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CMM inspection fundamentals

The factors that affect CMM measurement performance and your choice of probing solution

Issue 2

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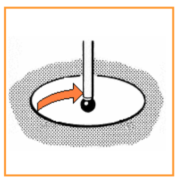
Which inspection solution will suit your application?

Probing applications

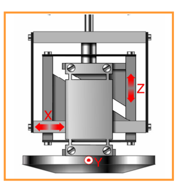
Touch-trigger or scanning?



Dynamic effects on scanning performance

Articulation or fixed sensors?

Stylus changing or sensor changing?



Active or passive scanning?

Probing applications - factors

Manufacturers need a range of measurement solutions.

Why?

- Machining processes have different levels of stability:
  - **Stable form :**
    - therefore control size and position
    - ⇒ **Discrete point measurement**
  - **Form variation significant :**
    - therefore form must be measured and controlled
    - ⇒ **Scanning**

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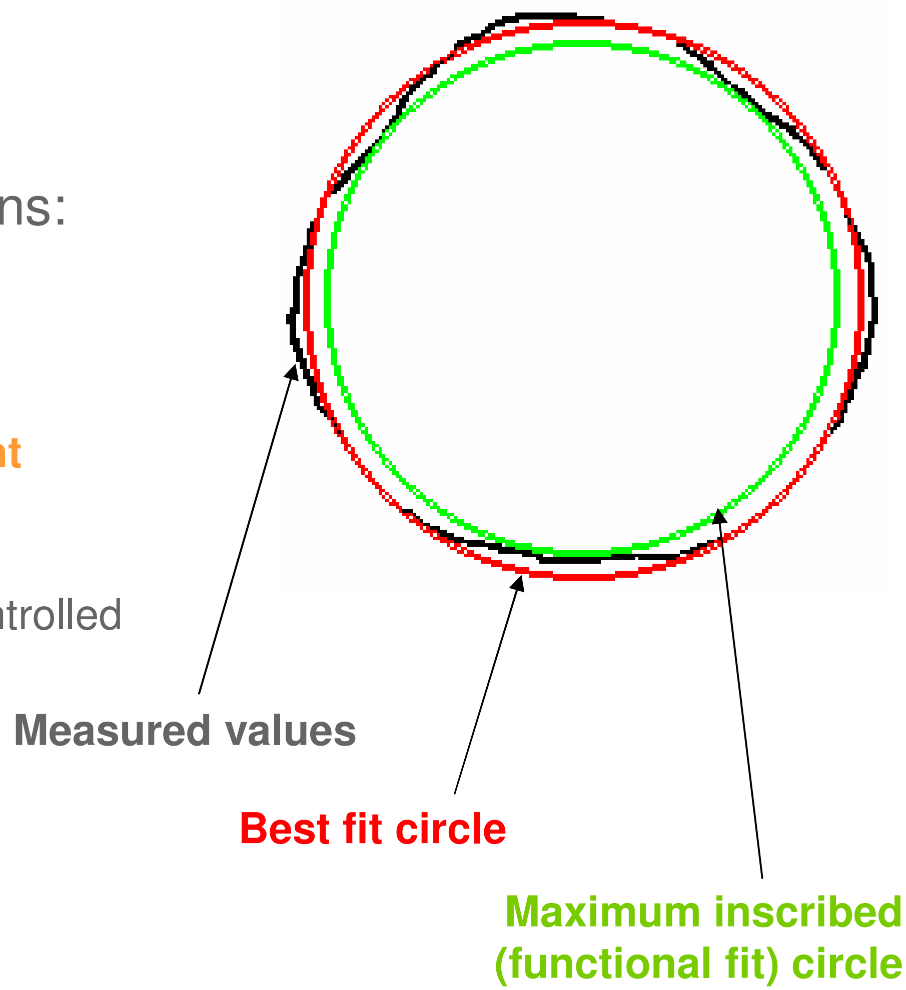
Probing applications - factors

Manufacturers need a range of measurement solutions.

Why?

- Features have different functions:
  - for **clearance** or **location**
    - –form is not important
    - ⇒ **Discrete point measurement**
  - for **functional fits**
    - –form is critical and must be controlled
    - ⇒ **Scanning**



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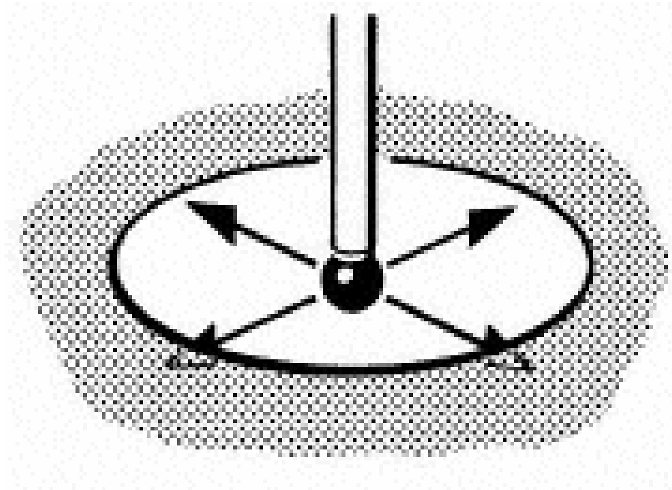
Discrete point measurement

Ideal for controlling the **position** or **size** of clearance and location features

- Data capture rates of **1 or 2 points per second**
- Avoids stylus wear



- **Touch-trigger probes** are ideal
  – lower cost, small size and great versatility

- **Scanning probes** can also be used
  – **passive probes** can probe quickly
  – **active probes** are slower because the probe must settle at a target force to take the reading

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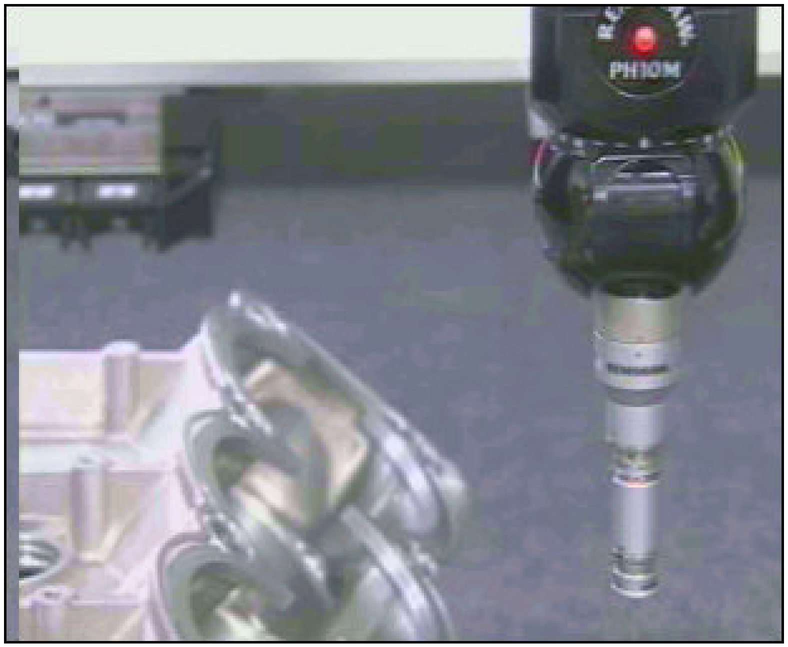
Discrete point measurement

Speed comparison



Touch-trigger probes are ideal for high speed discrete point measurement

Scanning probes can also measure discrete points quickly, and provide higher data capture rates when scanning

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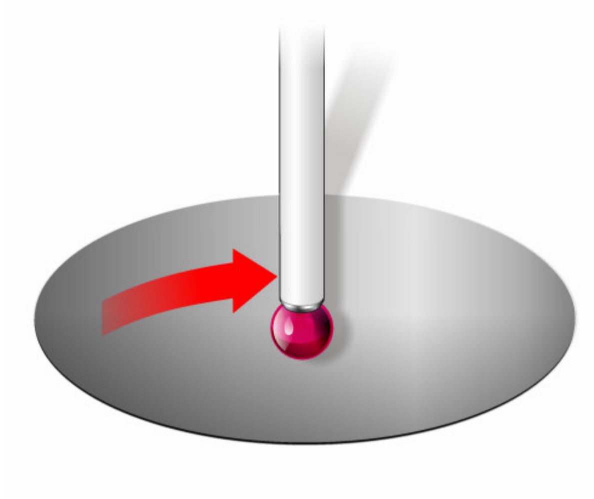
Scanning

Ideal for controlling the **form** or **profile** of known features that form functional fits with other parts

- Data capture speeds of up to **500 points per second**
- Incurs wear on the stylus



Scanning allows you to:

- Determine the feature **position**
- Accurately measure the feature **size**
- Identify errors in the **form** or shape of the feature

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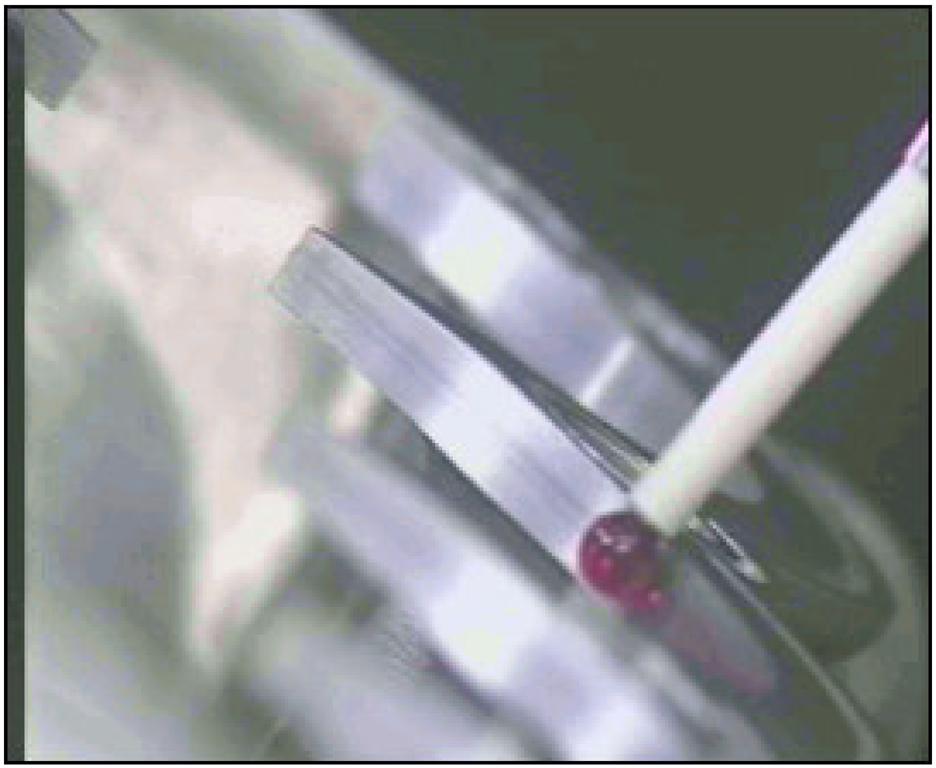
Scanning

