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Welcome

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Motion Workshop

DENIM XI – September 2022

Stephen Cox
Simon Cooper
Bradley Beynon
Liam Cantu
Luke Nisbet

Please direct any questions to:
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Welcome the Motion Workshop

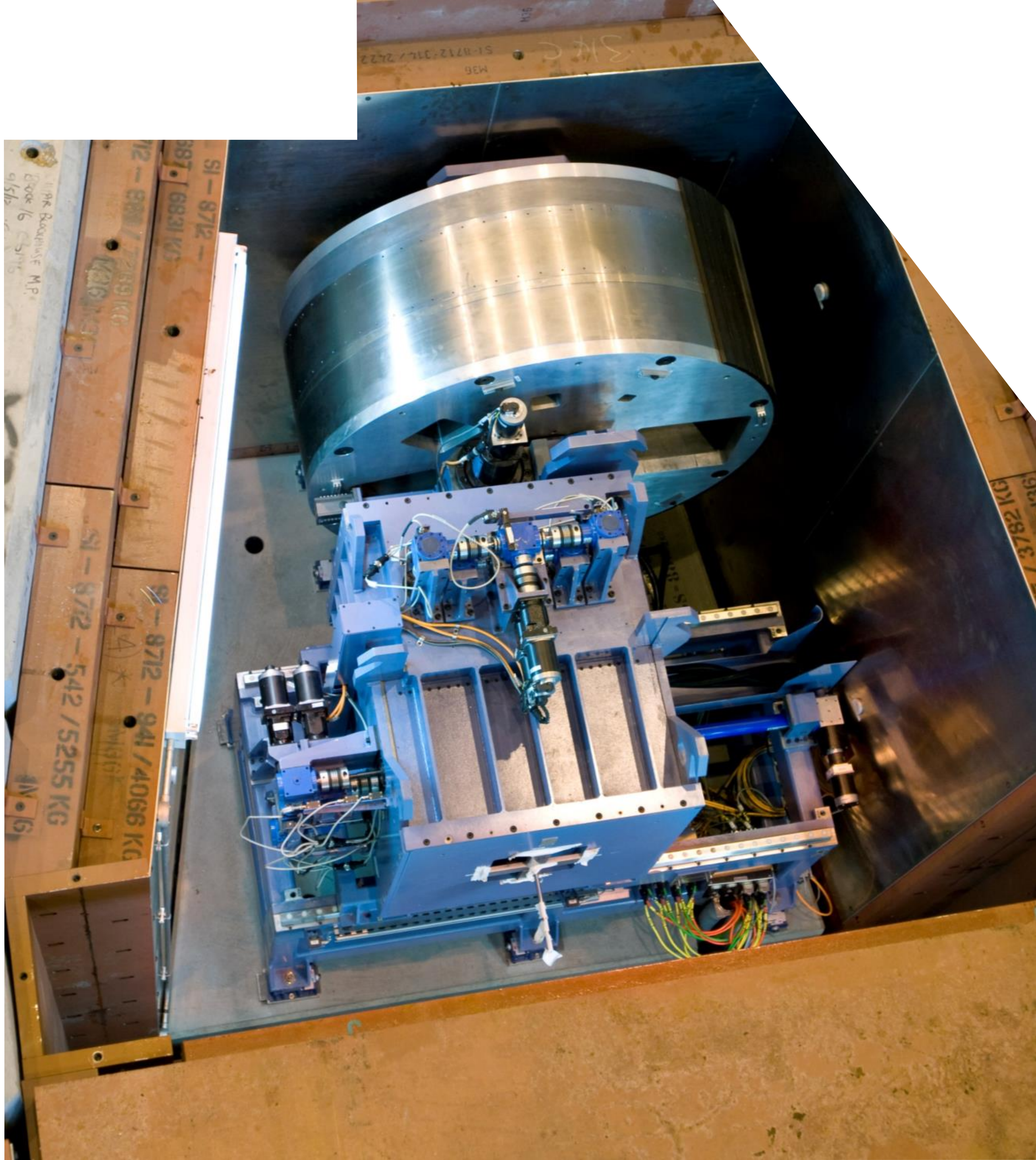
The engineering of the moving components to help us deliver the science

Meet the speakers:

- Stephen Cox
- Bradley Beynon
- Liam Cantu
- Simon Cooper
- Luke Nisbet

Format:

- Workshop - We want discussion and participation
- Please ask questions during the presentations



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Agenda

1. Neutron Motion Systems

The different uses of motion at neutron facilities and examples of motion systems

2. Motion Terminology

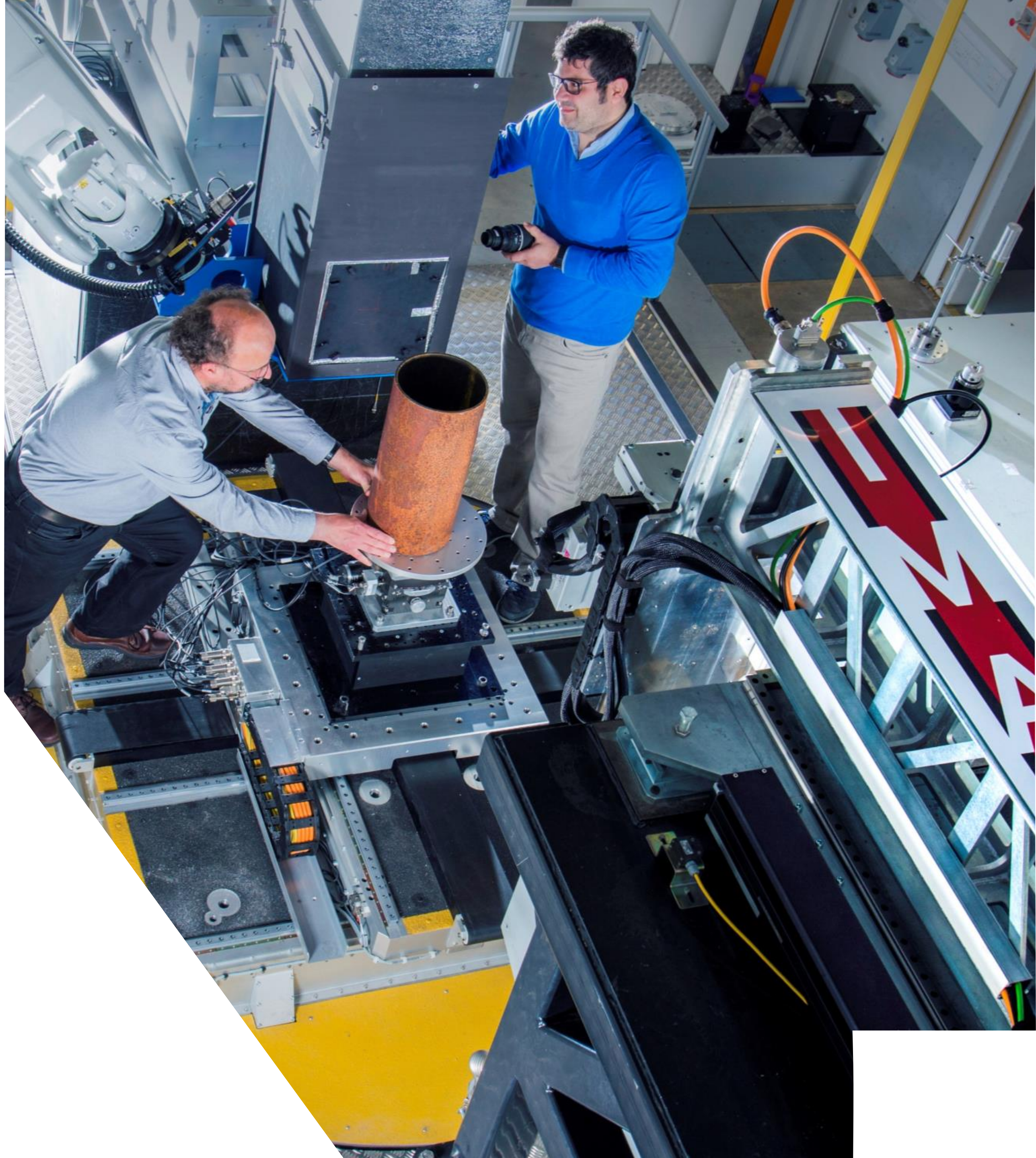
Explanation of the basic motion terms used for specifications and requirements

3. Science to Motion

How to convert scientific requirements in to motion requirements

4. Facility Specific Requirements

What aspects of a motion system may your facility standardise



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Agenda (continued)

5. Critical motion components

Selecting and specifying the critical parts of a motion axis

6. Neutron Specific Motion Components

Investigating additional challenges or restrictions on components as a result of neutron environments

7. Design for Control

How control systems can impact the design of motion systems

8. Motion Commissioning

How and why motion systems are commissioned and how to design for this

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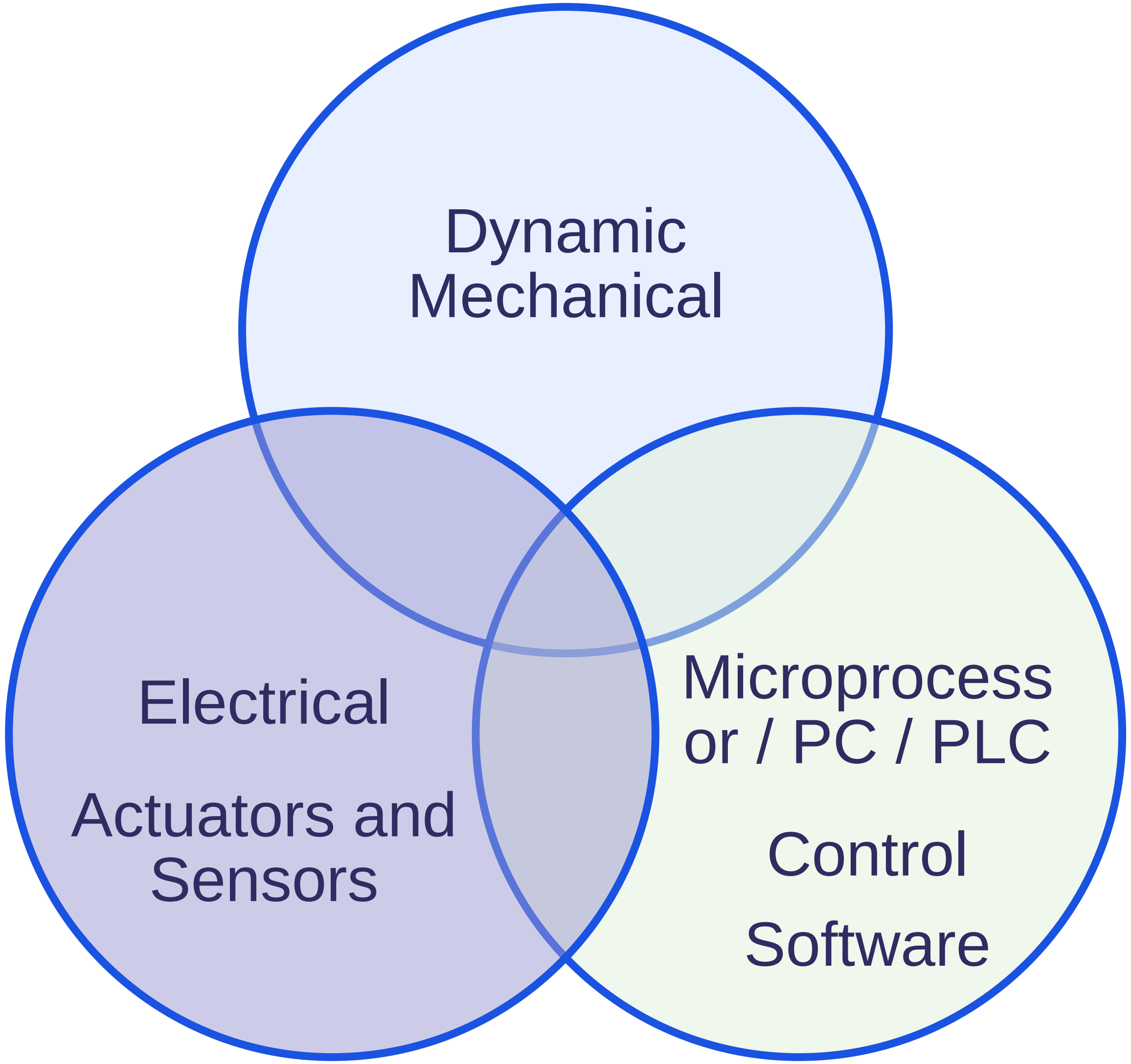
Mechatronics

- Mechatronic or Motion Design Engineer
    - Systems Integration Design
- From the start of the project
    - Cabling and wire routing
    - Control software for the application
    - User experience



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Neutron Motion Systems

The different uses of motion at neutron facilities and examples of motion systems

Neutron Motion Systems

Selection of the best energy of neutrons for the specific instrument:

Spallation Facilities - Chopper

- Neutrons come off the target in pulses but within each pulse you will have higher energy (faster) and lower energy (slower) particles
- Frequency of the spinning disc determines the particles that pass through

Reactor Facilities - Monochromator

- Reflection off a crystalline surface to select a particular kinetic energy. You might move these to tune and select

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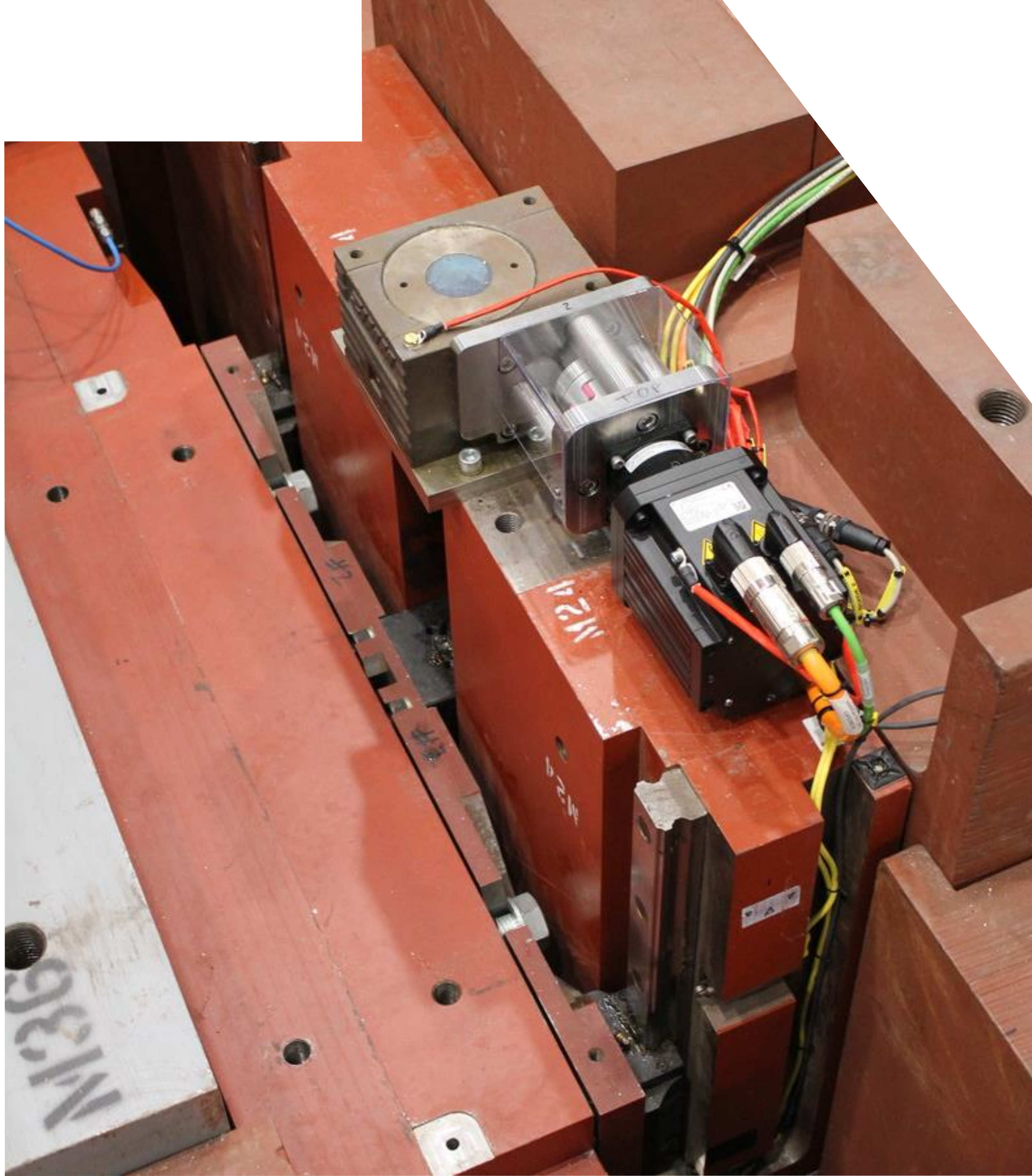
Neutron Motion Systems

Adjustable instrument neutron guides and collimation:

- Moving pieces of guide are used to tune the distance between the sample and the target in a spallation facility

- Works in a pair with motion to tune the distance between the sample and the detector



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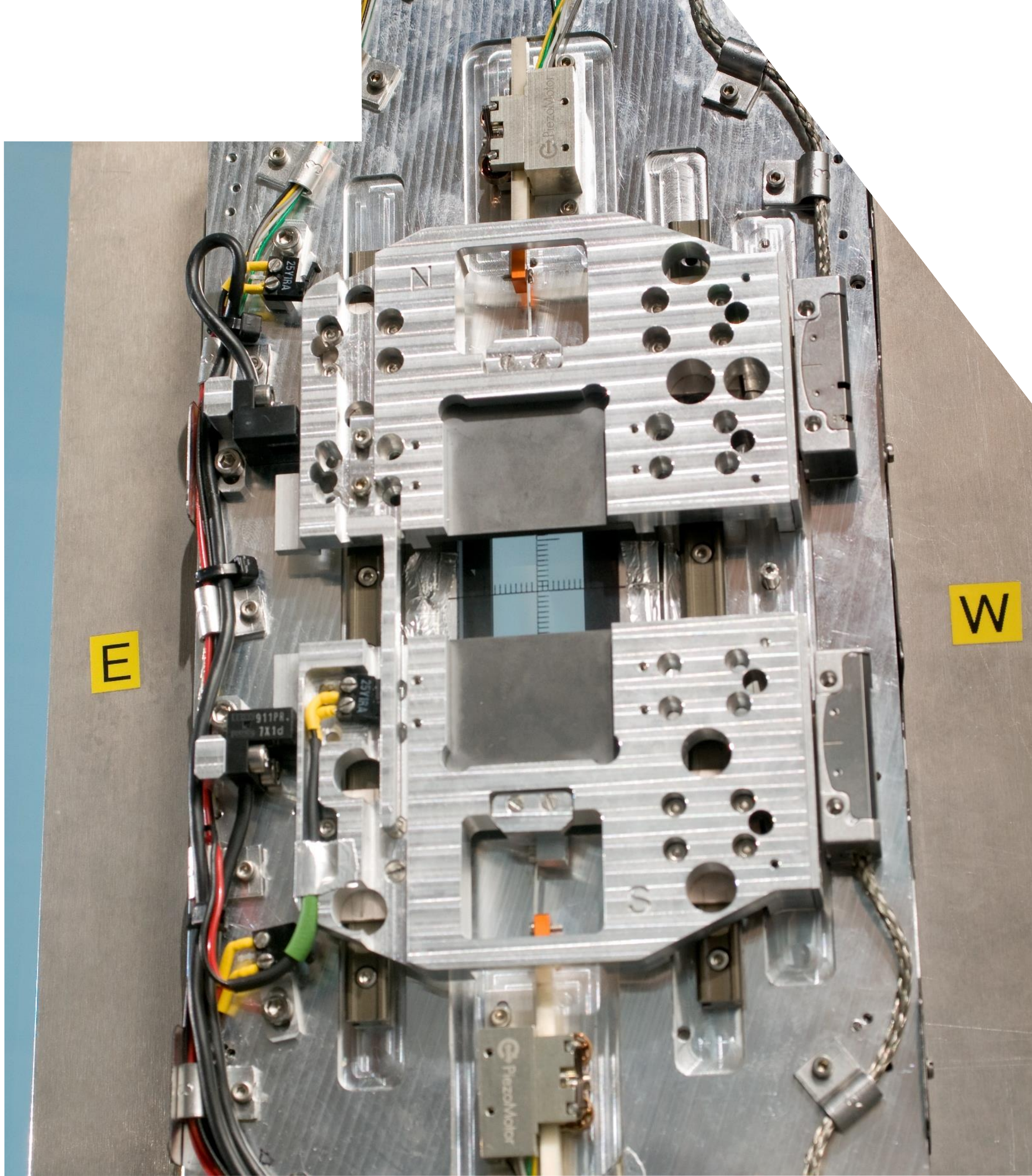
Neutron Motion Systems

Slit Set:

- A 4 axis device that is used to trim the edges of the neutron beam into a defined square of selected size
- Multiple slit sets are often used to gradually trim the beam
- Aiming to absorb beam rather than scatter it
- This reduces the amount of scattered neutrons, creating noise (unwanted signals on the detector) and radiation



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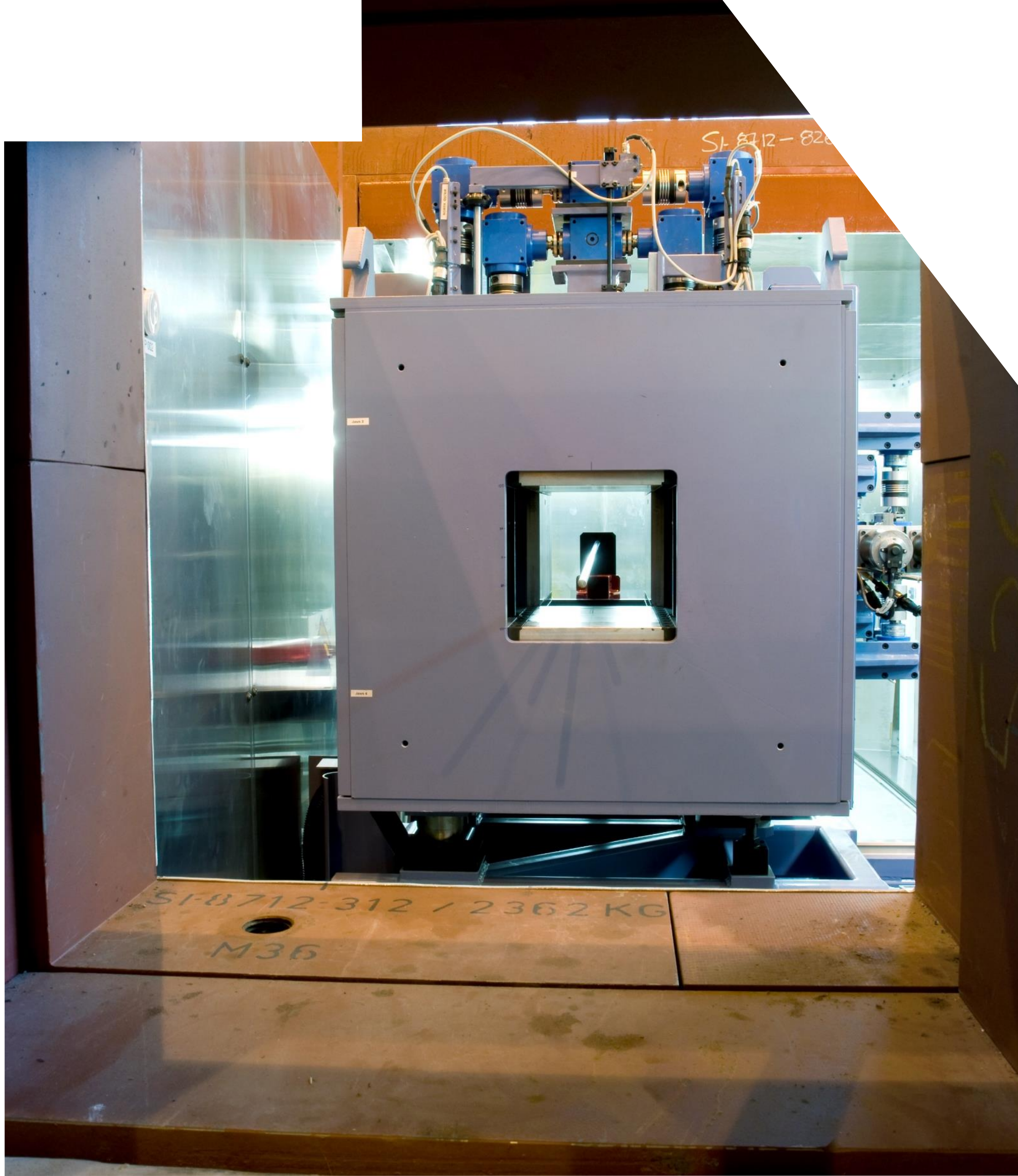
Neutron Motion Systems

Slit sets can be small or large:

- Depending on the energy of the beam
- Result is a very different motion specification and component selection



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Neutron Motion Systems

Sample Positioning System or ‘Sample Stack’:

- A multi-axis arrangement of stages
- Often has crossed linear axes to position a sample or change between multiple samples across the neutron beam
- Some applications will have adjustable height Z
- Some applications will also have stages to allow a sample to be rotated to a precise angular position
- Some applications will have rotation about Z axis
- Crossed or single arc stages

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Neutron Motion Systems

Sample Positioning System or 'Sample Stack':

- We need to include cable management into designs for these multi-axis systems
- Travel in the Z (height) direction is hard to achieve without available space under the instrument

Neutron Motion Systems

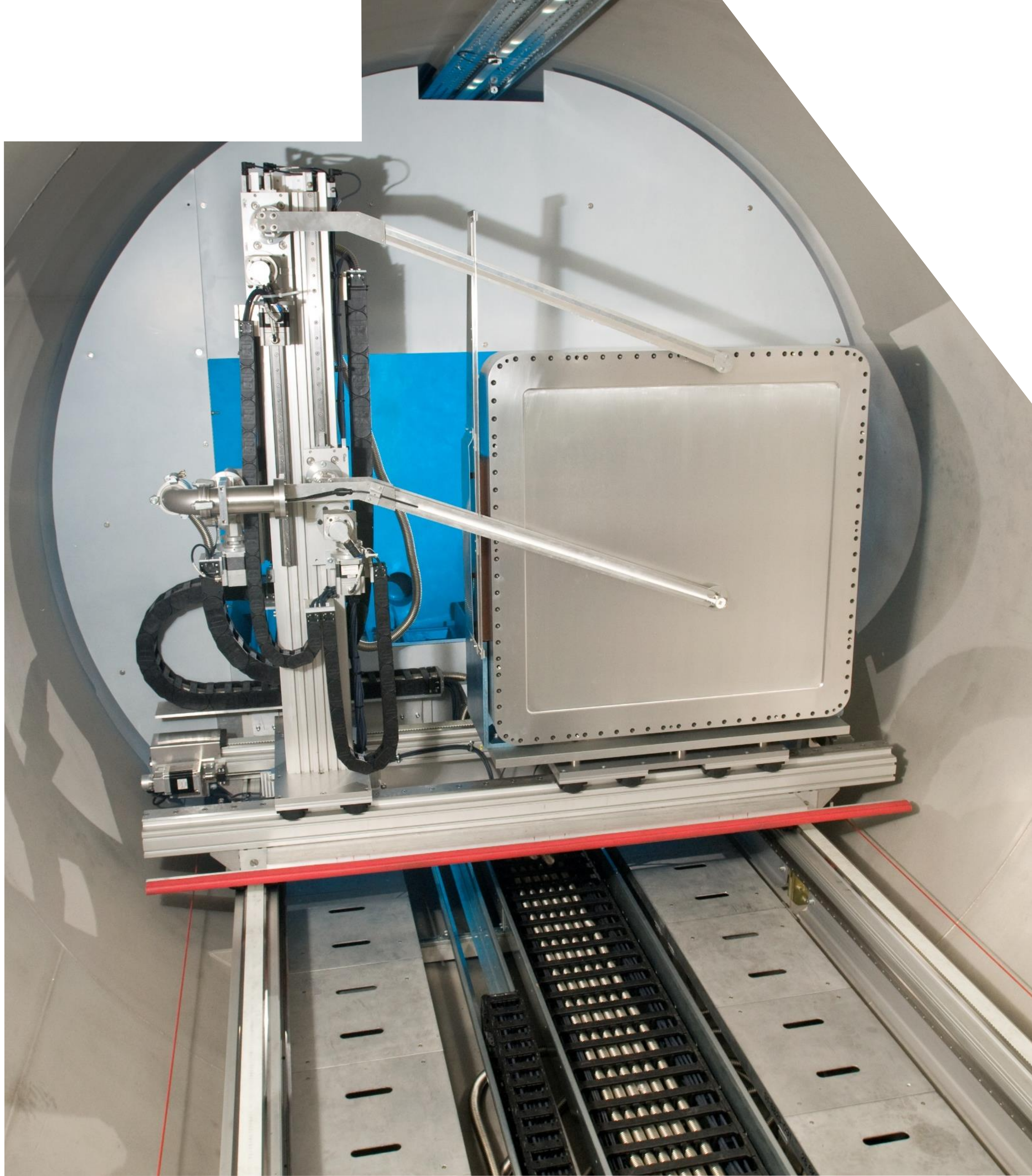
Sample Changer:

- Moving between multiple samples
- Automation to reduce the need to open the sample environment (cryogenics, furnace, etc.)
- Running overnight. Allowing the instrument scientist and users some sleep.

Neutron Motion Systems

Moving the detectors:

- Tune the distance between the sample and the detector
- Here the detector is moved inside a vacuum chamber
- In this application we also have moving arms to block sections of high intensity beam



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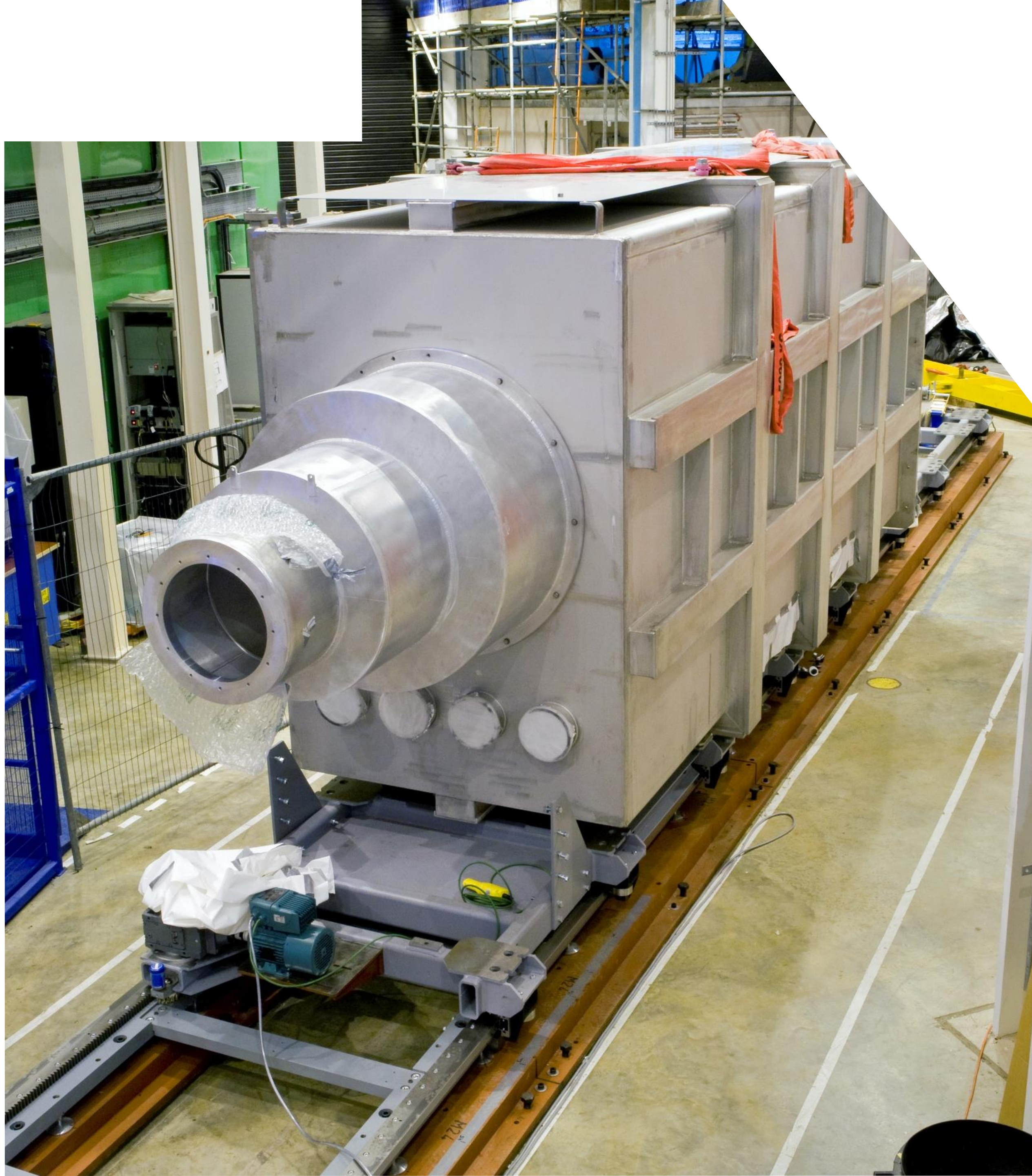
Neutron Motion Systems

Moving the detectors:

- We can also move the vacuum chamber itself, with the detector bank inside



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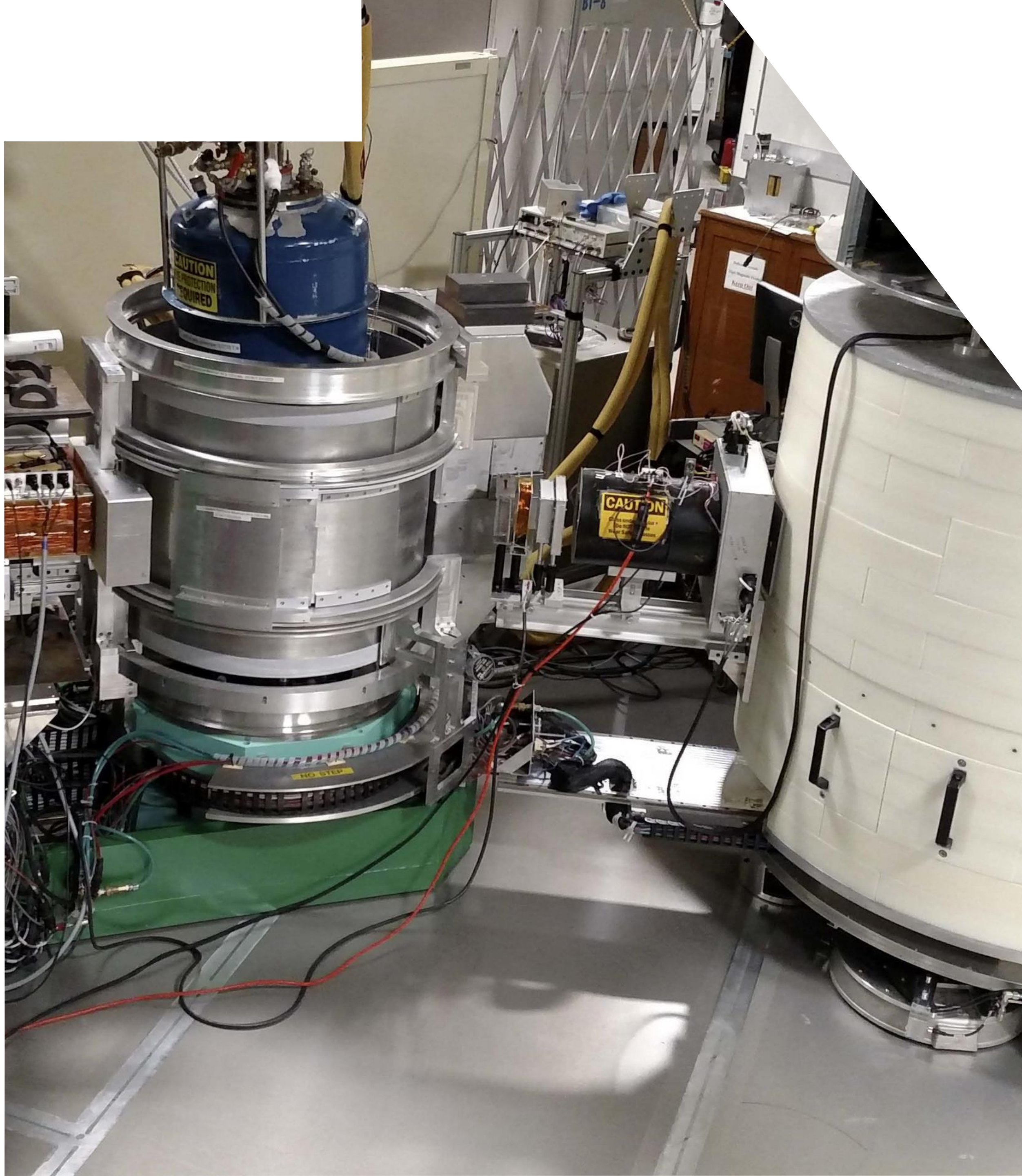
Neutron Motion Systems

Selection of the best energy of the neutrons for the specific instrument

- Reactor – Analyser
- Analysing crystals reflect neutrons of specific wavelengths to the individual detector elements
- An analyser can often be rotated about the sample point. Often floated on air pads.



