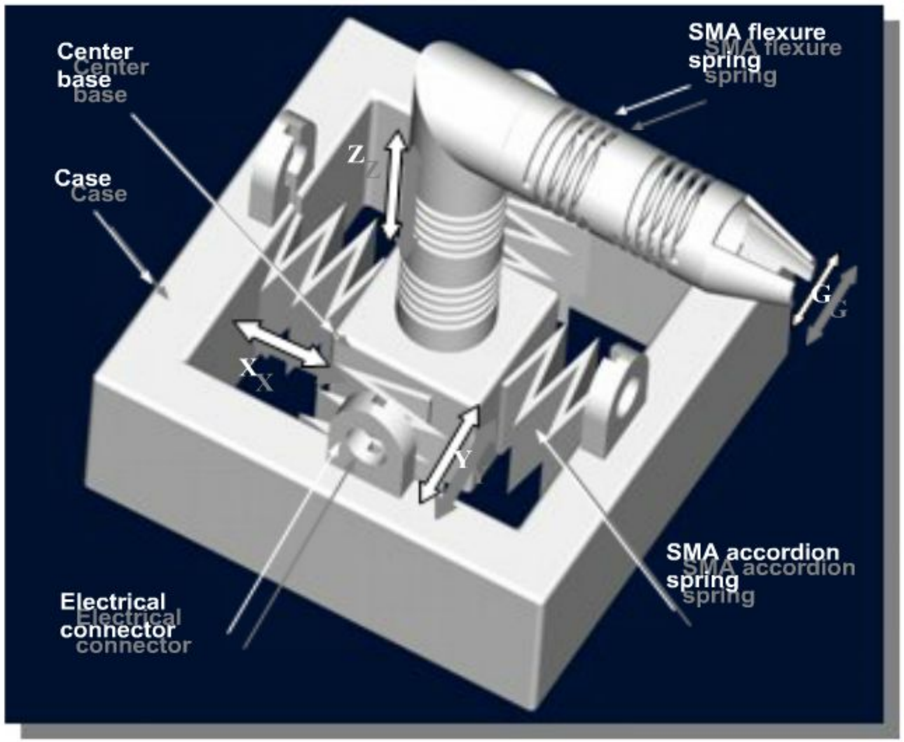


FEM analysis of the SMA XY-linear stage (no SMA effect, right spring is heated Q=10 W)

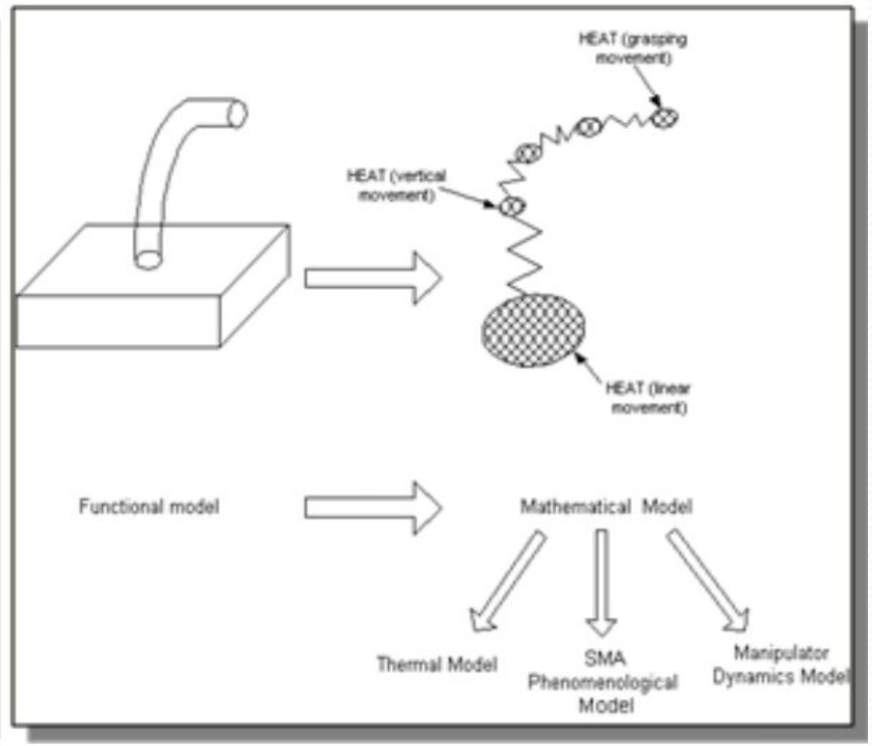
Meso/Micro/Nano Positioning systems

Conceptual Outline:

SMA – Shape Memory alloy



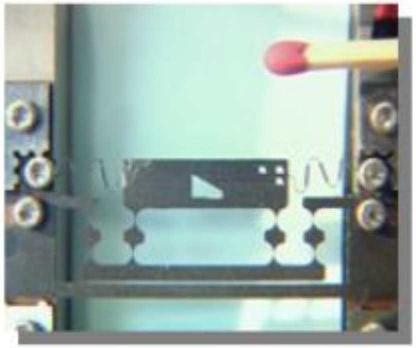
Topology of the SMA based mMM

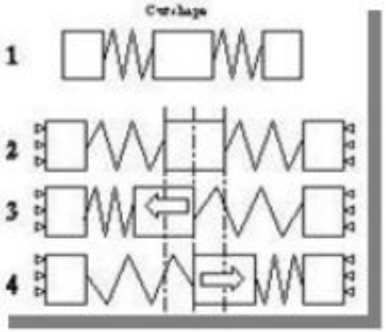


Schematics of the mathematical model of the SMA based mMM

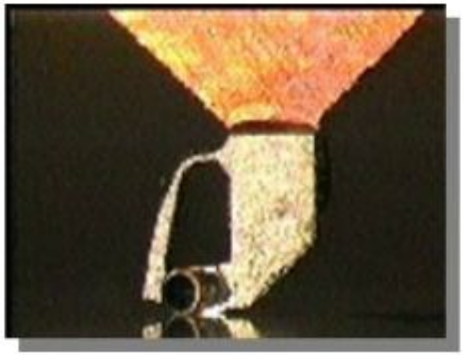
Micro/Meso Manipulator Development

Existing Elements:





SMA based linear stage design and actuation principle (Bellouard et al., 2001)

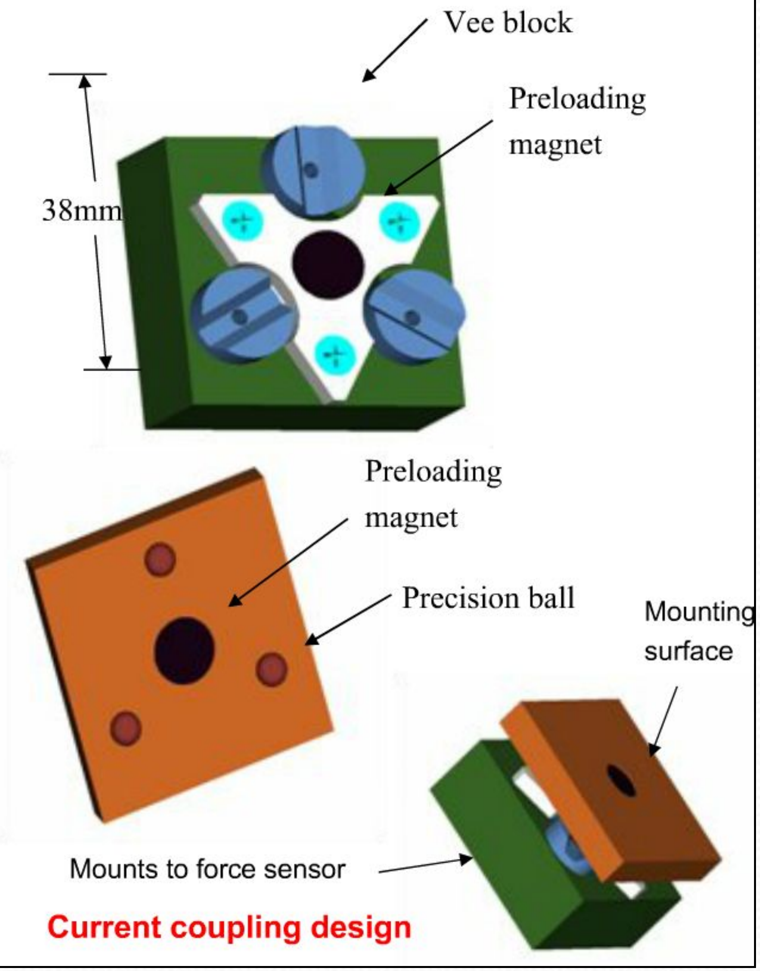


Monolithic microholder and microgripper made of SMA (Ni-Ti-Nb) (Bellouard et al., 2001)

Nickel- Titanium and Niobium

Work Holding Devices

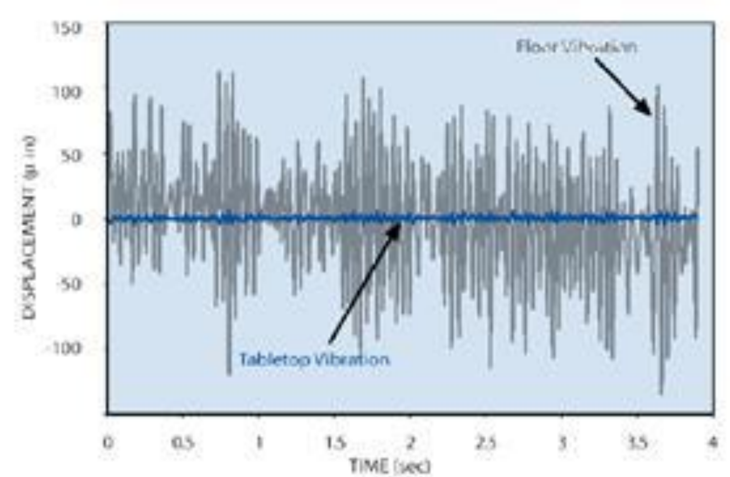
- **Workpiece holder design**
  - *Individual parts mounted to larger workpiece holders*
  - *Overall size: 38 x 38 x 27mm*
  - *Projected repeatability: ~0.5µm*
  - *Permanent magnet preload mechanism*
  - *Coupling base also serves as force sensor preloading plate*
- **Challenges**
  - *Size constraint*
  - *Preloading mechanism*
    - *Permanent magnet*
    - *Vacuum*