Scanning a cylinder block



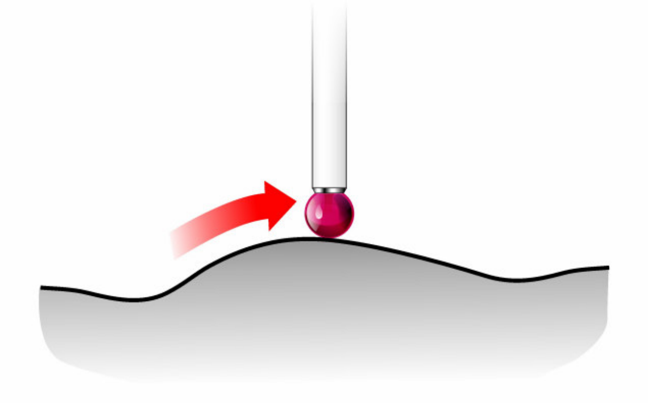
- Typical scanning routine, measuring precision features where form is critical to performance

Scanning provides much more information about the form of a feature than discrete point measurement

Digitising

Ideal for **capturing large amounts of data about an unknown surface**

- Uses many of the same techniques as scanning
- Deflection vector of the probe is used to determine the motion vector in which the machine moves next

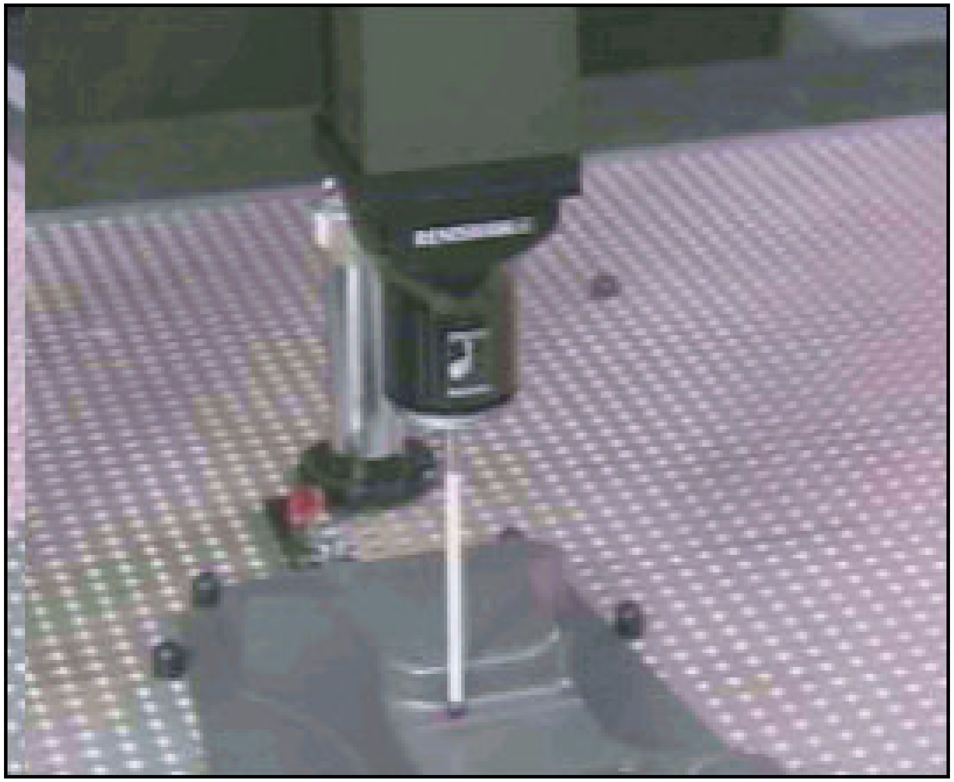


Digitised surface data can be:

- Exported to **CAD** for reverse engineering
- Used to generate a **machining program** for re-manufacture

Digitising

Re-manufacture and reverse engineering



Digitising provides large amounts of data to define unknown contoured surfaces

- Digitising a master part to acquire an accurate description of the surface
- Scanning cycle and data analysis handled by Tracecut software
- Digitising can be performed on CMMs, machine tools or dedicated platforms like Cyclone

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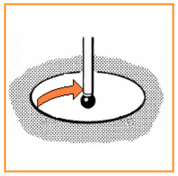
Which inspection solution will suit your application?

Probing applications

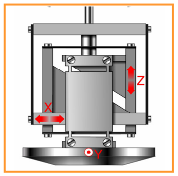
Touch-trigger or scanning?



Dynamic effects on scanning performance

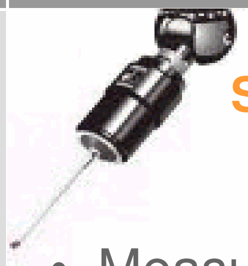
Articulation or fixed sensors?

Stylus changing or sensor changing?



Active or passive scanning?

Ideal applications



Scanning

- Measurement of size, position and form of precision geometric features
- Measurement of profiles of complex surfaces

Touch-trigger

- Inspection of 3D prismatic parts and known surfaces
- Size and position process control applications where form variation is not significant

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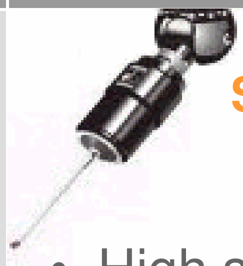
Speed and accuracy



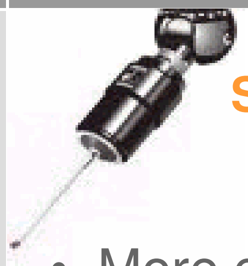
Scanning

- High speed data capture - up to 500 points per second
- Large volume of data gives an understanding of form
- High point density gives greater datum stability
- Dynamic effects due to accelerations during measurement must be compensated if high speed scans are to produce accurate measurement results

Touch-trigger

- Slower data capture rate
- Less information about the surface
- Simple calibration of probe and machine yields accurate point data
- Dynamic performance of the machine has little impact on measurement accuracy since probing is performed at constant velocity

Complexity and cost



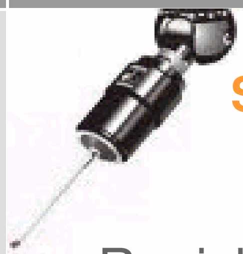
Scanning

- More complex sensors, data analysis and motion control
- Higher costs than basic touch-trigger systems
  - Conventional systems have higher purchase and maintenance costs
  - Renishaw scanning systems are more cost-effective and robust

Touch-trigger

- Simple sensors with a wide range of application software
- Lower costs than scanning systems
  - Robust sensors
  - Easy programming
  - Simple to maintain
  - Cost-effective replacement for lower lifetime costs

Flexibility



Scanning

- Renishaw scanning probes are supported by a range of articulating heads, probe and stylus changers
- Head and quill-mounted sensor options
  - Conventional scanning probes cannot be articulated and suffer restricted part access

Touch-trigger

- Renishaw touch-trigger probes are supported by a wide range of heads and accessories
  - long extension bars for easy part access
- wide range of touch-trigger sensors

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The ideal scanning system

Characteristics of the ideal scanning system:

- **High speed, accurate scanning** of the form of known and unknown parts
- **Rapid discrete point measurement** when measuring feature position
- **Flexible access** to the component to allow rapid measurement of all critical features on the part
- **Easy interchange** with other types of sensor, including touch-trigger probes and non-contact sensors.
  - Allows the sensor choice for each measurement to be optimised
- **Minimum stylus wear**

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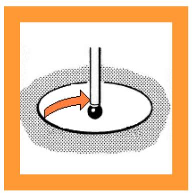
Which inspection solution will suit your application?

Probing applications

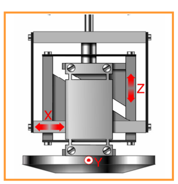
Touch-trigger or scanning?



Dynamic effects on scanning performance

Articulation or fixed sensors?

Stylus changing or sensor changing?



Active or passive scanning?

Dynamic effects on scanning performance

The scanning paradox…

- Modern CMMs can move quickly, yet conventional scanning is typically performed at low speeds
  - less than 15 mm sec (0.6 in/sec)

Why?

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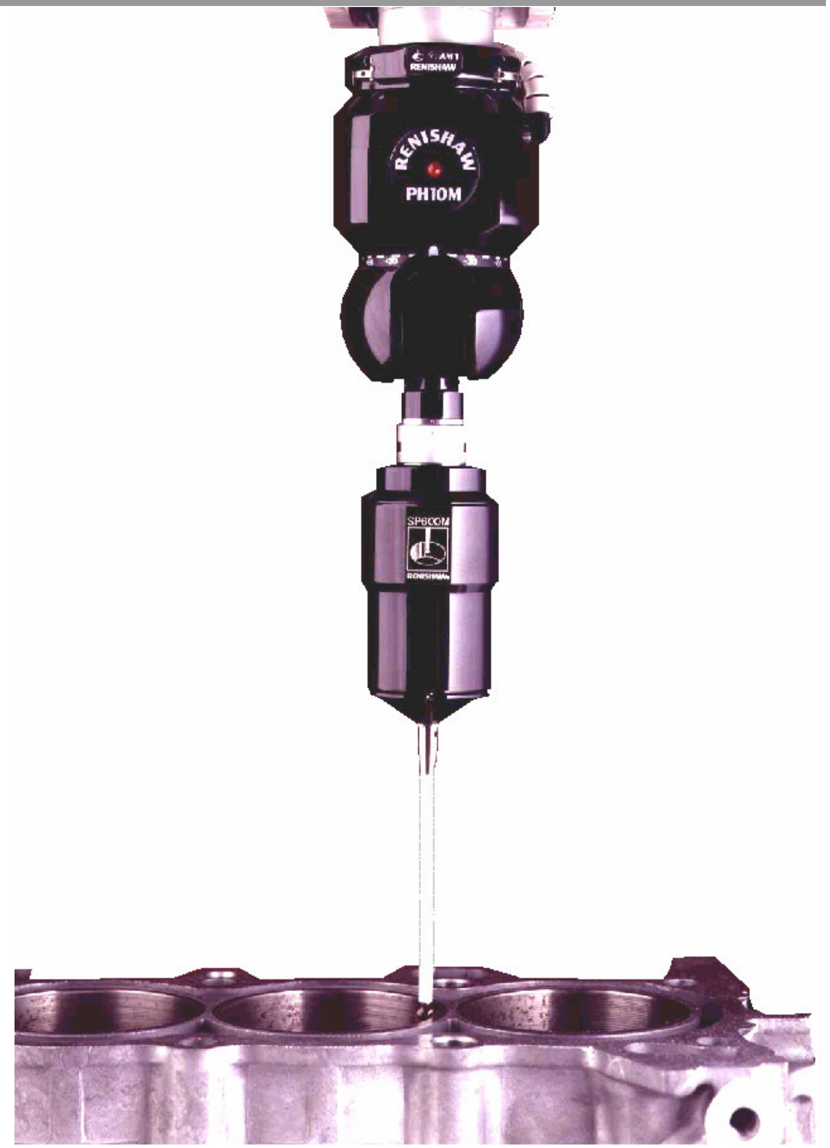
Dynamic effects on scanning performance

Scanning induces dynamic forces in the structure of the CMM and the probe itself, which can affect measurement accuracy

Dynamic errors are related to acceleration of the machine and probe as the stylus is moved over the surface of the component