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Motion Terminology

Explanation of the basic motion terms used for specifications and requirements

Definitions

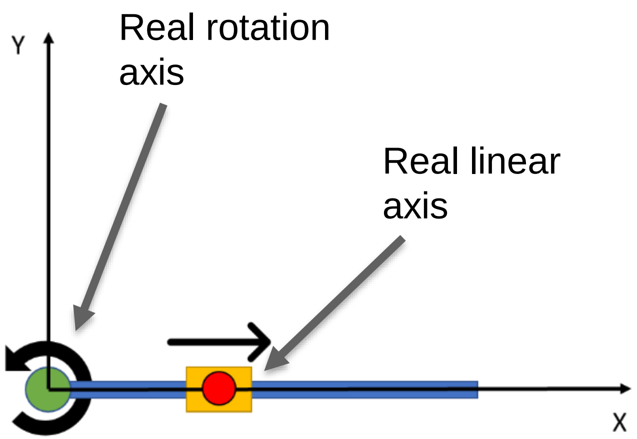
Motion Axis: A single Degree of Freedom in a system that is measured and controlled (linear or rotary)

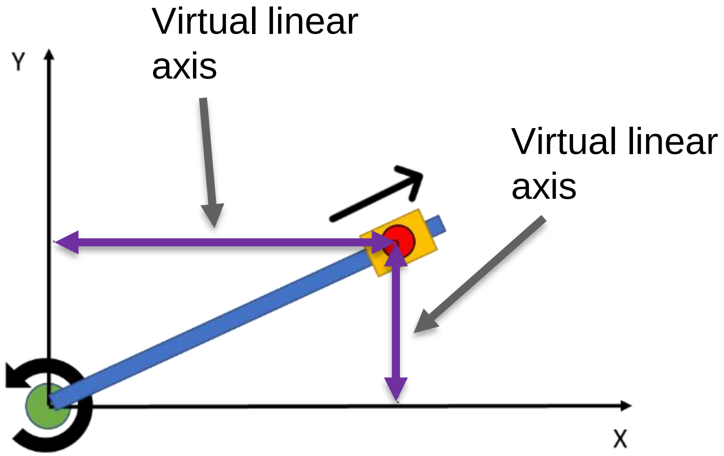
- *Real Axis*

  Consists of physical hardware that controls an output

- *Virtual Axis*

  Software-based axis whose output is driven and determined through indirect relationships with other axes e.g. position of sample in XY





Definitions

Motion System: A combination of real and virtual axes used to achieve a desired outcome

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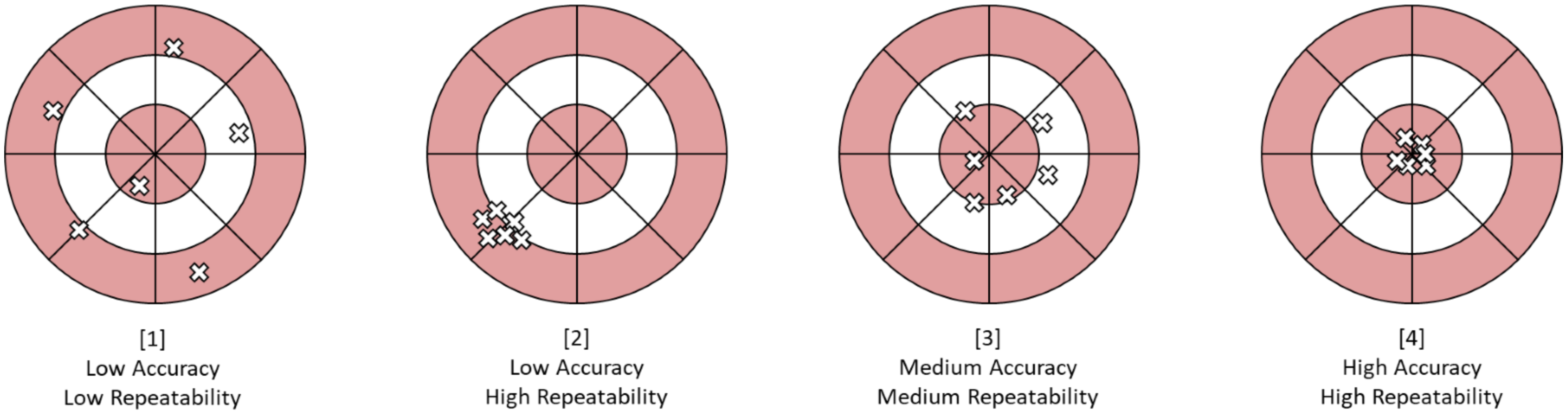
Definitions

- **Accuracy**:

The maximum positional error recorded between commanded and achieved position over the range of travel of an axis.

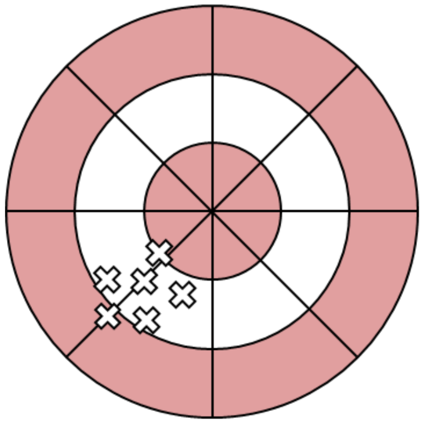
- **Repeatability**:

The position deviation measured for repeated commands to the same position.

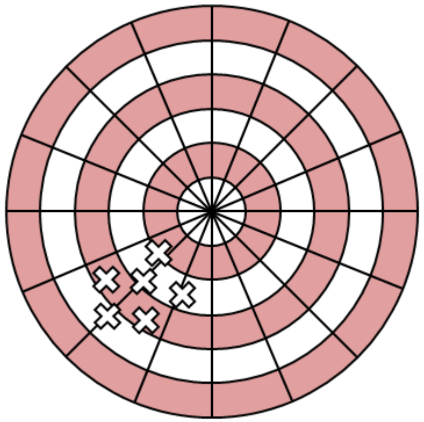


Definitions

Resolution: The smallest possible change in a value that can be measured and controlled.



[5]
Low Feedback Resolution



[6]
High Feedback Resolution

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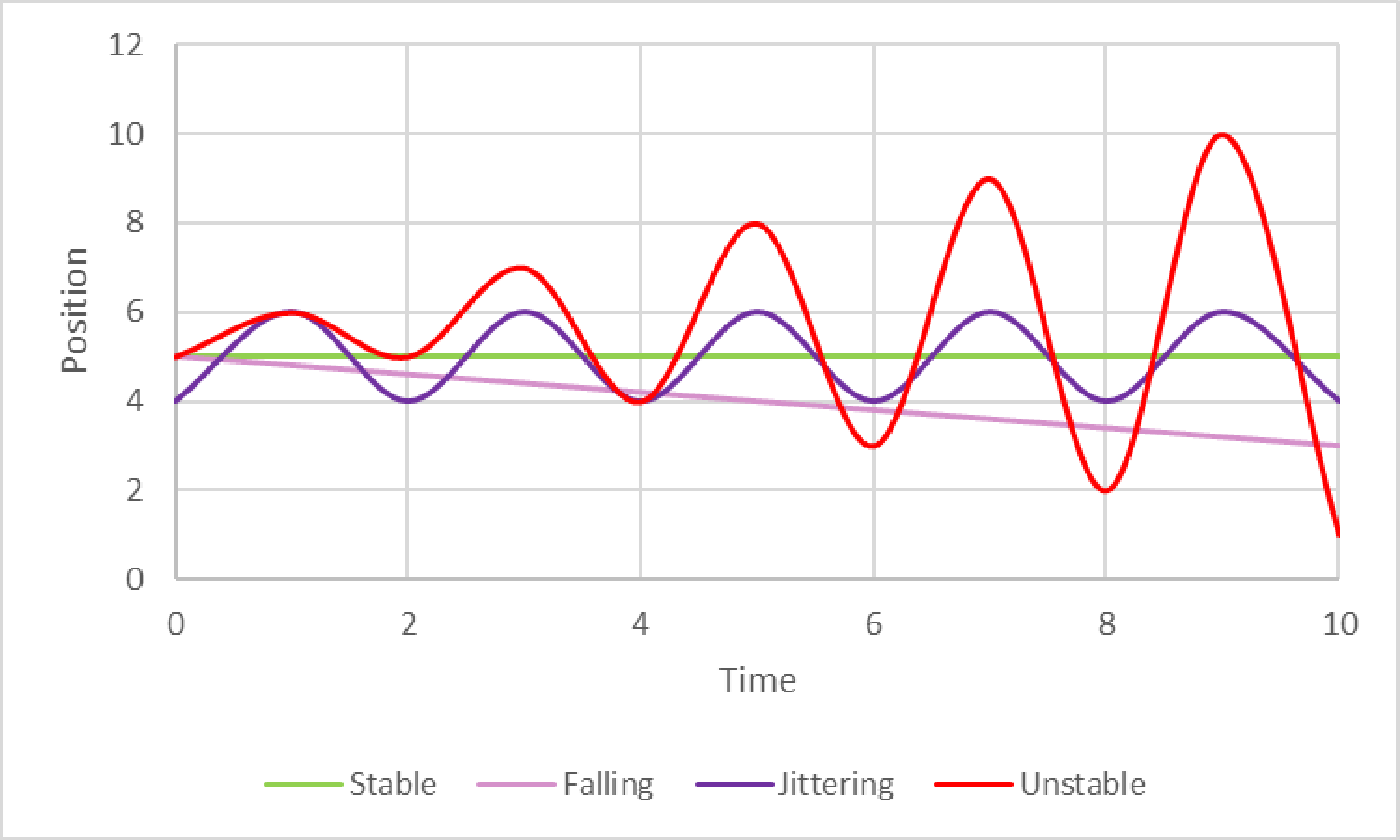
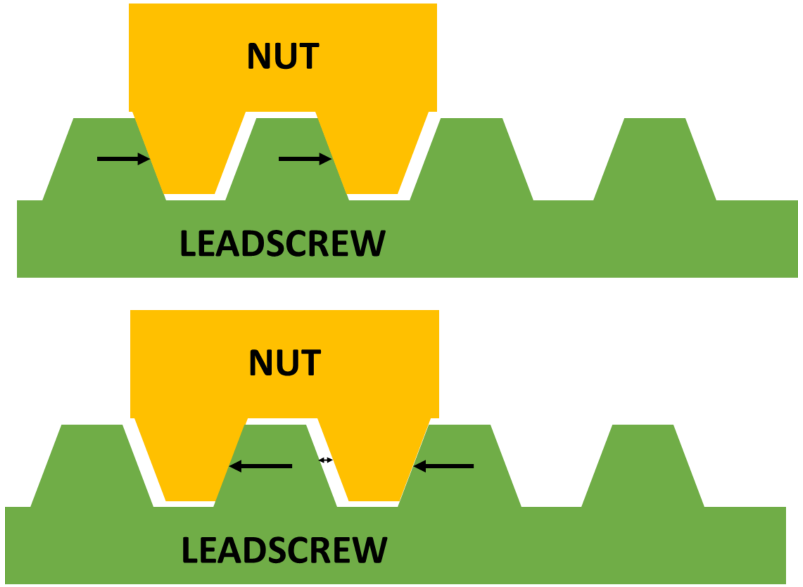
Definitions

Stability: How well an output position is held over time.



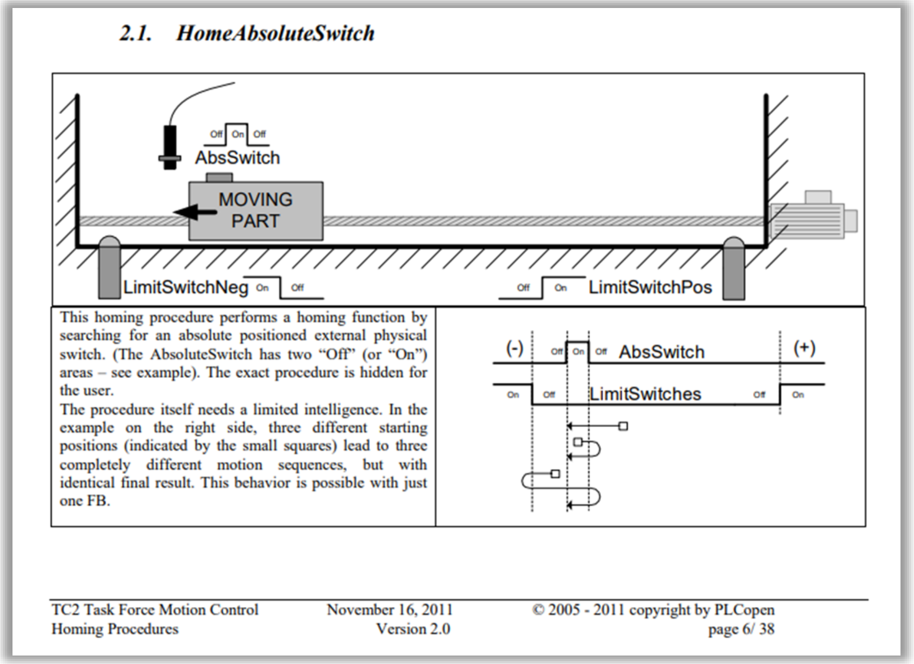
Definitions

Backlash (Play): Looseness in a system caused by clearance and gaps that results in lost motion. Often seen in lead screw systems.



Motion System Features

- **Motion Control System:** The combination of hardware and software to drive axes
- **Calibration:** Routines or procedures done to improve accuracy or repeatability.
- **Homing:** A procedure that couples a position to an axis. Used to move the axis to a known position, usually a limit or home switch.
- **Commissioning:** Ensuring motion systems meet specification. Involves running the system and measuring, modelling and compensating for inaccuracies.



2.1. HomeAbsoluteSwitch

This homing procedure performs a homing function by searching for an absolute positioned external physical switch. (The AbsoluteSwitch has two "Off" (or "On") areas – see example). The exact procedure is hidden for the user.
The procedure itself needs a limited intelligence. In the example on the right side, three different starting positions (indicated by the small squares) lead to three completely different motion sequences, but with identical final result. This behavior is possible with just one FB.

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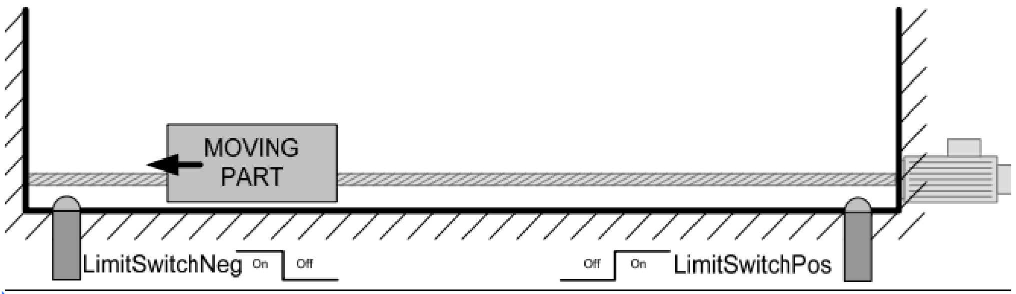
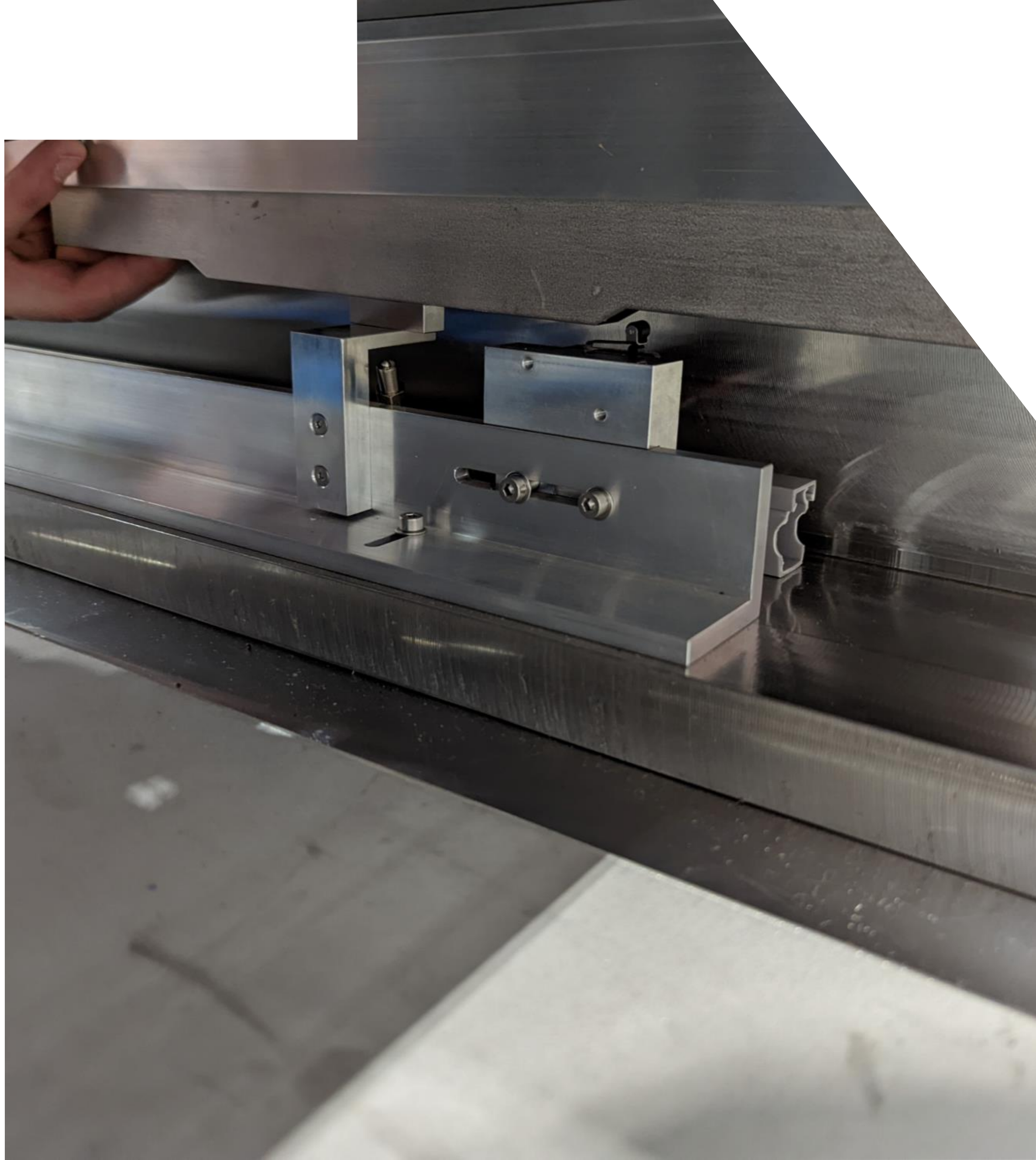
Motion System Features

Limits:

Used to define the operational range of motion for the system.

- **Hard limits:** Physical blocks such as end stops
- **Soft(ware) limits:** Virtual limits based on set up or configured during run time
- **Switches:** Physical switches that indicate travel range is reached when triggered.





Motion System Features

Machine Safeguards:

- Controls put in place to prevent occurrence of hazards and their severity, decided on following a risk assessment e.g.
    - Light curtains,
    - Bump strips
    - Enabling devices

- Enabling devices are used to confirm that the motion operation is performing correctly
    - Any issues, releasing the enabling switch stops motion

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Science to Motion

How to convert scientific requirements in to motion requirements

Science to Motion

A vital step is to define the requirements well and to then agree **AND FIX** the specification, before the design work starts.

We need to capture in words:

- How the new component will need to be used
- What are the common science setups

We then need to explore the limitations of the existing instrument:

- What can we measure at the detector?
- What are the environmental constraints?

We need something to test against at commissioning.

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Science to Motion

Then develop the motion requirements in numerical terms:

Axis title: Rotation	
Axis specification	**Value**
Type of axis	driven
Power off condition of motor i.e. braked	braked
Travel (mm)	10.5° @ R3.0m = 550mm [1]
Speed of travel (°/min)	>20 °/min
Positional accuracy (°)	radial motion ±20.0 m°
Positional repeatability (°)	Minimum required: <±4.0 m°
	Desired: ±2.0 m°
Motion resolution (°)	Minimum: 1.0 m°
	Desired: <1.0 m°
Type of encoder to be used	could be rotary or linear tape on an arc
Mass to be rotated without vessel extension [current situation] (kg)	Circa 800kg [detector + vacuum vessel]
Mass to be rotated with vessel extension in place (kg)	Circa 1000kg [detector + vacuum vessel + extension]
Distance travelled per average day (300 day/year).	8000mm/day

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Facility Specific Requirements

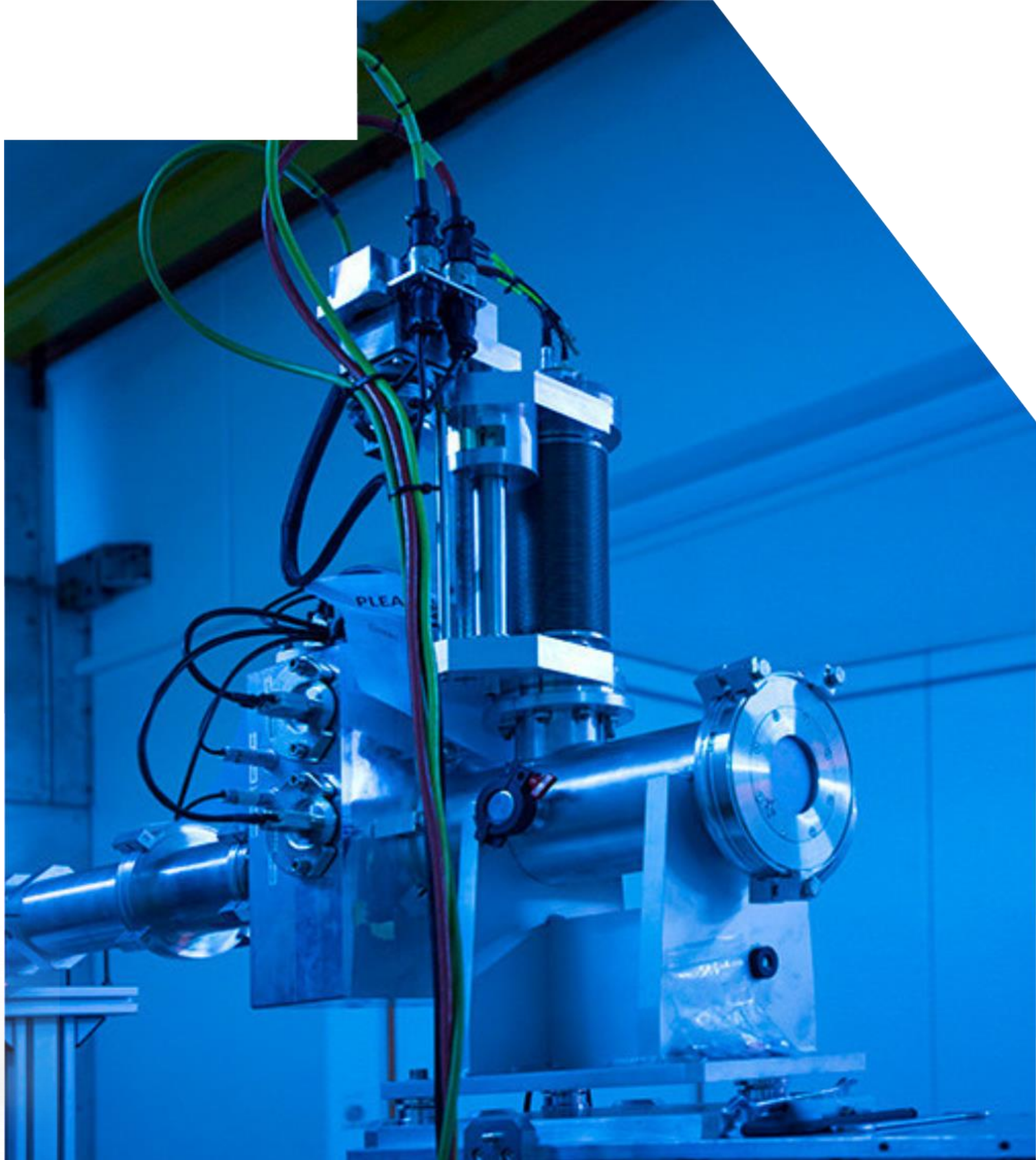
What aspects of a motion system may your facility standardise

Facility Specific Requirements

Each of our science facilities will have specific requirements that will impact the design.

Some examples are:

- Standard parts – We will only use this range of motors etc.
- Integration with Personnel Protection or Safety Systems (PPS, PSS)
- Machinery safety standards



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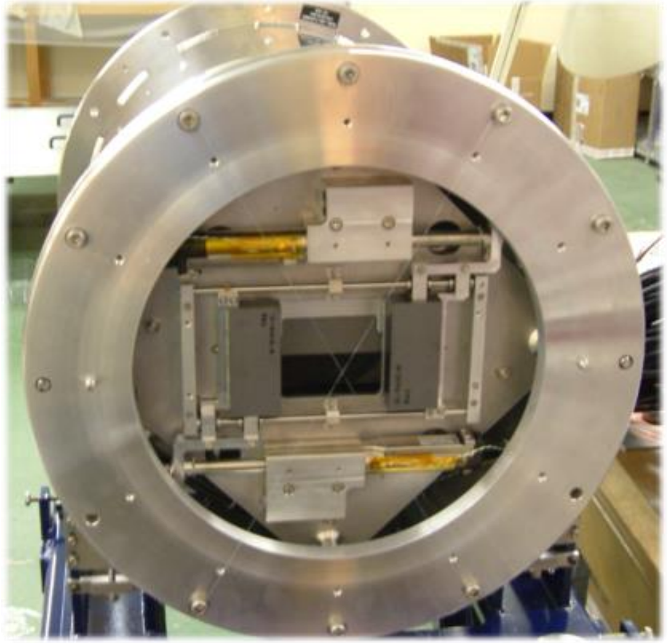
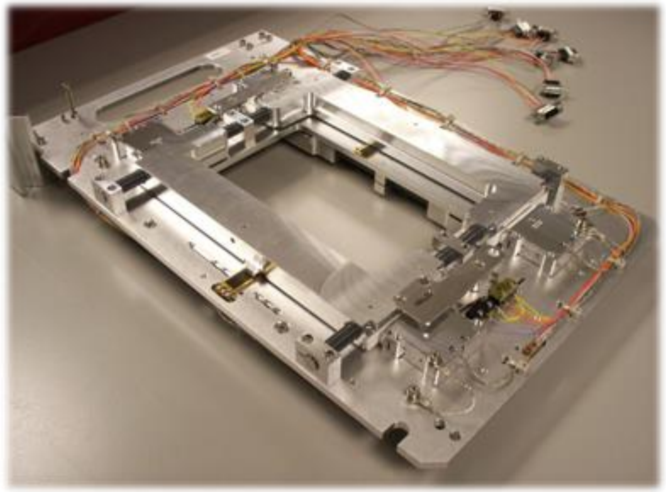
Critical Motion Components

Selecting and specifying the critical parts of a motion axis

System Components

- Motion Guides
- Mechanical Drive
- Motor and Gearing Selection
- System Feedback
- Cable Management





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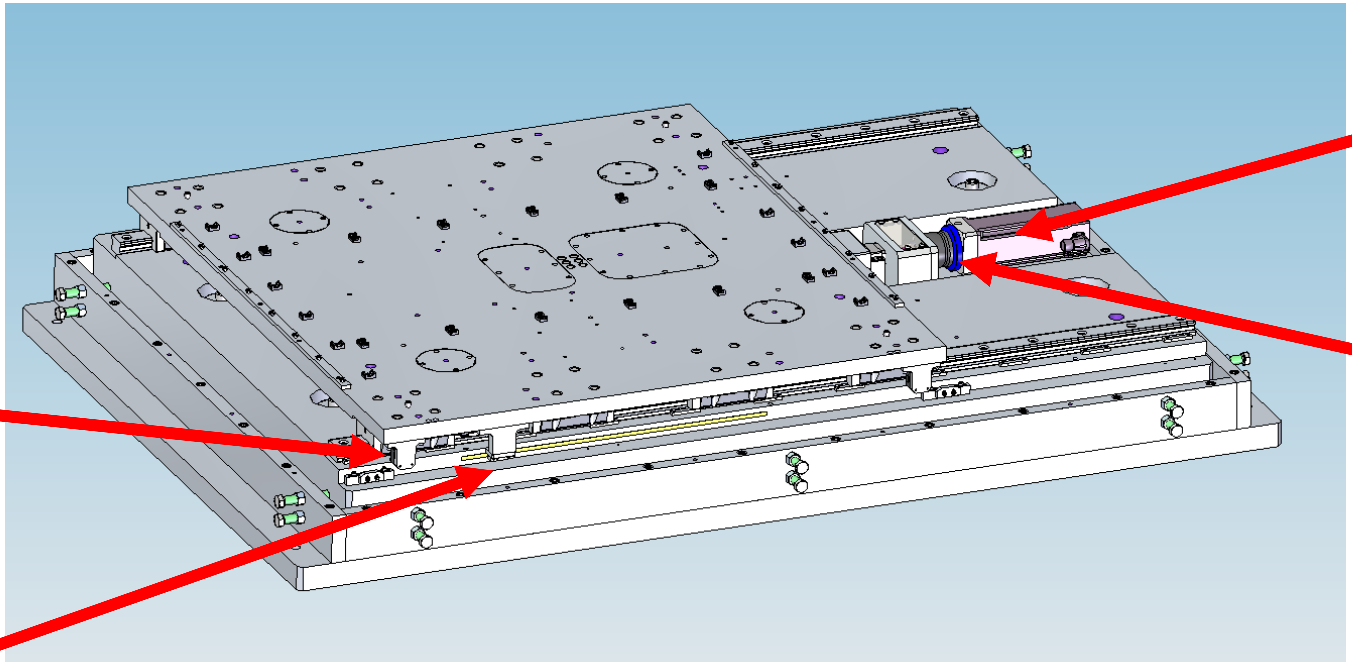
Example Motion System