Current coupling design

Other Components

Vibration isolation/Anti-vibration table



Isolation of vibration

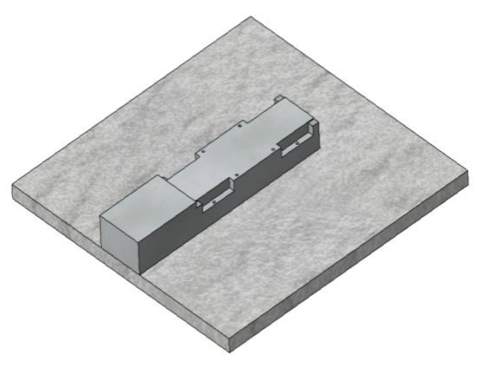
Measurement of Cutting forces

Micro Force Dynamometer

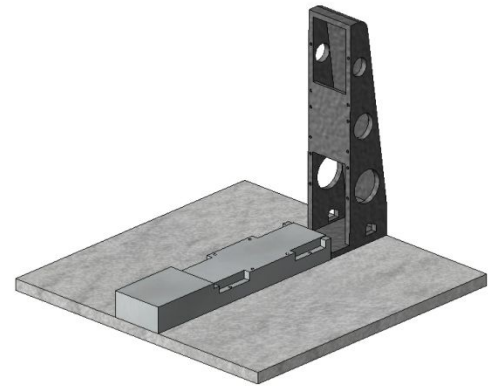
Minimum force measured: 0.002 Newton

Torque and cutting force forces in machining

Assembling of Miniaturized (Micro) Machine



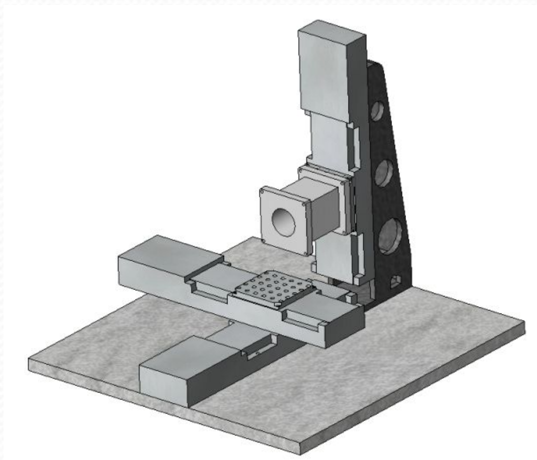
1. Linear stage ‘X’ was first assembled to the mild steel base plate using M6 align screws.



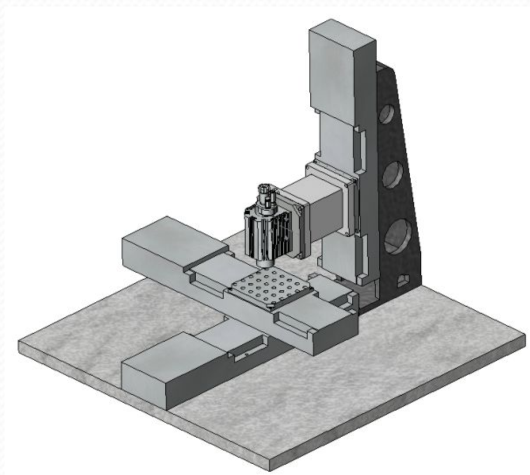
2. Right angle bracket was assembled to the mild steel base plate at right angle to the linear stage ‘X’ axis and at the its rear end.

3. On to the right angle bracket, linear stage ‘Z’ was assembled in line with the bracket at height of 58 mm from base plate.

4. Linear stage ‘Y’ was assembled on to the linear stage ‘X’ at right angle to its axis using M6 align screws.

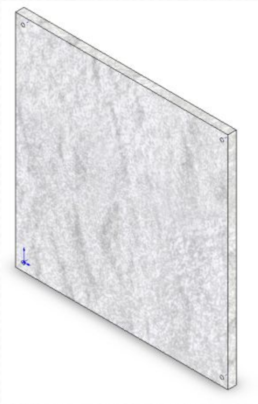


5. To the linear stage ‘Z’, supporting bracket was assembled. On to the supporting bracket, spindle fixture was assembled.

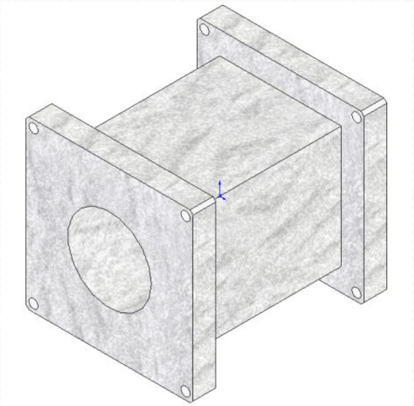


6. Spindle + Spindle bracket assembly was assembled to the spindle bracket fixture and finally to the supporting bracket to complete the setup.

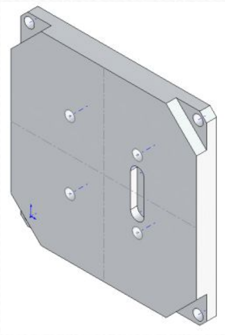
Components manufactured:



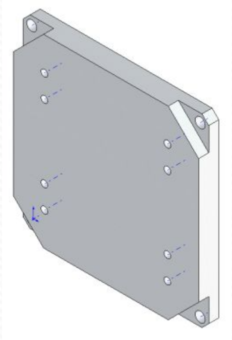
Base Plate
Material: Mild steel, 1 No.



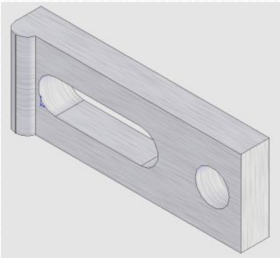
Supporting Bracket
Material: Aluminum, 1 No.



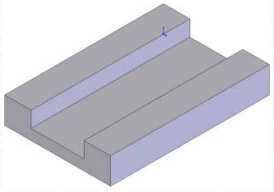
Fixture - Spindle Bracket
Material: Aluminum, 1 No.



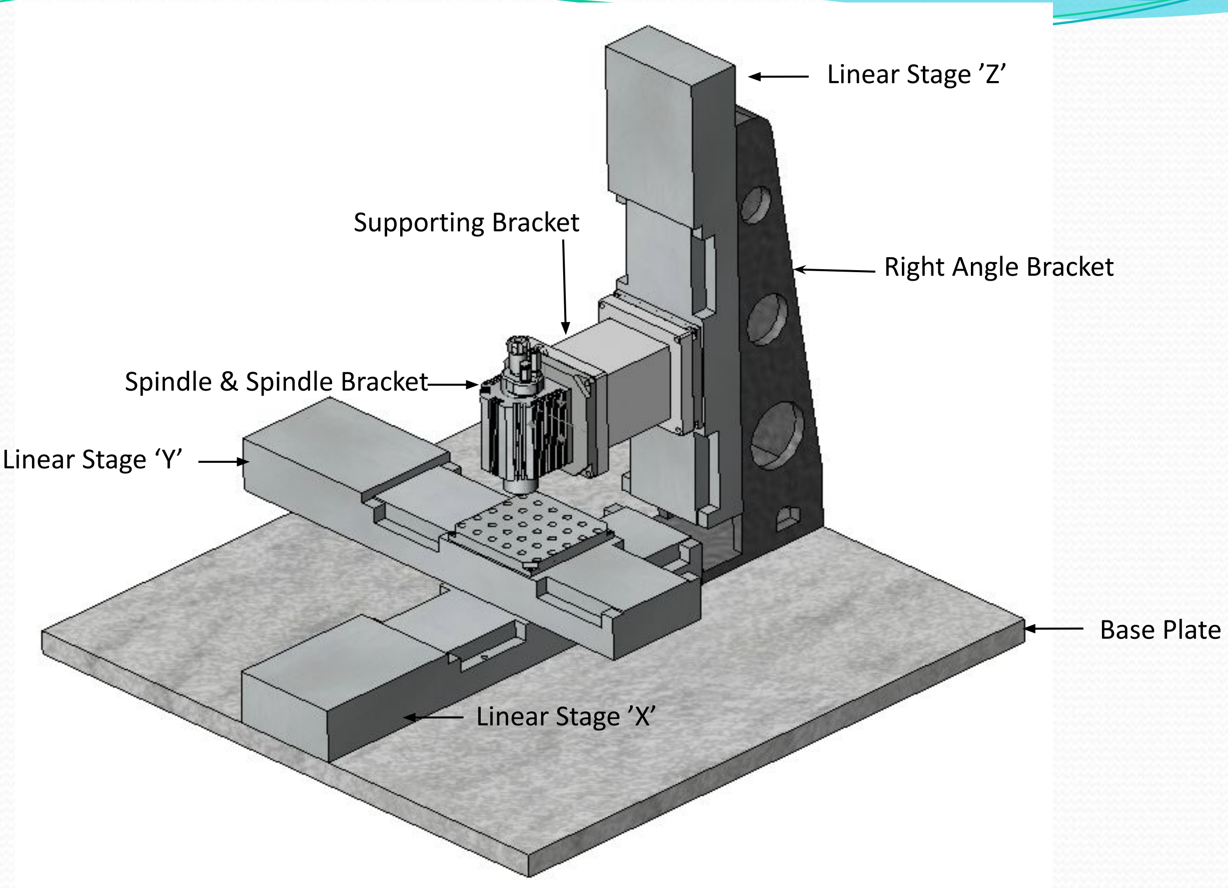
Fixture - Dynamometer
Material: Aluminum, 1 No.