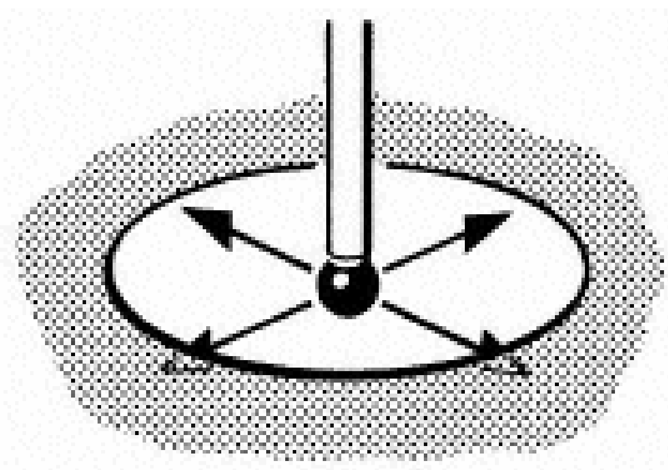


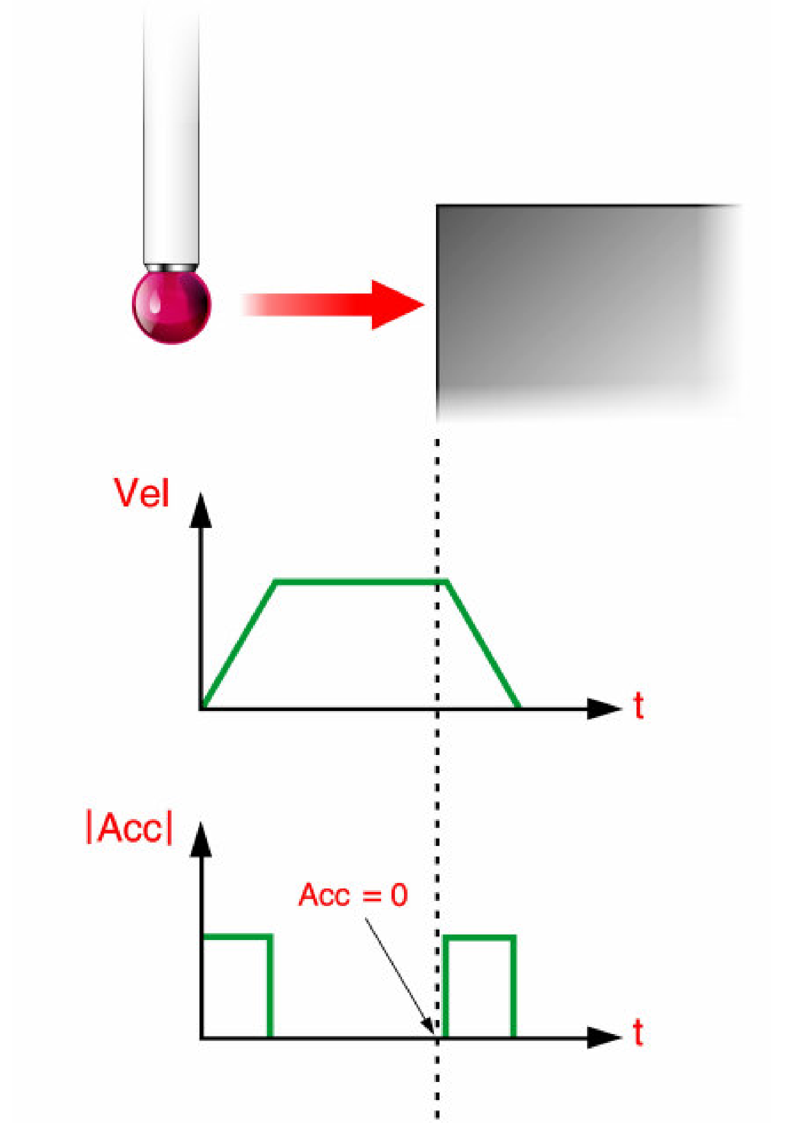
How do machine dynamic errors arise?

Discrete point measurement is done at constant velocity - acceleration is zero at the point of contact

– with critical damping

Consequently there are **no inertial forces** on the machine or probe



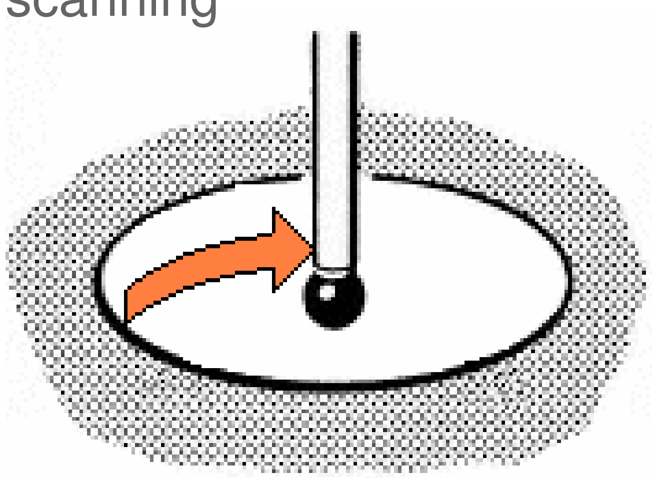


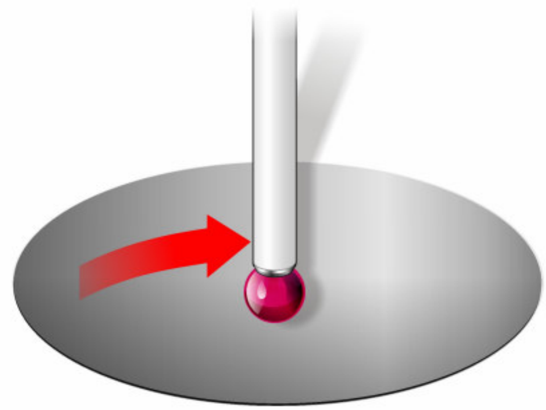
How do machine dynamic errors arise?

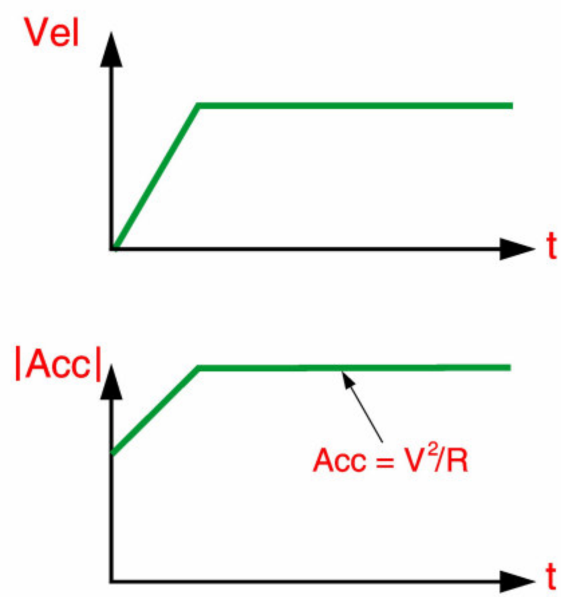
Scanning requires continuously changing velocity vectors as the stylus moves across a curved surface

Varying inertial forces are induced, which cause the machine to deflect

Vibration is also a factor when scanning







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What about scanning sensor dynamics?

During scanning, the deflection of the probe varies due to the difference between the programmed path and the actual surface contour

- The probe must accommodate rapid changes in deflection, without loss of accuracy or leaving the surface
- The ideal scanning sensor can accommodate rapidly changing profile due to:
  - a high natural frequency
  - low suspended mass
  - low overall weight

Whilst important, **probe dynamics have a very small effect compared to machine dynamics**

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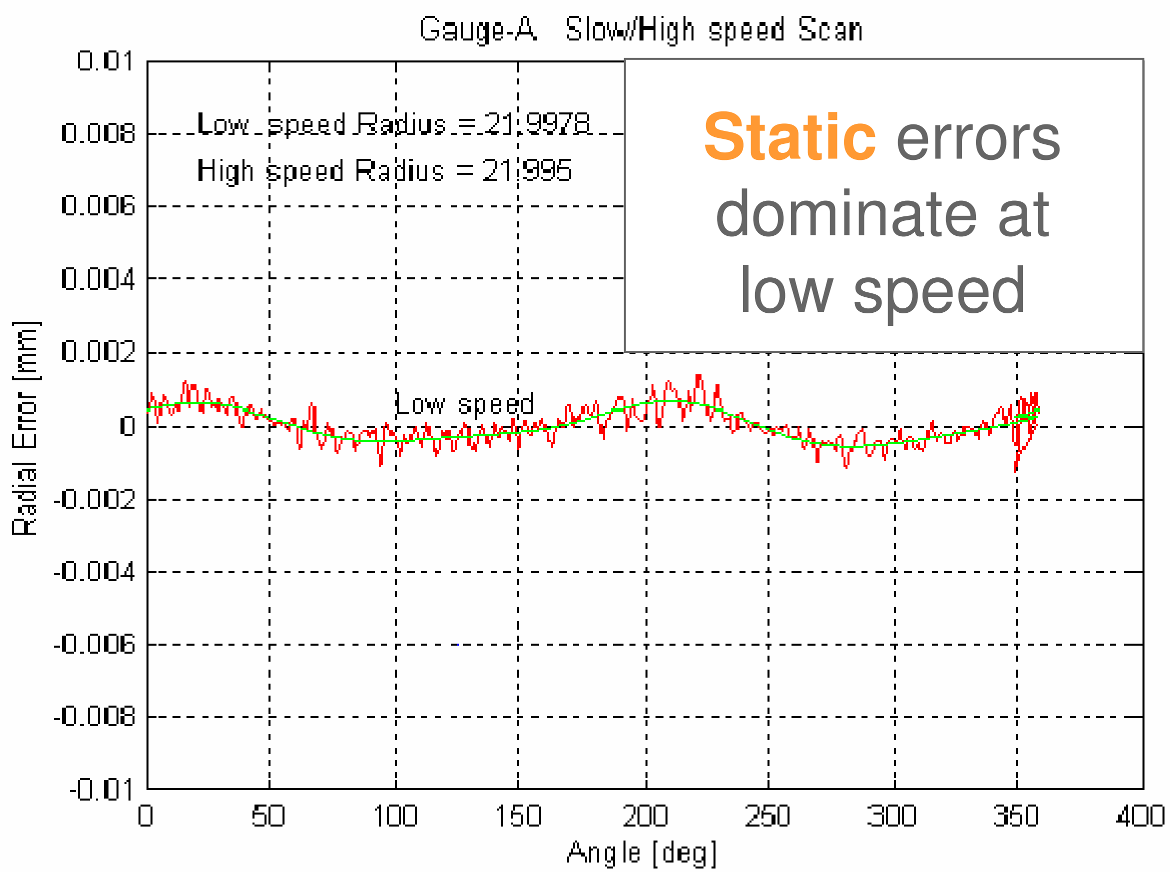
Dynamic errors in practice

Example: measure a Ø50 mm (2 in) ring gauge at **10 mm/sec (0.4 in/sec)** using a CMM with performance of **2.5 + L/250**