This is a horizontal axis for the INTER Instrument



Servo Motor

Planetary Gearbox

Limit Switch

Linear Encoder Readhead

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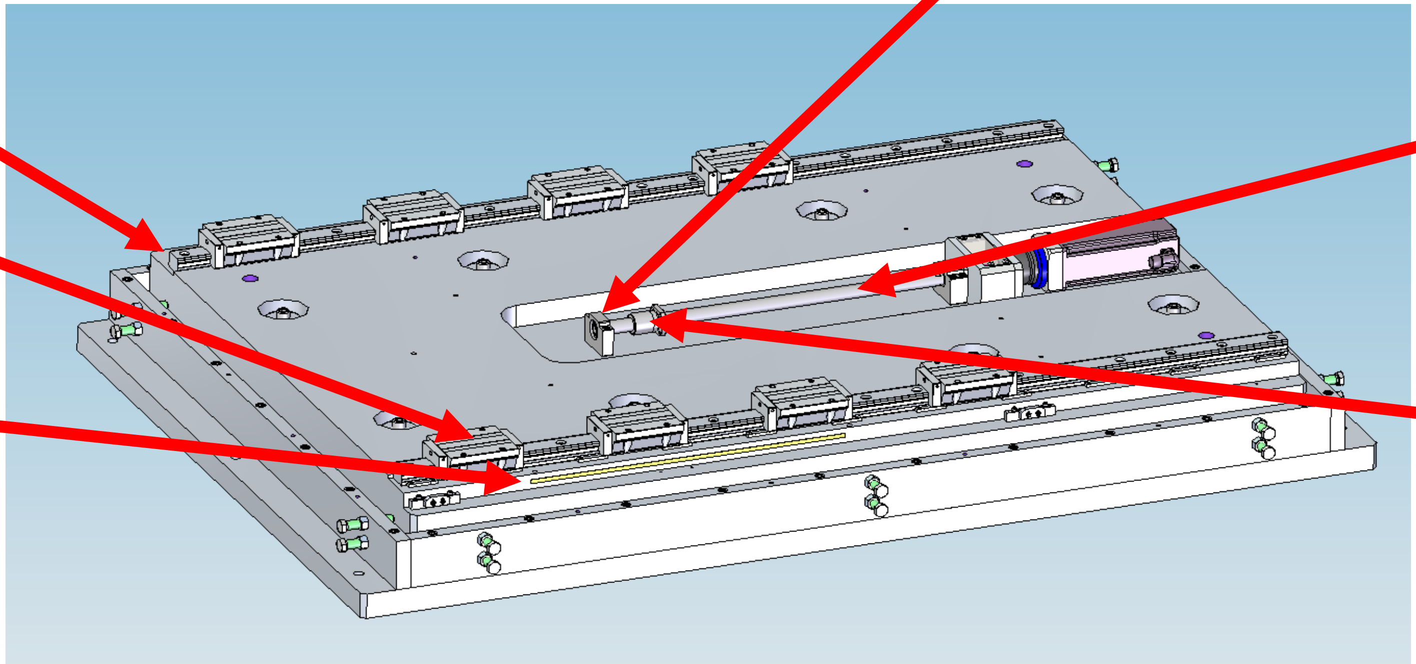
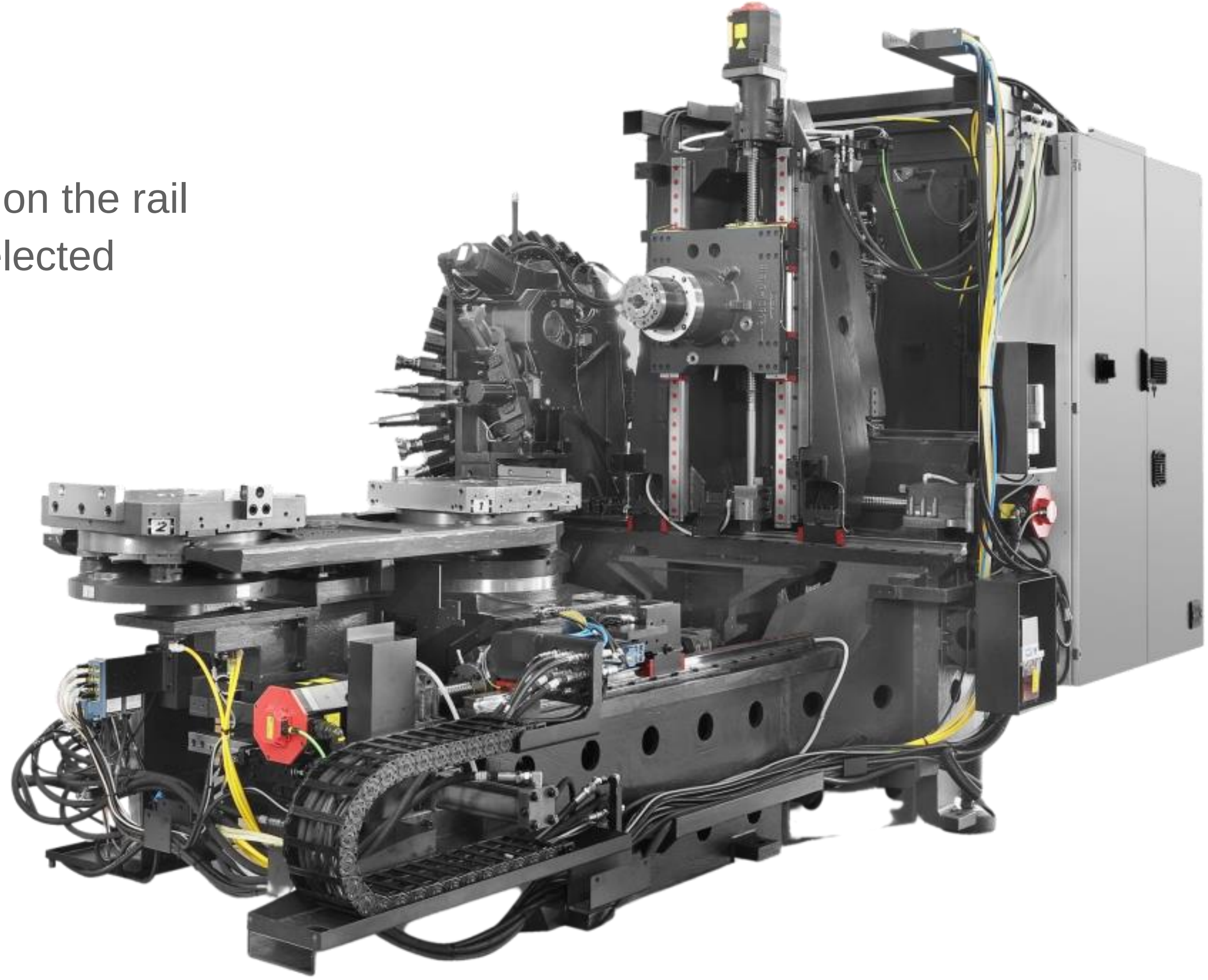
Example Motion System



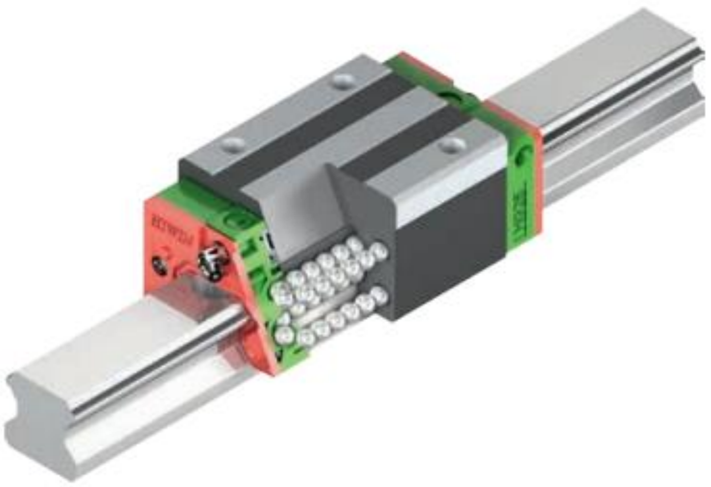
Selecting Motion Guides

1. **Select a style of motion guide**
2. Select the accuracy grade
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. Determine the preload and rigidity
6. Calculate the system lifetime
7. Select the type of lubrication

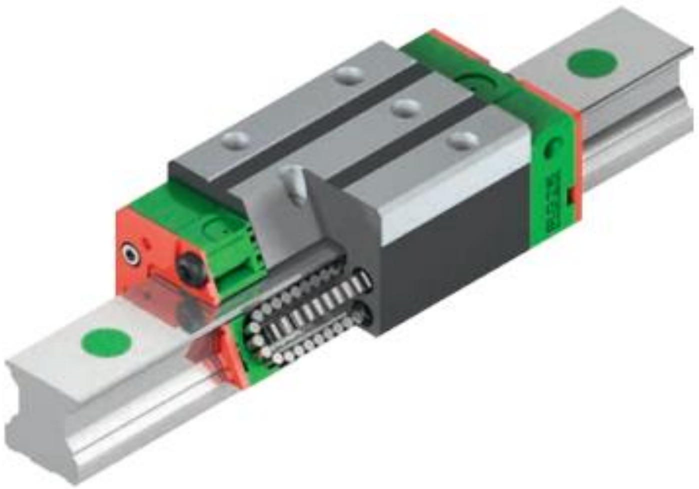


Motion Guide Styles

- Linear Rails
  - Ball type rolling guides
  - Roller type rolling guides



Design of the HG series



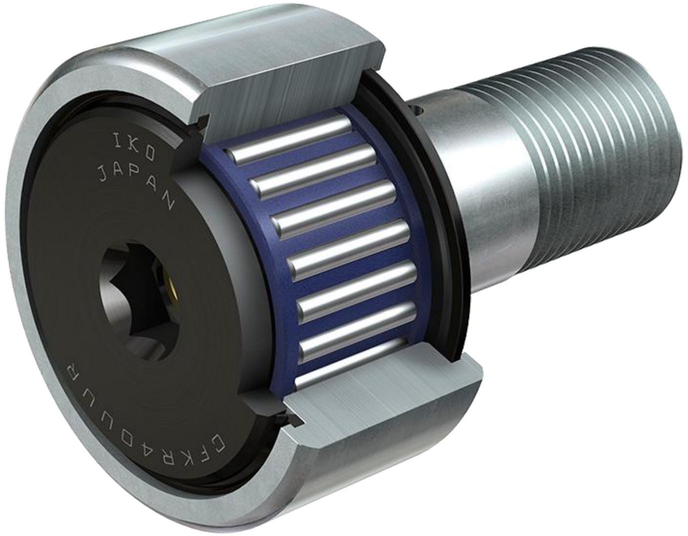
Design of the RG series

Motion Guide Styles

- Ball spline rolling guides
- Shaft guidance system

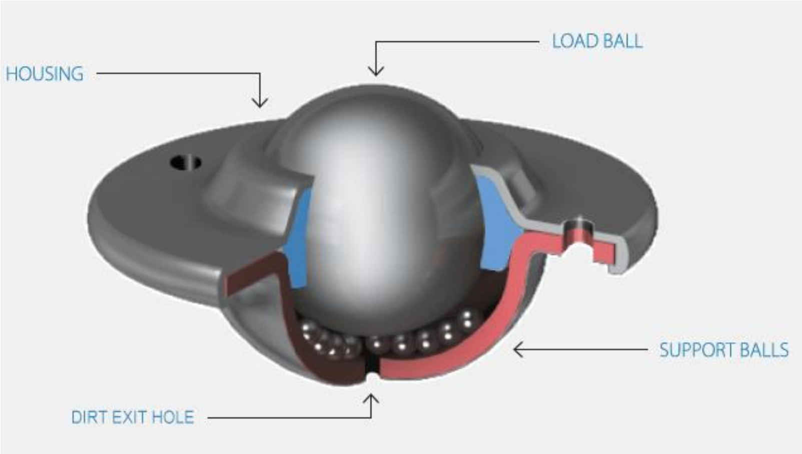
Motion Guide Styles

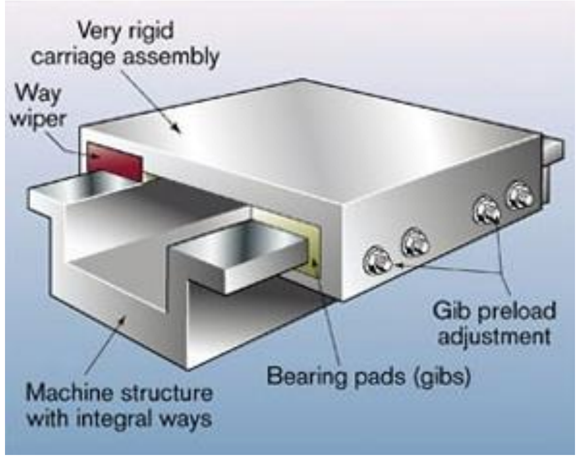
- Vee Wheel bearings
- Cam followers

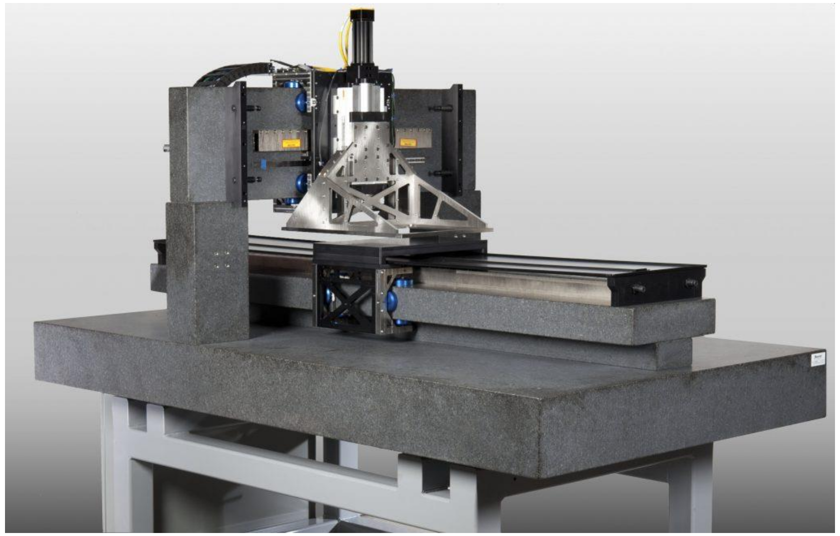


Motion Guide Styles

- Ball transfer units
- Plain linear bearing (Boxway slides)
- Air Bearings







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Selecting the accuracy grade

1. Select a style of motion guide
2. **Select the accuracy grade**
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. Determine the preload and rigidity
6. Calculate the system lifetime
7. Select the type of lubrication

Most linear rails have 5 accuracy classes

- Normal grade
- High accuracy grade (H)
- Precision grade (P)
- Super precision grade (SP)
- Ultra precision grade (UP)

Selecting the accuracy class will be based on your application and your accuracy requirements.

Although some things to consider before selecting very high accuracy classes are:

- Is the structure the rail is mounted onto rigid and stable enough for this level of accuracy? i.e don't put high accuracy rails on a thin or flexible structure
- What is your budget and time scales, as most high accuracy rails are custom made in Japan or other countries so have long delivery times

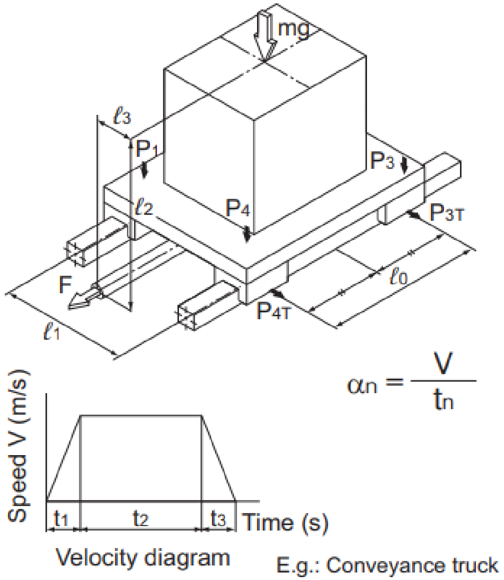
Selecting guide configuration

1. Select a style of motion guide
2. Select the accuracy grade
3. **Define the size and number of blocks on the rail**
4. **Calculate the maximum load of the selected blocks**
5. Determine the preload and rigidity
6. Calculate the system lifetime
7. Select the type of lubrication

Guide Configurations

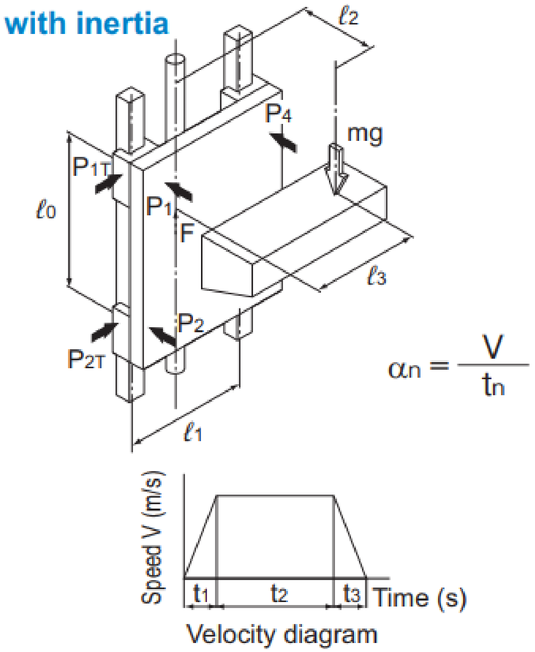
- There are lots of different guide configurations but the 2 most common are:
  - Horizontal mount with inertia
  - Vertical mount with inertia
- The inertia doesn't always have a large impact on systems, especially if they are slow moving, but it's always best practice to take it into account

Horizontal mount with inertia



E.g.: Conveyance truck

Vertical mount with inertia



E.g.: Conveyance lift

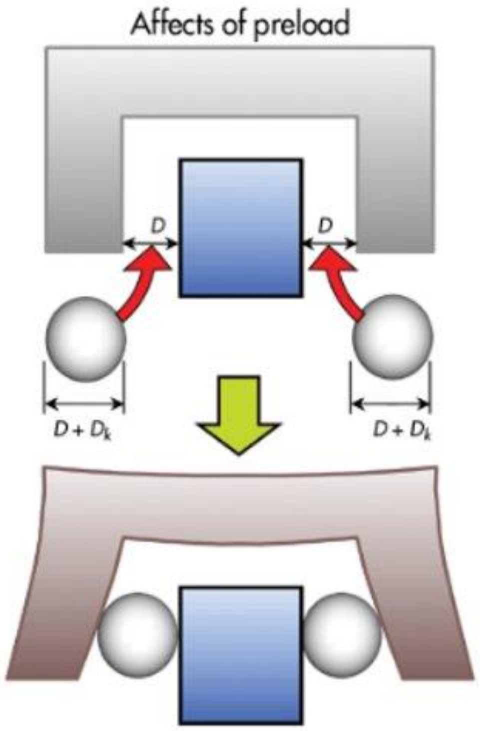
Determine the preload and rigidity

1. Select a style of motion guide
2. Select the accuracy grade
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. **Determine the preload and rigidity**
6. Calculate the system lifetime
7. Select the type of lubrication

Determine the preload

- The preload is usually application specific and some applications can be seen below:

	Normal Clearance	Clearance C1 (Light Preload)	Clearance C0 (Medium Preload)
Condition	• The loading direction is fixed, impact and vibrations are minimal and 2 rails are installed in parallel. • Very high precision is not required, and the sliding resistance must be as low as possible.	• An overhang load or moment load is applied. • LM Guide is used in a single-rail configuration. • Light load and high accuracy are required.	• High rigidity is required and vibrations and impact are applied. • Heavy-cutting machine tool
Examples of applications	• Beam-welding machine • Book-binding machin • Automatic packaging machine • XY axes of general industrial machinery • Automatic sash-manufacturing machine • Welding machine • Flame cutting machine • Tool changer • Various kinds of material feeder	• Grinding machine table feed axis • Automatic coating machine • Industrial robot • various kinds of material high speed feeder • NC drilling machine • Vertical axis of general industrial machinery • Printed circuit board drilling machine • Electric discharge machine • Measuring instrument • Precision XY table	• Machining center • NC lathe • Grinding stone feed axis of grinding machine • Milling machine • Vertical/horizontal boring machine • Tool rest guide • Vertical axis of machine tool



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Determine the rigidity

- The rigidity is dependant on the preload and size of the linear rail selected. The rigidity value for each rail type and preload is normally looked up from a table and then the deflection can be calculated using the calculated load.

$$\delta = \frac{P}{K}$$

K	: Rigidity value	(N/μm)
δ	: Deflection	(μm)
P	: Calculated load	(N)

Selecting guide configuration

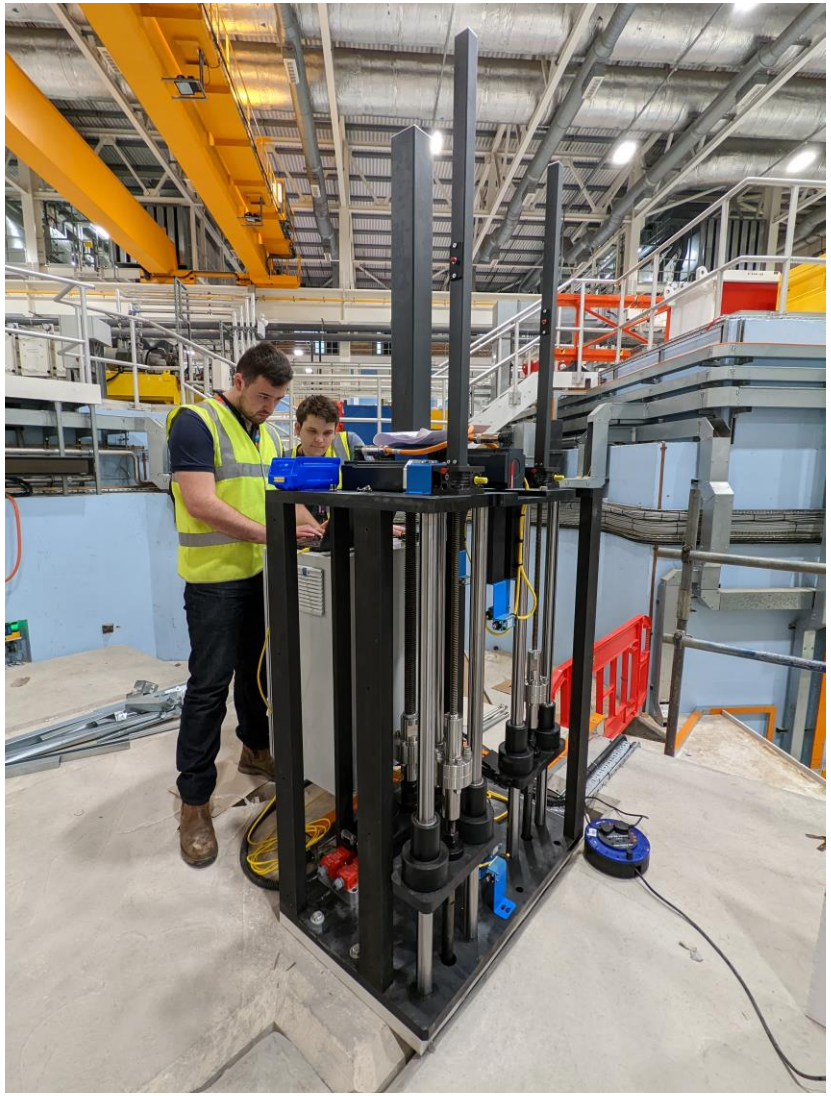
1. Select a style of motion guide
2. Select the accuracy grade
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. Determine the preload and rigidity
6. **Calculate the system lifetime**
7. **Select the type of lubrication**

Selection Tools

- Most Linear rail catalogues have step by step instructions for selecting and designing linear rails (for Example THK, IKO, Hiwin, SKF, Hepco, Schaeffler, Schneeberger)
- Also ask Linear rail suppliers to help specify rails for systems. Most have application engineers that are experts and can help specify an appropriate rail.
- THK have a linear rail online selection tool as well as a lifespan calculator

Selecting a drive mechanism

1. **Select a style of motion drive**
2. Select an initial motor type
3. Calculate system parameters such as
   - System speed / acceleration
   - Force required and subsequent motor torque
   - System inertia ratio
   - System resolution / accuracy
4. Select motor / gearbox / coupling combination to meet the system requirements
5. Recalculate system parameters if needed (i.e. if gearbox is added)
6. Select feedback method and accuracy
7. Check the system electrical hardware selected is compatible with the control system available



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Drive Mechanisms

Lead Screw

Pro's

- Height accuracy
- Can be custom machined fairly easily
- Can be used in vacuum
- Compact in size
- Often lead screws are self braking so ideal for positioning and Z axis applications

Con's

- The nut will have backlash so not ideal for bidirectional repeatability
- Not ideal for high-speed applications

Drive Mechanisms

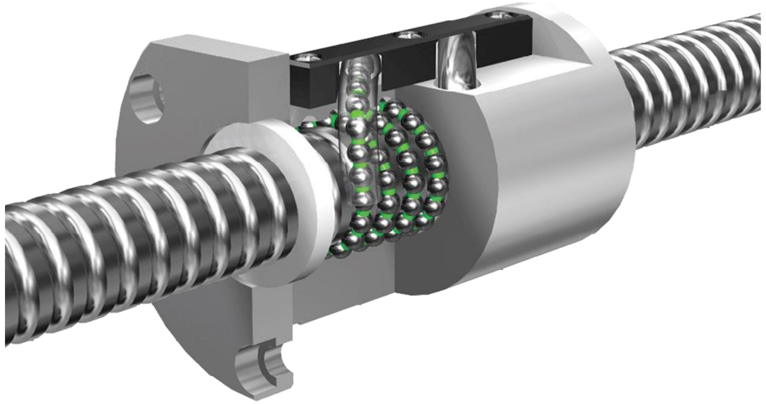
Ball Screw

Pro's

- Good for fast or dynamic linear motion
- Height accuracy
- Provides very smooth operation
- Can be preloaded to minimise back lash
- Often made of hardened steel, so very high wearing

Con's

- Needs lubrication
- Not self braking so not ideal for z axis applications
- The nut requires recirculating balls so often larger than a lead screw
- Recirculating balls require lubrication so not ideal for vacuum or high radiation areas as standard



Drive Mechanisms

Rack and Pinion

Pro’s

- Can be used for linear or rotary motion
- Simple and robust method of operation
- Good for large force applications
- Racks can be added together for very long travel lengths
- Can be used in vacuum

Con’s

- Can have backlash between the rack and the pinion
- Large rack and pinons can be expensive
- Not always the best option for very high accuracy

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Drive Mechanisms

Pneumatic

Pro’s

- Control and mechanics are basic
- Can be fast acting
- Good for in – out of the beam type of operations
- Air won’t become active the same way as oil will
- Clean (no hydraulic oil to leak)
- Can be designed to fail-safe if air is lost

Con’s

- Noisy
- Control is basic
- Accuracy defined as dead stop
- Compressed air is expensive to make

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Drive Mechanisms

Hydraulics

Pro’s

- Very high force output can be available
- Smooth operation/motion profile
- System has some natural damping to it and can be designed to withstand shock loading
- Can be position/velocity controlled with similar methods to motors
- Very suited to linear motion applications
- Compact installation, as the pump can be located away from where force/motion is required
- Possible to run many actuators of different sizes off a single pump

Con’s

- Hydraulic fluid (different fluids are available) can become active when used with neutrons
- Different design skill-set to electrical systems
- Requires maintenance staff trained in risks of hydraulic systems
- Can be messy
- Users around hydraulics must be aware of the health hazards associated with hydraulic fluid and high-pressure systems or the area must be controlled to prevent unauthorised access

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Drive Mechanisms

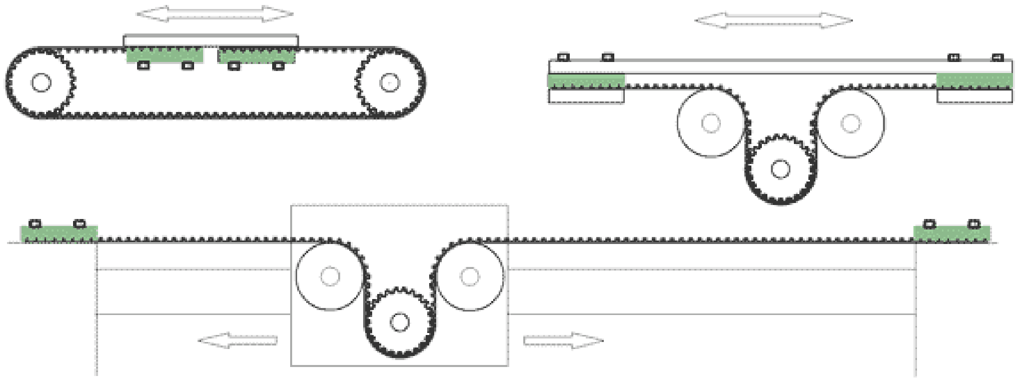
Belt Drive

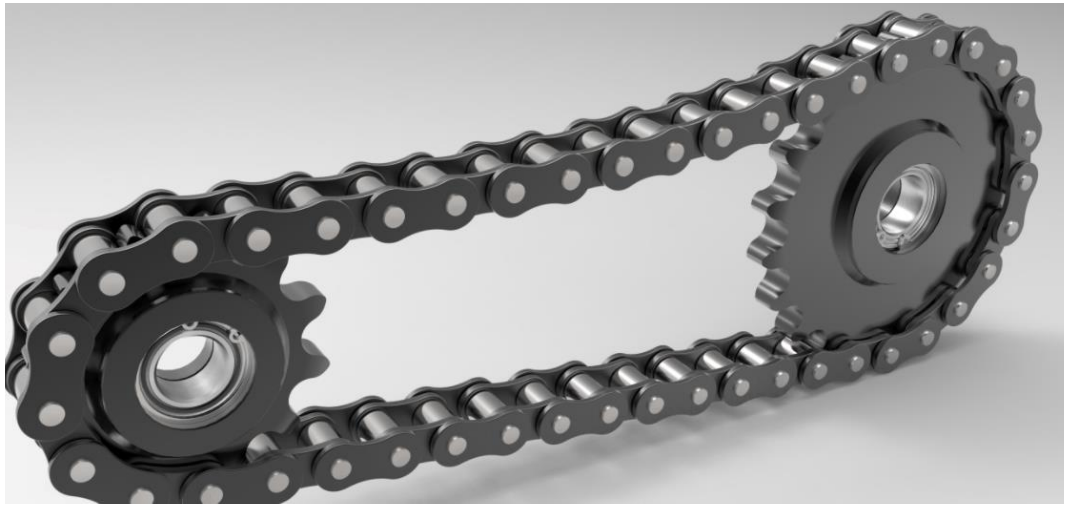
Pro's

- Belts can provide smooth motion
- Pulleys can be used to offer gearing
- Timing belts can be used for applications where accuracy is needed
- Much cleaner and quieter than chain drives
- Can be used for rotary or linear motion applications

Con's

- Belts have a limited lifespan and can snap
- Belts can stretch when first installed
- Belt positioning systems often have lower resolution than lead screw designs





Drive Mechanisms

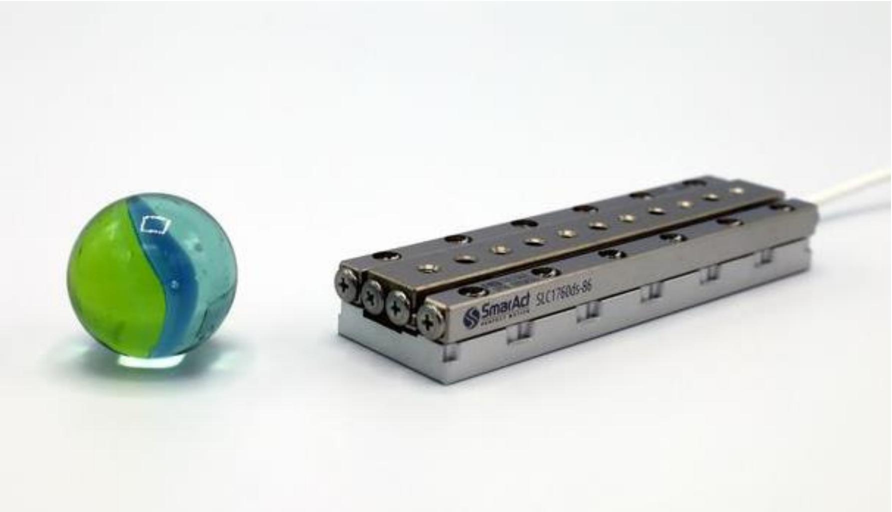
Piezo drives

Pro’s

- Offer a very high resolution and repeatability (nm’s, but only at final position, not during travel)
- They are non-magnetic (suitable for polarised beamlines)
- They are very compact
- They have options that work well up to ultra-high vacuum
- Maintenance-free
- Can be used for rotary or linear applications

Con’s

- Complex control, but provided by manufacturer with an extra controller
- Compactness also means small travel ranges and low payloads
- Cable length can be limited
- Cables connecting piezo actuators can be small and fragile
- They are expensive



Drive Mechanisms

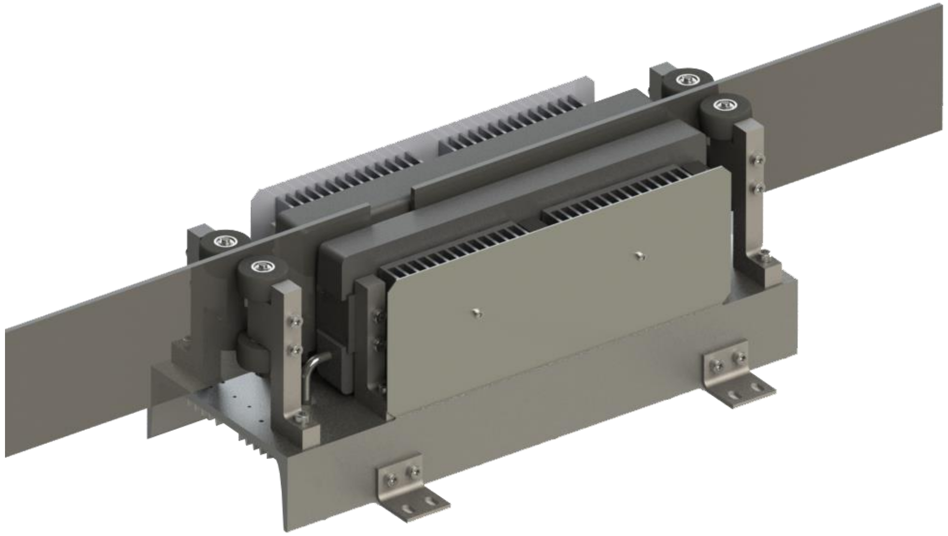
Linear Induction Motor

Pro’s

- Long travel lengths possible
- Ideal for heavy-duty linear applications
- Good power-to-weight ratio
- Low maintenance costs and effort
- Can give levitation effect, can be used for contactless force
- No backlash

Con’s

- Complex construction and controls
- Large attractive magnetic forces produced during operation
- Large in size
- High power consumption and less efficient, can require cooling
- No force at standstill



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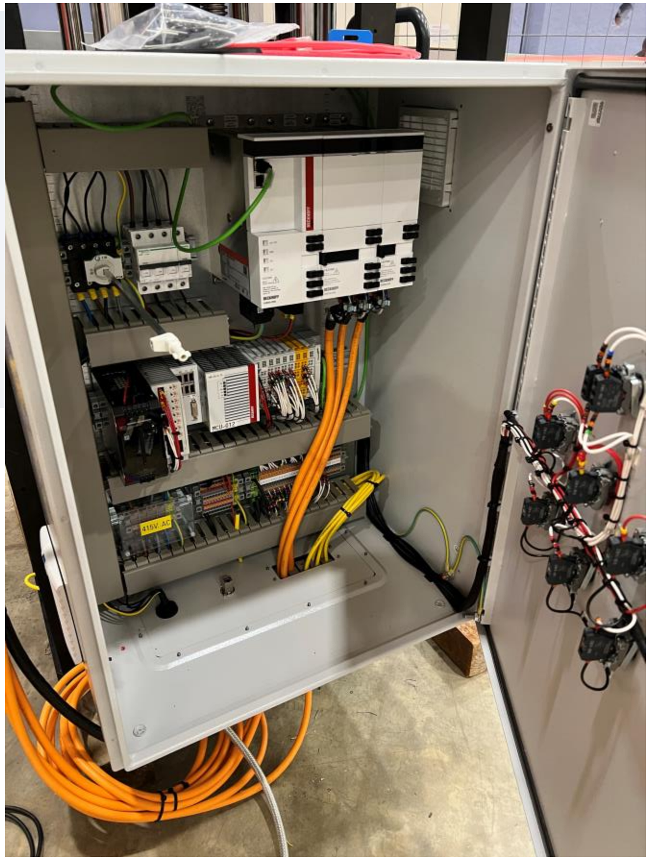
Selecting a drive mechanism

1. Select a style of motion drive
2. **Select an initial motor type**
3. Calculate system parameters such as
   - System speed / acceleration
   - Force required and subsequent motor torque
   - System inertia ratio
   - System resolution / accuracy
4. Select motor / gearbox / coupling combination to meet the system requirements
5. Recalculate system parameters if needed (i.e. if gearbox is added)
6. Select feedback method and accuracy
7. Check the system electrical hardware selected is compatible with the control system available

Motor Types

- Stepper motor
- Induction motor
- Linear induction motor
- Servo motors
  - Stepper Servo Motor
  - AC Asynchronous servo motor
  - Synchronous servo motor

- What is a servo motor?
  - A servomotor is a closed-loop servomechanism that uses position feedback to control its motion and final position.