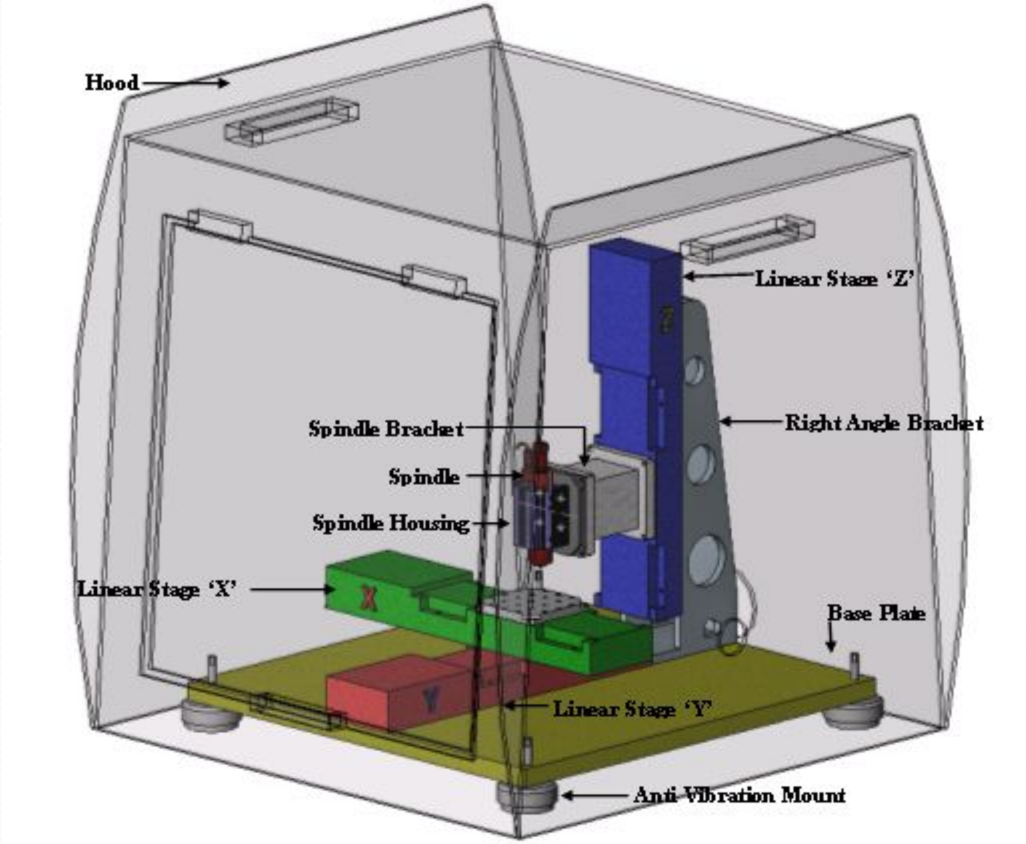
Work Holding Clamp
Material: Aluminum, 4 No.



Work-piece mounting fixture
Material: Aluminum, 2 No.

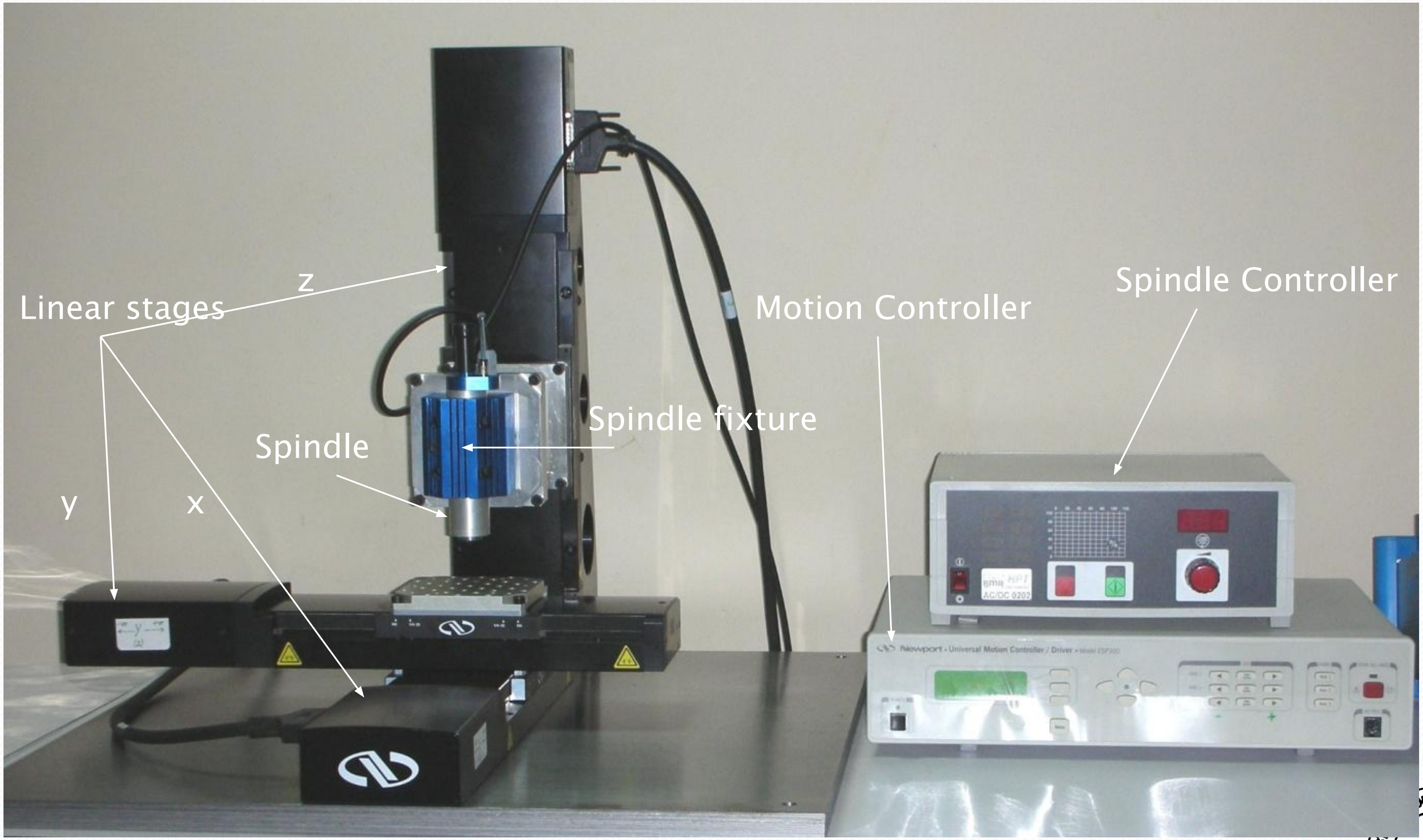


Assembly of the Micro Machining Setup



Complete Assembly of the Micro Machining Setup with Enclosure

Close up view of the set up



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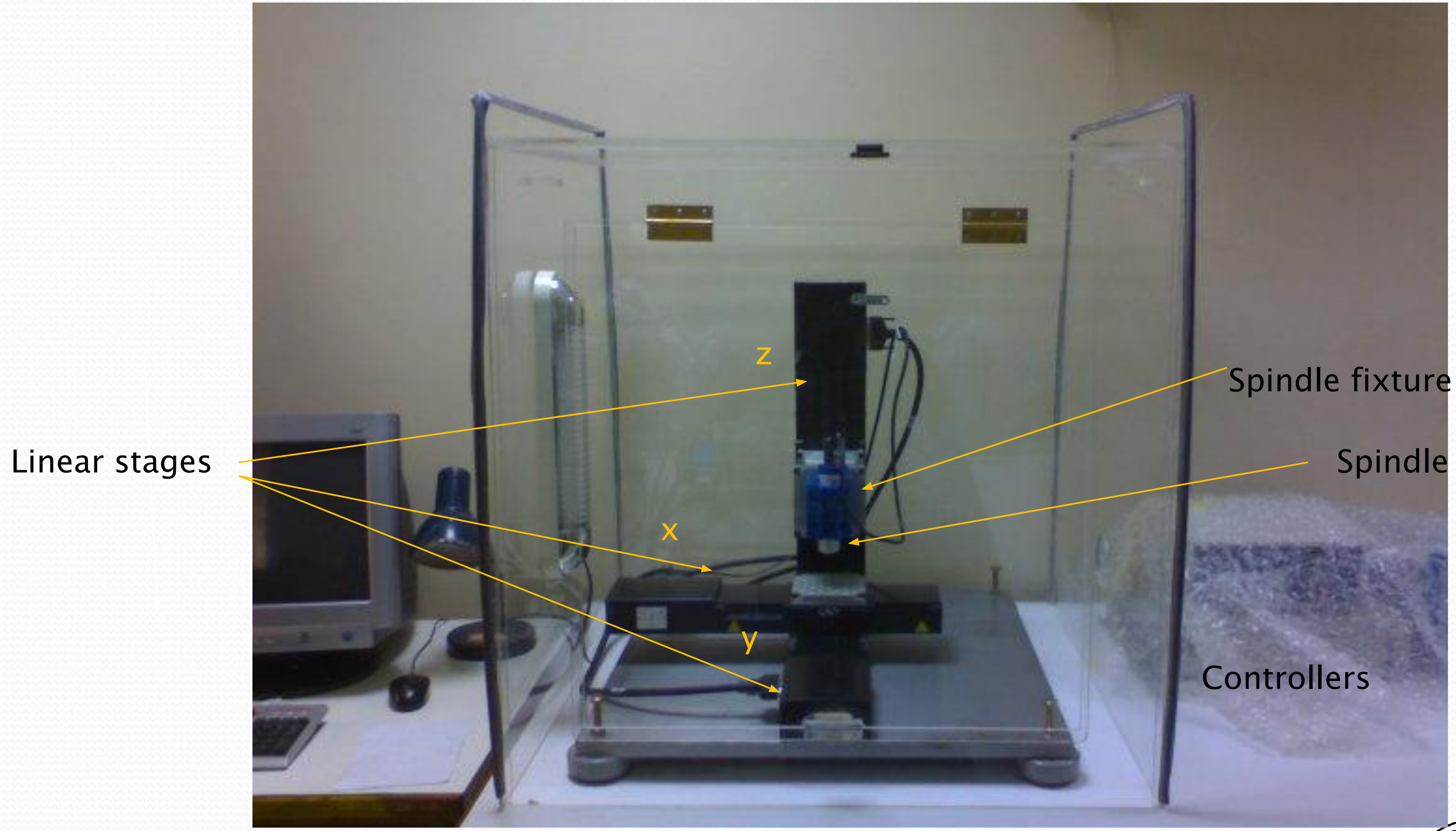
Set up with the enclosure



Salient Features of the project

- An experimental setup for micro machining has been set up which can be used for machining micro features in metals and composites.
- The experimental studies conducted on composites has given insight in to the cutting forces and torque that will be produced during machining.
- These experiments can be extended for other type of materials to perceive the feasibility of producing micro features using mechanical micro machining process
- Students and scholars have been introduced to micro machining concepts, who have potential to take up this area in their future research

Conventional and micromachining

- In general, most macro-domain (or conventional) approaches are not applicable in the micro-domain.

- With such small parts and feature sizes, accuracy takes on a completely new meaning in micromachining.