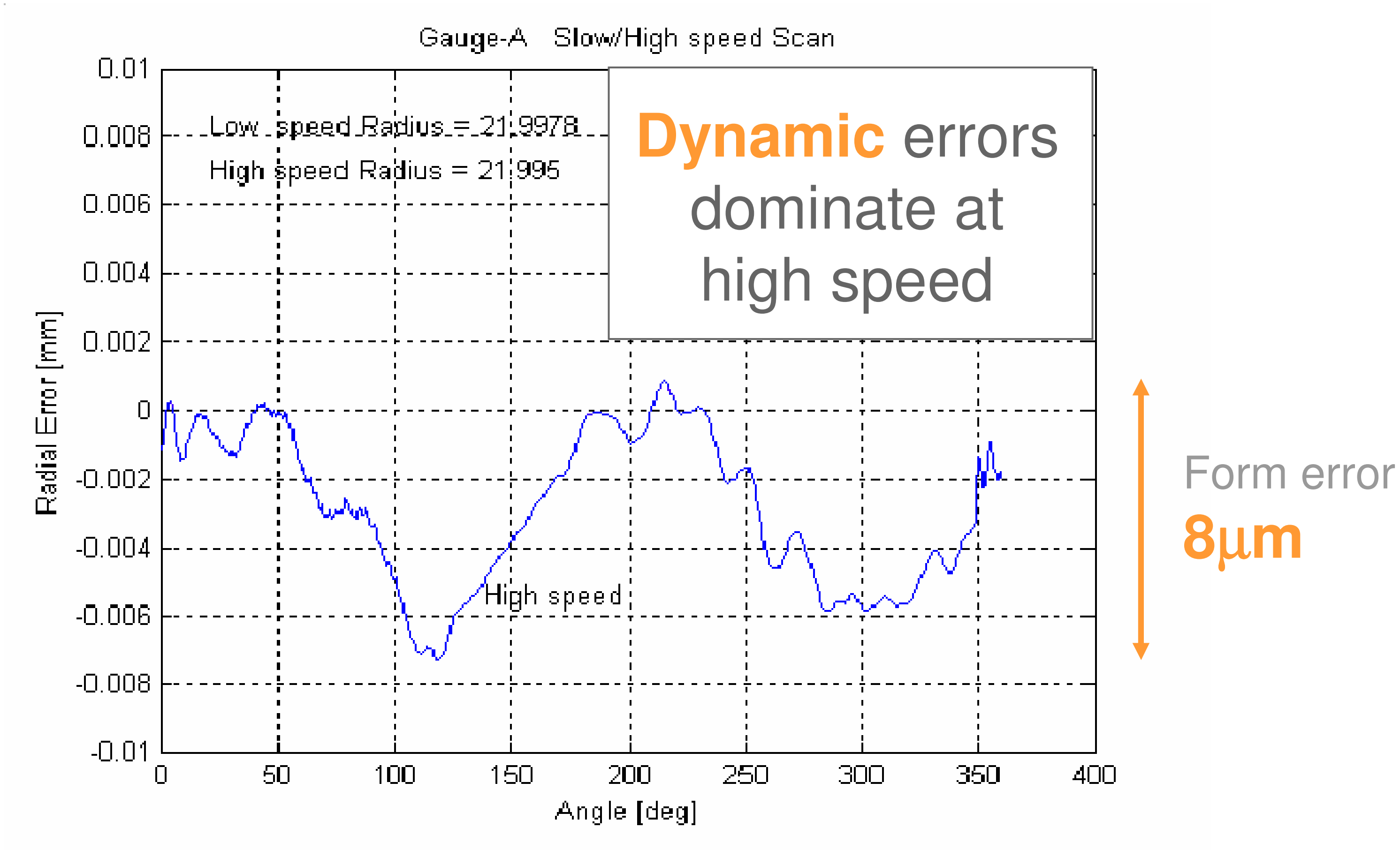


Static errors dominate at low speed

Form error **2μm**

Dynamic errors in practice

Example: re-measure ring gauge at **100 mm/sec (4 in/sec)** on the same CMM



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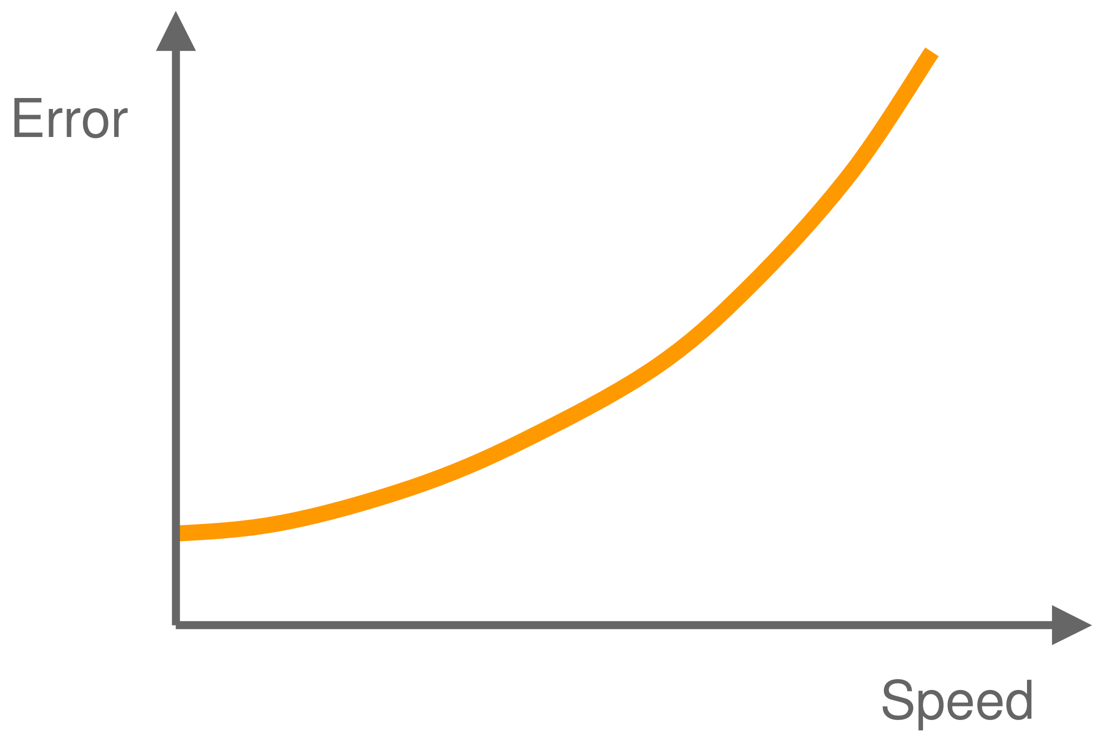
The dynamic performance barrier

Dynamic errors increase as speeds rise

At higher scanning speeds, machine dynamics becomes the dominant source of measurement error



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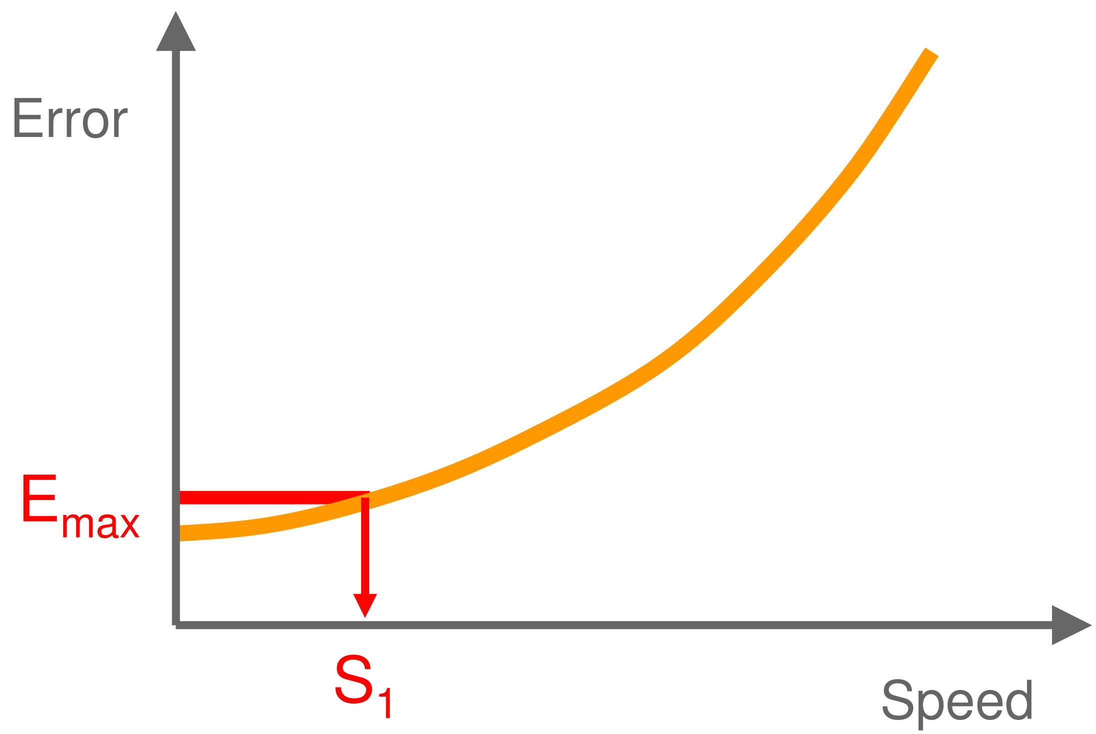
The dynamic performance barrier

Scanning speeds have to be kept low if tight tolerance features are to be inspected

Left uncorrected, machine dynamics present a dynamic performance barrier to accurate high speed scanning



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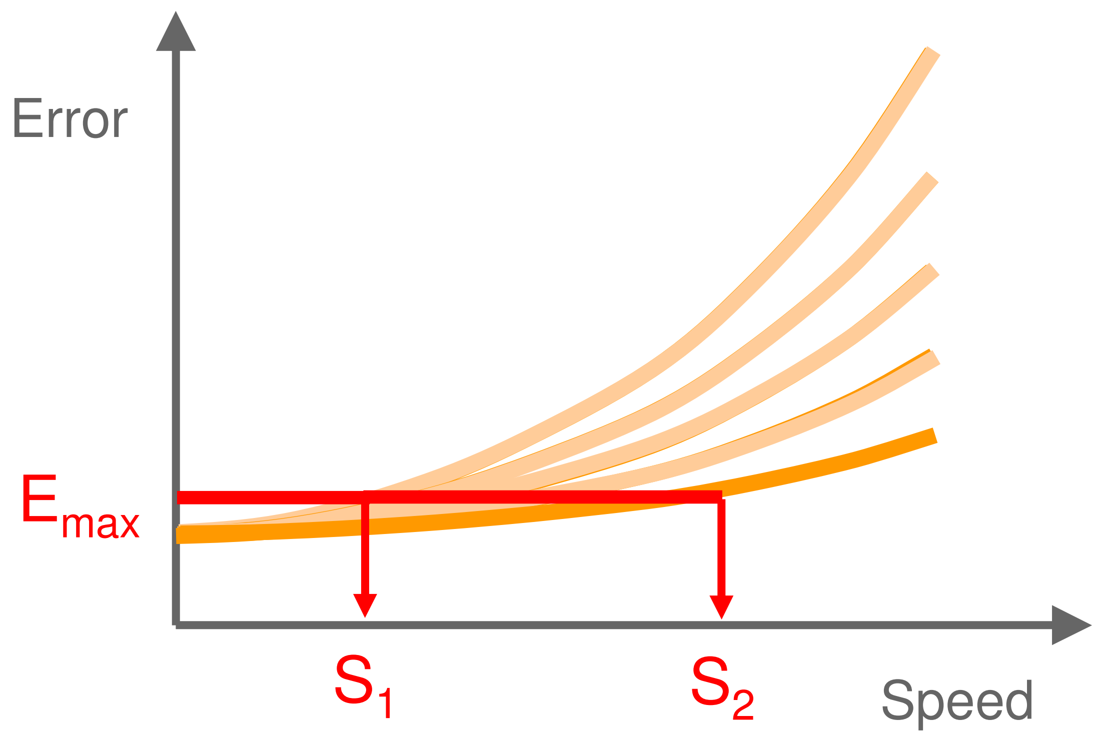
The dynamic performance barrier

We need a way to break through the dynamic performance barrier, making high speed scanning more accurate



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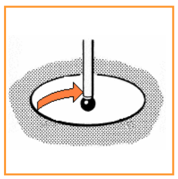
Which inspection solution will suit your application?