Stepper Motor vs AC Servo Motors

Stepper Motor

Pro’s

- Have a finite number of steps so ideal for positioning applications
- Can be run without feedback by counting steps
- Low cost
- Extra Low voltage so fairly safe

Con’s

- Generally they are low speed <1000RPM
- Don’t always produce a lot of torque
- Often very poor in dynamic applications

AC Servo Motor

Pro’s

- Can operate at high speeds usually 3000RPM+
- Can run at up to 300% torque for short periods
- Can provide a lot of torque for a small motor
- Great for high speed and dynamic applications

Con’s

- They can be expensive compared to a stepper system
- The control is generally more complex
- They can’t be run open loop if the encoder fails

Selecting a drive mechanism

1. Select a style of motion drive
2. Select an initial motor type
3. **Calculate system parameters such as**
    - **Force required and subsequent motor torque**
    - **System inertia ratio**
    - **System resolution / accuracy**
    - **System speed / acceleration**
4. Select motor / gearbox / coupling combination to meet the system requirements
5. Recalculate system parameters if needed (i.e. if gearbox is added)
6. Select feedback method and accuracy
7. Check the system electrical hardware selected is compatible with the control system available

Calculating system Parameters - Force

- The first system parameter to calculate is the force required to move the motion stage and the following should be considered:
  - The force to move the object
    - $F = \mu R$ for horizontal applications
    - $F = mg$ for vertical applications
  - The frictional forces from the movement mechanism i.e. linear rails
  - The force to accelerate the object dependant on the motion profile of the stage

Calculating system Parameters – Torque

- Once the total force to move the stage has been calculated the torque to drive the lead screw is needed to be calculated using the following
- The total torque is the drive torque plus the torque due to acceleration

Load, Pitch

$$\text{Drive torque: } M_G = \frac{F\,[kN] \cdot P\,[mm]}{2 \cdot \pi \cdot \eta_{gearbox} \cdot \eta_{screw} \cdot i} + M_L\,[Nm]$$

Efficiency, Efficiency, Idling torque

$$T_a = M_G + T_{acc}$$

T_a = total torque during acceleration (Nm)
T_{acc} = torque due to acceleration (Nm)

$$T_{acc} = J.\,\omega'$$

J = inertia of the system (kgm2)
ω' = angular acceleration (rad/s2)

$$\omega' = \frac{2\pi.N}{60.t}$$

N = angular velocity (rpm)
t = acceleration time (s)

Calculating system Parameters – Inertia

- Inertia is an object's resistance to a change in speed.
- Controlled by mass of object and distance of mass from axis of rotation $J = \sum mr^2$
- Calculating the inertia ratio of a system is critical for systems with high performance or dynamic motion profiles as this gives an indication as the systems ability to control the movement of the axis. For height dynamic systems an inertia ratio of 1:1 should be aimed for but for slower less responsive or positioning systems a ratio of up to 10:1 may be acceptable.

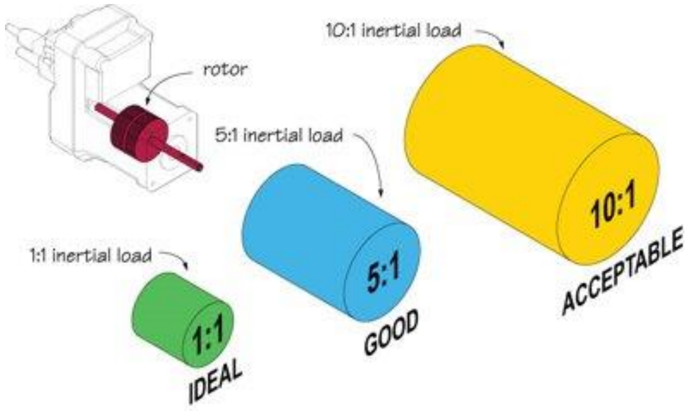
$$Inertia\ Ratio = \frac{Inertia\ of\ load\ reflected\ to\ the\ motor}{inertia\ of\ motor}$$

$$J = J_m + J_s + J_l$$

J_m = inertia of the motor (provided by manufacturer) (kgm2)
J_s = inertia of the screw shaft (provided by manufacturer) (kgm2)

J_l = inertia of the load (kgm2)

$$J_l = m \cdot \left(\frac{p}{2\pi}\right)^2 \times 10^{-6}$$



Calculating system Parameters – System resolution

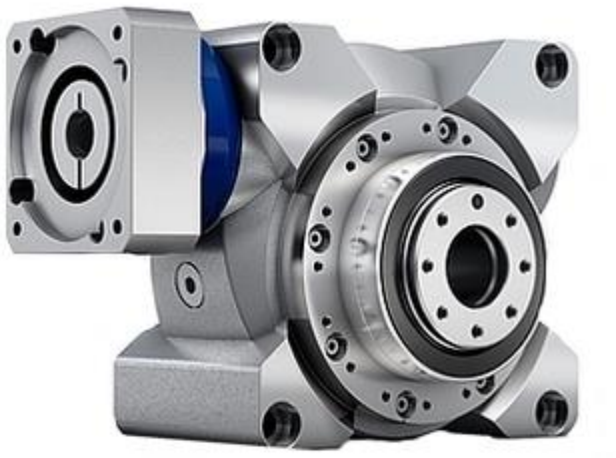
- The system resolution is generally calculated using the equation below for a lead screw system but this equation may vary if the mechanics of the system change.
- System Resolution (mm) $= \frac{Screw\ Pitch(mm)}{No\ Steps\ per\ turn\ of\ the\ motor\ \times Gear\ Ratio}$
- When calculating the accuracy of a system other factors such as part manufacturing tolerances and component backlash need to be taken into account so it can often be easier to verify accuracy using real tests not just using theoretical calculation

Selecting a drive mechanism

1. Select a style of motion drive
2. Select an initial motor type
3. Calculate system parameters such as
    - System speed / acceleration
    - Force required and subsequent motor torque
    - System inertia ratio
    - System resolution / accuracy
4. **Select motor / gearbox / coupling combination to meet the system requirements**
5. Recalculate system parameters if needed (i.e. if gearbox is added)
6. Select feedback method and accuracy
7. Check the system electrical hardware selected is compatible with the control system available

Gearboxes

- Bevel Gearbox
- Planetary Gearbox
- Worm and wheel gearbox
- Harmonic Drive gearbox



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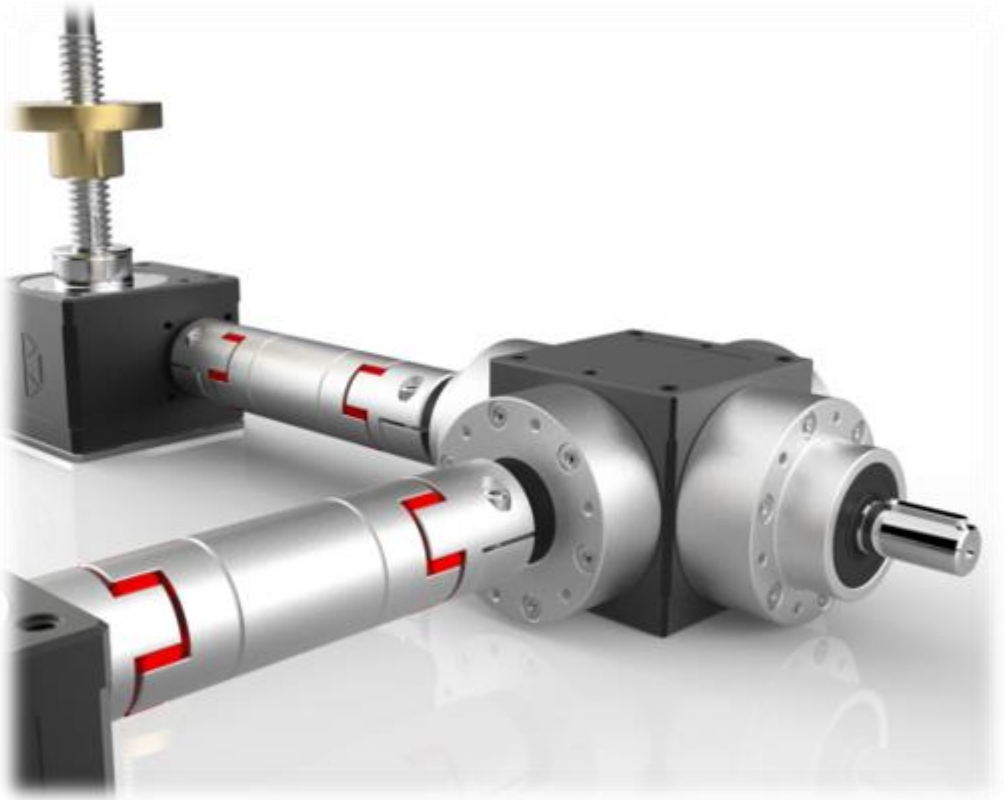
Bevel Gearboxes

- 90˚rotation change
- Can drive multiple axes from 1 motor
- Low friction
- Multiple ratio choices
- Choice of gear mesh:
    - Spiral
    - Straight



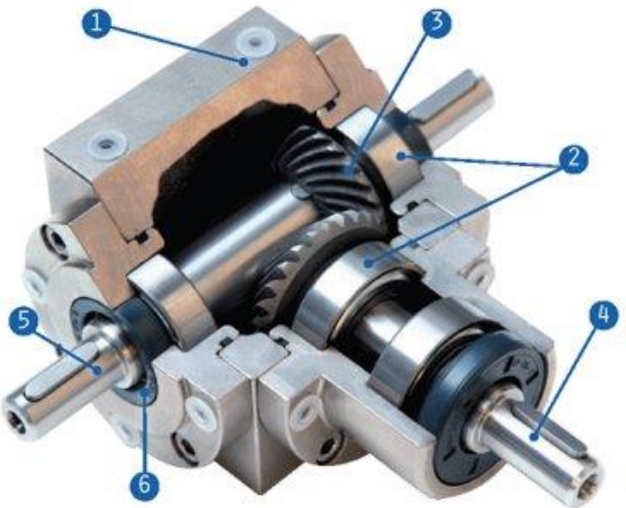
Choice of gear mesh

Straight

- Less Friction
- Cheaper
- Force all in one direction
- Need lower spec bearings
- Less heat
    - Needs bigger gear to transmit force
    - Noise
    - Back lash

Spiral (Helical)

- Lower noise
- High contact area
- Transmit more force
    - More friction
    - Expensive
    - Thrust force
    - Run hotter



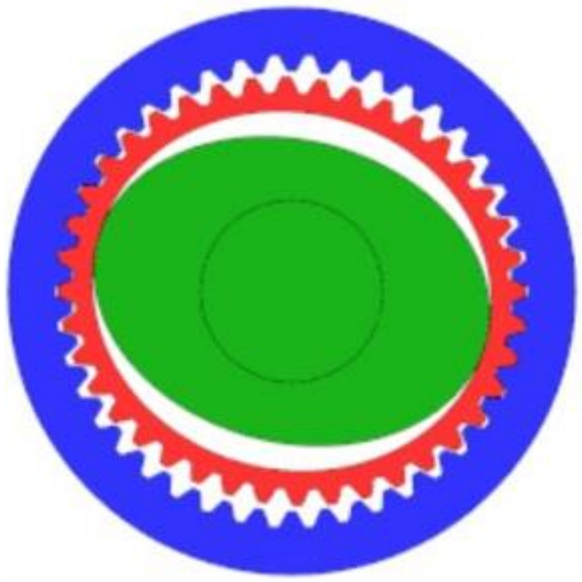
Planetary or Harmonic

Pro’s

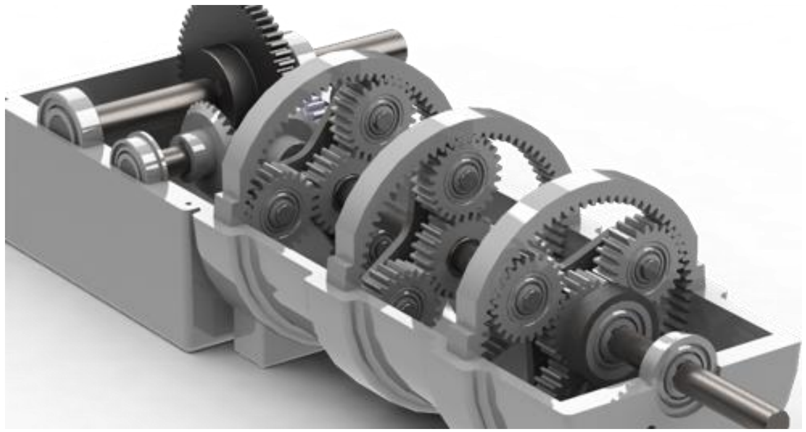
- No backlash (in the arc seconds)
- Compactness and lightweight
- High gear ratios 30:1 up to 320:1
- Good resolution and excellent repeatability
- High torque capability

Con’s

- Cost; they can be expensive
- Efficiency can be difficult to calculate



Blue (outer circle): circular spline (fixed)
Red (middle flexible circle): flex spline (attached to output shaft, which is not shown)
Green (inner oval): wave generator (attached to input shaft; inner ball bearing and shaft are not shown)



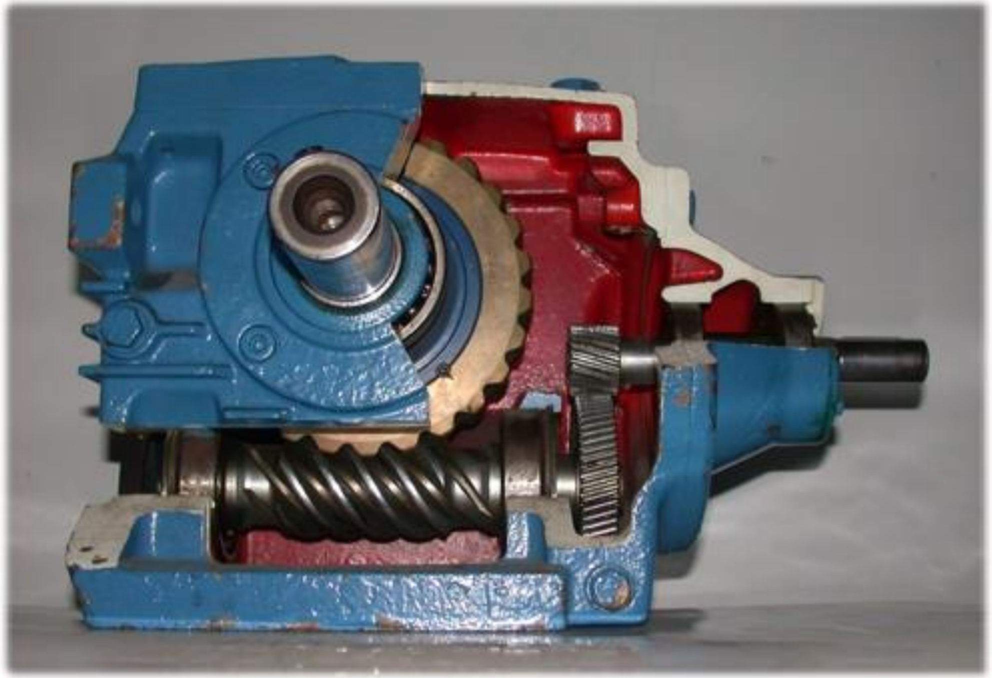
Worm and wheel

Pro’s

- High speed reduction
- Silent operation
- Self locking due to efficiency
- Compact geartrain
- Can be high precision

Con’s

- Cost; they can be expensive to buy or make
- Extra force needed to drive
- Lots of forces created in the housing, so it is often a heavy casting
- They can generate lots of heat



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Selecting a drive mechanism

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6. **Select feedback method and accuracy**
7. Check the system electrical hardware selected is compatible with the control system available

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Coffee Break

System Feedback

All motion systems generally need 3 basic components

- Limit Switches
- Home switches
- Type of position feedback
    - Incremental or Absolute
    - Direct and Indirect
- Form of feedback device
    - Encoders (Linear or rotary)
    - Resolvers
    - LVDT's (linear variable differential transformer)
    - RVDT's (Rotary variable differential transformer)
    - Counting steps in software (Open Loop Control)

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Limit and Home Switches

Limit Switch

- A limit switch is a switch that triggers when a motion system reaches the extent of its travel. this is used to prevent a system crashing or traveling beyond its designed motion range

Home Switch

- A home switch is a switch that is used to indicate a known reference (home) position. This is critical when using incremental encoders.

Position feedback

Incremental position Feedback

- Incremental position feedback works by reporting changes in position. So a system needs to be homed to a known position and then it can move relative to the known point

Pro’s

- Generally cheaper than absolute feedback
- Requires a simpler control system hardware

Con’s

- Requires homing of axes if position is lost
- If a system is moved whist the control system is turned off this movement will not be seen
- Often requires more software for homing routines

Position feedback

Absolute position Feedback

- Absolute position feedback just gives a defined position so there is no need for homing as the system always knows its true position

Pro's

- Always gives a true position so no danger of incorrect position readings
- Easier user operation, as no need to home axes regularly
- Allows for simple position control with no need for homing

Con's

- Hardware is often much more expensive
- The range of an encoder is limited by its resolution; it only has a fixed number of bits

Position feedback

Direct Feedback

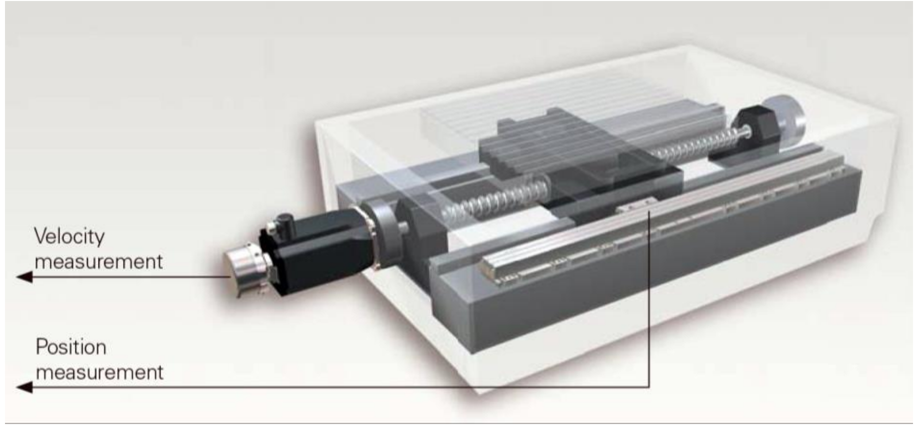
- Direct feedback is when the feedback device is directly attached the axis being moved and its position is directly measured. For example using a linear encoder on an axis

Pro's

- Always gives a true axis position so no danger of incorrect position readings due to system backlash
- Easier to integrate no math required to convert an angular reading into a linear distance

Con's

- Hardware is often much more expensive
- The encoder can be hard to mount to some axes



Position feedback

Indirect Feedback

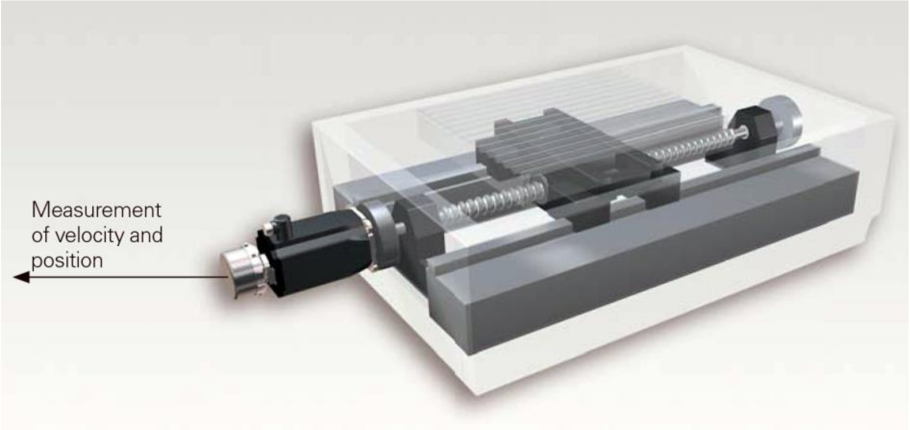
- Indirect feedback is when the feedback device is attached the motor or another part of the system that is not the axis being moved. The position of the axis is then calculated taking into account axis mechanics. For example using a motor back axel encoder on an axis

Pro's

- Feedback devices such as motor back axel encoders are often small and cost effective to integrate

Con's

- The position reading is not direct and may not account for mechanical inaccuracies such as backlash in the system and things like lead screw pitch error



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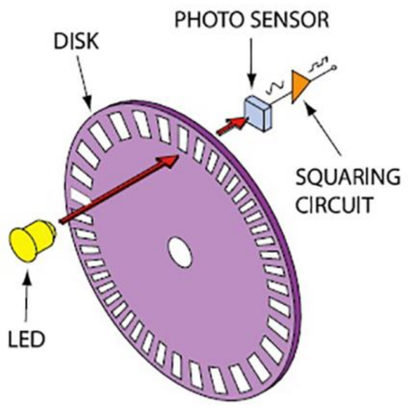
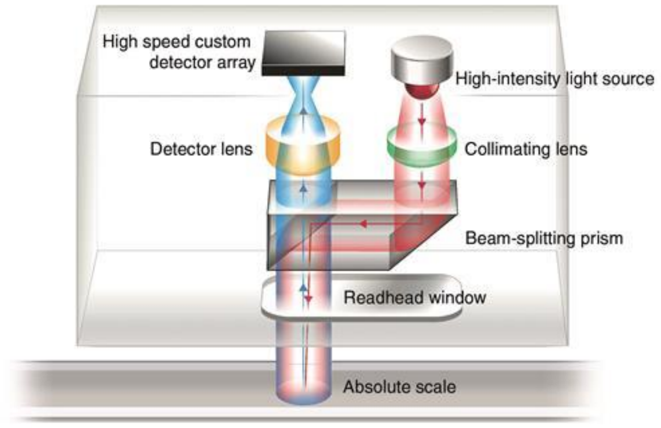
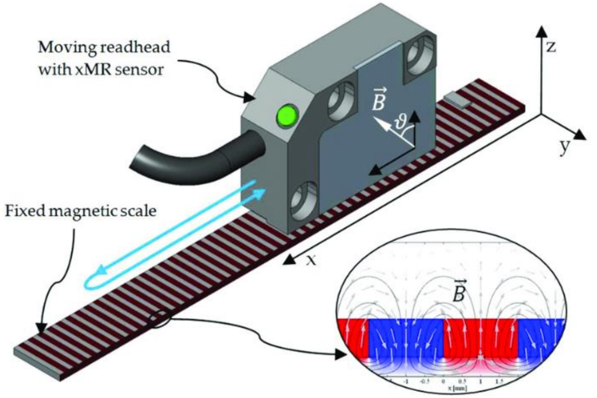
Forms of position feedback



Encoders

- In general an encoder is a device or process that converts data from one format to another. In position sensing, an encoder is a device which can detect and convert mechanical motion to an analogue or digital coded output signal
- Encoders are probably the most common form of position feedback and come in may variants both incremental and absolute as well as linear and rotary
- Two common types of encoder are optical and magnetic. Optical encoders are very commonly used in industry but aren't always ideal for neutron applications are in higher radiation areas the radiation can cloud the encoder lens and cause it to fail.





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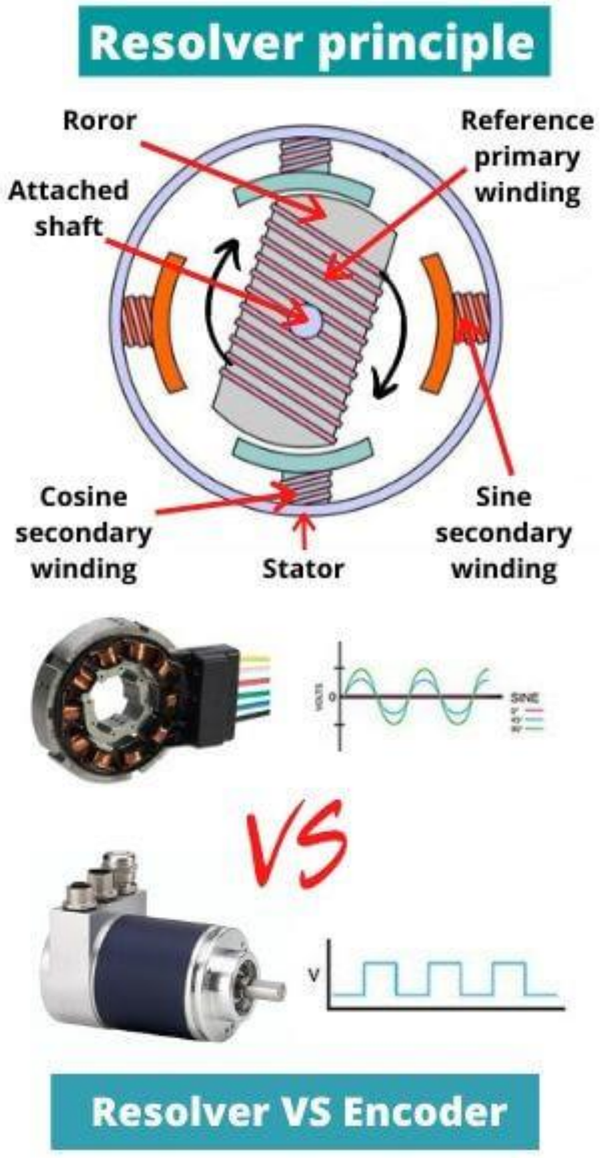
Forms of position feedback

Resolvers

- Resolver is a rotary transformer that determines the angle and displacement speed of its rotor.
- Resolvers are well suited to harsh environments with no onboard electronics, resolvers can survive extreme temperatures and tolerate shock, vibration and radiation making resolvers suitable in applications where encoders would fail.



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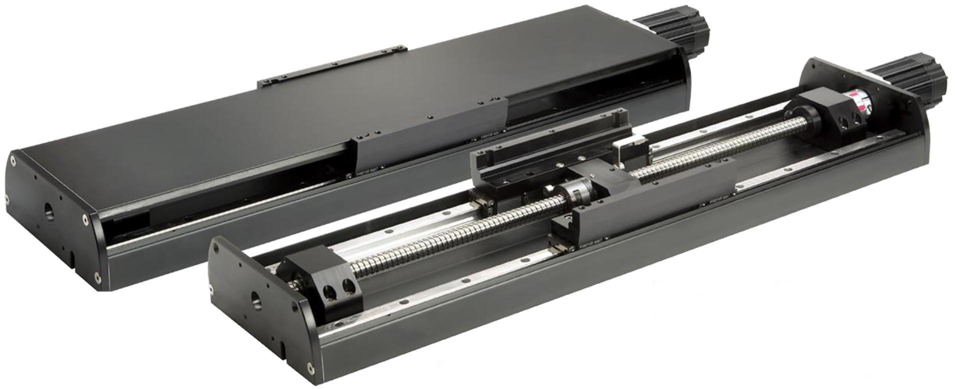
Direct Position feedback Resolution Calculation

So when selecting a direct feedback device it important to select a device with at least twice the system resolution to hit the Nyquist limit.

Lets take the following application a 200 step/rev motor with a 10:1 gearbox and a 2mm pitch lead screw

1. Calculate the resolution of the system using the following
2. System Resolution (mm) $= \frac{Screw\ Pitch(mm)}{No\ Steps\ per\ turn\ of\ the\ motor \times Gear\ Ratio}$
3. System Resolution (mm) $= \frac{2}{200 \times 10} = 0.001mm$
4. So direct feedback device will need to have a resolution of 0.0005mm or greater to have complete control of the system



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Cable managment

Before we look at selecting cable management. There are a few basic rules when it comes to motion control cable management.

- Generally less cables is better
- Try to maximise cable separation and run high current cables in separate trunking to feedback cables to reduce the effects of EMC
- Where possible provided plugs for cables at the device end. This will make it easier to swap out components if they fail. As connectors are often not needed at the rack end as the cables will rarely fail and the cables can be hard to remove from the cable routes.
- Remember to design cable routes especially on moving stages so add cable chains to mechanical designs and even model connectors with cables shing the minimum bend radius to give a sense of scale.

Selecting Cable Management

1. Determine the type of control system to be used
2. Determine what cables are required and where they go in the system
3. Determine the details of the cable route
    - Minimum size for the cable route
    - Minimum bend radius of the cable route
    - Fixed or moving cable route
4. Select a cable routing method
    - Fixed trunking
    - Cable chains
    - 3D cable chains
5. Design the cable route and add it to the mechanical design

Selecting Cable Management

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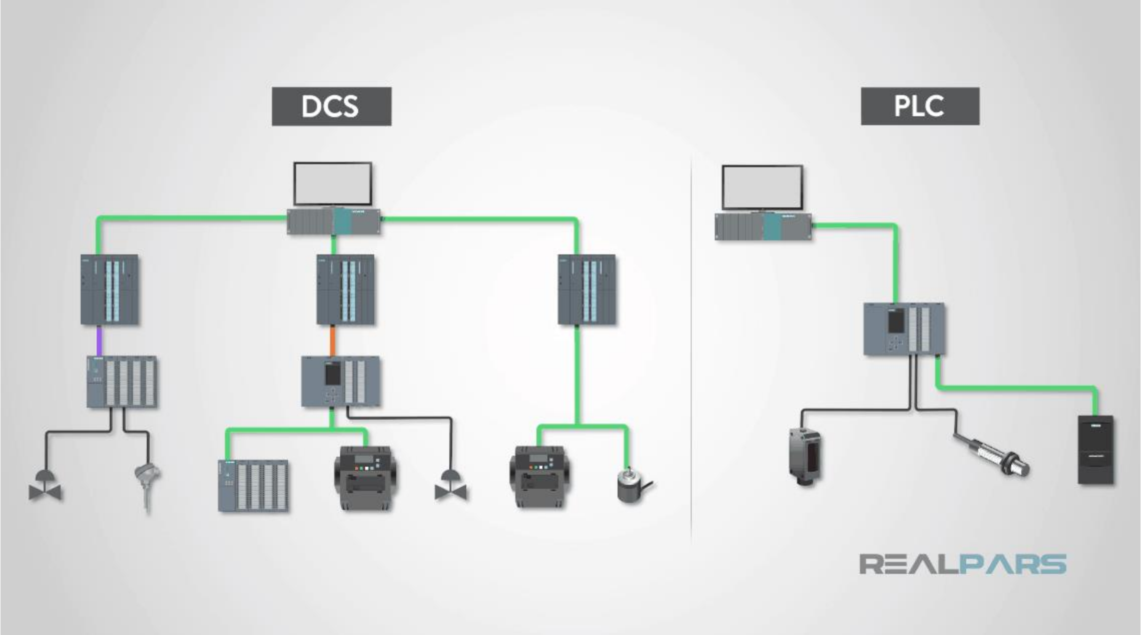
    - Fixed trunking
    - Cable chains
    - 3D cable chains
5. Design the cable route and add it to the mechanical design

Types of Control System layout

There a 2 basic types of control system layout central and distributed control.

Central Control

- All the components for the control system such as the controller and motor drives are in one central cabinet. Then cables are run from this cabinet to every device



Distributed Control

- The Components of the control system are distributed around the system. The devices are then cabled to the closest distributed control and then these distributed control units are connected.
- On larger systems that are spread out distributed control can often reduce the amount of field cabling

Selecting Cable Management

1. Determine the type of control system to be used
2. Determine what cables are required and where they go in the system
3. Determine the details of the cable route
    - Minimum size for the cable route
    - Minimum bend radius of the cable route
    - Fixed or moving cable route
4. **Select a cable routing method**
    - Fixed trunking
    - Cable chains
    - 3D cable chains
5. Design the cable route and add it to the mechanical design

Selecting a Cable routing method

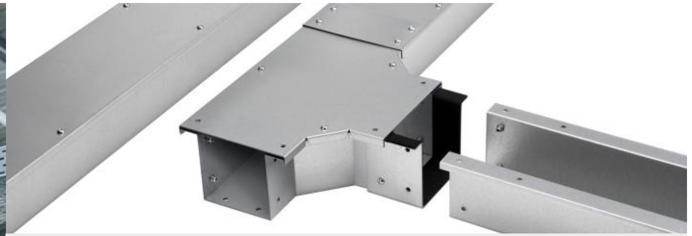
There is fixed and moving cable routing.