Difference between Micro & Macro machining

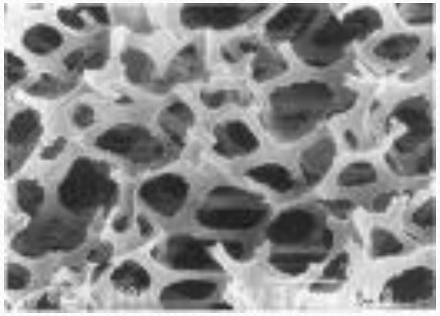
Sl. No	Parameters	Macro machining	Micro Machining
1	Cutting Force	Higher	Lower
2	Cutting Tool 1. Cutting tool materials 2. Cost 3. Quality	 Ordinary Lower Lower	 Advanced Higher Higher
3.	Chip formation Mechanism. 1.Feed/tooth radius ratio	 Higher(>1)	 Lower(<1)

Difference between Micro & Macro machining

Sl. No	Parameters	Macro machining	Micro Machining
4.	Instability Chatter 1. Vibration 2. Feed rate 3. Higher Speed	 Less No effects on stability No Effects produced.	 High It affects the stability Centrifugal and gyroscopic effects produced.
5.	Run out (or) Unbalance	Less	High

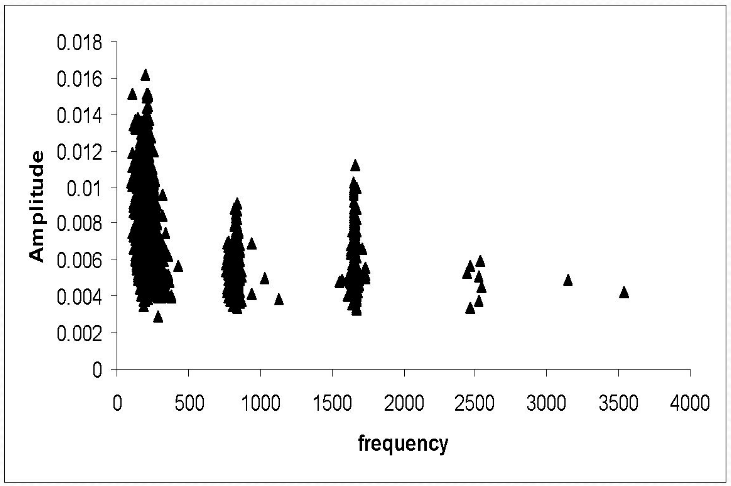
Composite Materials

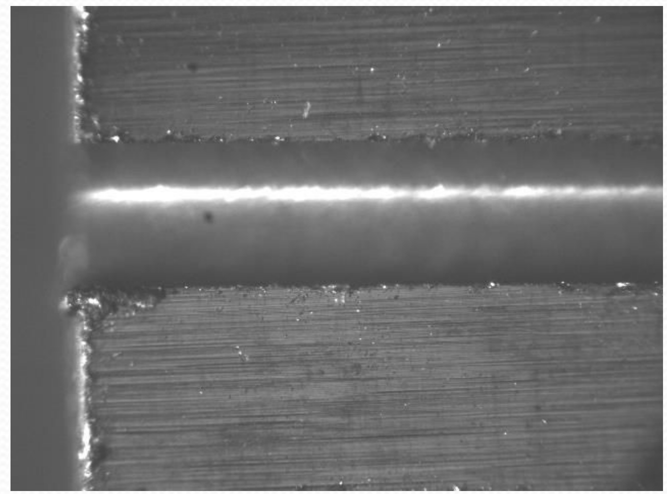
- Composite materials are one to play a significant role in current and future aerospace components.
- Attractive to aviation and aerospace applications,
- Higher strength and stiffness-to- density ratios and superior physical properties.
- Higher strength-to-weight ratio, and design and manufacturing flexibility.



Composite Material

Micro End Mill Of Diameter 0.4 mm, Channels In Mild Steel Work-piece

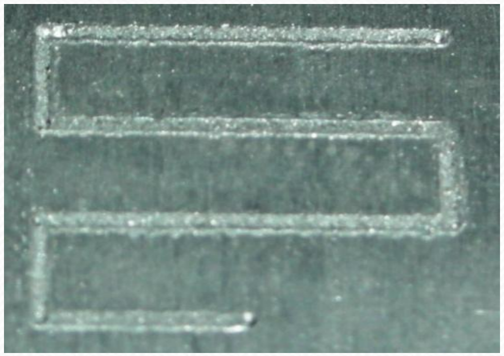




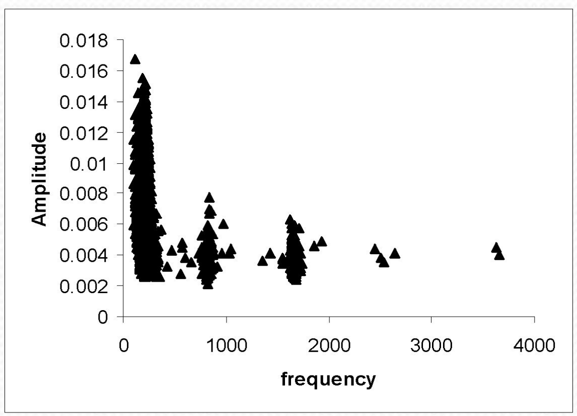
(c) Speed 50000 rpm, Feed 0.05 mm/sec

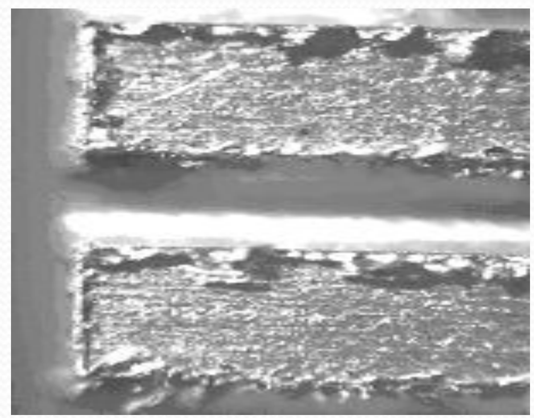
Frequency domain plot and surface of micro channels milled on Mild Steel workpiece

Micro End Mill Of Diameter 0.4 mm, Channels In Aluminum Work-piece specimen



Micro Channels (0.4 x 0.2 mm) in aluminum work-piece





(c) Speed 50000 rpm, Feed 0.05 mm/sec

Frequency domain plot and surface of micro channels milled on Aluminium workpiece

Details of staff in position (indicating change, if any):

Sl.No	Designation of post(s) with pay as sanctioned	Name(s)	Qualification and experience
1	Project Associate	V. S. Sankar	B.E (MECH) & 2 YEARS

http://www.powershow.com/view/1c46c6-Mjk1O/MICROMACHINING_RESEARCH_WITH_INDUSTRIAL_APPLICATIONS_powerpoint_ppt_presentation

v. Classification of sensors

Form of signal	Measurands
Thermal	Temperature, heat, heat flow, entropy, heat capacity etc.
Radiation	Gamma rays, X-rays, ultra-violet, visible and infrared light, micro-waves, radio waves etc.
Mechanical	Displacement, velocity, acceleration, force, pressure, mass flow, acoustic wavelength and amplitude etc.
Magnetic	Magnetic field, flux, magnetic moment, magnetisation, magnetic permeability etc.
Chemical	Humidity, pH level and ions, gas concentration, toxic and flammable materials, concentration of vapours and odours, pollutants etc.
Biological	Sugars, proteins, hormones, antigens etc.

- classification is based on the function that the sensor performs
  - pressure
  - position
  - Acceleration
  - Temperature
  - Force etc.

vi. Contact versus Non-contact

- **Contact sensor:** There is physical contact between the sensor an the parameter it measures
- **Non-contact sensor:** : Also called proximity sensors - Proximity indicates that the object is near, equired.

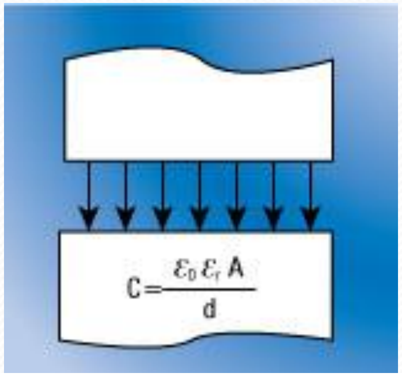
Non-contact Speed Sensor
a Doppler radar sensor

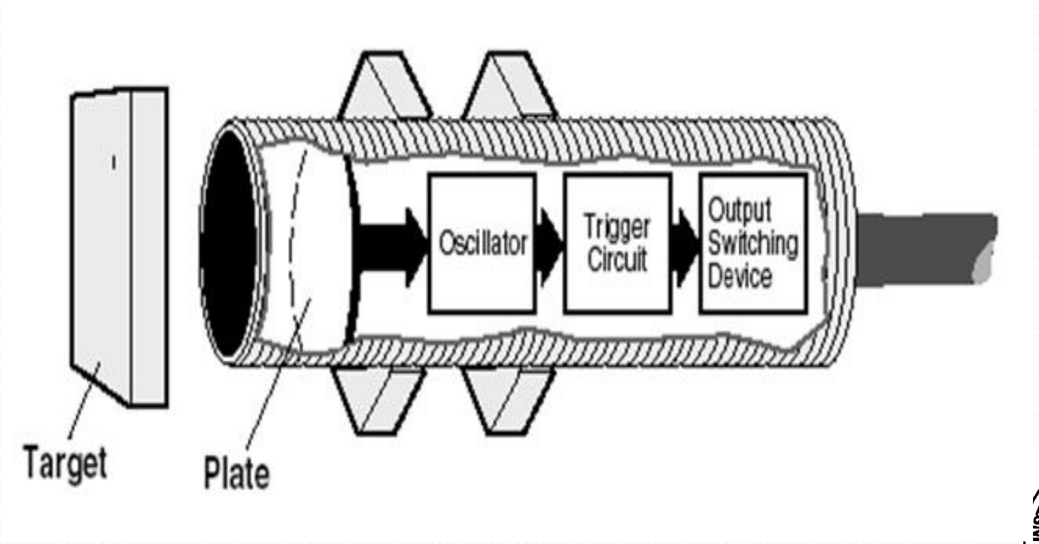
Non-contact infrared thermometer for use with Arduino, or any microcontroller.