Probing applications

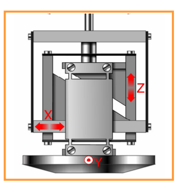
Touch-trigger or scanning?



Dynamic effects on scanning performance

Articulation or fixed sensors?

Stylus changing or sensor changing?



Active or passive scanning?

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Articulation or fixed sensors?

Articulating heads are a standard feature on the majority of computer-controlled CMMs

– Heads are the most cost-effective way to measure complex parts

Fixed probes are best suited to applications where simple parts are to be measured

– Ideal for flat parts where a single stylus can access all features

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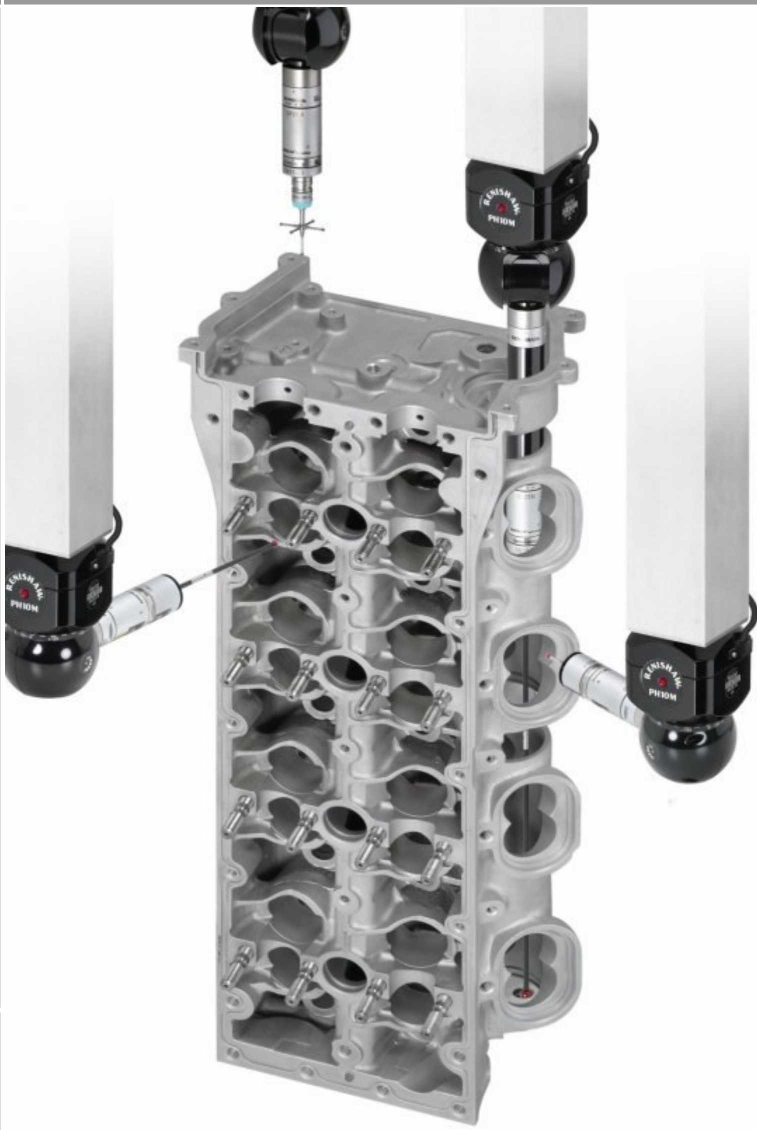
Articulating heads - benefits



- **Flexibility** - a single, simple stylus can access features in many orientations
  - Indexing and continuously variable solutions

Articulating heads - benefits

Repeatable indexing using kinematic principles:

- **Method:**
  - 50 measurements of calibration sphere at {A45,B45}, then 50 with an index of the PH10M head to {A0,B0} between each reading
    - TP200 trigger probe with 10mm stylus
- **Results:**

Result	Span fixed	Span index	Δ [Span]	**Δ [Repeatability]**
X	0.00063	0.00119	0.00056	**± 0.00034**
Y	0.00039	0.00161	0.00122	**± 0.00036**
Z	0.00045	0.00081	0.00036	**± 0.00014**

- **Comment:**
  - Indexing head repeatability has a similar effect on measurement accuracy to stylus changing repeatability

Articulating heads - repeatability

Indexing repeatability affects the measured position of features

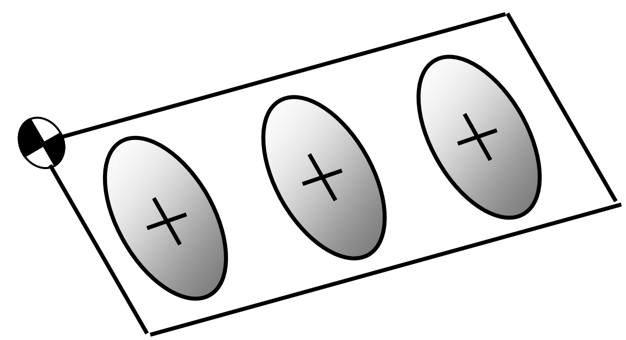
– Size and form are unaffected

Most features relationships are measured ‘in a plane’

– Feature positions are defined relative to datum features in the same plane (i.e. the same index position)

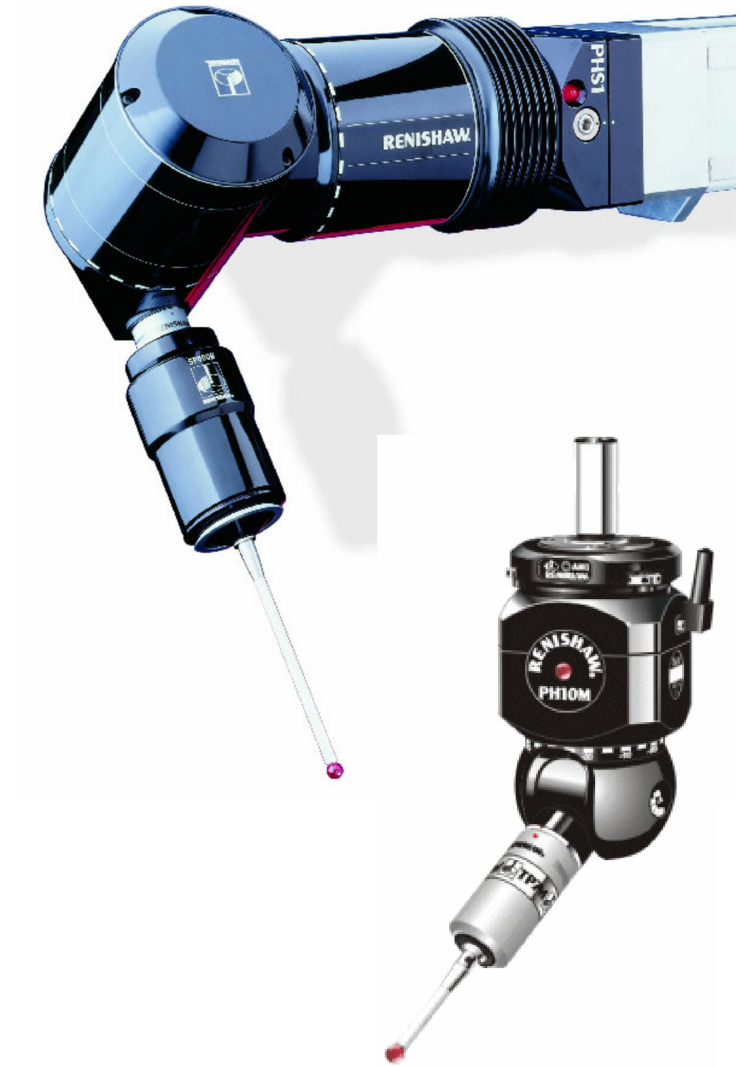
  • Datum feature used to establish a part co-ordinate system

– Therefore indexing repeatability typically has **no negative impact** on measurement results, but many benefits



Articulating heads - benefits

- **Speed** - indexing is faster than stylus changing (done during CMM moves)
- **Dynamic response** - simple, light styli make for a lower suspended mass
- **Costs**
  - simple styli with low replacement costs
  - small, low cost stylus change racks



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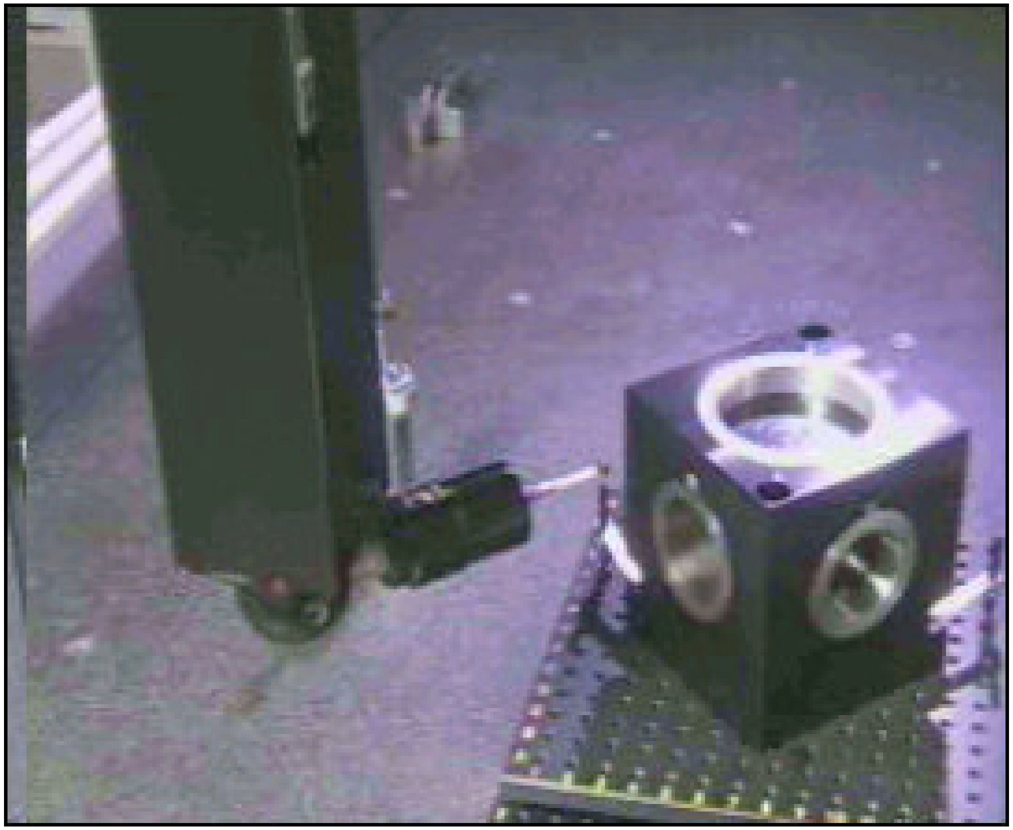
PH10M indexing head - design characteristics