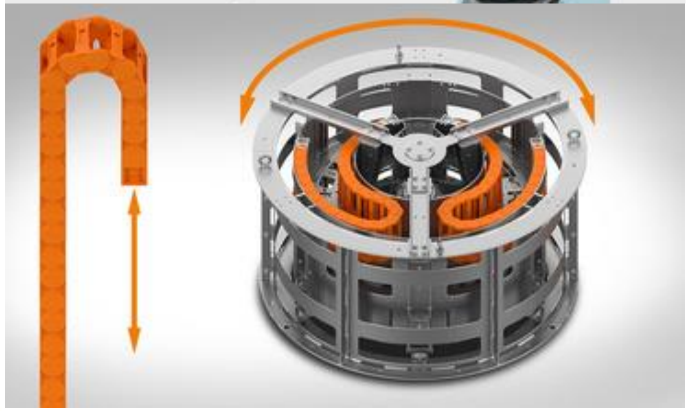
Fixed Cable routing includes:

- Trunking
- Cable tray

Moving Cable routing includes:

- Cable Chains
- 3D Cable Chains





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Selecting Cable Management

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    - Minimum size for the cable route
    - Minimum bend radius of the cable route
    - Fixed or moving cable route
4. Select a cable routing method
    - Fixed trunking
    - Cable chains
    - 3D cable chains
5. **Design the cable route and add it to the mechanical design / 3D model (Most Critical Step)**

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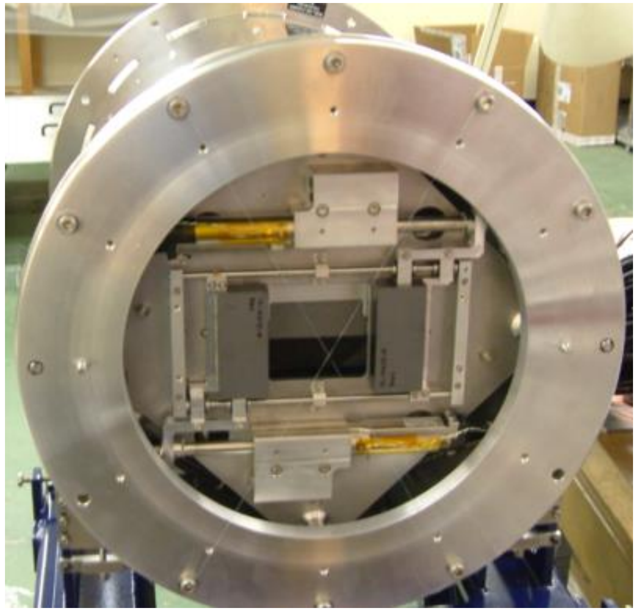
Neutron Specific Motion Components

Investigating additional challenges or restrictions on components as a result of neutron environments

Neutron Specific Motion Components

- High Radiation
- Vacuum
- Non Magnetic



High Radiation – Design Considerations

When designing a motion system for a high radiation area, these are a few basic considerations to try and follow:

- Minimise the amount of electronics in the high radiation areas, especially components with embedded electronics and processing
- Try and avoid components that require lots of lubrication
- Make the design as simple and robust as possible
- Material selection: try and avoid materials that are easily irradiated or produce unwanted radiation.

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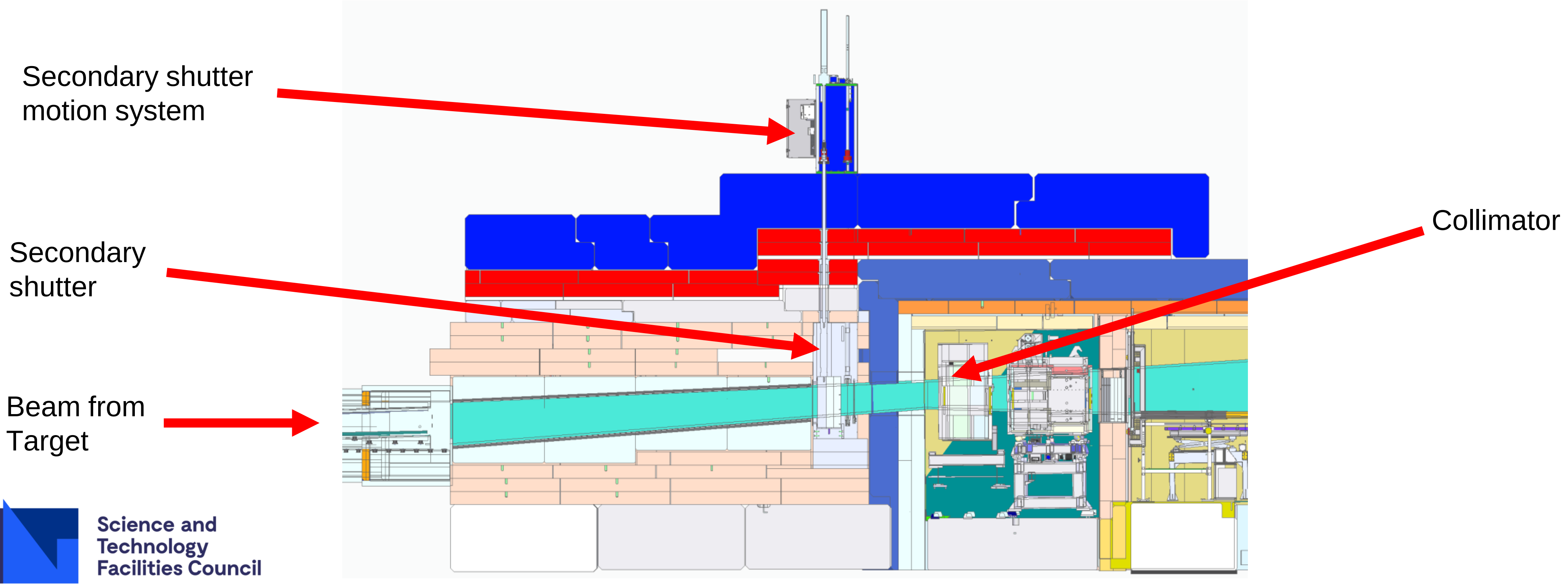
High Radiation Application (ChipIR Secondary shutter)

ChipIR is the instrument with the highest radiation levels at ISIS, as the instrument has no moderator and takes neutrons straight from the target. The radiation levels were so high that the primary shutter did not fully reduce the radiation levels in the instrument blockhouse so a secondary shutter was added.



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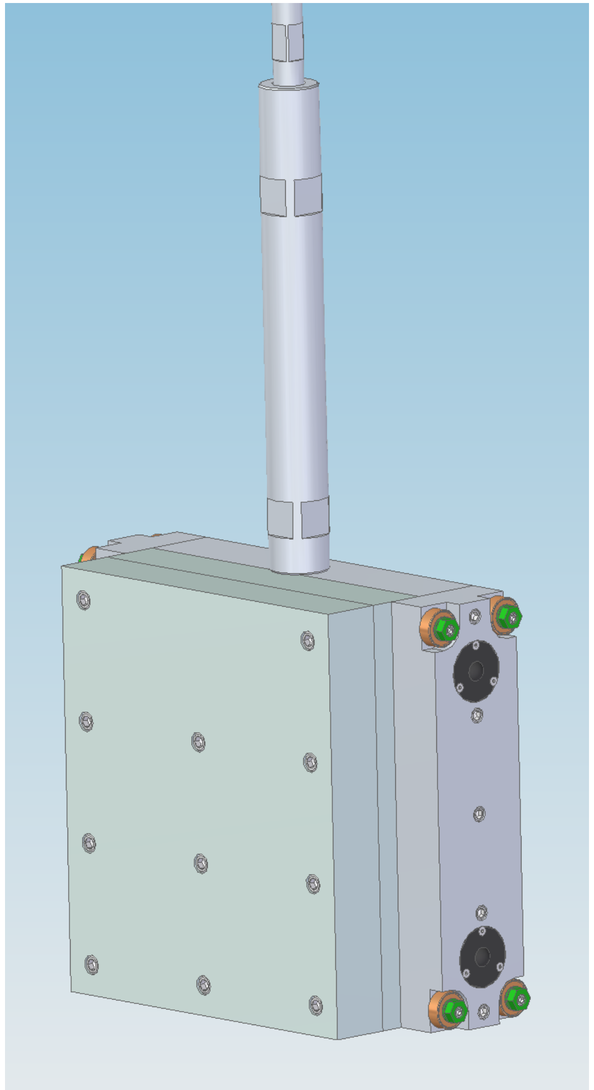
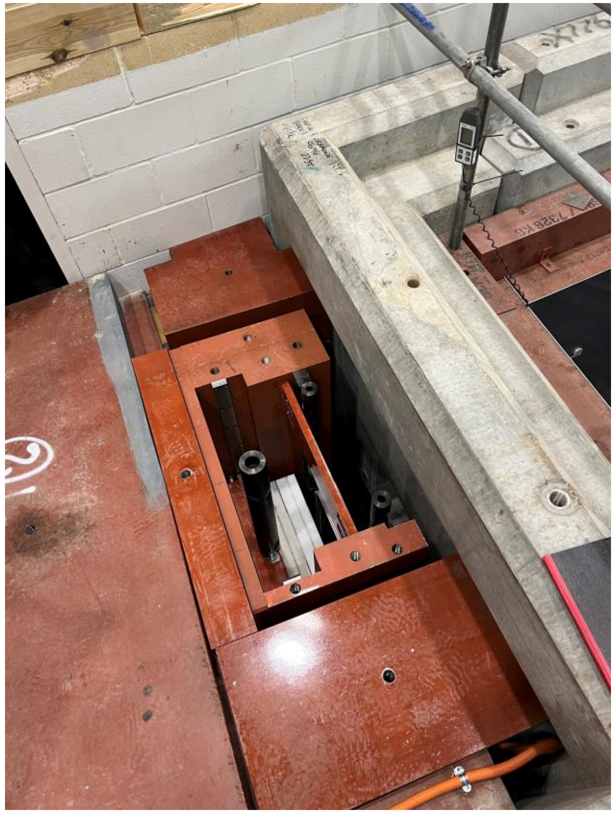
High Radiation Application (ChipIR Secondary shutter)

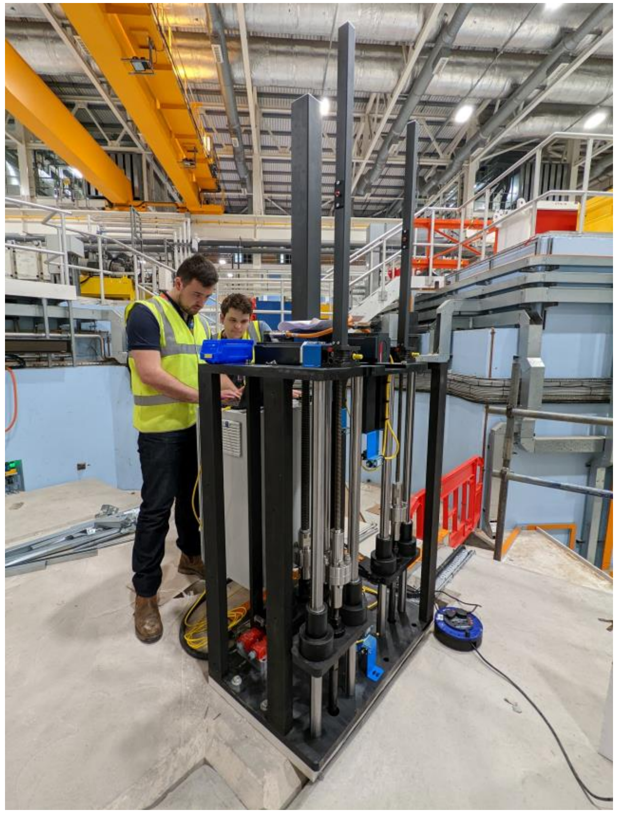
- The shutter and filter assembly was designed with no electronics connected to the moving shutter and all the motion system was placed outside the shielding. The shutter was then connected to the motion system using a drawbar
- For simplicity the shutter motion was guided using cam followers and spring loaded ball transfer units. This minimised the lubrication required and offered robust maintenance-free operation.
- The connecting drawbar was also stepped to reduce the shine path of stray neutrons



High Radiation Application (ChipIR Secondary shutter)

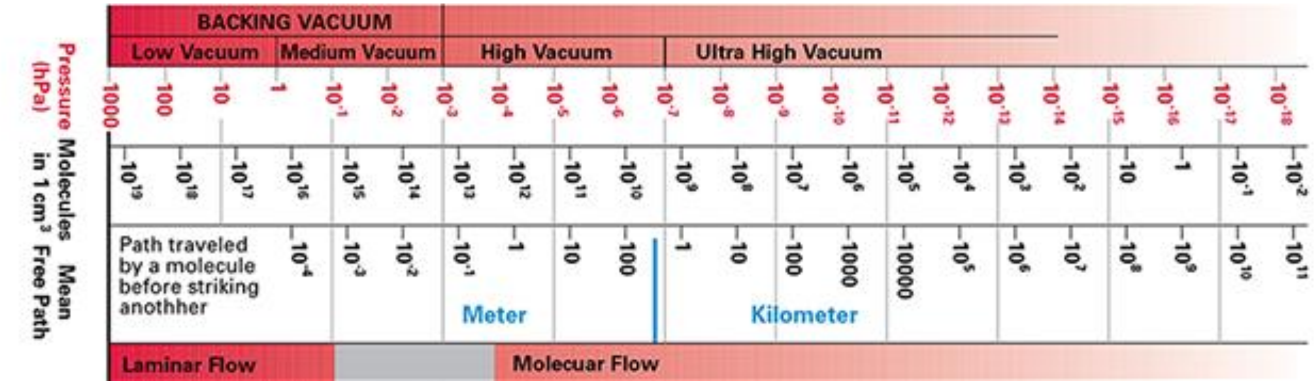
- The shutter and filter assembly was designed with no electronics connected to the moving shutter and all the motion system was placed outside the shielding. The shutter was then connected to the motion system using a drawbar





Vacuum – Design

- Usually the first step for vacuum design is finding out the vacuum level. At ISIS we usually have 2 types of vacuum system
  - Rough - medium vacuum systems up to 10^{-3} mbar
  - High vacuum systems up to 10^{-7} mbar
- With any vacuum system its always best practice to follow good vacuum design principles but this is especially critical for high vacuum systems. For rough vacuum this is often less critical but good vacuum practice should be followed where possible.



Vacuum – Design Considerations

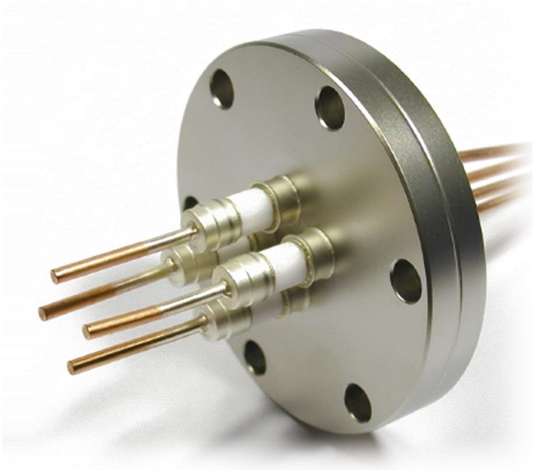
When designing a motion system for a vacuum environment these are a few basic considerations to try and follow:

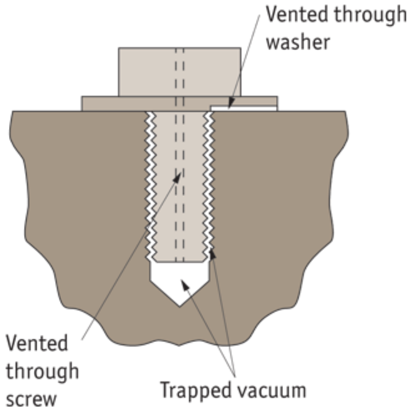
- Control outgassing by selecting/designing components with vacuum-compatible materials (avoid plastics, adhesives, porous metals and porous ceramics)
- Standard lubrication and grease are also a significant source of outgassing, so only use vacuum-compatible products or self-lubricating parts
- Determine if components need to be baked-out based on the application and if they do, make sure that they can withstand the bake-out temperature

Vacuum – Design Considerations

When designing a motion system for a vacuum environment these are a few basic considerations to try and follow:

- Without air to dissipate heat by convection, electrical components must be designed to avoid overheating
- If using components from suppliers, make sure they are vacuum compatible
- Minimise electronics inside of vacuum, as they are the most likely parts to fail
- Use appropriate vacuum feedthroughs for cabling or linear/rotary motion
- When designing components minimise trapped volumes by using vented screws and vented parts





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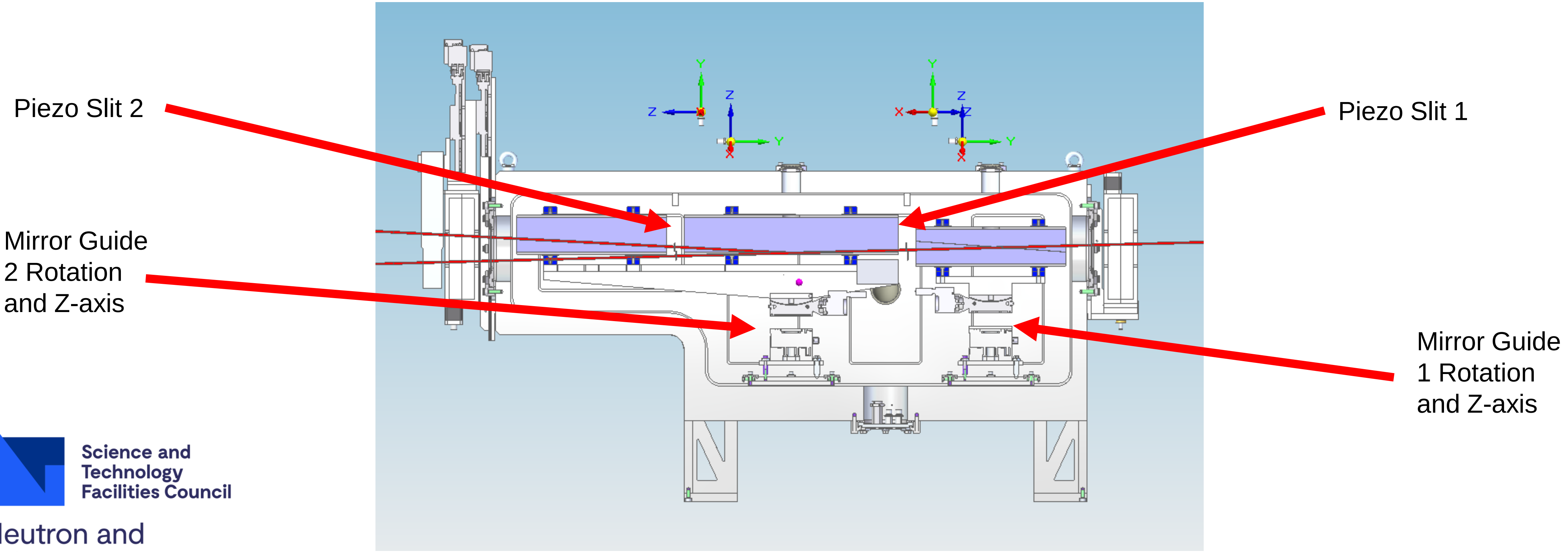
Rough Vacuum Application (SURF Mirror Guide Upgrade)

SURF is a reflectometer at ISIS and the front end of the instrument is being upgraded by inserting a vacuum tank with three mirror guides inside it. The new mirror guides need to be both rotated along the y axis and moved along the z axis and two half-slits need to be inserted in the tank in each gap between the mirror guides.



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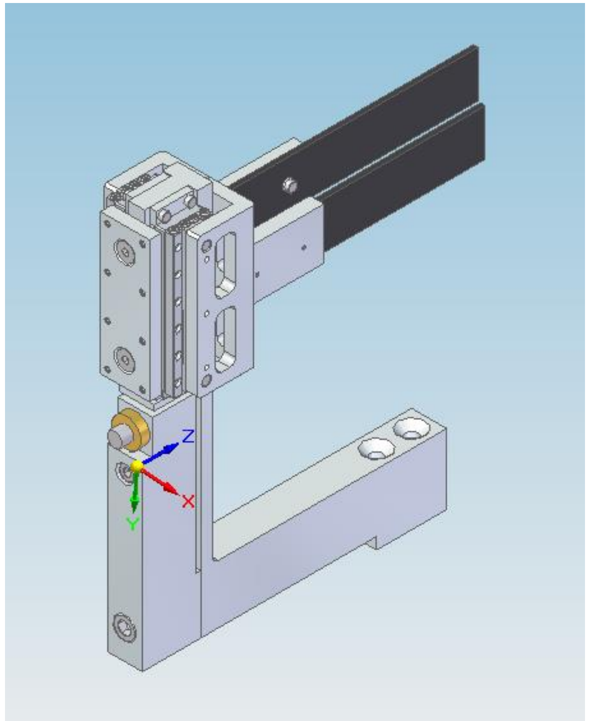
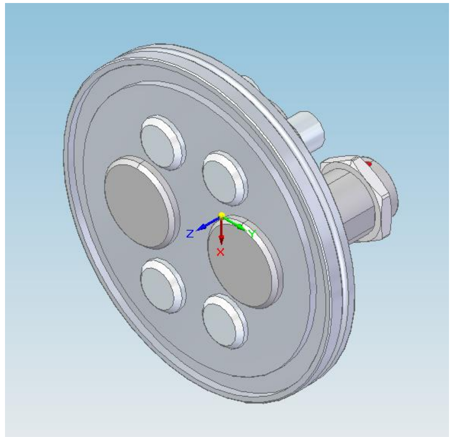
Rough Vacuum Application (SURF Mirror Guide Upgrade)

- The rotation and translation stages for the mirror guides were purchased from Huber. The purchased stages are compatible with vacuum up to 1e-7 mbar
- The half-slits were constructed using piezo stick-slip positioners by Smaract. These are compatible with a vacuum of up to 1e-6 mbar and offer a very high resolution. The assembly containing these stages was designed to contain only vacuum compatible materials and following best design practice
- As this application is a rough vacuum, there wasn't too much worry about trapped volumes
- All the cabling associated with these stages is passed through appropriate feedthroughs using vacuum-compatible connectors
- Electronics inside of vacuum is minimised to the electronics needed at the stages





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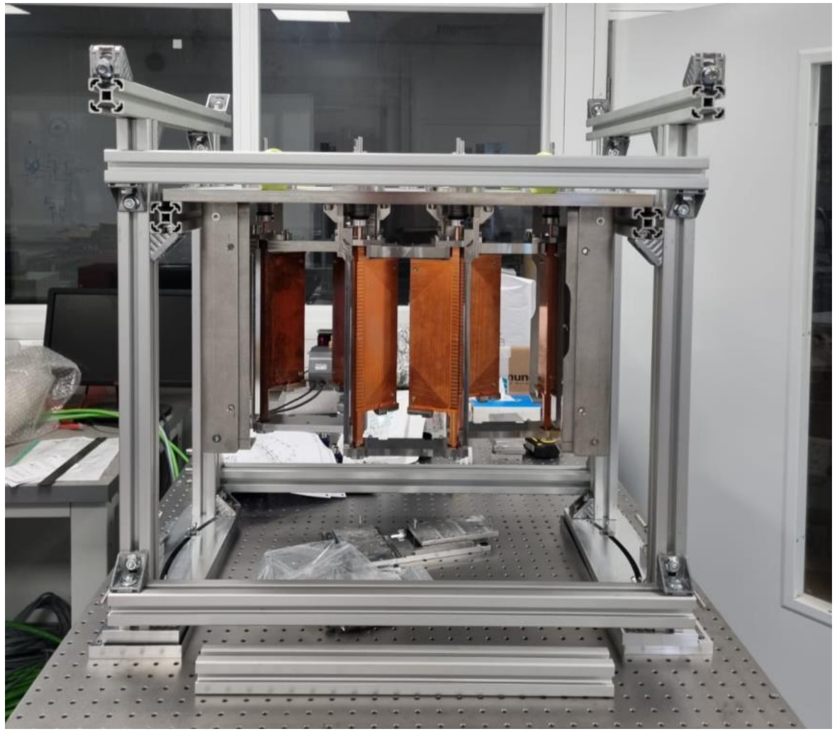
High Vacuum Application (Muon Collimating Gates)

The muon collimating gates project consists in designing 3 pairs of copper gates which will allow for the sizes and sideways positions of the 3 beams downstream of the kicker that supplies the muon pulses to Emu, MuSR and Hi-Fi (muon instruments at ISIS) to be controlled. The gates will be inside vacuum and connected to the EPB, so a vacuum of 10^{-6} mbar or better is required.



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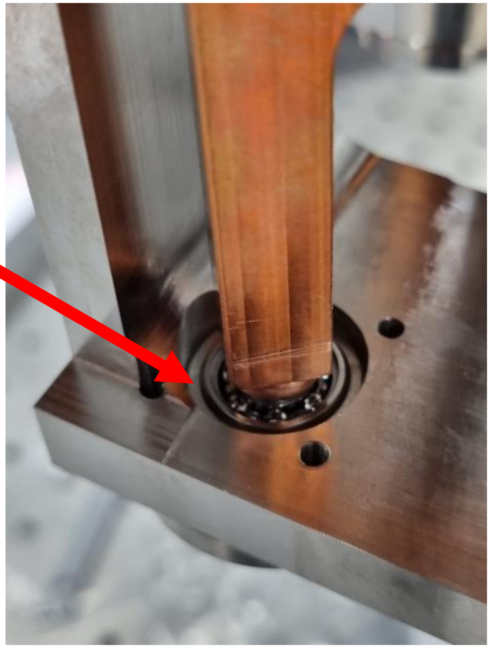
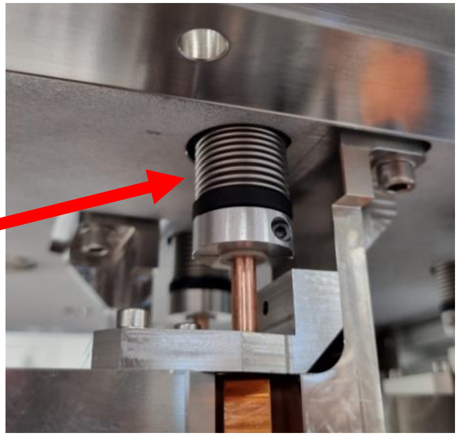
High Vacuum Application (Muon Collimating Gates)

As the vacuum level that needs to be achieved in this application is much higher than with the previous one, some extra steps needed to be taken as seen below:

Stainless steel bearings were used with no seals and vacuum compatible grease



Coupling joining the mechanical feedthrough to the copper gate. Mechanical feedthroughs were used to connect the motor to the gate.



Mechanical feedthroughs on the outside of the tank

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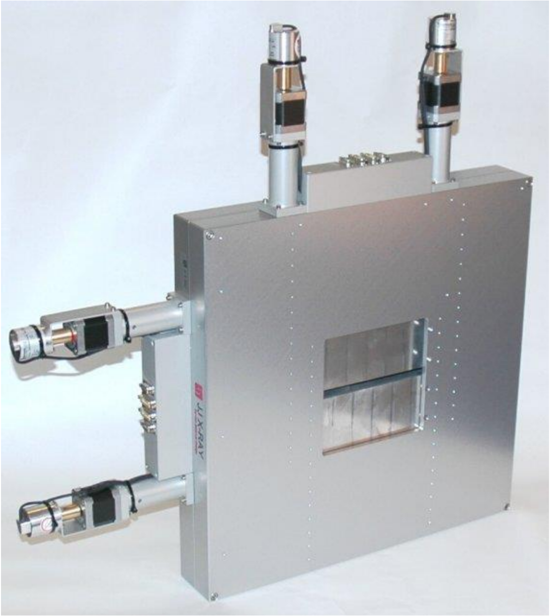
Non Magnetic Applications

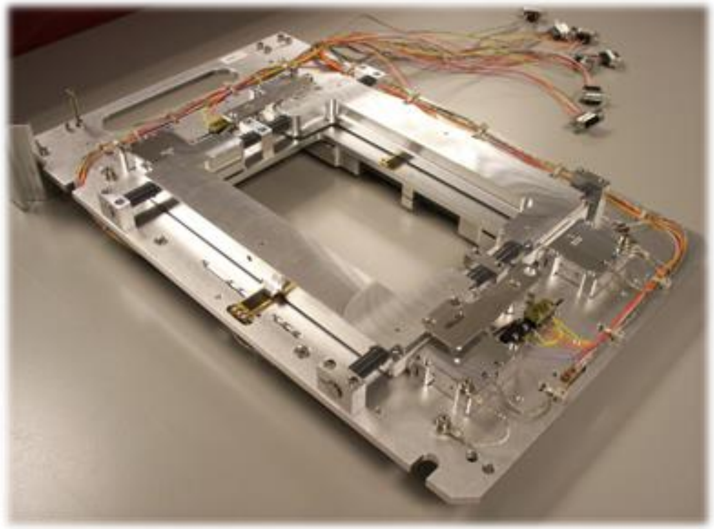
There are a few instances when non magnetic motion systems are required.

- One instance is on polarised beamlines. These often use large magnets, so using a magnetic motion system will affect the magnetic field created
- The second instance is applications where a large magnet is used at the sample point and again using a magnetic motion system will disturb the magnetic field created

Non Magnetic Applications

- One of the most common non magnetic motion applications at ISIS is non magnetic slit sets
- These are typically constructed by using Piezo actuators which can be bough for both vacuum and nonmagnetic applications
- However slit sets can also be made using non magnetic materials and spacing the motors off the slit housing to increase the distance of the motor from the beam and reduce the affects of the magnetism.





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Design for Control

How control systems can impact the design of motion systems

What is the Motion Control System?

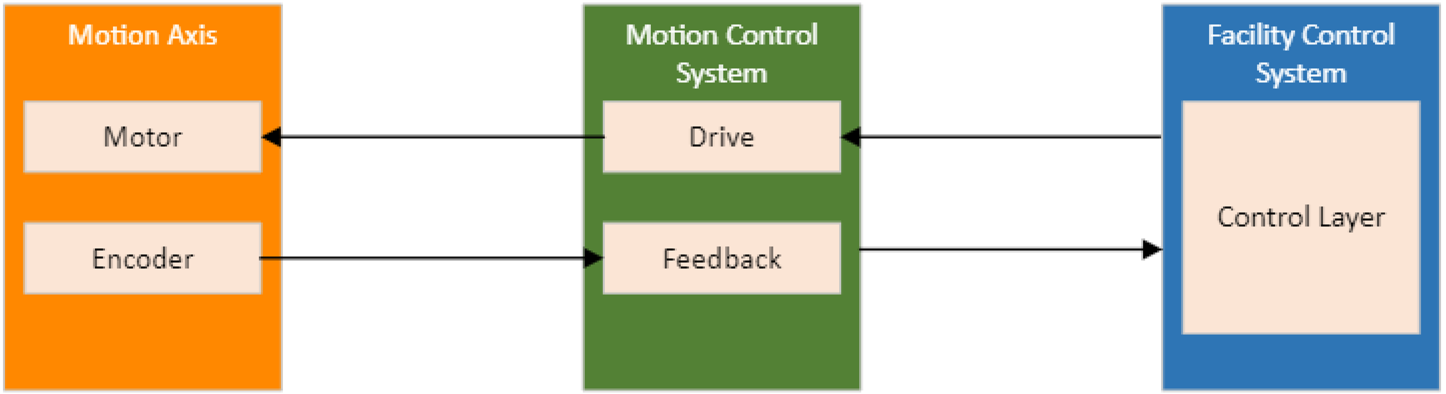
The Motion Control System:

- The hardware and software that links together the axis mechanics and how your users or automation processes interact with that axis
- It is responsible for the controlled positioning of the axis

Dependent on your facility, the Control System could be basic or complex which will determine what sort of control elements you can incorporate in to your motion designs and where the software logic for that system “lives”.