A Doppler radar is a specialized radar that uses the Doppler effect to produce velocity data about objects at a distance. It does this by bouncing a microwave signal off a desired target and analyzing how the object's motion has altered the frequency of the returned signal.

vii. Capacitance Sensors

Working Principle



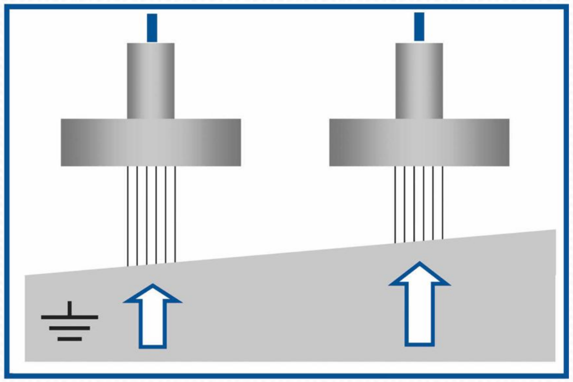


Capacitance Sensor Measurement System…..

- Probe that uses changes in capacitance to sense changes in distance to the target
- Driver electronics to convert these changes in capacitance into voltage changes
- Data Acquisition Device to indicate and/or record the resulting voltage change

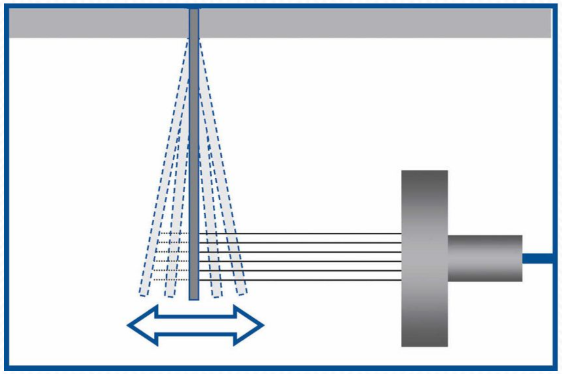
Capacitance sensor Measurement Applications…..

Position Measurement/Sensing



The quantity to be measured is the change of capacitance between the surface of the sensor head and the target surface using a homogenous electric field.

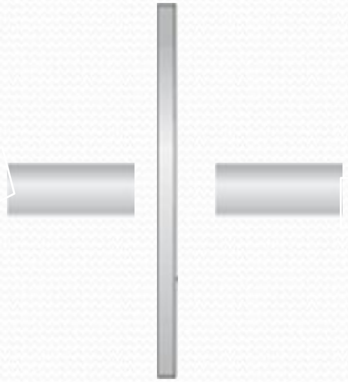
Dynamic motion sensing



measurement with excellent resolution of vibrations and oscillations.

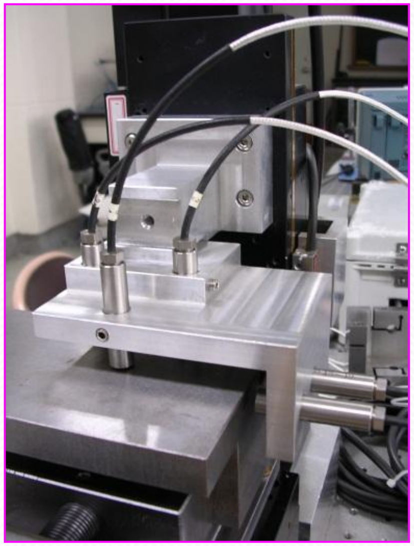
Capacitance sensor Measurement Applications…..

Thickness Measurement



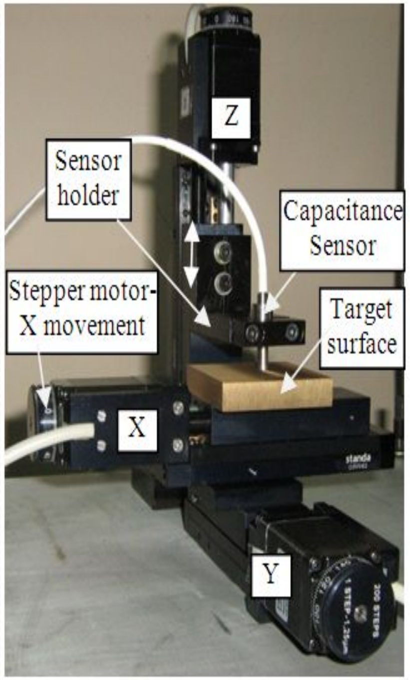
Measurement, Evaluation and Compensation of Geometric Errors in Miniaturized Machine Tool using capacitance sensor

Miniaturized Vertical Machine Tool



Error measurement system

Set-up for measurement of Surface Profile using capacitance sensor



XYZ linear stage

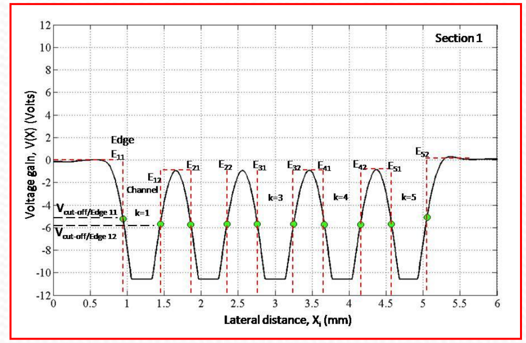
Travel range: 50 mm

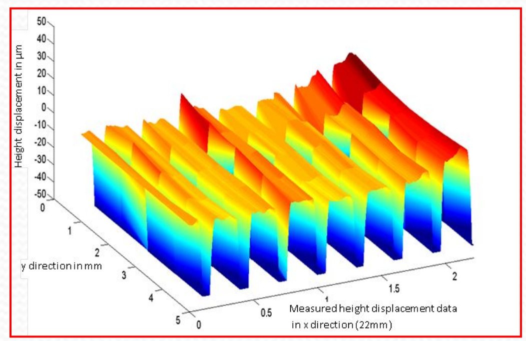
Resolution: 0.156 µm (1/8 step)

Min. incremental speed:0.1mm/s

Data capturing device

- NI PCI 6250 DAQ system



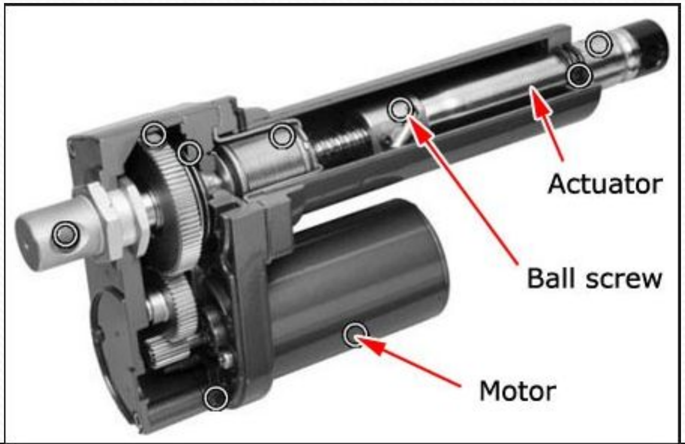


2D and 3D profiles measured using the set-up

2. Actuators

Hardware devices that convert a controller command signal into a change in a physical parameter

1. The change is usually mechanical (e.g., position or velocity)
2. An actuator is a **transducer** because it changes one type of physical quantity into some alternative form
3. An actuator is usually activated by a low-level command signal, so an amplifier may be required to provide sufficient power to drive the actuator



i. Types of Actuators

A. Electric
   a. Electric motors
   b. Solenoids

B. Hydraulic

   Use hydraulic fluid to amplify the controller command signal

C. Pneumatic

   Use compressed air as the driving force





a. Electric Motors

1. DC motors

   Common type: DC servomotor

2. AC motors
   1. Synchronous motors
   2. Induction motors
3. Stepper motors
4. Linear motors

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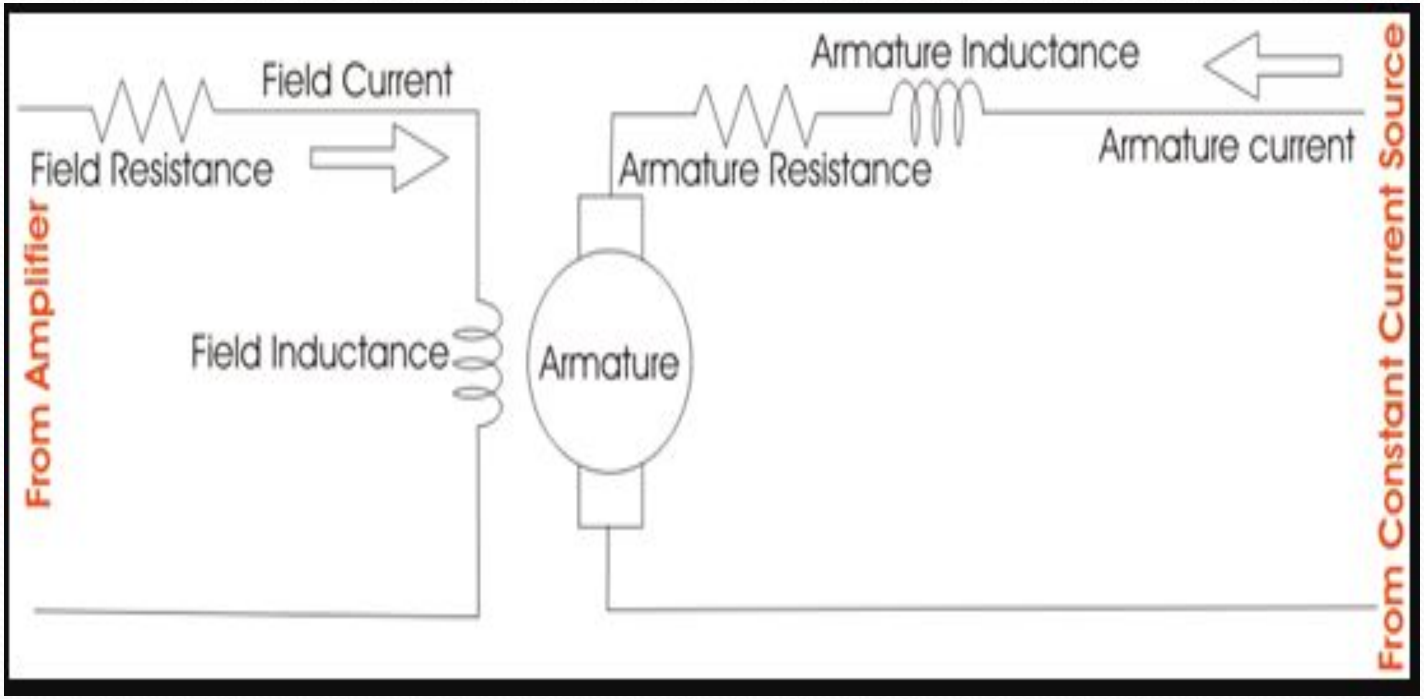
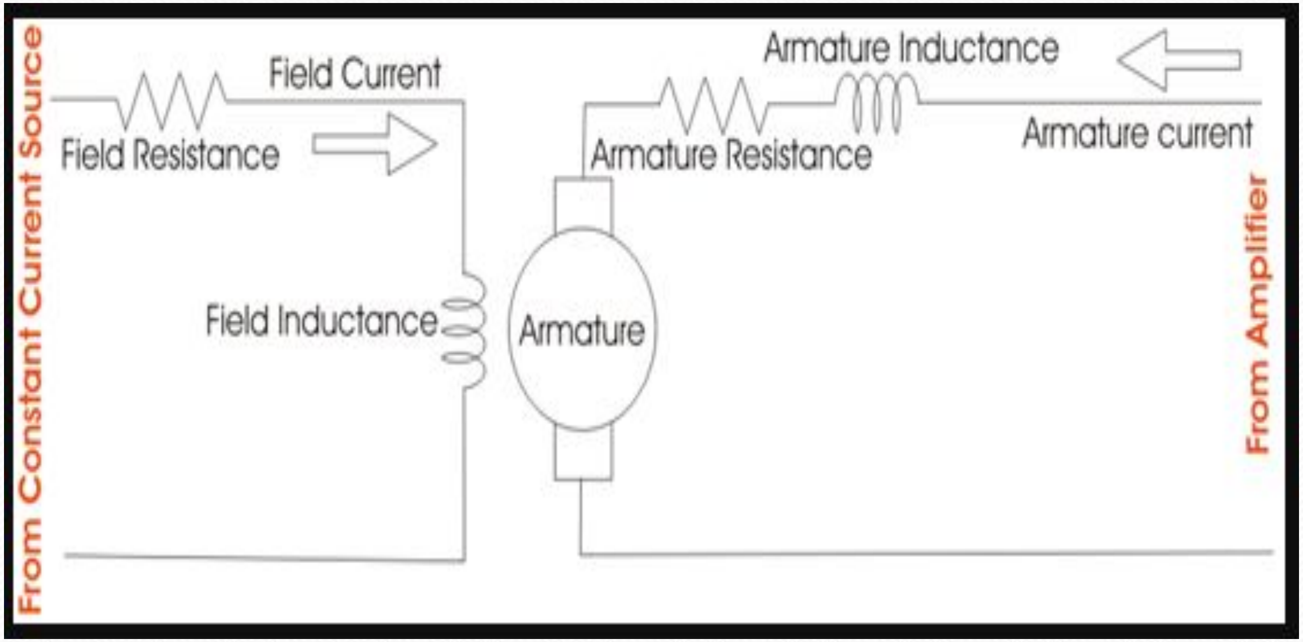
1. DC Servomotor: Construction…