Flexible part access



Rapid indexing during CMM positioning moves give flexible access with no impact on cycle times

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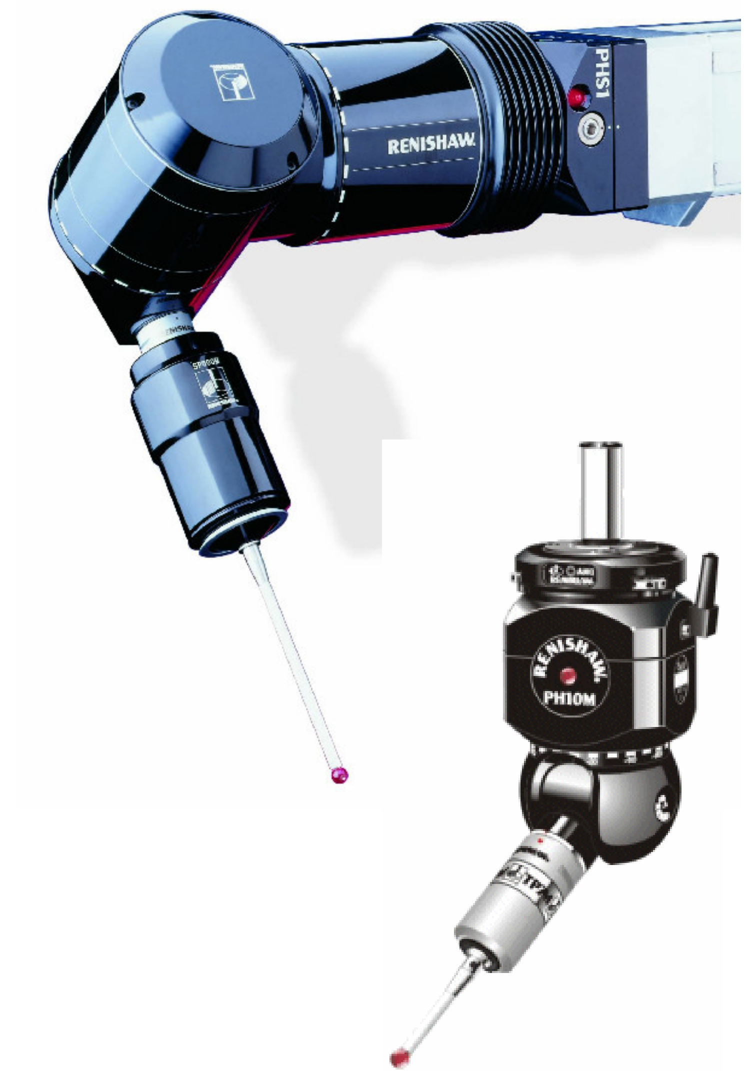
Articulating heads - benefits

- **Automation** - programmable probe changing with no manual intervention required
  - touch-trigger, scanning and optical probing on the same machine

- **Stylus changing** - even greater flexibility and automation
  - optimise stylus choice for each measurement task

Articulating heads - disadvantages

- **Space** - a head reduces available Z travel by a small amount - can be an issue on very small CMMs

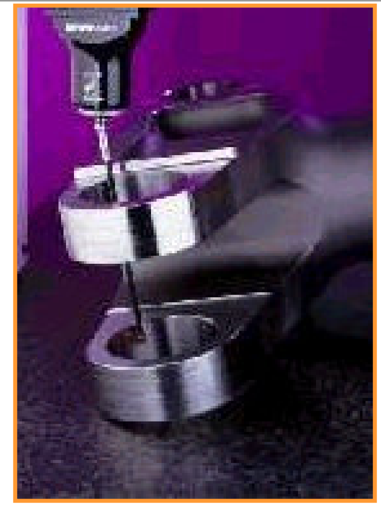


PH10MQ in-quill version of PH10 indexing head reduces Z travel requirements

Fixed sensors - benefits

- **Compact** - reduced Z dimension makes minimal intrusion into the measuring volume - ideal for small CMMs
- **Simplicity** - fixed passive sensors are less complex for lower system costs
  - **Note:** an active sensor is more complex and often more expensive than a passive sensor and an articulating head combined

Articulating head



Fixed sensor

- **Stylus length** - fixed sensors can be larger than those fitted on articulating heads, making it possible to carry longer styli

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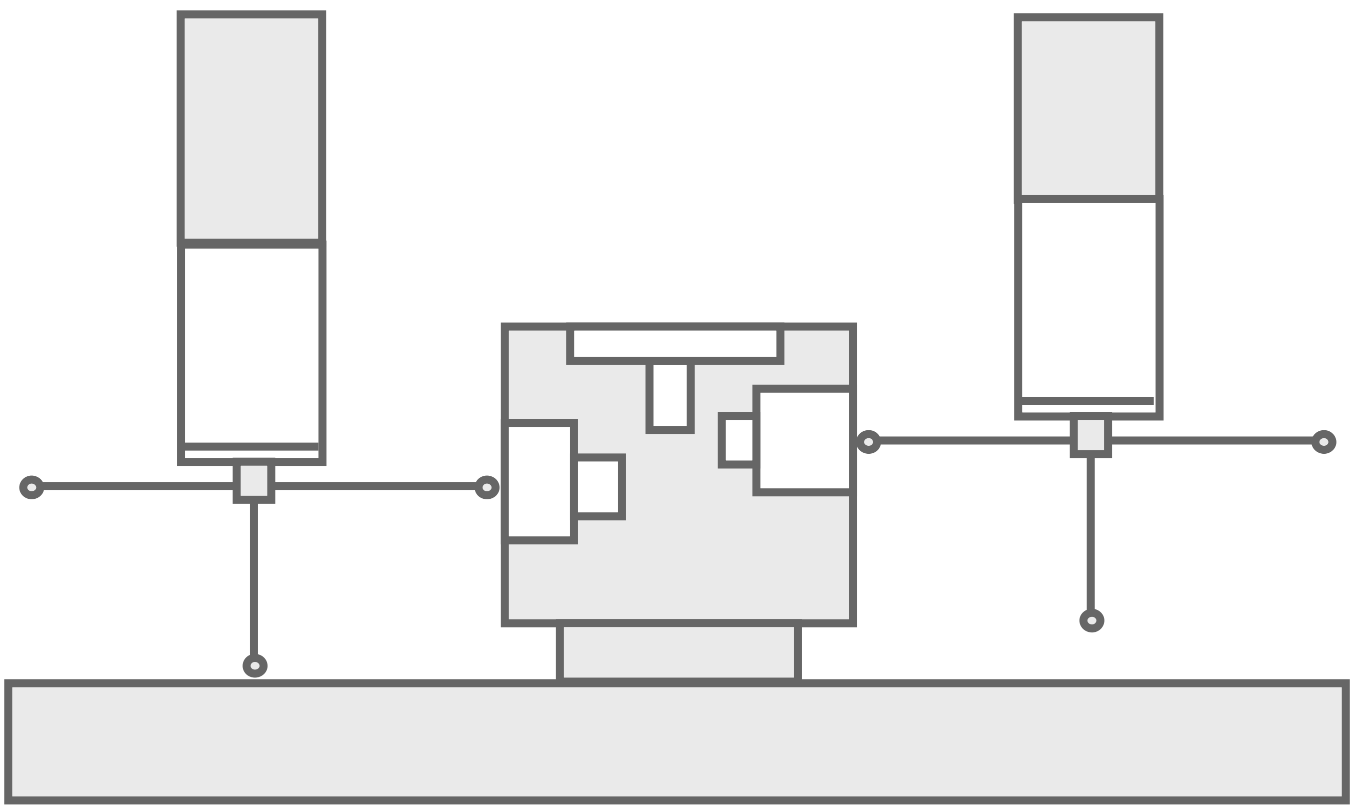
Fixed sensors - disadvantages

- **Feature access** - large and complex stylus arrangements are needed to access some features



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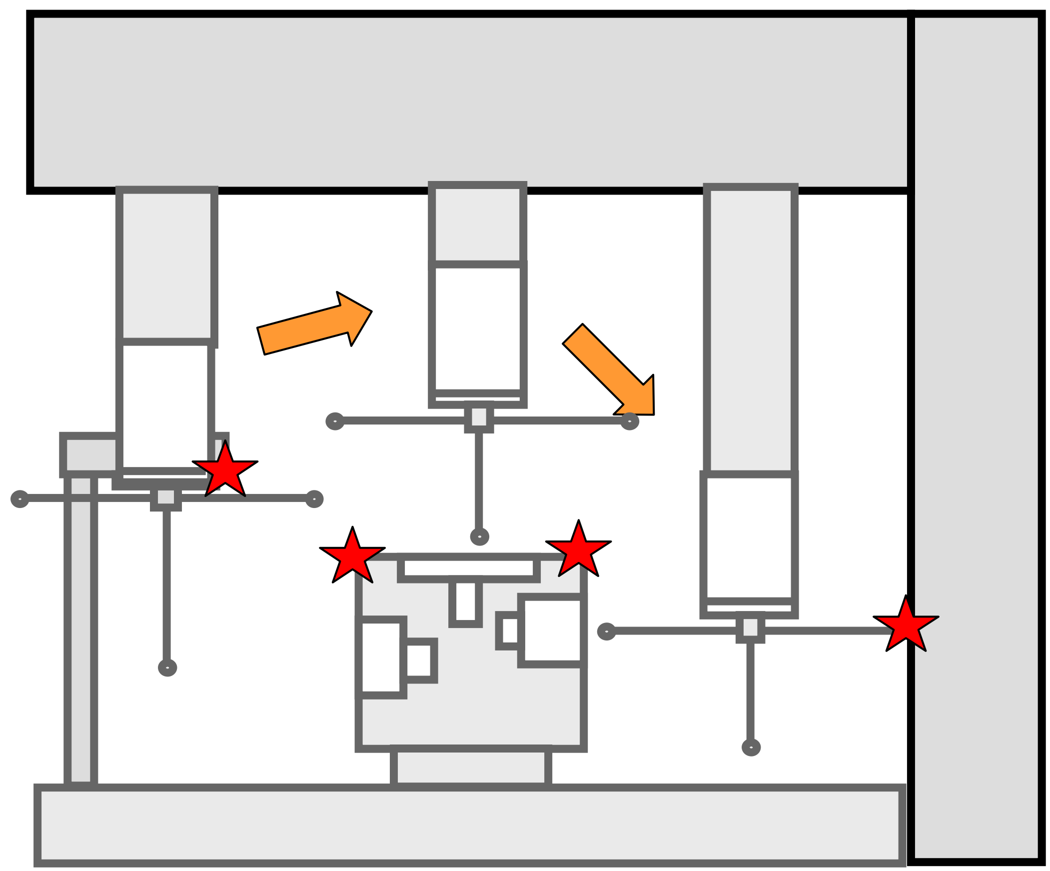
Fixed sensors - disadvantages

- **Programming complexity** - complex stylus clusters mean more attention must be paid to collision avoidance

DANGER!