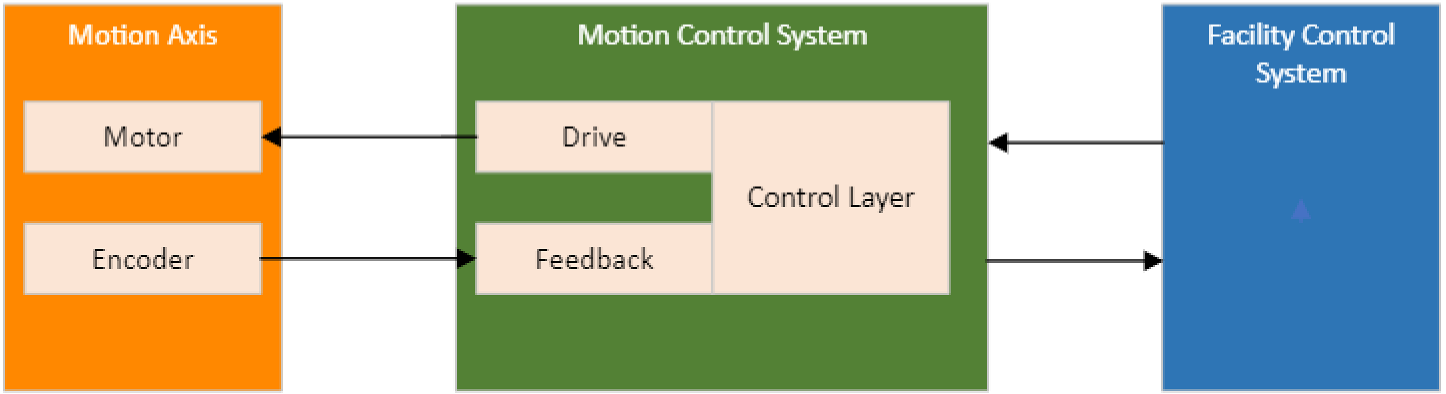
Motion Control Architecture - Simple

- In a very basic setup, the Motion Control System may be doing very little actual control and instead passes responsibility on to some higher up Control System, for example:
  - The drive receives step commands from a user that it then uses to move a stepper motor
  - An incremental encoder is read by a feedback device and passes a raw count value back to the higher level control system
- The Facility Control System here is responsible for:
  - Converting a movement command in to the steps required
  - Converting the raw counter value to a position value
  - Any position error correction



Motion Control Architecture - Isolated

- In an alternative approach, the responsibilities for the controlled motion can be left to the Motion Control System
- Here, the Facility Control System is only responsible for sending position commands to the Motion Control System and then receives a position feedback back from this System
- Any position error correction and conversion of raw counts to engineering units, and vice-versa (e.g. mm or degree) is isolated to the Motion Control System



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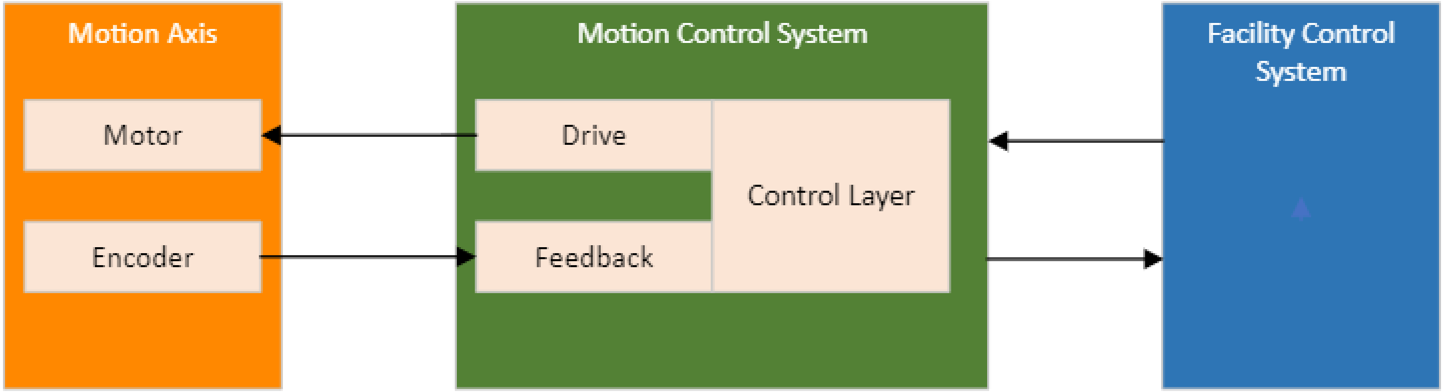
Motion Control Architecture - Isolated

- Typically, the Motion Control System should be better suited to motion control than the Facility Control System resulting in better positioning and freeing up resources of your Facility Control System
- You may have additional control elements still at the Facility Control System level if you want to limit or change how users interact with the equipment



Motion Control Architecture

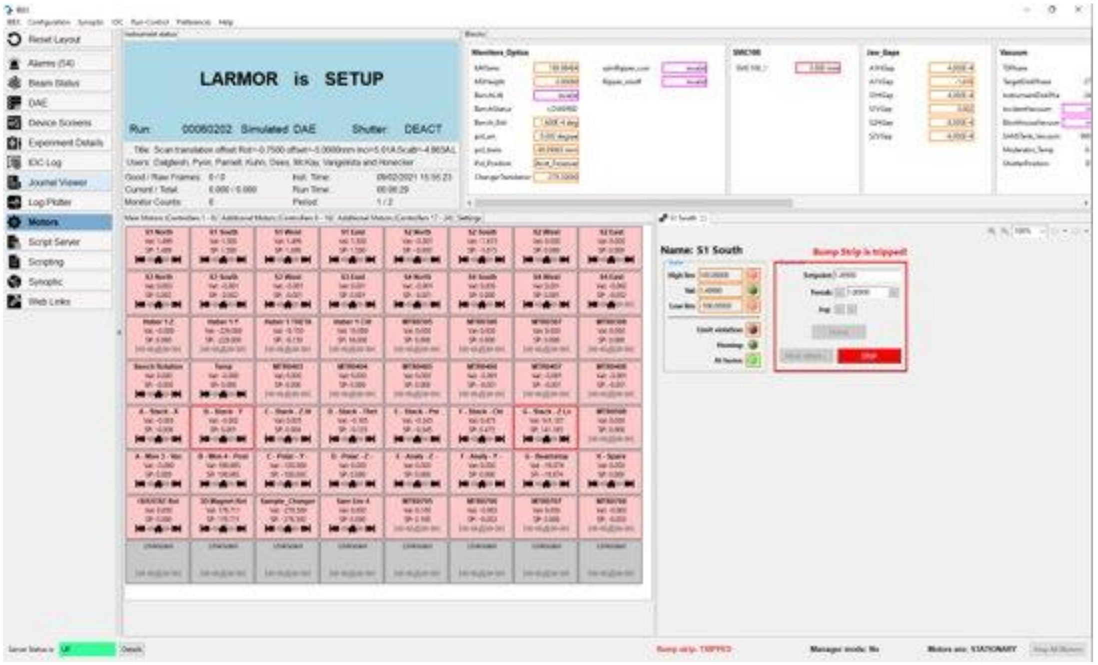
- A Motion Control System does not need to strictly rely on some higher level Facility Control System. Jog boxes, panel buttons and lights, and HMIs directly installed on the Motion Control System are all valid approaches
- There is no correct approach to the architecture but it will impact your options when it comes to designing motion axes

Architecture at ISIS

Here at ISIS (most of) our instruments use EPICS (**E**xperimental **P**hysics and **I**ndustrial **C**ontrol **S**ystem)

- An open-source set of tools and applications
- Utilises a channel access protocol to allow equipment on an instrument to communicate with each other
- This is our Facility Control System layer

Users and scientists interact with equipment using IBEX, an in-house developed User Interface.



IBEX Motors Table

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Motion Control Architecture at ISIS

We are in the process of deploying a new Motion Control System so currently have two systems being supported.

GALIL System (Old)

- The rack mounted hardware consists of independent drive and feedback cards with EPICS being used to close the position control loop which results in generally poor positioning performance
- Hardware options for axes is very limited; stepper motors and incremental encoders only
- The style of the system makes support and maintenance easy
- Any sort of advanced applications and setup have to be completely handled at the EPICS layer, the controllers themselves only have support for a few hundred lines of code

GALIL System

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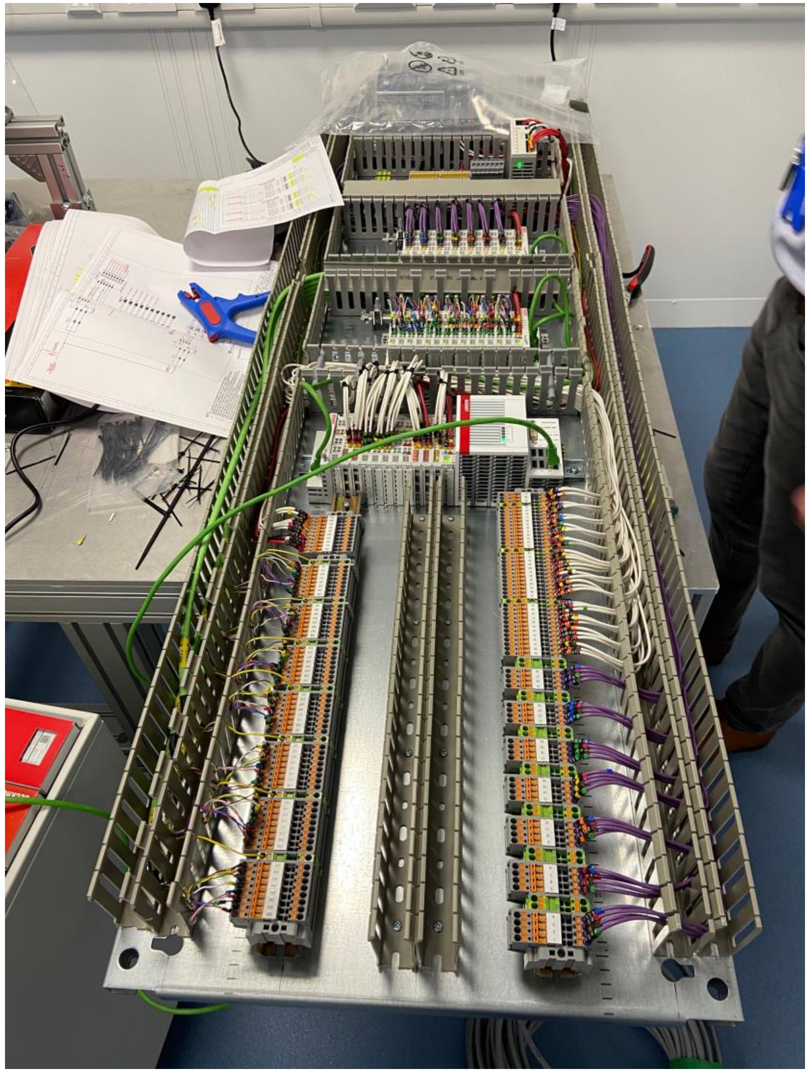
Motion Control Architecture at ISIS (continued)

Beckhoff System (New)

- PLC based motion controller following the approach of isolating motion control to just the motion control system layer
- These real-time controllers are capable of more advanced P2P (point-to-point) position control and have much greater support for different hardware
- Support of the system is more complicated than the older system. There are more “parts” and layers in the system that can go wrong so it needs the correct maintenance support staff in place for this



Design for Control

Before designing your system, you must understand the capabilities and limitations of the Motion Control System in use at your facility. The Motion Control System will determine:

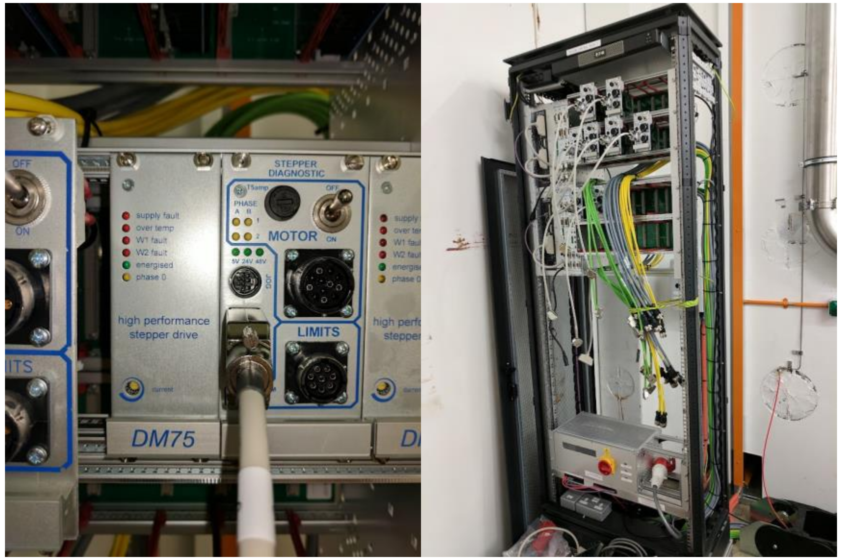
- What hardware you are allowed to use
- What kinematics options are available
- What user control options are available
- How you implement any machine protection functionality

Hardware selection

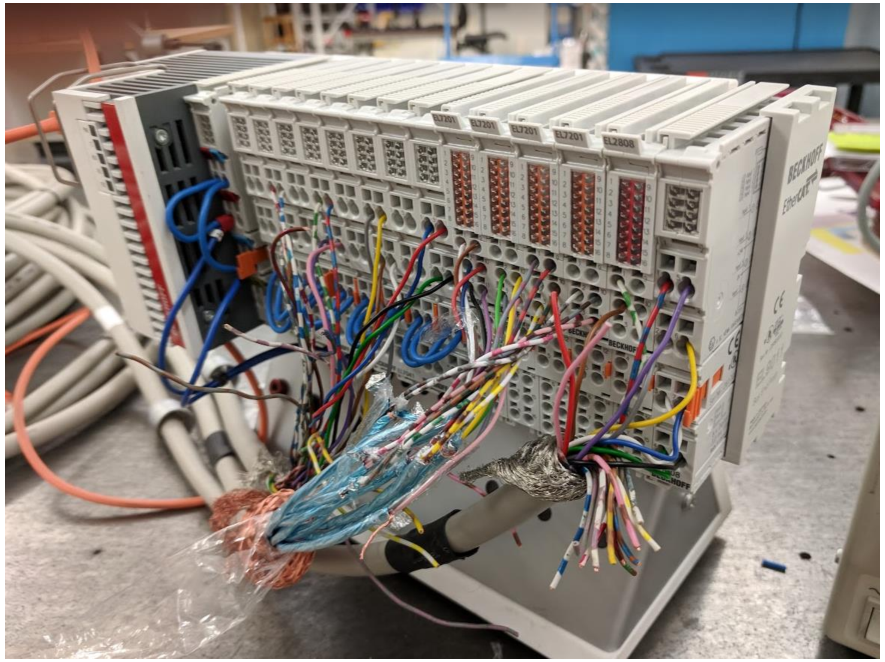
The Motion Control System will impact:

- Drive selection:
  - Stepper
  - Servo
  - BLDC (etc)
- Feedback selection:
  - Incremental single-ended/differential
  - SSI/BISS-C
  - ENDAT
  - Resolvers
- I/O assignment:
  - Limit and home switch technologies
  - Additional sensors (e.g. temperature and vibration)

A PLC style system greatly enhances options as the system can be custom configured for each design.



GALIL Drive card and Rack



PLC Control system with interchangeable terminals

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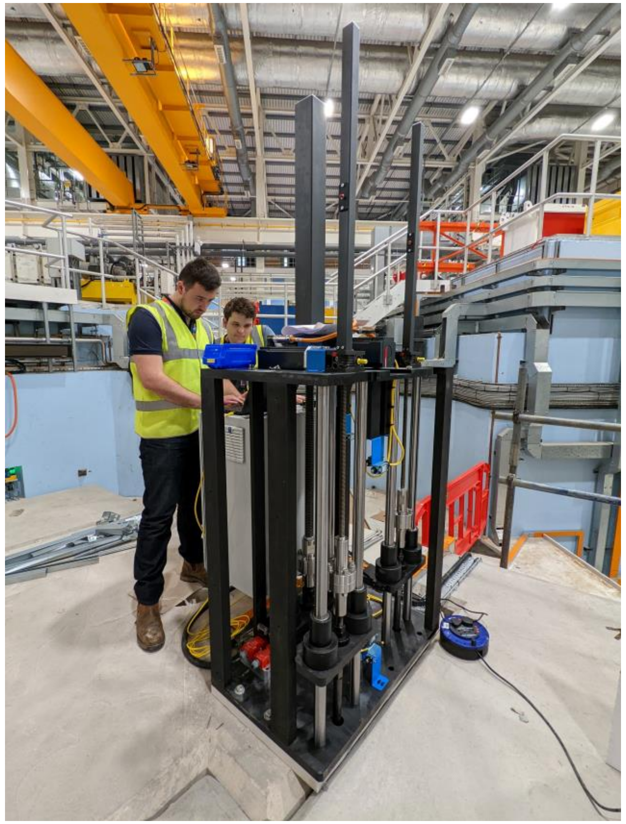
Hardware Selection Example

CHIPIR Secondary Shutter System

- If this had been designed for our old GALIL control system we would have been limited to 10A stepper motors:
  - This would have required higher gear ratios and additional gearboxes to achieve the torque required to move the 700kg shutter
  - This would have greatly restricted the velocity of the system so it did not meet the specification of 600mm travel in 30s
  - Using a 2000RPM servo motor we could run the screw jack at its max speed of 25mm/s with no additional gearboxes and meet the specification
- Using our new Beckhoff control system we were able to specify higher torque and higher velocity motors. Enabling us to meet all the requirements of the motion system



CHIPIR Attentuator/Secondary Shutter Control

Kinematics and User Control Options

We would expect our Motion Control System to allow Users to control any arrangement of real axes, but what if these axes don’t directly control what your user wants to control?

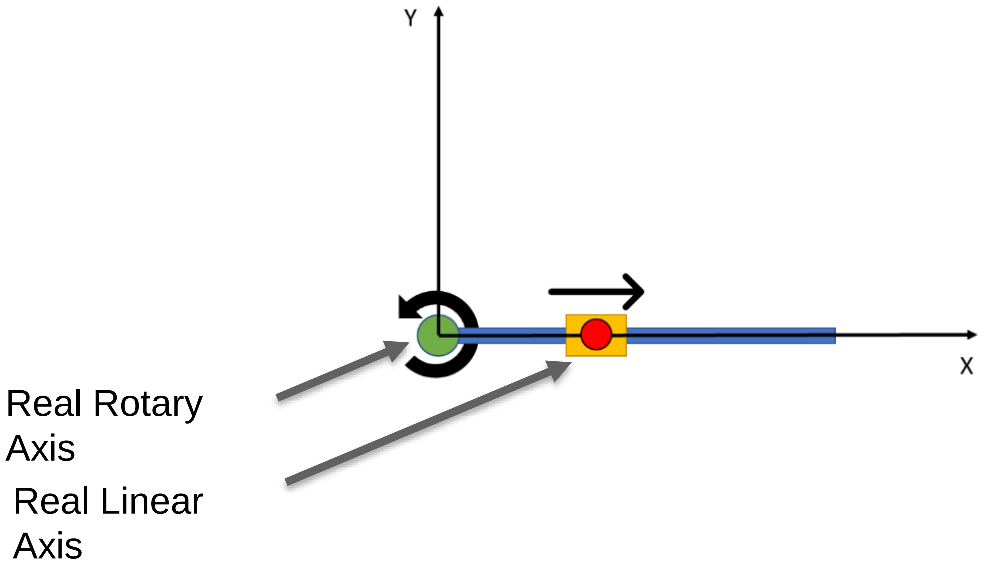
For example:

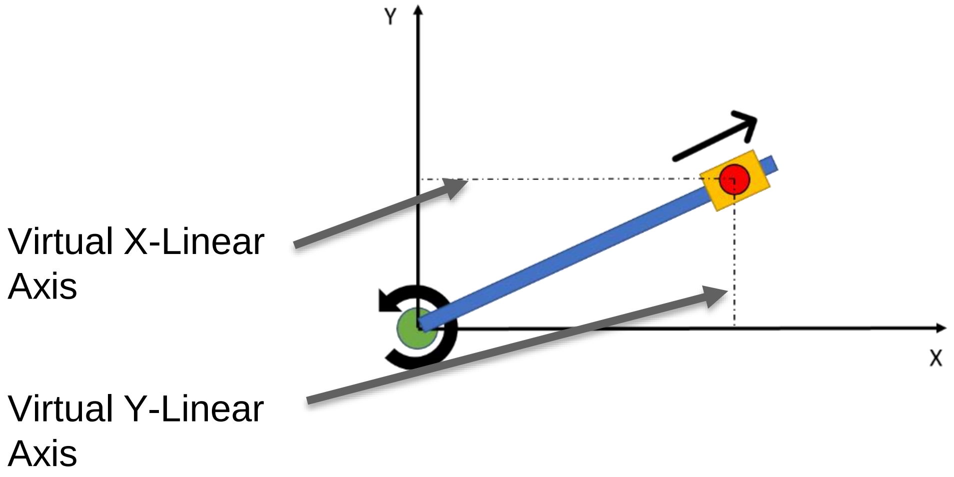
- An end effector is driven in to position by a rotation axis and a linear, these are the real axes of the system

A solution:

- Virtual software only axes can be created that represent the X,Y position of the end effector such that the user doesn’t need to know the conversion between the real axis and the virtual axis positions

Having these alternative control options opens up the mechanical design to new and unique approaches without compromising the user requirements or experience.





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Kinematics and User Control Options

You need to be considering when you design your equipment:

- How does your User want to control and use the motion equipment
  - This should then be included in the specification
- If you are relying on virtual axis control, you need to ensure that your control system is capable of providing this functionality, and that resource and effort is available to create that functionality

Our approach at ISIS is that virtual axes should be indistinguishable from real axes to the scientists and users, the same functionality, level of interaction, and control should be available to all types of axes.

Slit Example

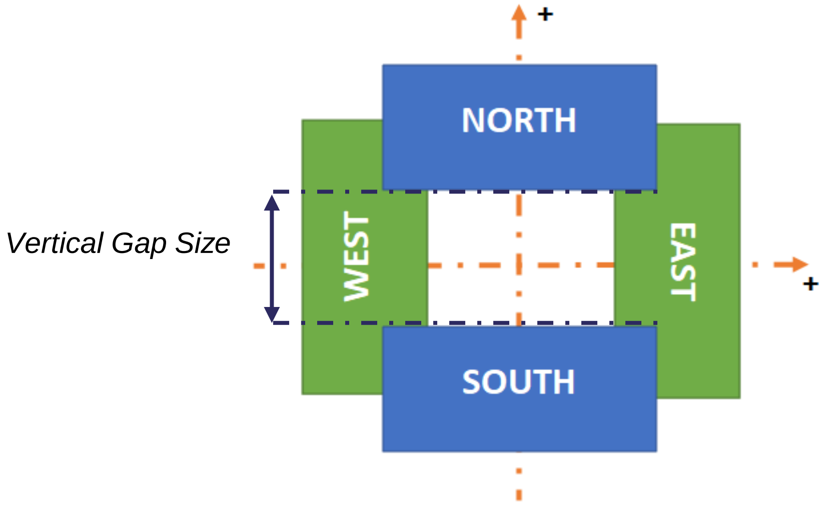
A neutron slit has 4 individually actuated blades that form an aperture/gap.

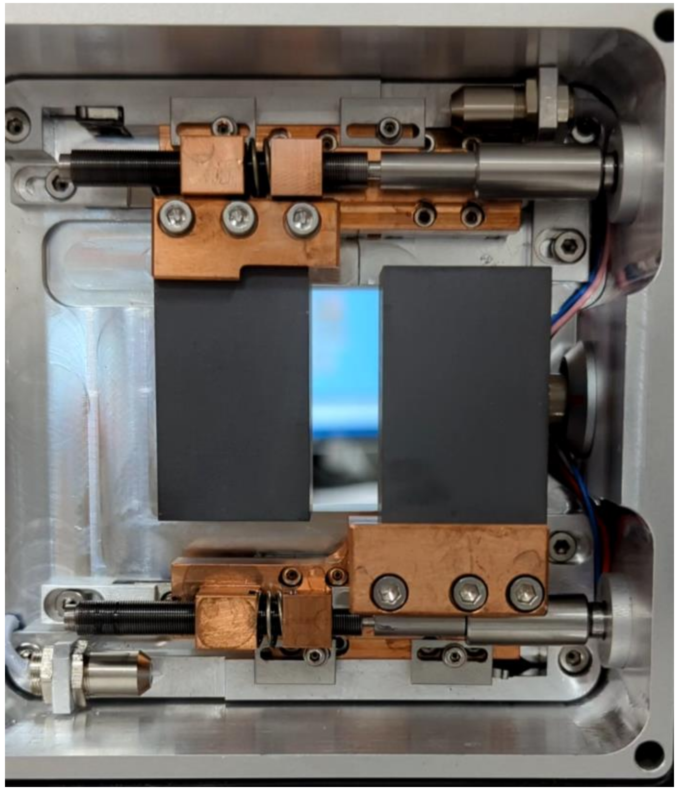
Users have two ways in which they want to interact with this equipment:

1. Control individual blade positions
2. Control the vertical/horizontal gap size and gap centre position created by these blades

With no virtual axes in place, users do not have the possibility of option 2. To control the vertical gap size they need to position the North and South blades separately.

This isn’t complicated for them but we can improve upon the user experience by creating virtual axes too give them that second control option.





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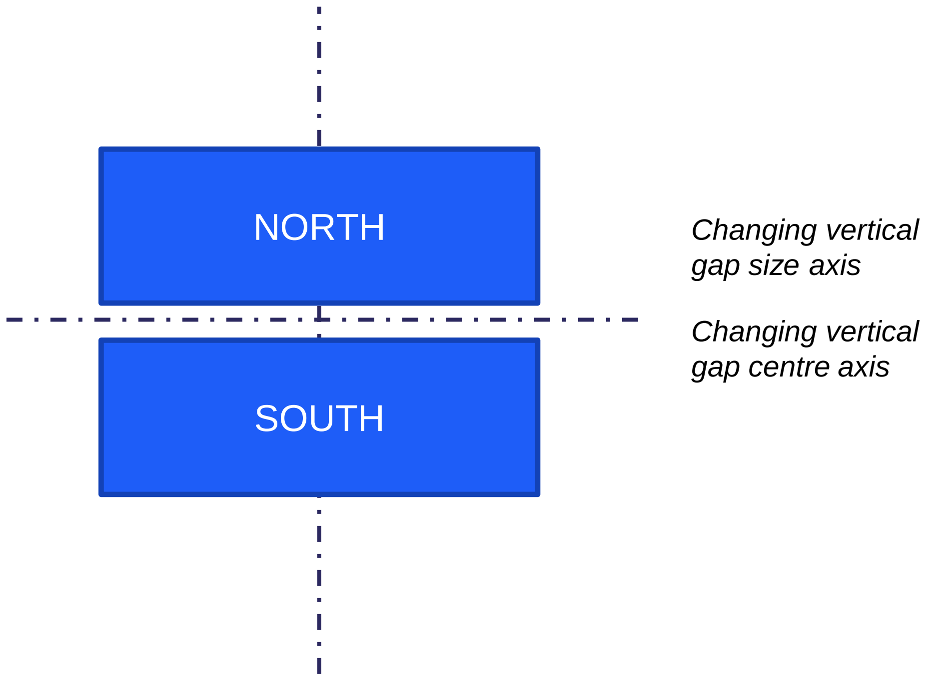
Slit Example

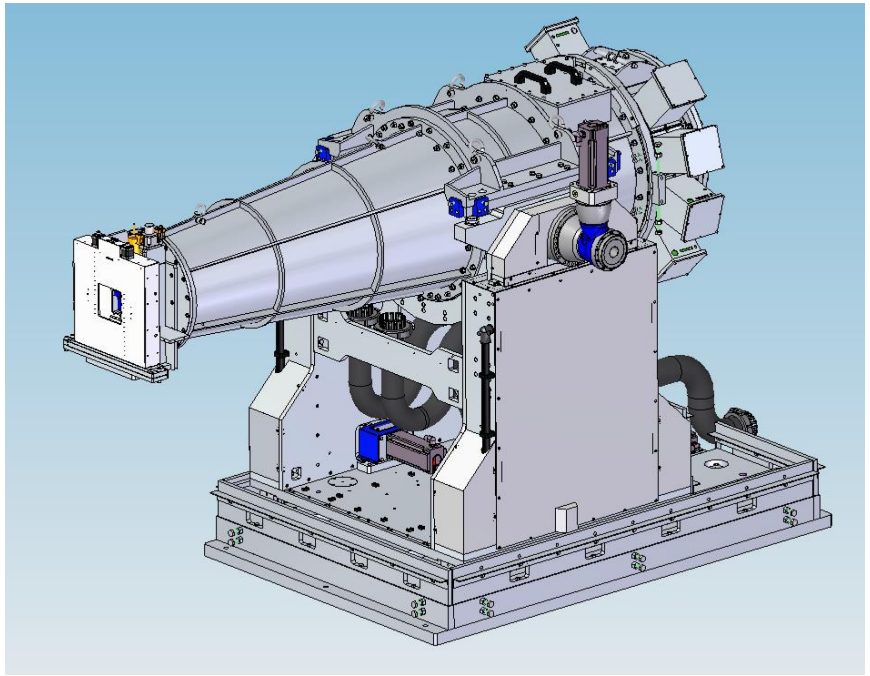
These virtual axes are kinematically coupled to the real blade axes such that actuating a virtual “vertical gap size” axis would move both the North and South blade together.

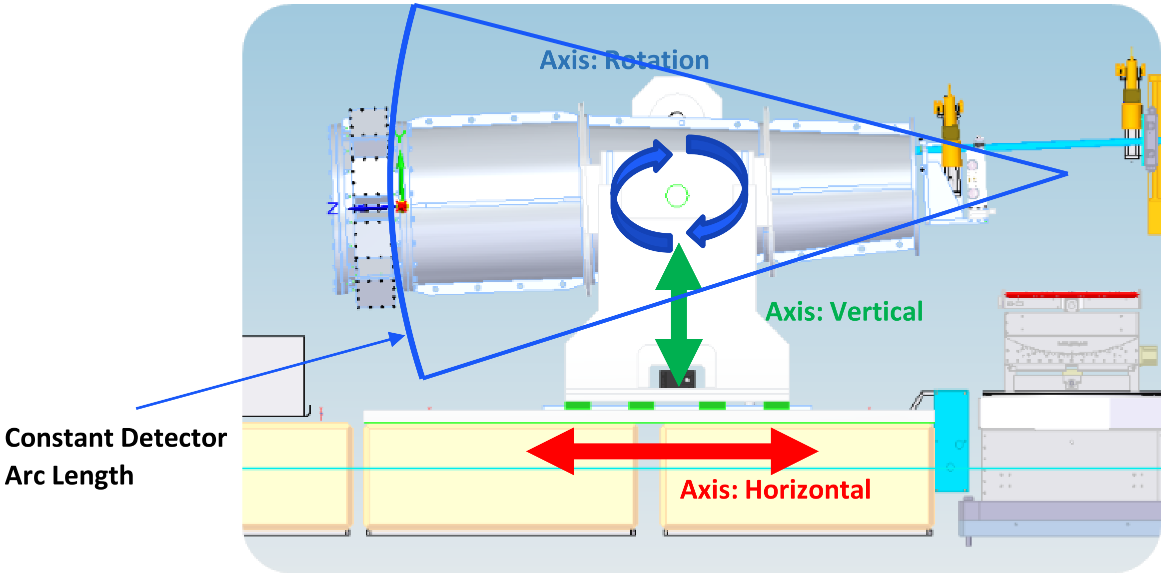


Reflectometry Example

Reflectometry instruments usually involve a lot of axes that have to move to setup and align an instrument at a specific “Theta” neutron measurement angle.

We could eliminate the need for interacting with a lot of individual axes if we kinematically linked them all in to one virtual Theta axis.





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Reflectometry Example

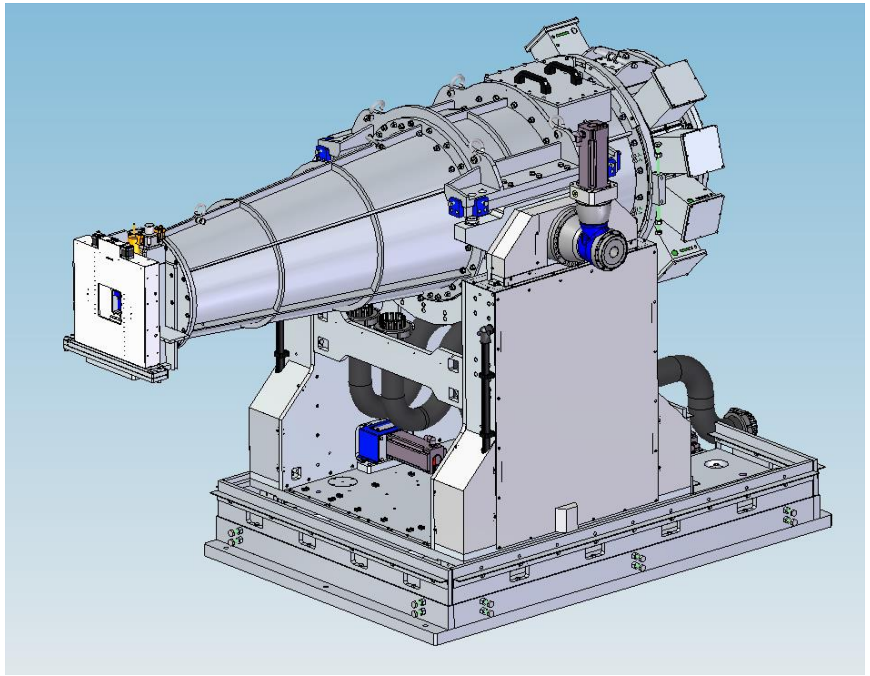
In this example system, a reflectometer detector tank has 3 real axes:

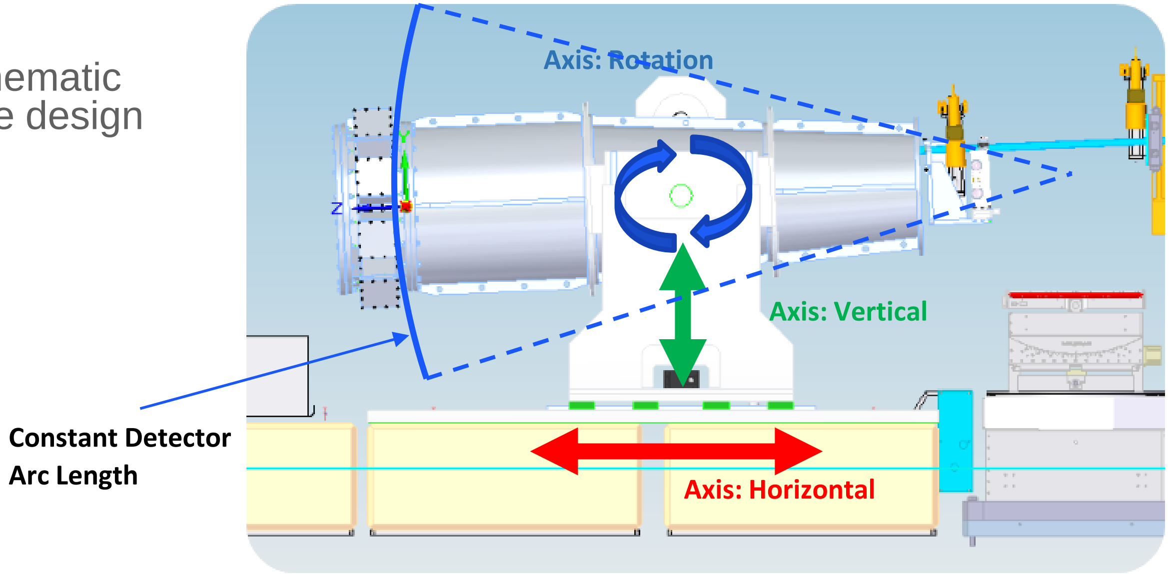
- Horizontal translation
- Vertical translation
- Rotation

These 3 independent axes have to work together to track a constant arc length around a sample point.