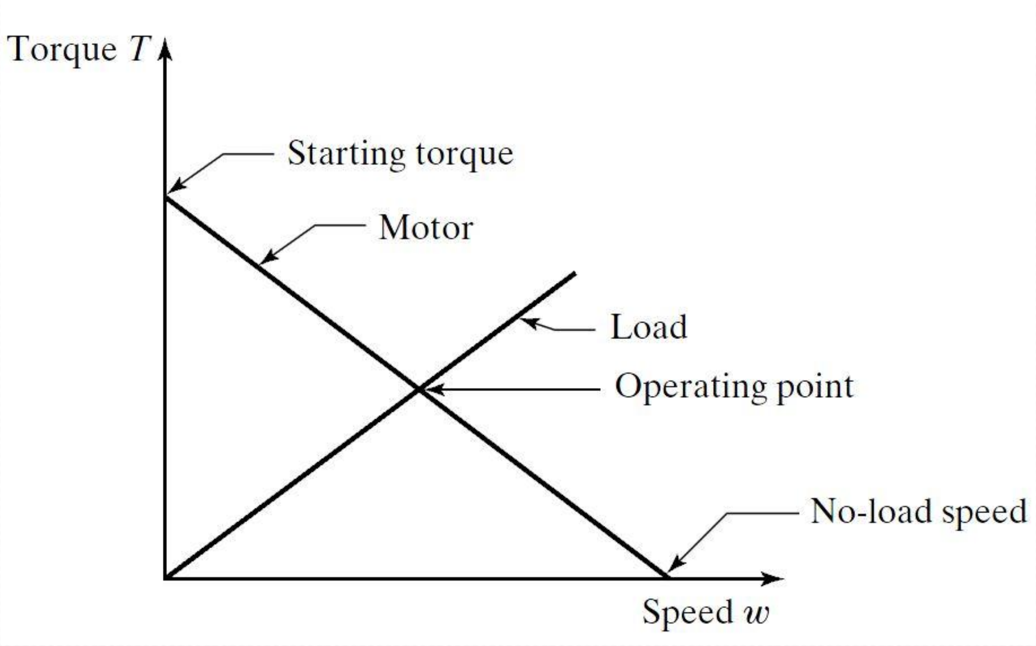
Field controlled DC Servomotor….



Armature controlled DC servomotor….



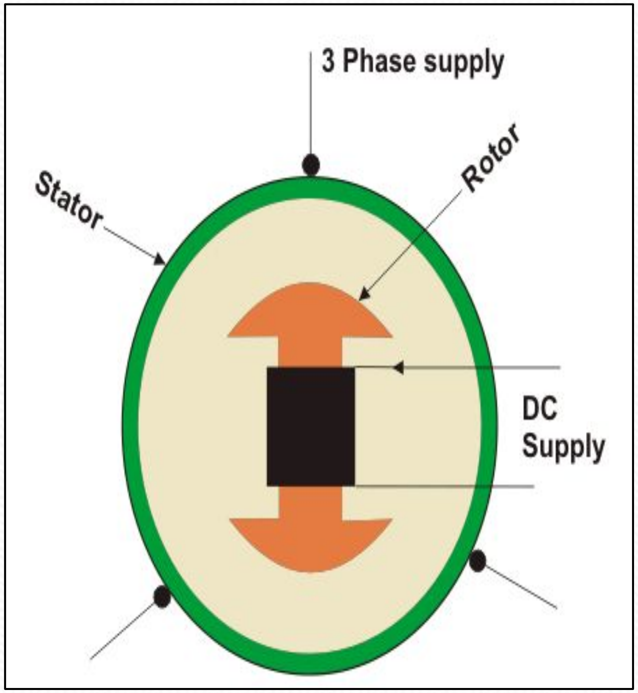
Torque-Speed Curve of a DC Servomotor and Load Torque Plot…



The torque developed by the motor and the torque required by the load must be balanced.

2. AC Motor : Synchronous Motor….

A synchronous electric motor is an AC motor in which, at steady state, the rotation of the shaft is **synchronized with the frequency of the supply current**; the rotation period is exactly equal to an integral number of AC cycles.



Synchronous motor finds application where operating speed is less (around 500 rpm) and high power is required

- Synchronous motor is a motor that operates at synchronous speed,

i.e. **speed of the rotor is equal to the stator speed of the motor.**

It follows the relation $N = N_S = 120f/P$,

where N= The Synchronous Speed (in RPM – i.e. Rotations Per Minute)

f = The Supply Frequency (in Hz)

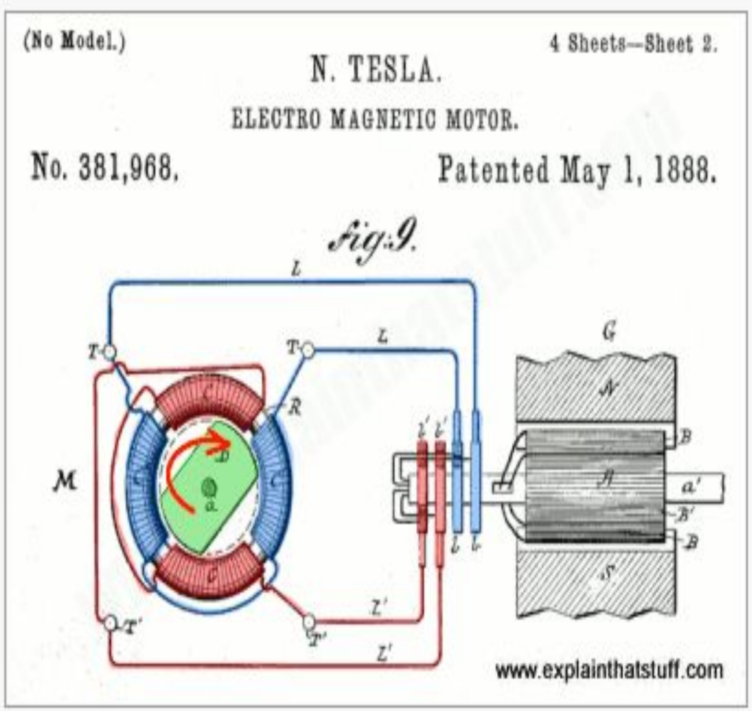
p = The number of poles

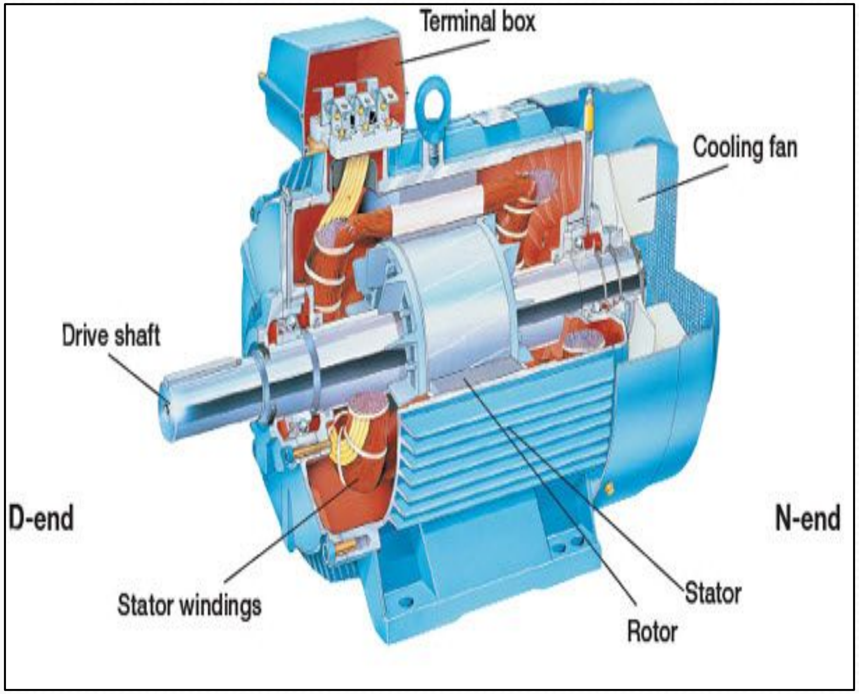
Asynchronous motor is an AC Induction motor.