Possible collisions with:

- component
- fixturing
- stylus change rack
- other styli in rack
- machine structure



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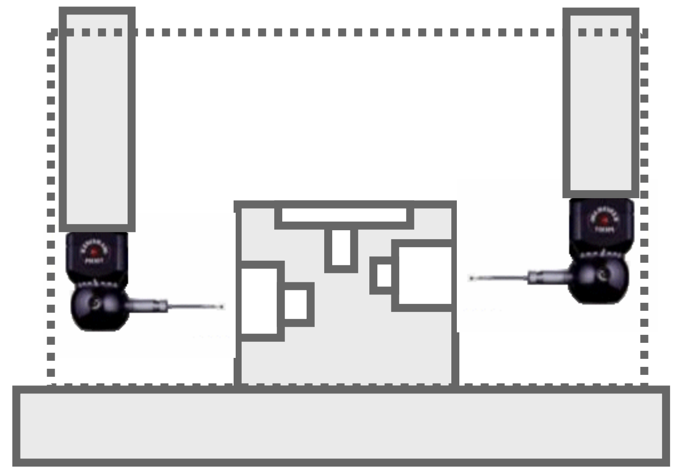
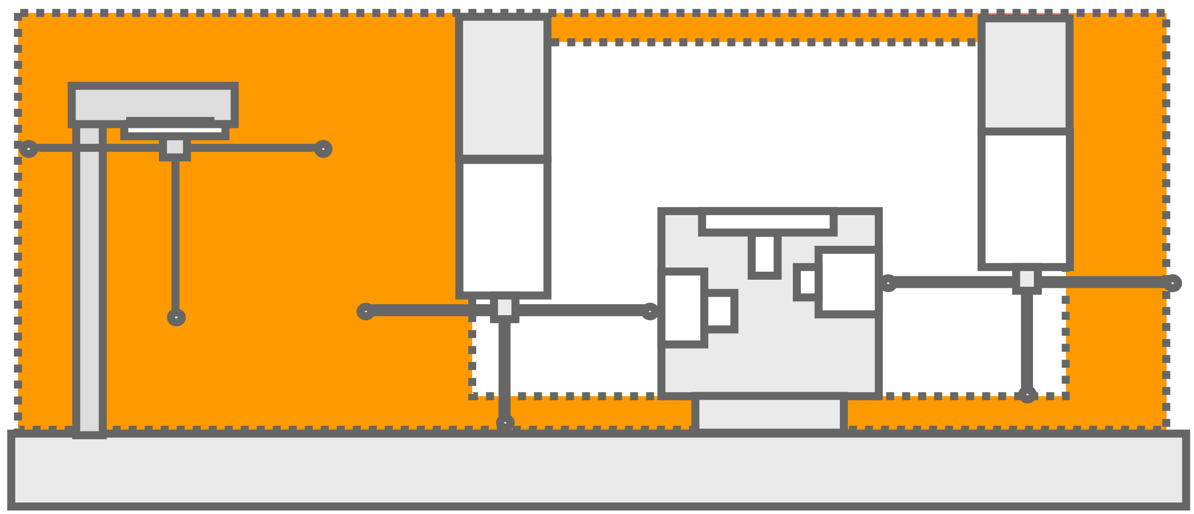
Fixed sensors - disadvantages

- **Machine size**
  - large stylus clusters consume measuring volume
  - much larger stylus change racks consume more space
  - you may need a larger machine to measure your parts



Star styli and large changer consume more working volume



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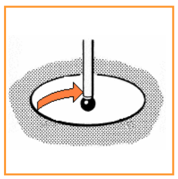
Fixed sensors - disadvantages

- **Speed** - stylus changing takes longer than indexing
  - up to 10 times slower than indexing
  - indexing can be done during positioning moves
- **Dynamic response** - heavy styli increase suspended mass and limit scanning speed
- **Accuracy** - complex styli compromise metrology performance

Which inspection solution will suit your application?

Probing applications

Touch-trigger or scanning?



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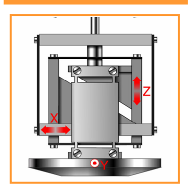

Active or passive scanning?

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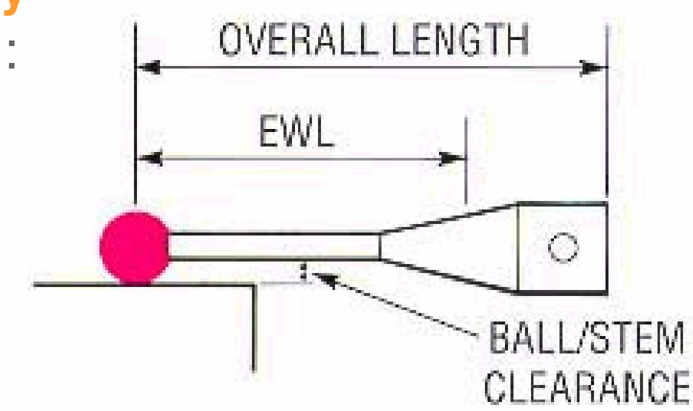
Why change styli?

Optimise your measurement repeatability

for each feature by selecting a stylus with:

- **Minimum length**
  - Longer styli degrade repeatability
- **Maximum stiffness**
- **Minimum joints**
- **Maximum ball size**
  - Maximise the effective working length (EWL)



Test results:

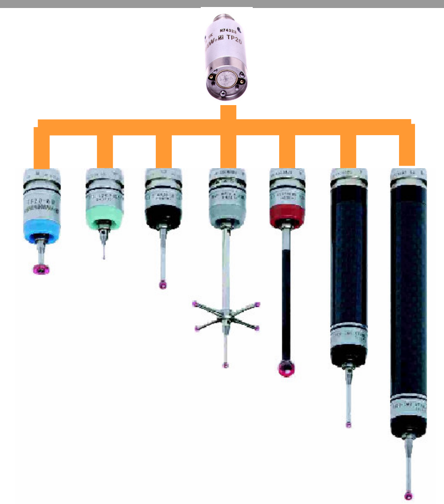
TP200 repeatability with stylus length

Stylus length	**10mm**	**50mm**
Uni-directional repeatability	0.30 µm	0.40 µm
2D form deviation	±0.40 µm	±0.80 µm
3D form deviation	±0.65 µm	±1.00 µm

Stylus changing

Many probe systems now feature a **repeatable stylus module changer**

- access to features that demand long or complex styli
- different tips (sphere, disc, cylinder) needed for special features



- **Automated stylus changing** allows a whole part to be measured with a single CMM programme
  - reduced operator intervention
  - increased throughput

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SP600 stylus changing

Stylus changing

Rapid stylus changing with the passive SCR600 stylus change rack

Why change sensors?

Not all parts can be measured with one sensor:

- **Scanning probe**
  - ideal for features with functional fits where form is important
  - digitising contoured surfaces
- **Touch-trigger probe**
  - ideal for discrete point inspection, for size and position control
  - compact for easy access to deep features
- **Optical probes**
  - ideal for pliable surfaces
  - inspection of printed circuit boards

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Probe sensor changing

The requirement...

If the range of features and parts that you must measure demands a range of sensors, then a **sensor changing system** is essential

The solution…

- **Automatic, no requalification, easy programming**
  - automatic switching
  - automatic sensor recognition
  - automatic electrical connections
  - automatic alignment of sensor

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New ACR3 probe changer for use with PH10M

Probe changing

Quick and repeatable sensor changing for maximum flexibility

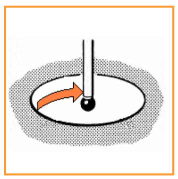
Video commentary

- New ACR3 sensor changer
- No motors or separate control
- Change is controlled by motion of the CMM

Which inspection solution will suit your application?

Probing applications

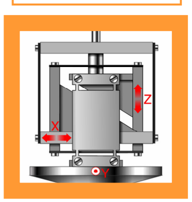
Touch-trigger or scanning?



Dynamic effects on scanning performance

Articulation or fixed sensors?

Stylus changing or sensor changing?



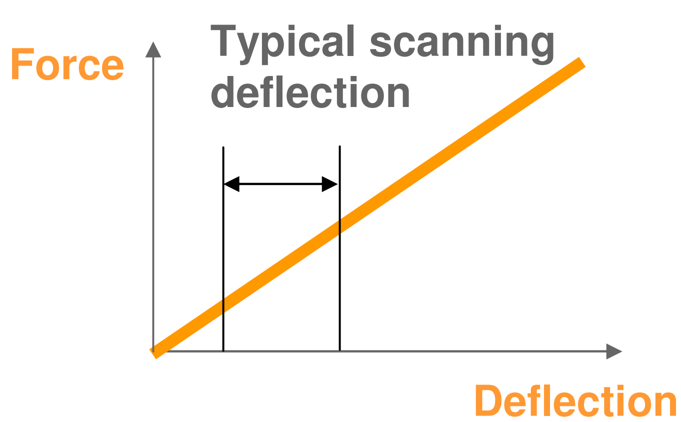
Active or passive scanning?

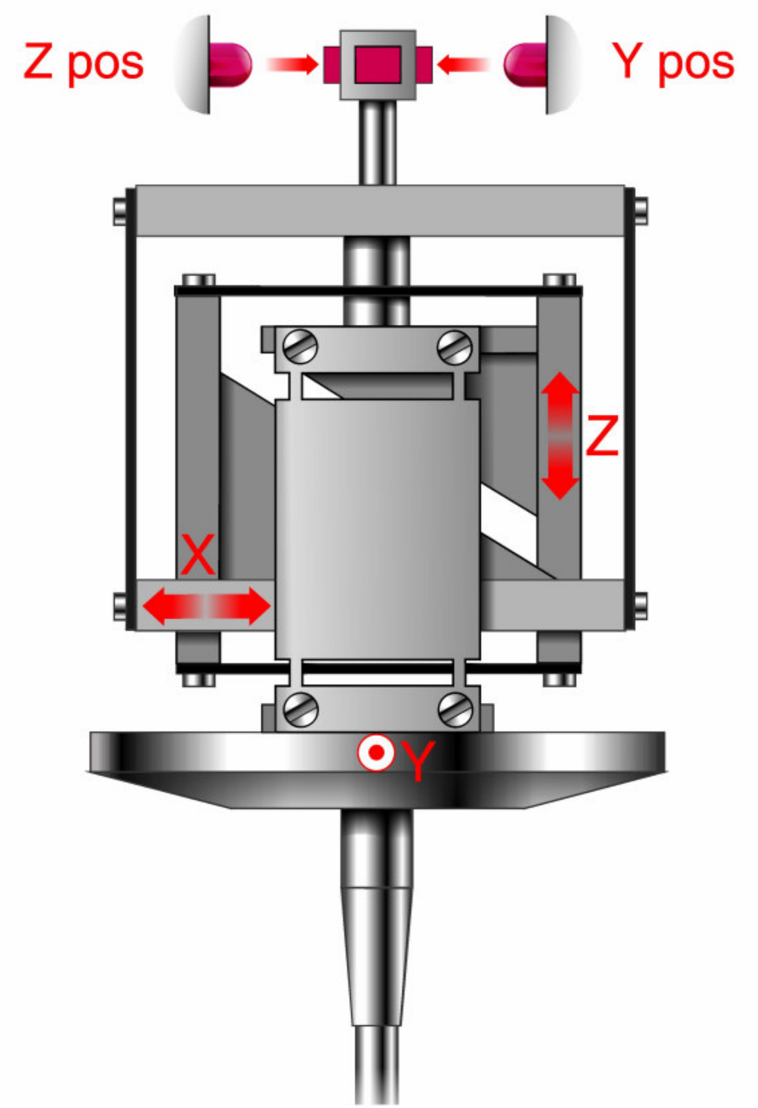
Passive sensors

Simple, compact mechanism

- no motor drives
- no locking mechanism
- no tare system
- no electromagnets
- no electronic damping