The implementation of a virtual **Theta** axis and virtual **Arc Length** axis greatly complicates the control setup of the system but provides a better and simplified user experience with the equipment which improves the experimental process.

There is a lot of extra work involved in setting up a robust kinematic solution and this time and effort needs to be factored in to the design process.





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Synchronised Axes

Large systems can often require mechanical drive at multiple locations. For example a detector bench may require a screw jack at all four corners to provide sufficient mechanical support to the system.

A mechanical design approach would be a single big motor with linkages and gearboxes translating this motion to all four corners:

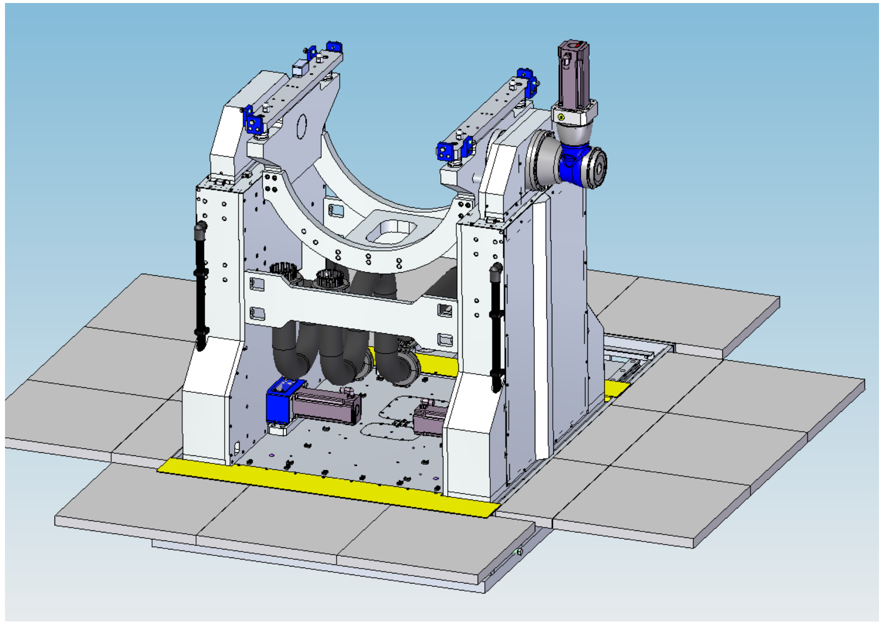
- The mechanical connection means any differing pitch between the screw jacks cannot be compensated
- Each of these linkages and gearboxes introduces inefficiencies and failure point that need to be supported and maintained
- Each of these linkages and gearboxes require covers and guarding from users

With a control-oriented approach, each corner could be instead driven by it's own lower power motor.

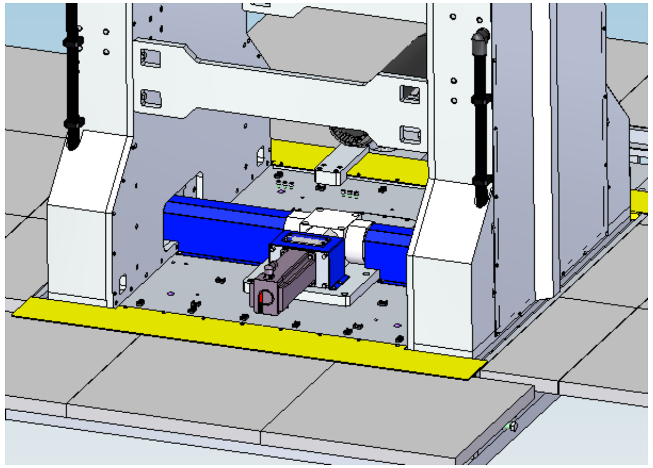
Synchronised Axes

The pictures here show a detector stage with two different configurations for controlling the height.

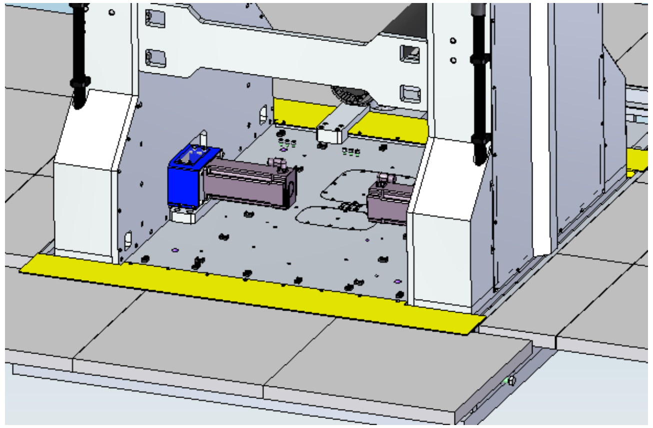
Just because your control system is capable of synchronised axis control, doesn't necessarily mean it's the right solution for every design.



Detector system for INTER instrument at ISIS



Single motor with linkages



Synchronised motors

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Machine Protection

Controls can be used to provide machine protection options based on the logical state of the axis or system it is part of.

These controls could include:

- Position limiting
- Velocity limiting
- Axis enable/disabling

A good use-case for this is collision avoidance.

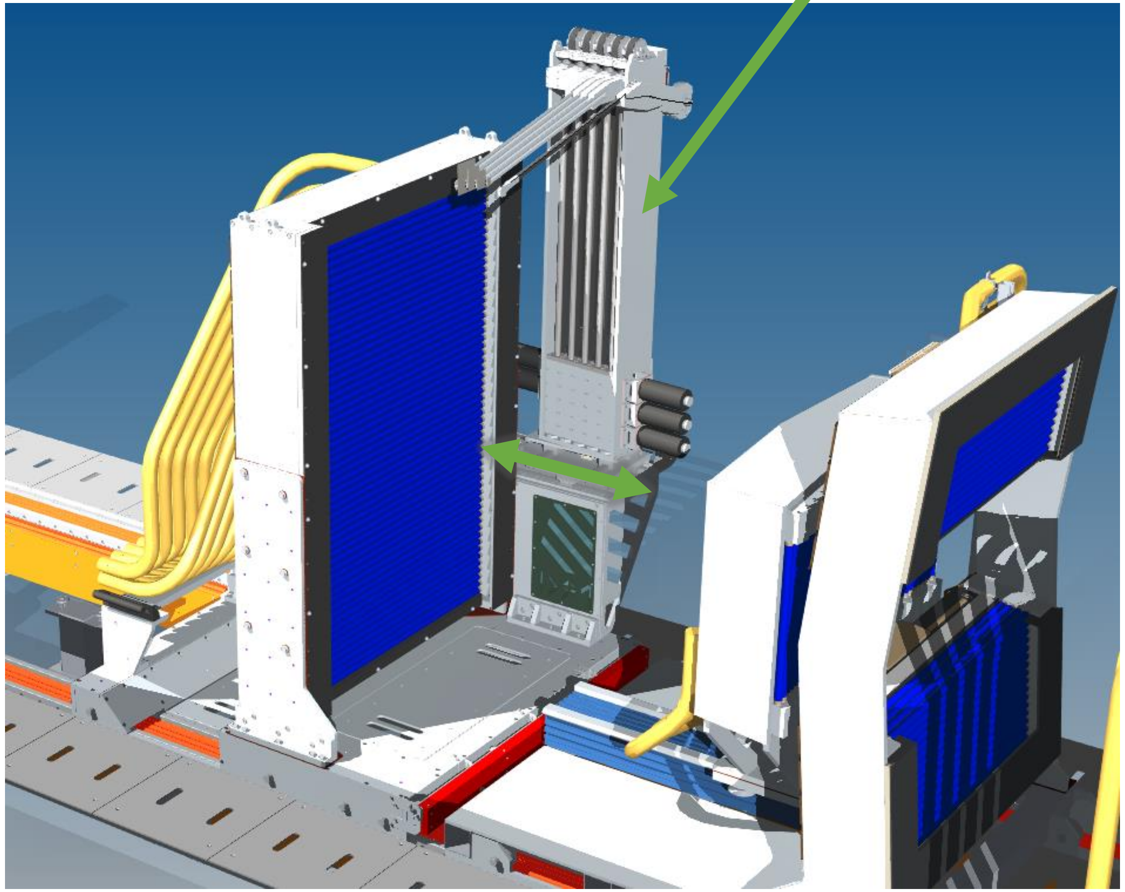
Machine Protection Example

The beamstop shown consists of:

- 5 independent beamstop height axes for selecting different beamstop masks
- X-Translation along the beam for positioning masks close to the detector
- Y-Translation across the beam for fine positioning of the mask at the centre position

It was very difficult to fit everything in to the tight space constraints available, this means when positioning masks closer to the detector it is possible to crash components in to the detector frame!

Beamstop



Beamstop and detector system designed for the new LOKI instrument at ESS.

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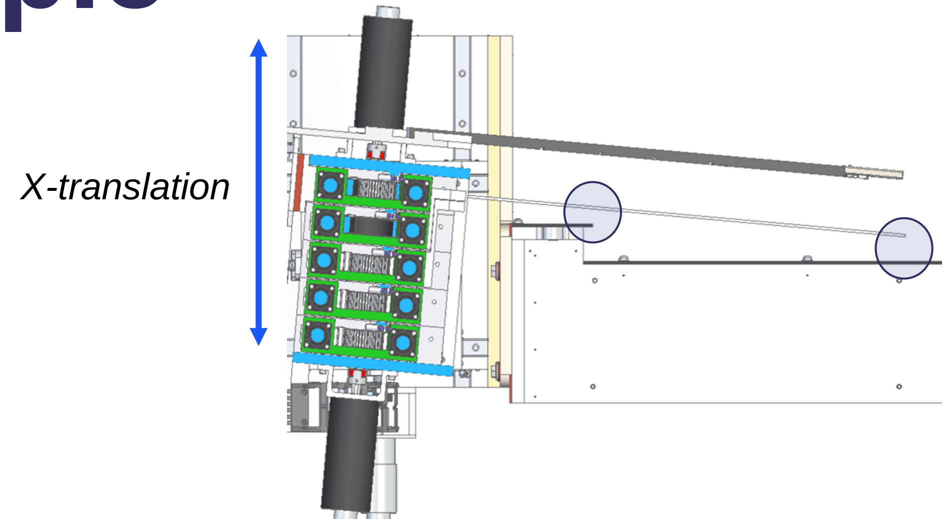
Machine Protection Example

With a control-oriented approach, additional “park” position switches have been included when each of the beamstop arms clears the detector frame.

- The X-translation is setup with dynamic software limits that adjust dependent on which beamstop arms are clear allowing it to position closer to the frame
- When the arms are positioned over the frame, they are disabled until the X-translation stage positions such that they can lower without crashing

It was agreed early in the design process that the Motion Control System could be used for machine protection and collision avoidance logic.



Testing some of the beamstop axes

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Motion Commissioning

How and why motion systems are commissioned and how to design for this

What is Motion Commissioning

The process of setting up the mechanical and electrical systems that form motion equipment and making, then ensuring, this equipment meets specification.

We do this by:

- *Ensuring the mechanical and electrical aspects work and are free of defects*
- *Configuring the equipment in software and parameterising the motion of the axis including calibration when required*
- *Writing and configuring application specific software required for the operation of the system*
- *Testing the equipment against the specification*

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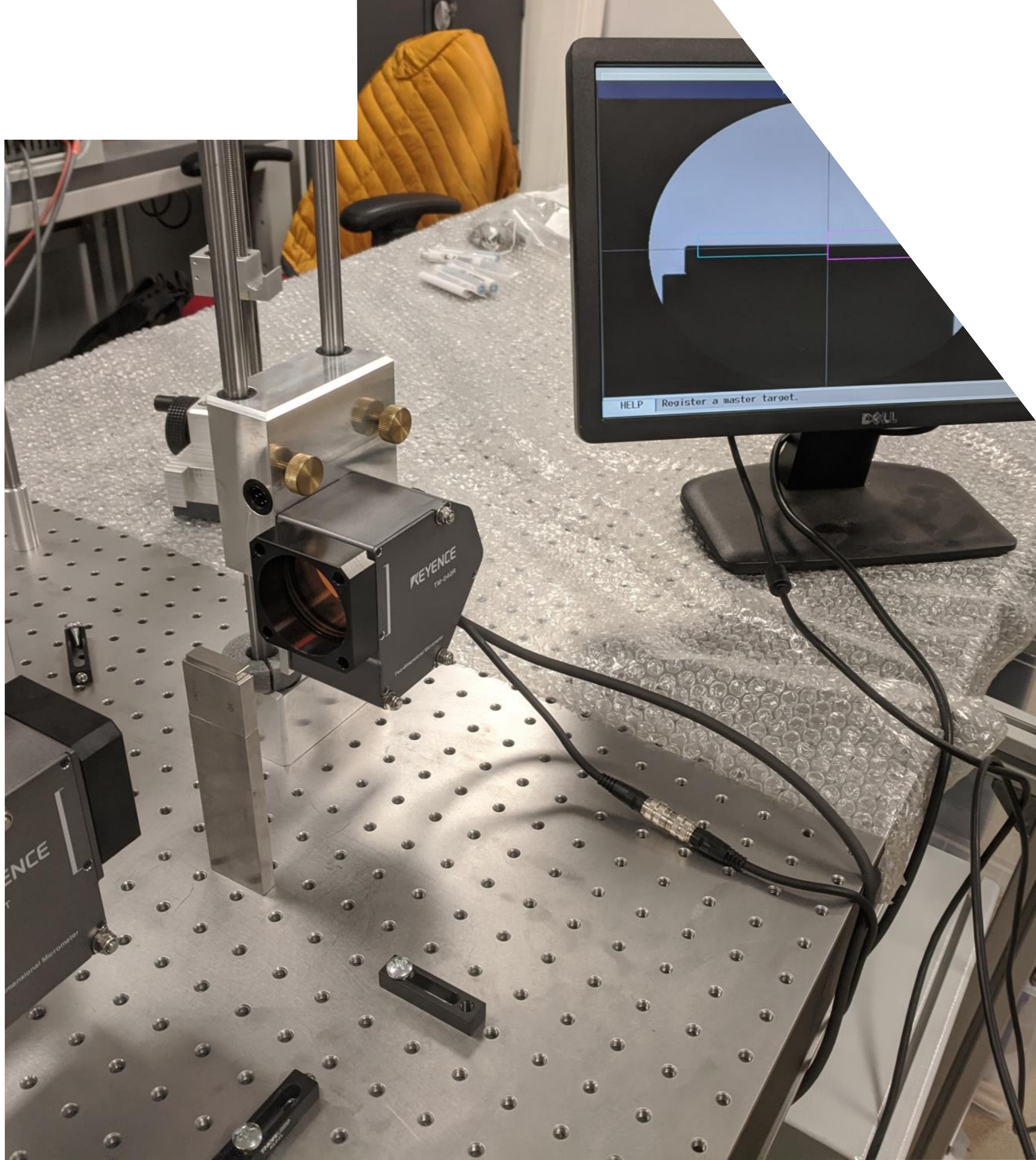
Why do we Commission

- *Parts we make and buy have tolerances*
- *Assemblies will have misalignment*
- *Designs can have hidden issues that aren't immediately visible*

All of these small errors can have a huge impact on accuracy when we're looking at micron resolution.

Just because an encoder tells you a system is at 'X' position does not mean it is at 'X' position in the real-world.



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Pitch error example – Manufacturing Tolerances

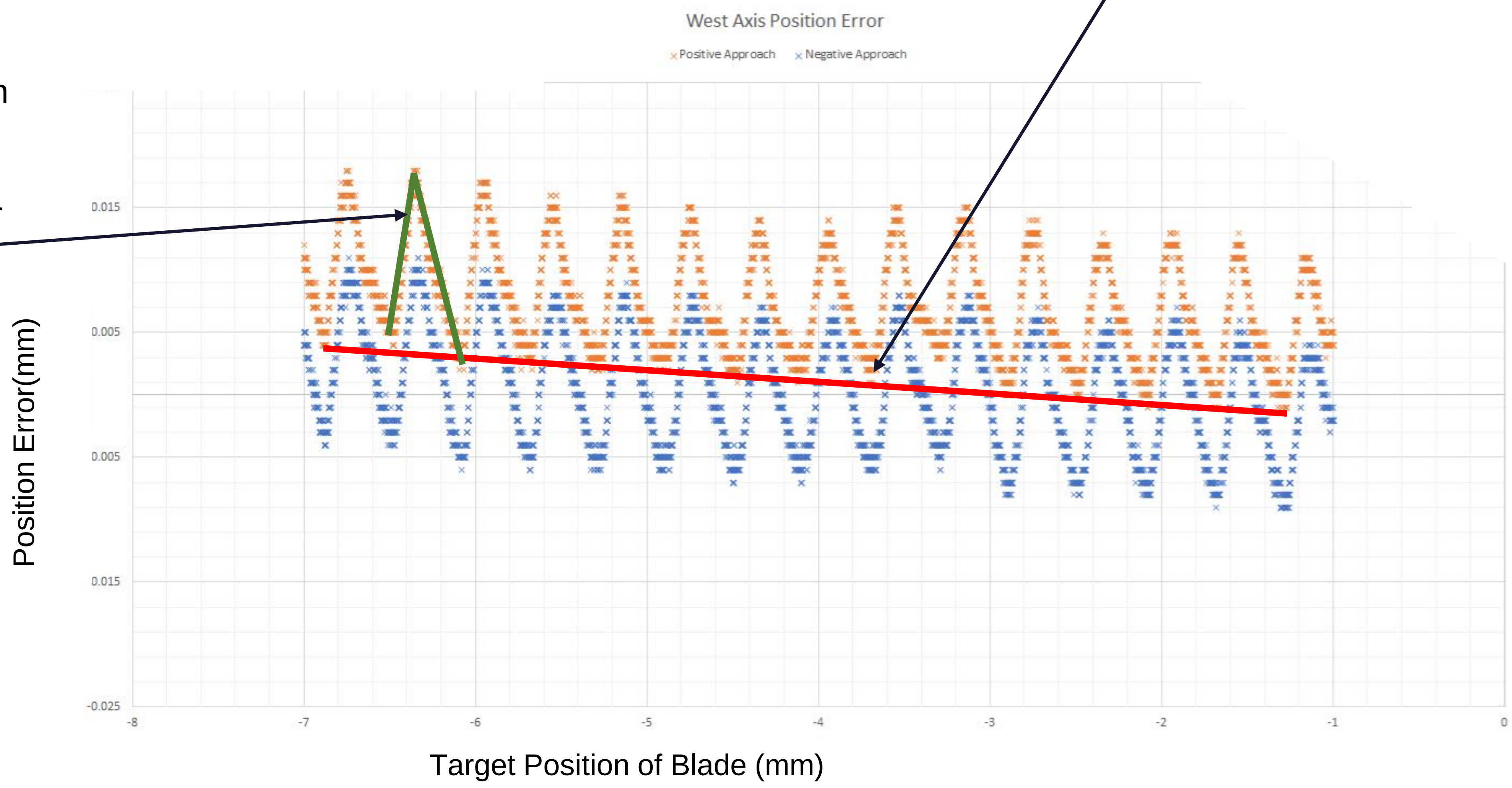
- Components such as lead screws and ball screws are sold with accuracy grades (guaranteed performance).
- This can result in axes on the same system where a 1mm move is slightly different on them all.
- In the recent Sandals slit commissioning we found a pitch error of 2.7μm/mm on one blade.
- It is possible to measure this error and correct for it. (Which we will discuss later)

Grade	% Accuracy	Real terms
Precision Leadscrew	0.1%	±0.5μm per mm / ±50μm over 100mm
Ballscrew C7	0.04%	±0.2μm per mm / ±20μm over 100mm
Ballscrew C5	0.018%	(±0.09μm per mm / ±9μm over 100mm

Pitch error example – Manufacturing Tolerances

The gradient is remaining uncorrected pitch error after a basic correction approach (discussed later)

This is the error within a single rotation of a leadscrew (the non-linearity, much harder to correct)



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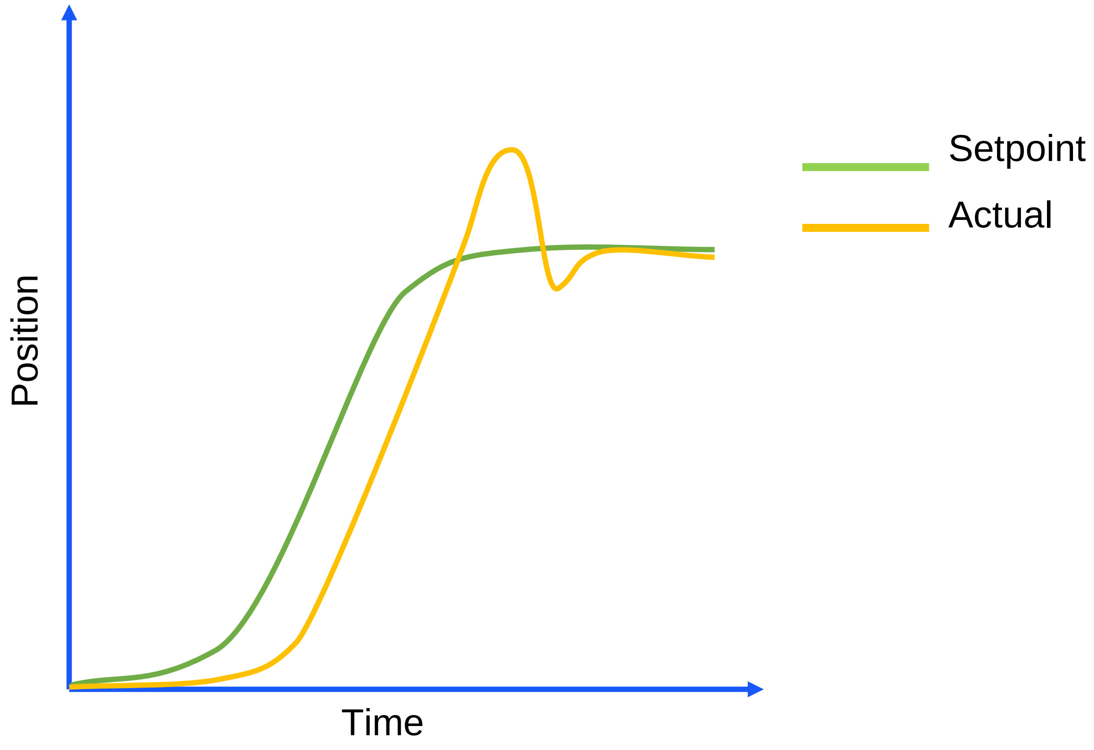
Why we care: Control response

Default proportional control loops can be quite aggressive and lead to a lot of overshoot. These require manual tuning to bring under control.

System dependent as to whether this behaviour matters but a poor control loop can lead to slow response times or oscillatory/juddery behaviour.



Why we care: Designed and assembled by humans who make mistakes

Issues can easily slip by unnoticed and be incredibly difficult to diagnose or rectify with equipment installed. It’s easier to catch them and resolve them before installation lowering the risk of experiment downtime.

On Sandals slits:

- Multiple wiring issues, badly terminated cables that could have failed over time, damage of insulation shorting the housing to 24V

- Damaged feedback mounting and poor design that affected repeatability and caused one blade to jam; small impacts to resolvers during operation or installation could have replicated this issue on any axis

Why we care: No performance baseline

- We have no idea how good our systems are or if they're meeting specification.
  - Difficult to assess the requirements of new systems if they are being compared against un-confirmed performance levels of existing systems.
- We’re not able to learn what works well in a design.
- There is no baseline for future comparison
  - Cannot assess how motion systems degrade over time nor their expected lifetime
  - Data would help improve maintenance planning and obsolescence planning for replacement of components.

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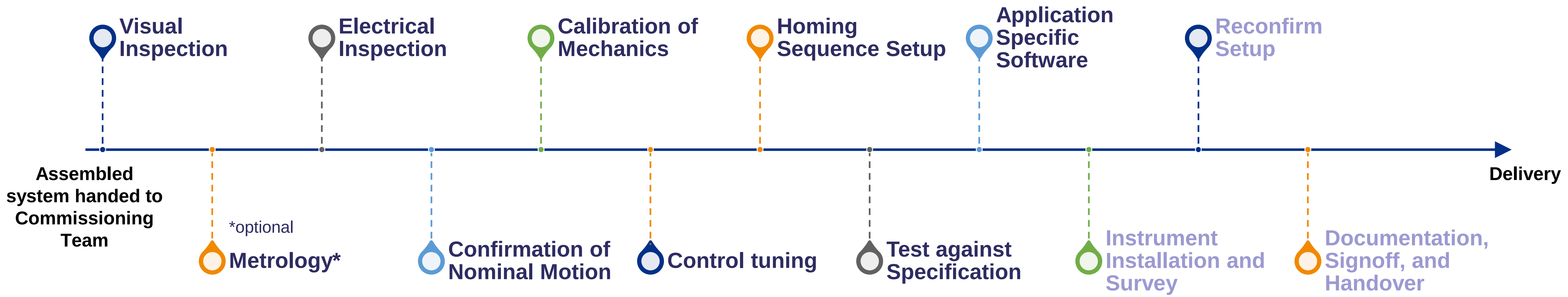
Commissioning Steps

The Quality Assurance Process

Nominal Commissiong Timeline



All systems will ideally go through these steps during the commissioning workflow.

The depth, complexity, and time for each of these steps is dependent on the system under test. There is an initial time cost associated with most of these steps the effect of which is lessened in multi-axis systems.

Failing a step early in the process can require rework of a system or acceptance that it may not meet required specification.

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Visual Inspection

- Assessing the condition of a system
- Checking for signs of obvious issues
- Checking for missing components or poor installation
- Identifying limitations of our own motion testing
  - E.g. are we going to have issues testing the component against specification

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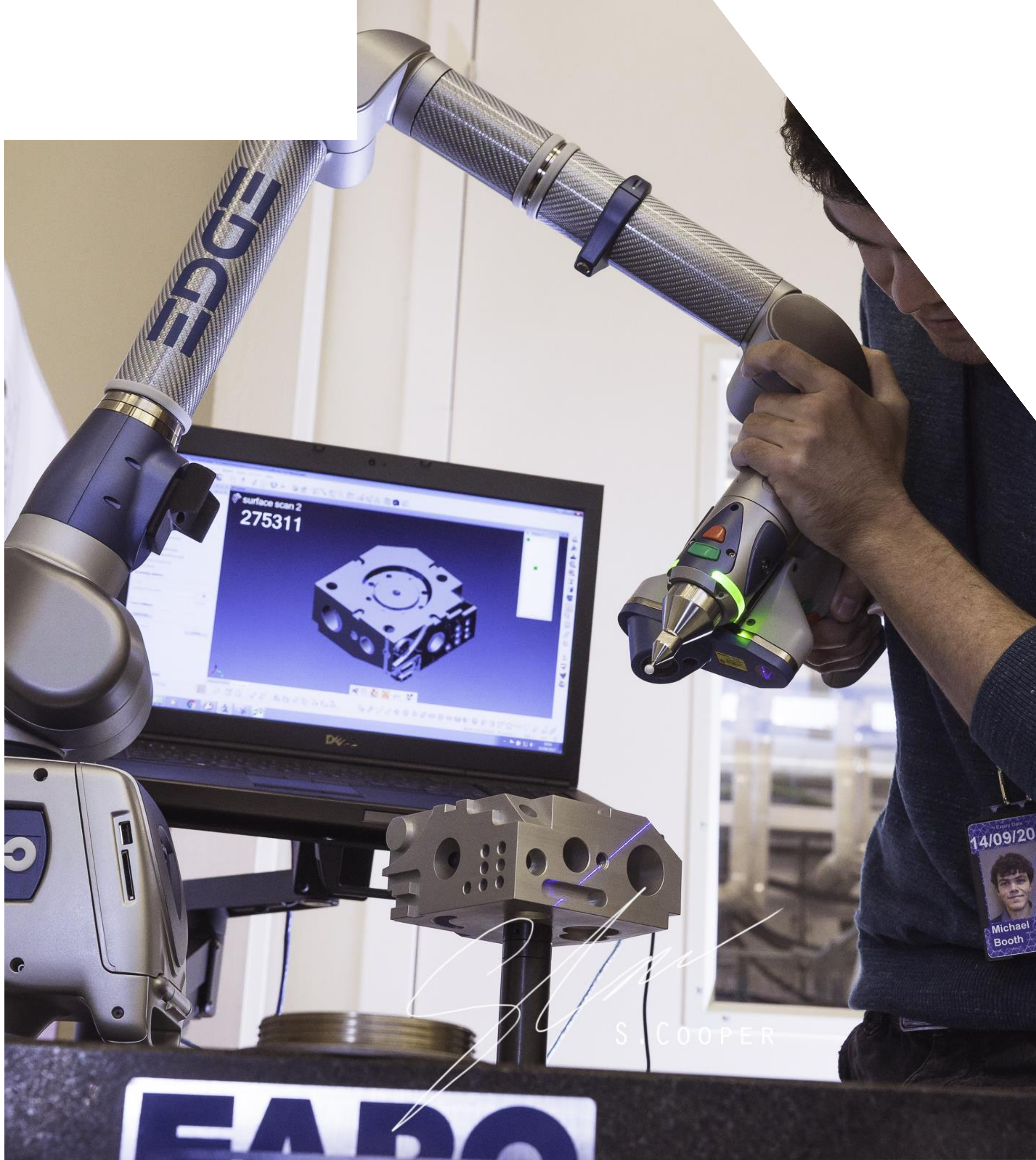
Metrology

- Used to confirm parts meet specified tolerances
- Used for precision installation and alignment of parts critical to operation of system
  - E.g. installation of slit blades

This is an optional step that is only used if there is a requirement for precision installation of components or there is reason to suspect that a manufacturer has not delivered a part to specification.



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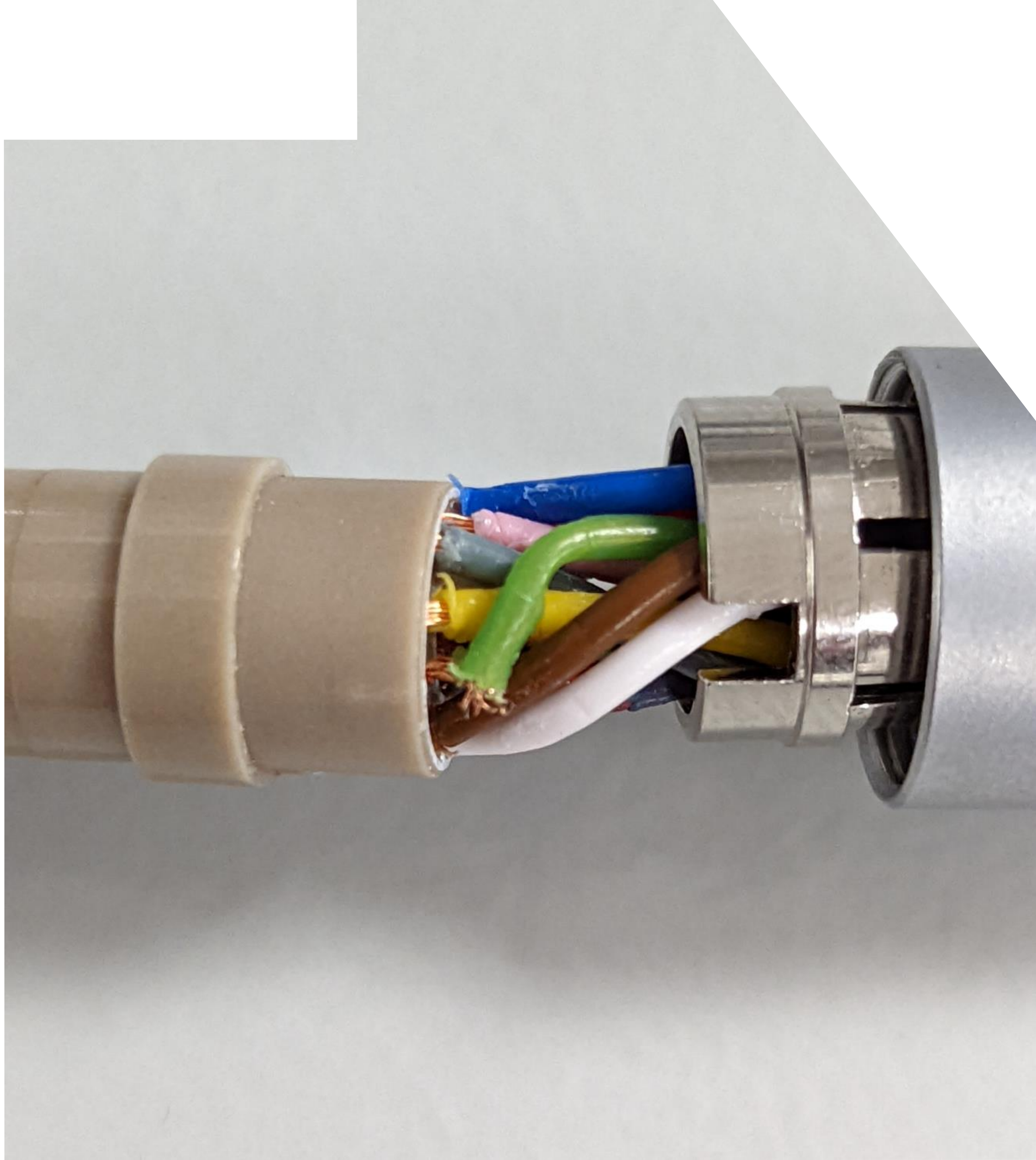
Electrical Inspection

- Checking and recording resistances of components to detect faults or shorts

- Checking components are wired correctly

Helps prevent damage from powering on incorrectly wired systems. Provides a baseline for support in the future.