The rotor of the Asynchronous motor rotates at the speed less than the synchronous speed, i.e. $N < N_S$

AC Motor: Induction motor…

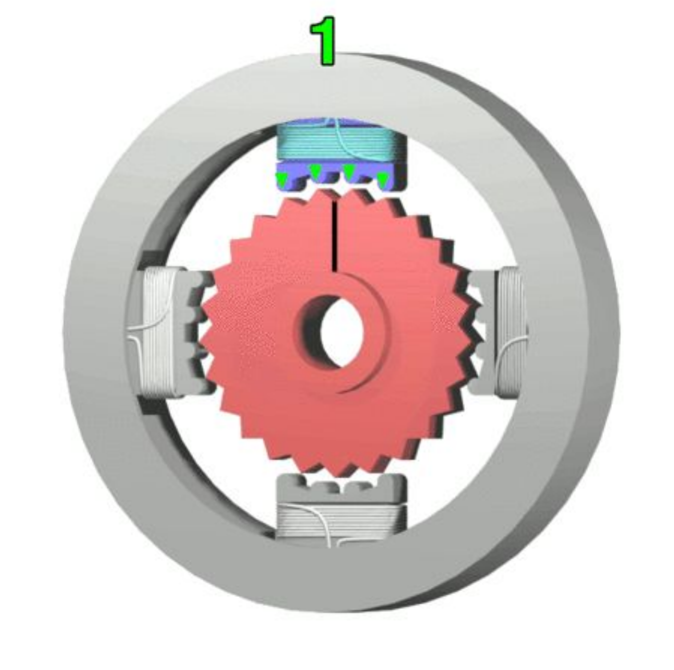
An *induction motor* or *asynchronous motor* is an AC electric *motor* in which the electric current in the rotor needed to produce torque is obtained by electromagnetic *induction* from the magnetic field of the stator winding.





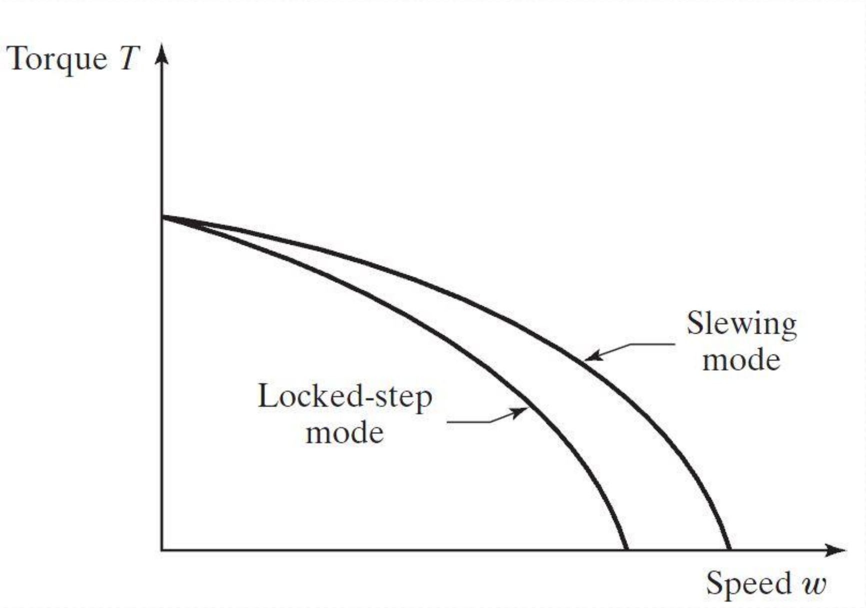
Nikola Tesla's original design for the AC induction motor

3. Stepper motor: Animation….



- electric motor that can divide a **full rotation into an expansive number of steps**
- The stepper motor uses the theory of **operation for magnets to make the motor shaft turn a precise distance** when a **pulse of electricity** is provided.

Typical Torque-Speed Curve of a Stepper Motor….



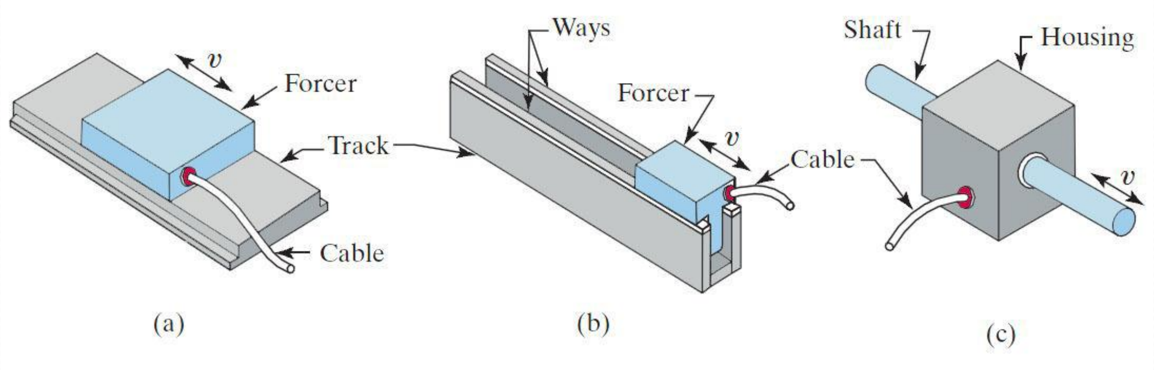
In the locked-step mode, each pulse received by the motor causes a discrete angular step to be taken; the motor starts and stops (at least approximately) with each pulse.

In the slewing mode, usually associated with higher speeds, the motor's rotation is more or less continuous and does not allow for stopping or reversing with each subsequent step.

rotational speed is related to pulse frequency in the stepper motor, torque is lower at higher pulse rates.

4. Linear Motors…

A linear electric motor provides a linear motion directly, without requiring rotary-to-linear conversion



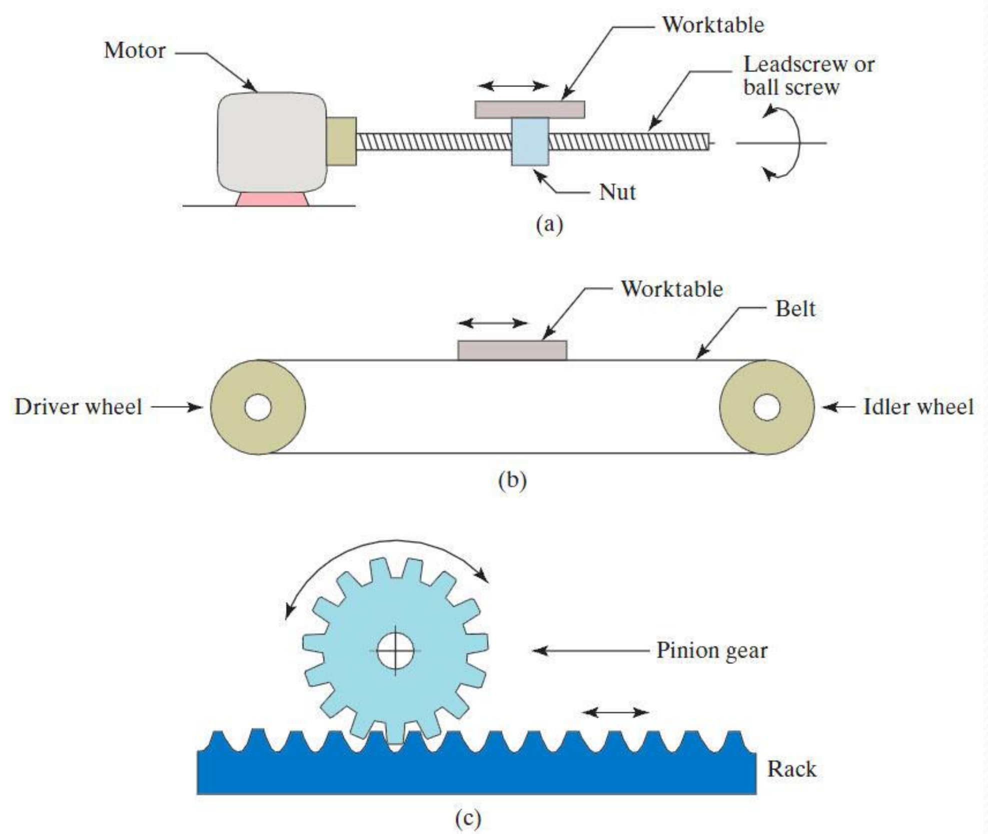
(a) Flat, (b) U-channel, and (c) cylindrical.

Rotary-to-Linear Conversion….