- springs generate contact force
  - force varies with deflection





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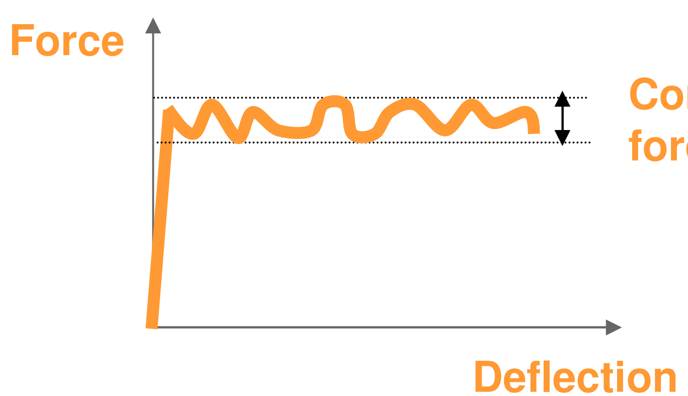
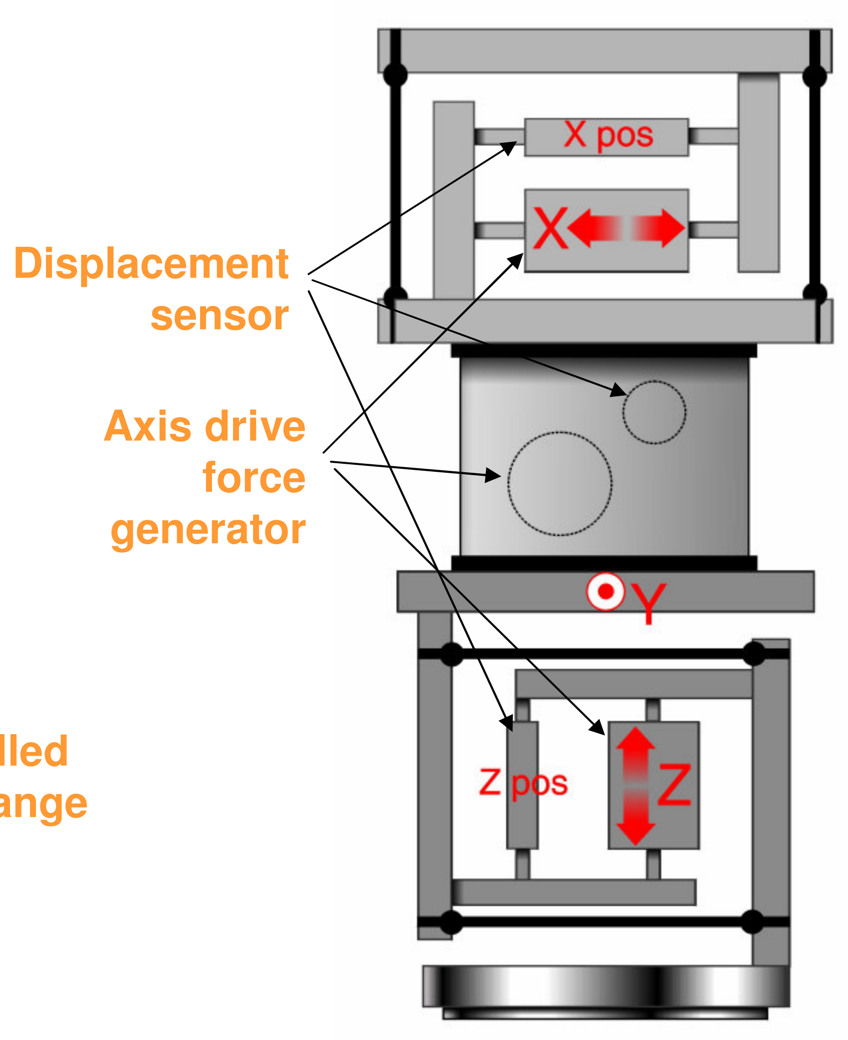
Active sensors

Complex, larger mechanism

- force generators in each axis
- force is modulated but not constant
- deflection varies as necessary
  - – longer axis travels





Scanning a ‘defined’ surface

Most scanning is performed on ‘known’ or ‘defined’ features

– feature size, position and form vary only within manufacturing and fixturing tolerances

- **Renishaw passive scanning:**
  – CMM moves around feature
    - adaptive scanning keeps deflection variation to a minimum

  – small form errors accommodated by sensor mechanism

  – small force variation due to deflection range

- **Active scanning:**
  – CMM moves around a pre-defined path

  – form errors accommodated in the sensor

  – force variation is controlled by probe motors

Active force control does not significantly reduce force variation in most scanning applications

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Scanning sensor design factors

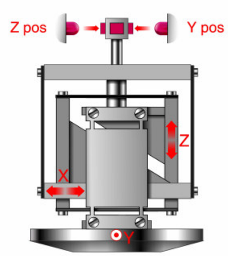
Passive sensors

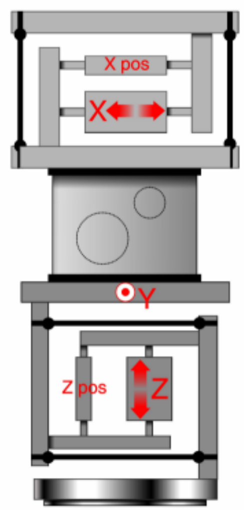
- contact force is controlled by CMM motor drive
- compact sensor that can be mounted on an articulating head
- short, light, simple styli
- low spring rates

Active sensors

- contact force is controlled by probe motor drive
- large, fixed sensor
- long, heavy styli
- motors required to suspend the stylus to avoid high contact forces

Compact passive sensor





Complex active sensor

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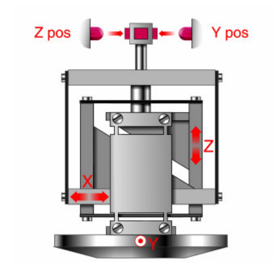
Scanning probe calibration

Passive sensors

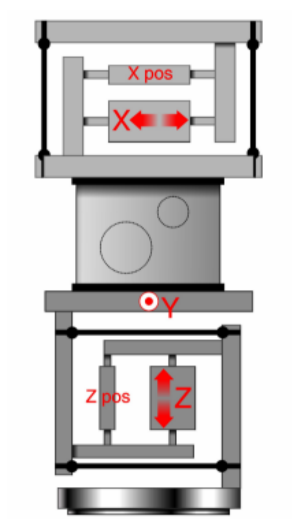
- probe characteristics, including stylus bending, are calibrated
- simple calibration cycle
- sophisticated non-linear compensation

Compact passive sensor



Active sensors

- smaller variation in contact force, but styli are less stiff
- calibration of probe mechanism characteristics and stylus bending effects at fixed force still required



Complex active sensor

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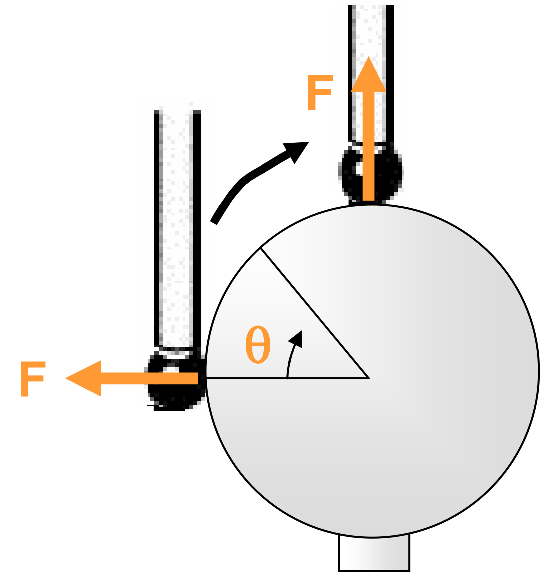
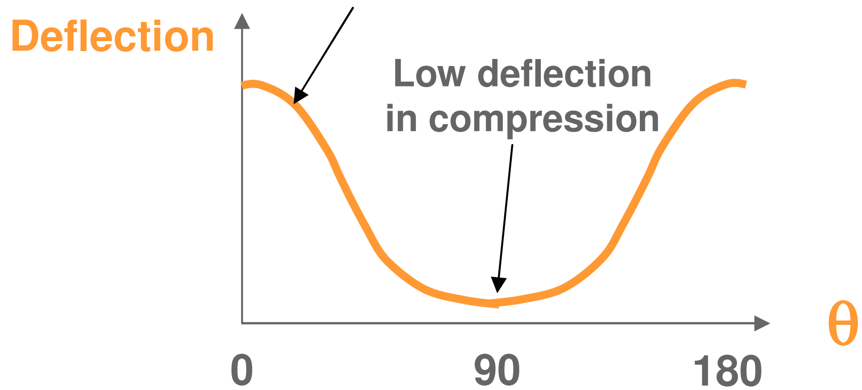
Scanning probe calibration

Constant force does not equal constant stylus deflection

- although active sensors provide constant contact force, stylus bending varies, depending on the contact vector
- stylus stiffness is very different in Z direction (compression) to in the XY plane (bending)
- if you are scanning in 3 dimensions (i.e. not just in the XY plane), this is important
  - e.g. valve seats
  - e.g. gears





Scanning probe calibration

∴ constant force does not result in better accuracy

- how the probe is calibrated is what counts

Passive sensors

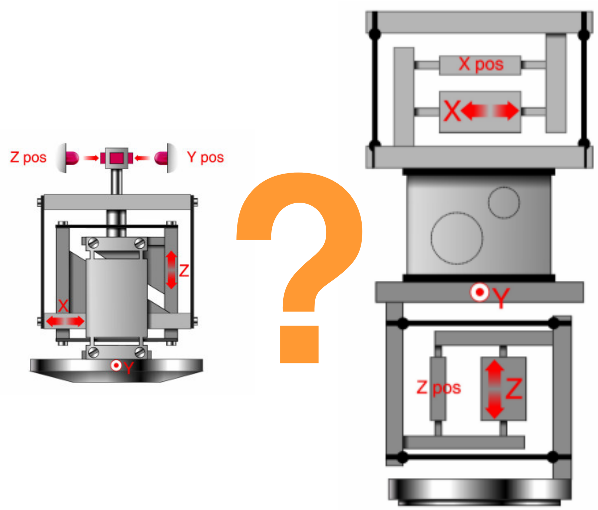
- passive probes have contact forces that are predictable at each {x,y,z} position
- scanning probe axis deflections are driven by the contact vector
- sensor mechanism and stylus bending calibrated together

Active sensors

- contact force is controlled, and therefore not related to {x,y,z} position
- no relationship between contact vector and probe deflections
- separate calibration of sensor mechanism and stylus bending

Active or passive scanning - conclusion

- Both active and passive systems achieve the basics - accurate scanning within their calibrated operating range
- Their performance and costs differ
- **Look at the specification of the system before making your choice**



Questions to ask your metrology system supplier

- **Do my measurement applications require a scanning solution?**
  - How many need to be scanned?
  - How many need discrete point measurement?
- **If I need to scan, what is the performance of the system?**
  - Scanning accuracy at high speeds
  - Total measurement cycle time, including stylus changes
- **If I also need to measure discrete points, how fast can I do this?**

Questions to ask your metrology system supplier

- **Will I benefit from the flexibility of an articulating head**
  - Access to the component
  - Sensor and stylus changing

- **What are the lifetime costs?**
  - Purchase price
  - What are the likely failure modes and what protection is provided?
  - Repair / replacement costs and speed of service

Questions?

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