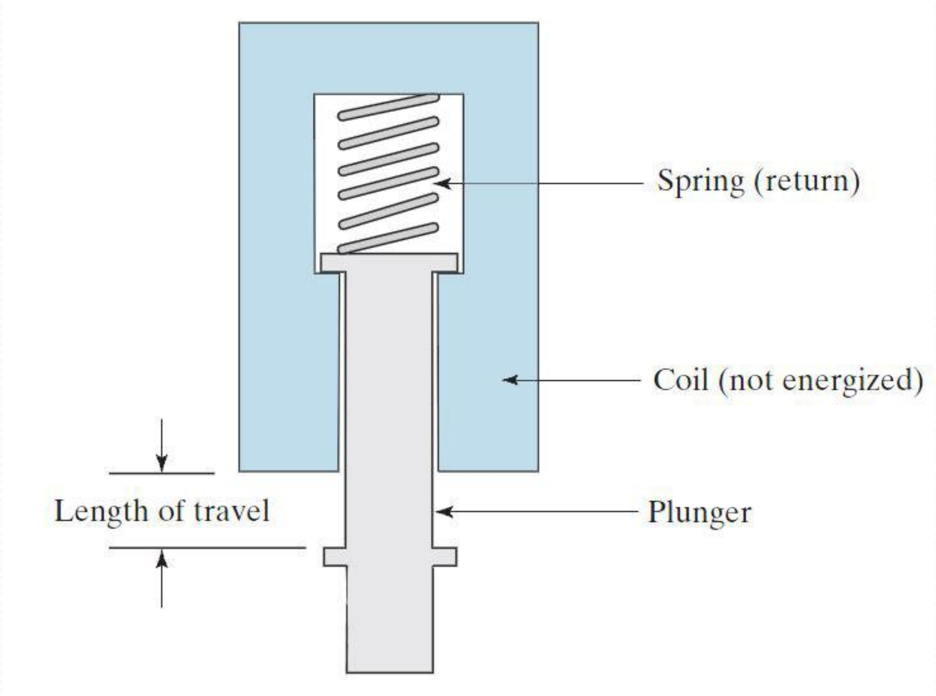
(a) Leadscrew or ball screw and nut

(a) Pulley system

(a) Rack and pinion



b. Solenoid



i. Types of Actuators

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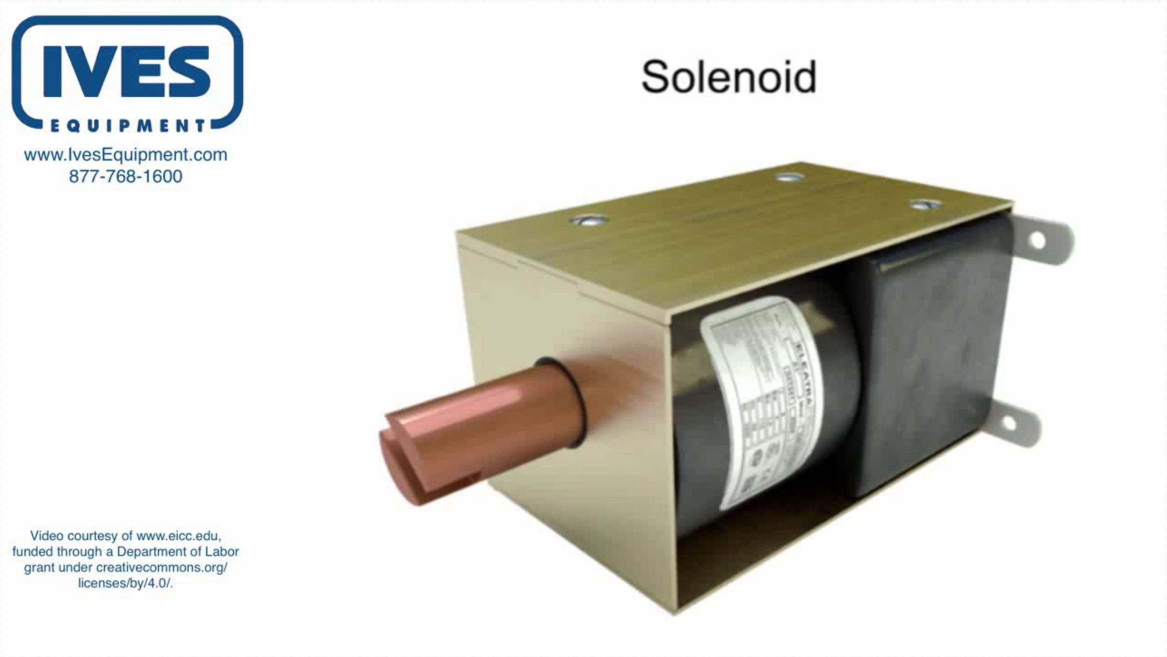
Solenoid : Working principle..

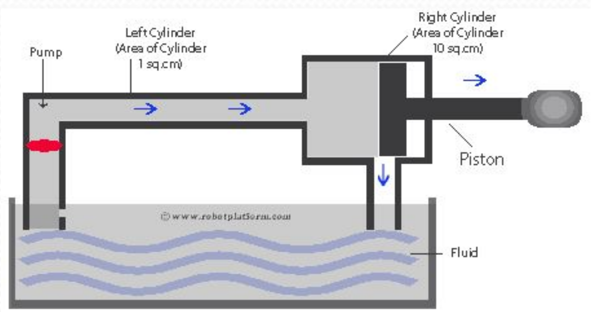
- VIDEO



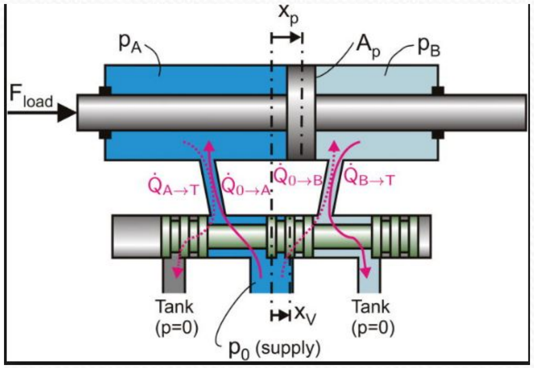
https://www.youtube.com/watch?v
=fiJa7vNuIvA

B. Hydraulic Actuators

- Hydraulic
  - Use oil
    - Incompressible, high forces, low speed operation



Hydraulic Actuator



i. Types of Actuators

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   Use hydraulic fluid to amplify the controller command signal

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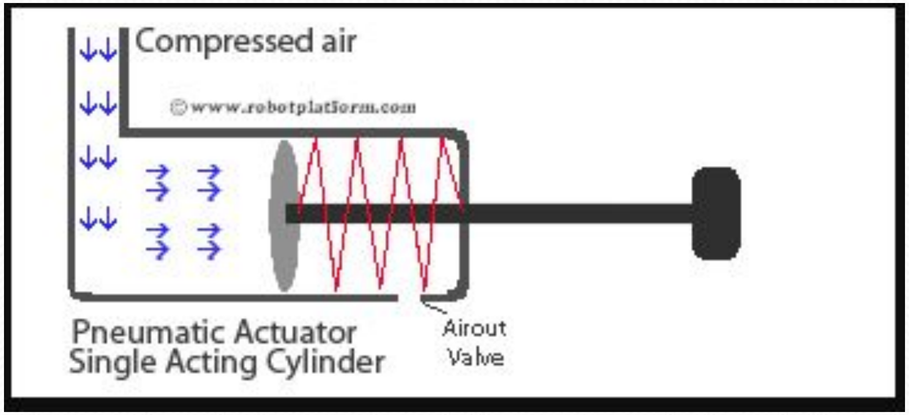
C. Pneumatic Actuators…

- Pneumatic
  - Use compressed air
    - Compressible, low forces, high speed operation



i. Types of Actuators

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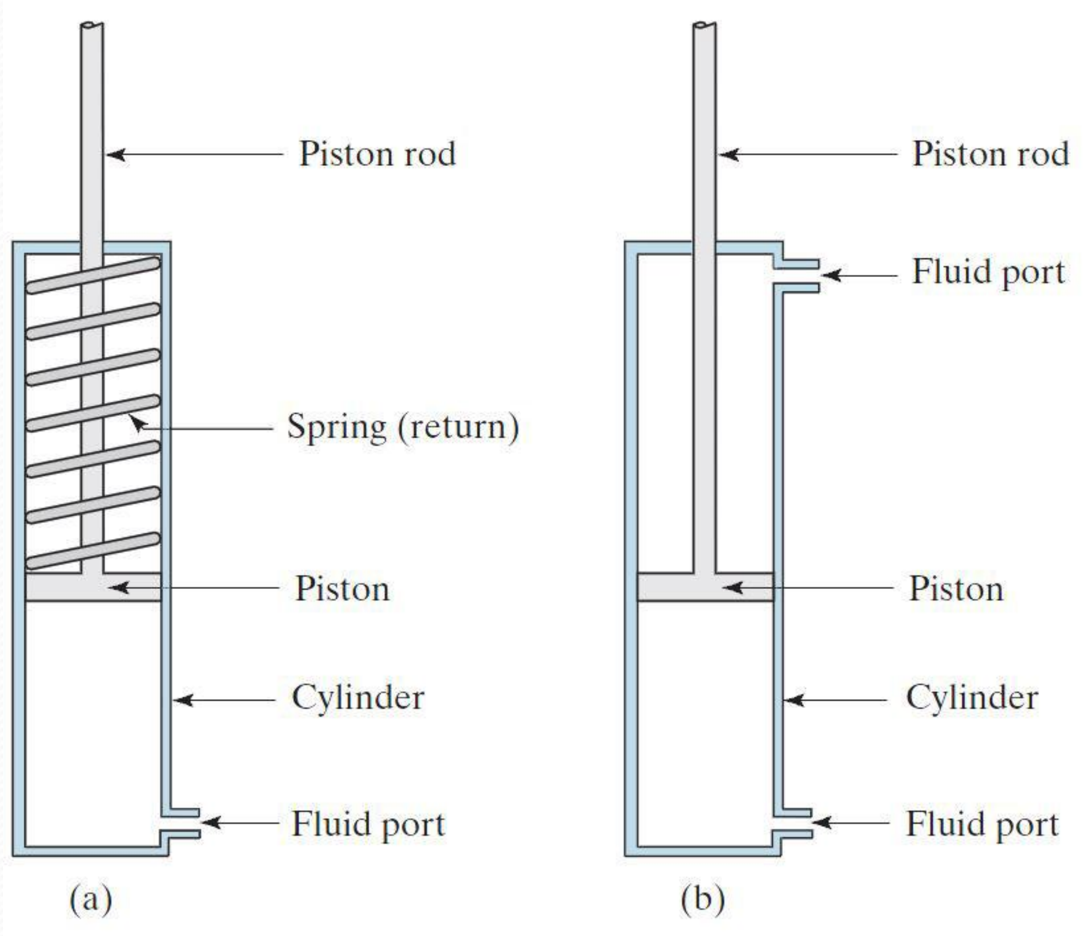
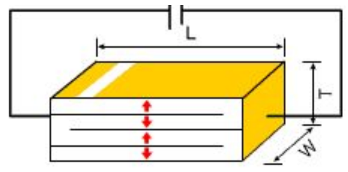
Cylinder and Piston: (a) Single-Acting and (b) Double-Acting..

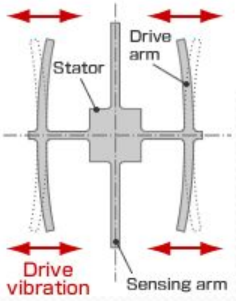


D. Piezoelectric Actuators…

- Piezoelectric
  - Electrical energy to Mechanical Engineering
    - Piezo Actuators



- Mechanical energy to Electrical Engineering
  - Gyro sensors



i. Types of Actuators

Electric
- Electric motors
- Solenoids

Hydraulic
- Use hydraulic fluid to amplify the controller command signal

Pneumatic
- Use compressed air as the driving force

Piezoelectric
- Uses electrical or mechanical energy