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Confirmation of Nominal Motion

- Setting up the components to their theoretically nominal setup
- Axis configured with closed loop control
- Axis polarity configured to user requirements

Non-standard hardware can take considerably longer to setup

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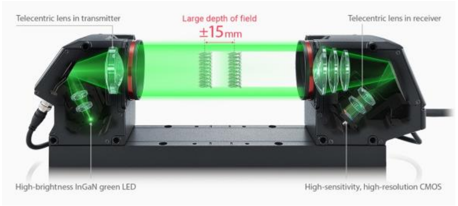
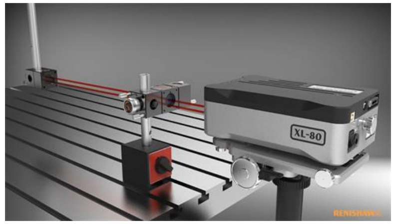
Measuring Hardware





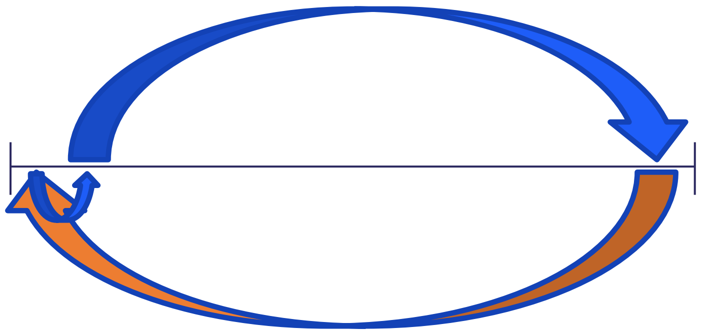
Device	Measurement	Range	Accuracy	Contact
Callipers	Linear	0-300mm	±0.03mm	Yes
Dial Indicator	Linear	0-12.7mm	±0.003mm	Yes
Laser Distance Sensor	Linear	50-250mm	±0.001mm	No
Optical Micrometre	Linear+ Interpolated	0-40mm	±0.002mm	No
Interferometer	All 6 DoF	0-40,000mm	±0.5µm/m	No (Requires mounting on the axis)
Coordinate Measuring Machine (CMM)	Coordinate	1200x100x700mm	0.28µm	yes

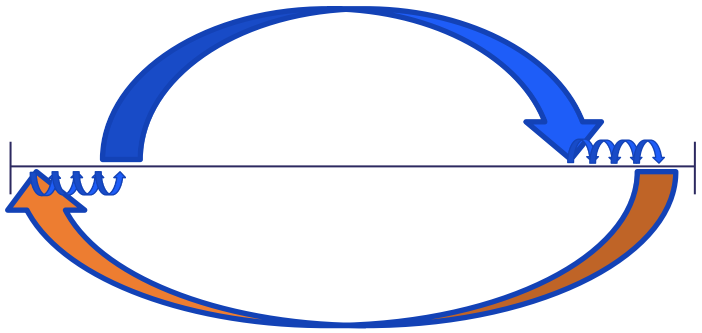
Calibration of Mechanics

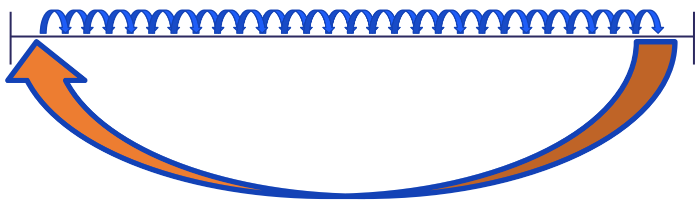
- Nominal motion calibrated against real-world feedback to try and compensate for mechanical tolerances and alignment

Three approaches possible with increasing complexity and performance gains:

1. Measure and scale over two semi-arbitrary points within the measurable range of travel, will get you to within a few microns of error per range of travel tested over.
2. Min/max approach, measure the entire pitch range at two points within the measurable range to identify matching points within a single rotation and use these positions as the scaling points. This helps eliminate the additional few microns left over from approach 1 but takes longer to measure.
3. Look-up table, map the entire motion of the movement over its range of travel and apply compensation at every point. Takes much longer to measure but provides excellent accuracy (how high accuracy manufacturing machines work). Not possible with our current equipment.







Control Tuning and Homing

- Configuring the control parameters for the axis to define its positioning response
- Setting filters and motion dynamics (velocity, acceleration, jerk, etc)
- Choosing and testing home sequences for repeatable referencing
- Ensures that no user combinations of set values could error or damage the axis

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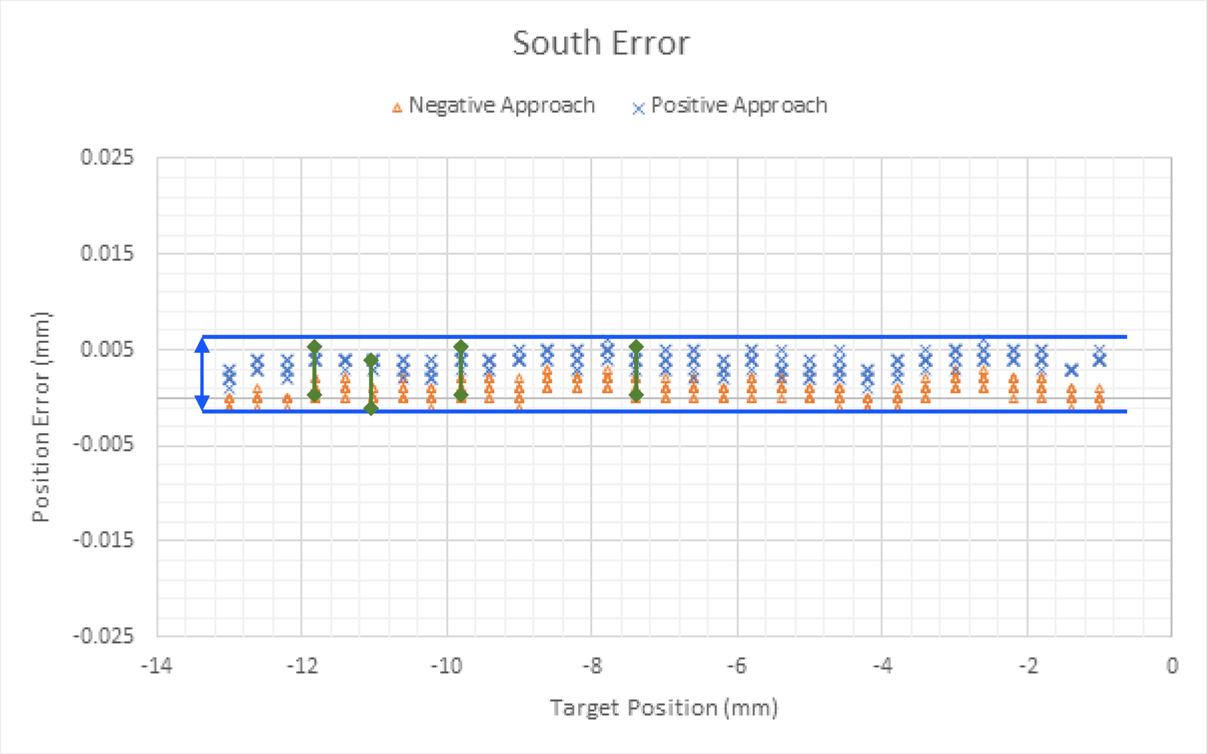
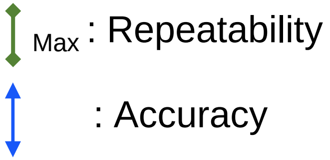
Test against specification

- Physically testing if the system meets the agreed specification
- Final offline chance to identify any performance issues
- Provides useful data to feedback to designers
- Provides a performance baseline for future maintenance

Automatic testing and data collection tools really help increase the quantity and quality of data collected





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Automated Testing

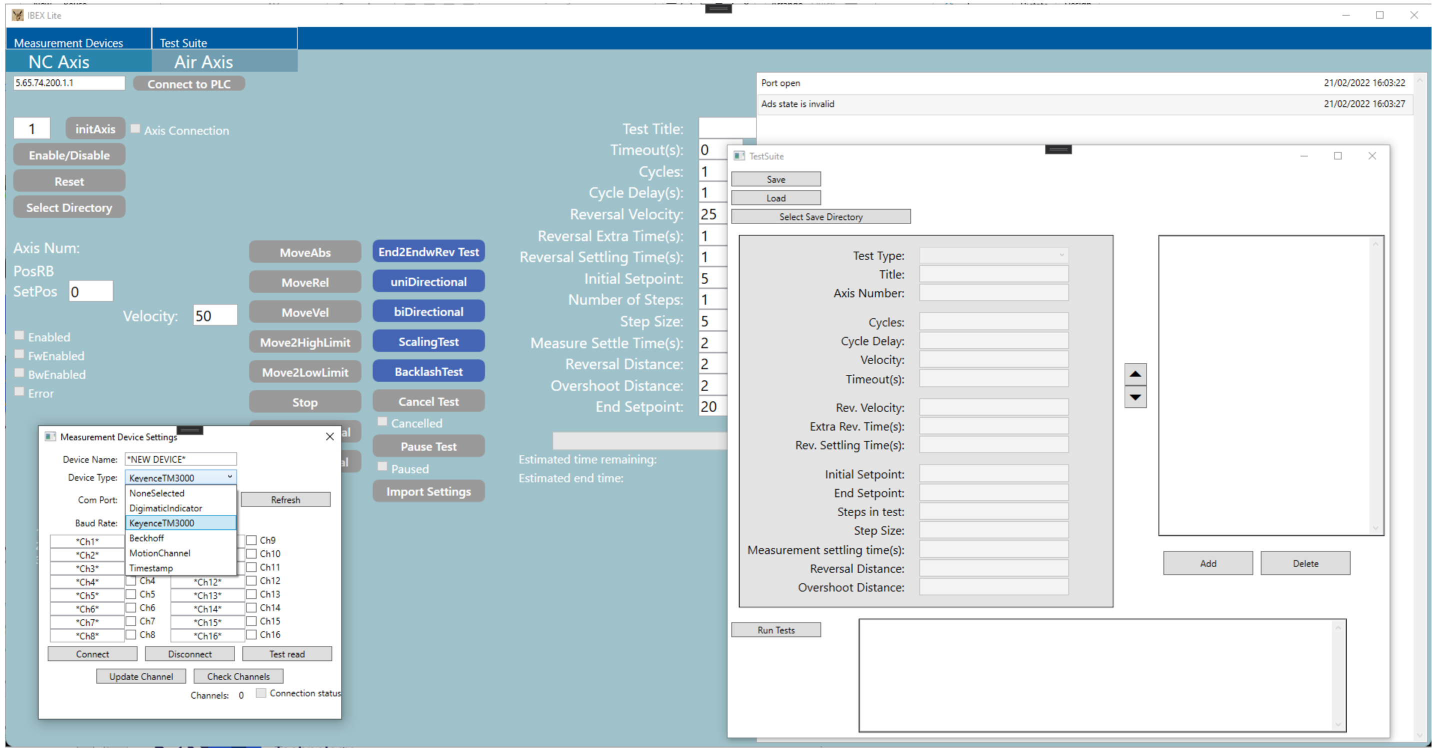
We've written software to automate some steps of the commissioning process with configurable tests for:

- Uni/bi-directional accuracy and repeatability
- Scaling the mechanics
- Checking range of travel
- Detecting backlash

Tests can be scheduled to run in sequence overnight or over several days.

Software enables connection of measurement devices that are sampled during tests:

- RS232 devices such as the Keyence and indicators
- Additional Beckhoff data collection crates for temperatures and analogue signal sampling
- System timestamping
- Additional channels on controller such as secondary encoders



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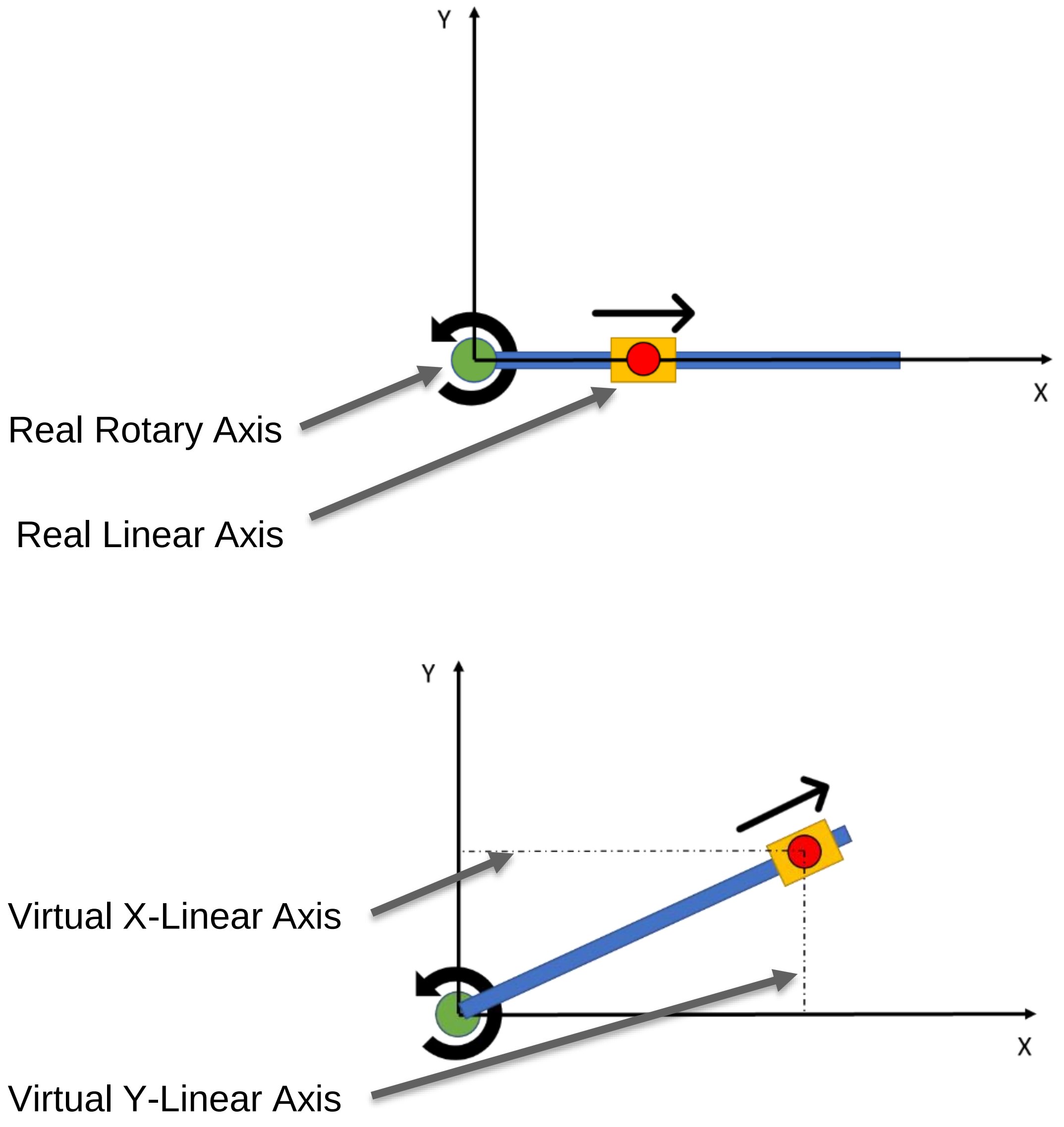
Design For Commissioning

A system that's easy to commission is a system that gets commissioned efficiently and to a higher standard

What and How Do You Want To Measure

- Does only the moving axis need measuring, or do you need to measure some interpolated motion?
- Are you happy with it all being measured with a ruler?



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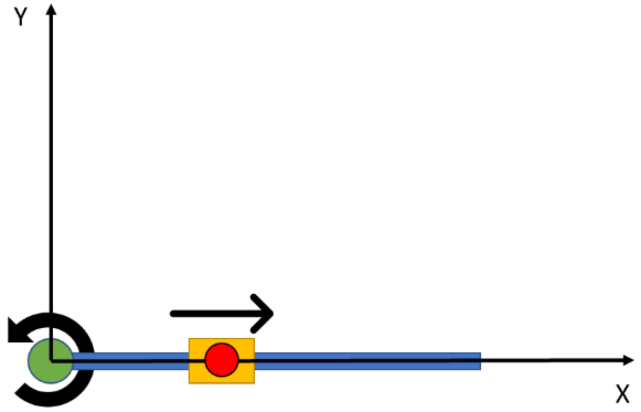
What and How Do You Want To Test

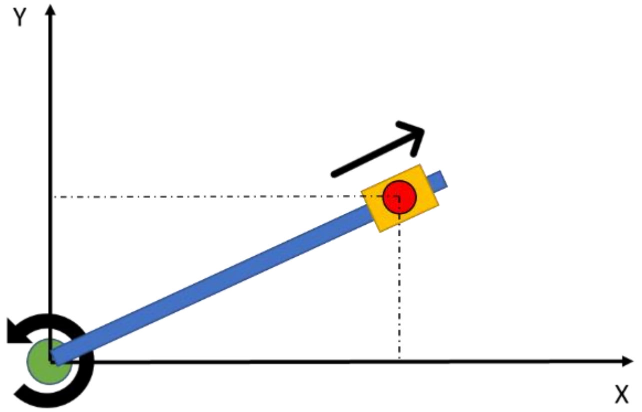
- How many cycles for an endurance test?



- Bi-directional or Uni-directional?

- How many points for a repeatability test?

- Do you want a temperature-controlled environment?



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Ease of Adjustment

- Can you fit a tool + fingers in to adjust the component?
- How do you know when it's been adjusted correctly?
- Is there a specific order thing's need to be adjusted?

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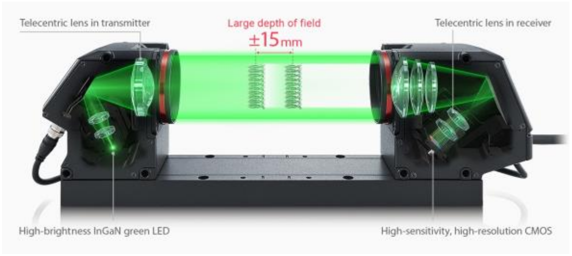
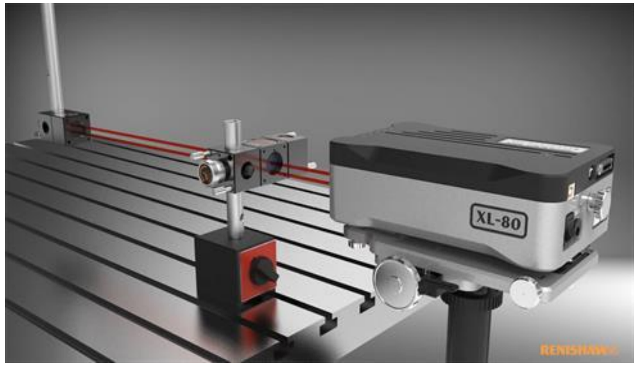
Ease of Measurement

- What measuring hardware is available for commissioning?
- How do you mount the measuring hardware?

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Summary

1. Neutron motion systems

The uses of motion at neutron facilities and examples of motion systems

2. Motion terminology

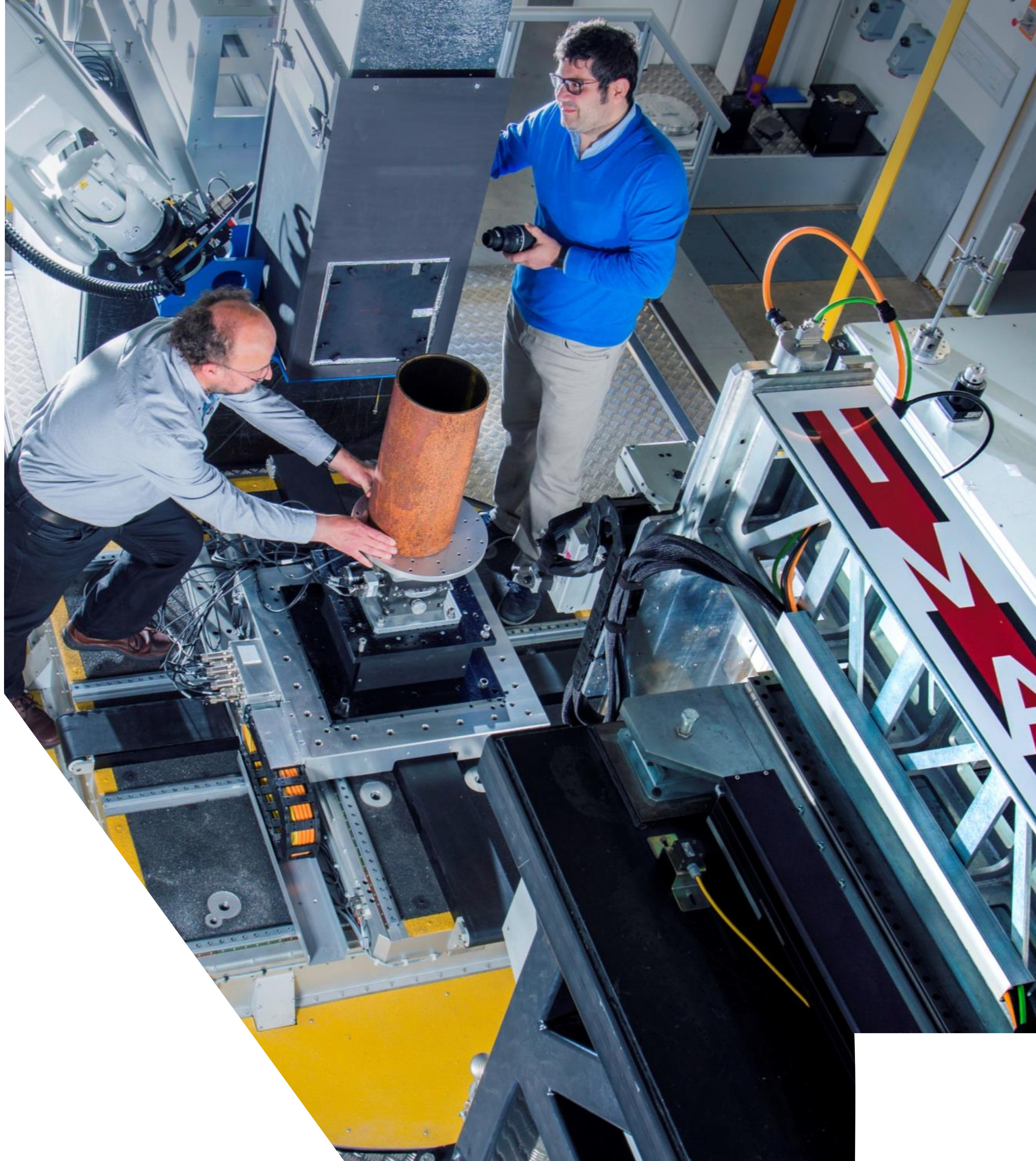
Explanation of the basic motion terms used for specifications and requirements

3. Science to motion

How to convert scientific requirements in to motion requirements

4. Facility specific requirements

What aspects of a motion system may your facility standardise



Summary (continued)

5. Critical motion components

Selecting and specifying the critical parts of a motion axis

6. Additional considerations

Investigating addition challenges or restrictions on components as a result of neutron environments

7. Motion Control

Looking at how users at your facility will interact with motion equipment and basic setup

8. Commissioning

Testing motion systems against specification and deploying on to instruments

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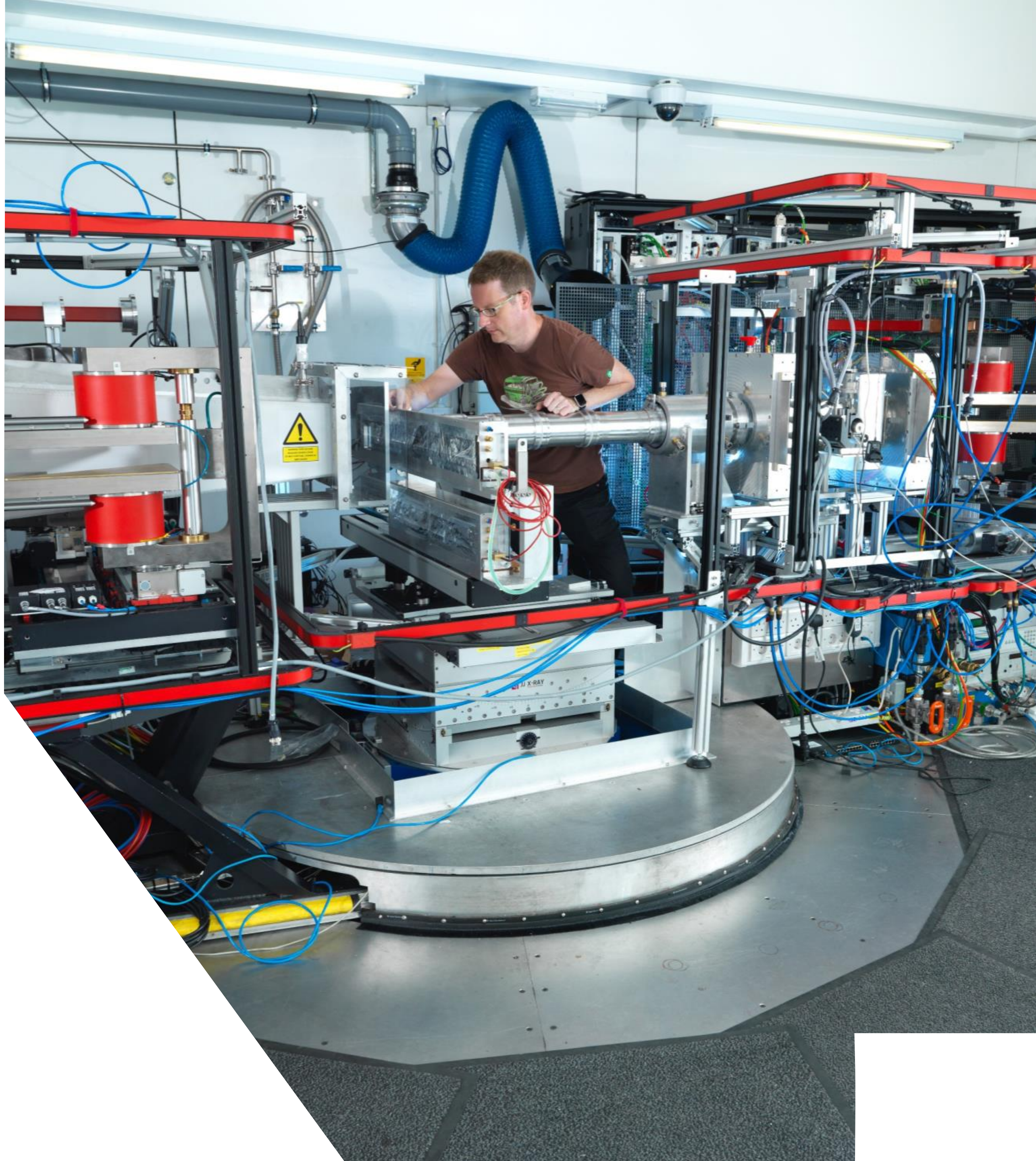

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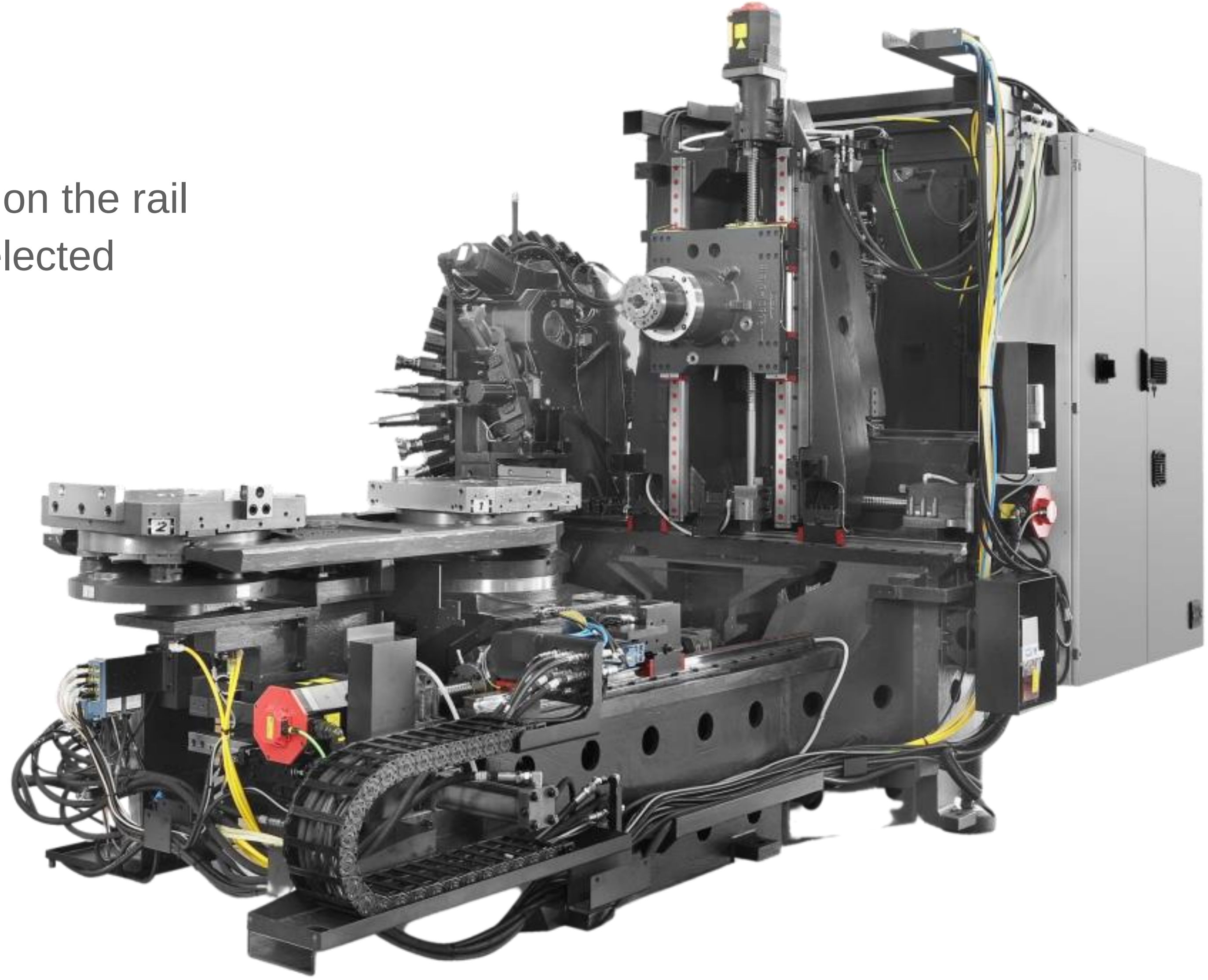
Additional Info

Selecting Motion Guides

1. **Select a style of motion guide**
2. Select the accuracy grade
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. Determine the preload and rigidity
6. Calculate the system lifetime
7. Select the type of lubrication



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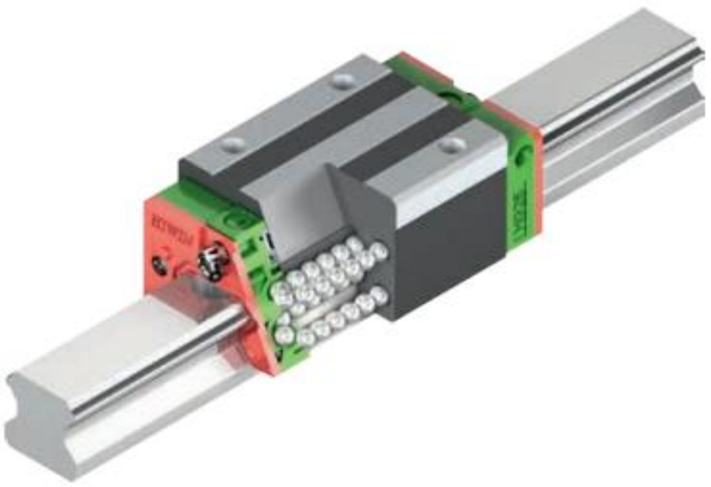
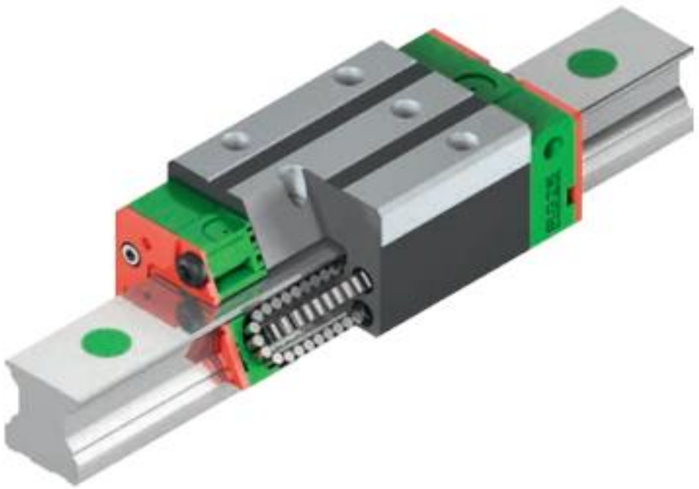
Motion Guide Styles

- Linear Rails
    - Ball type rolling guides
    - Roller type rolling guides



Design of the HG series



Design of the RG series

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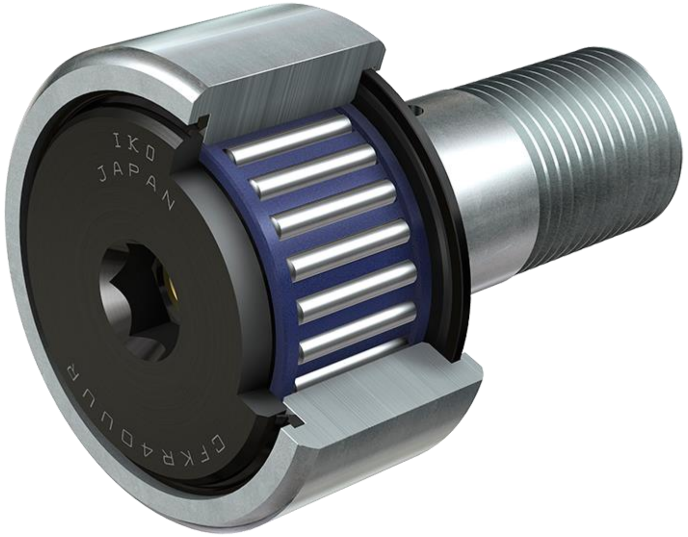
Motion Guide Styles

- Ball spline rolling guides
- Shaft guidance system

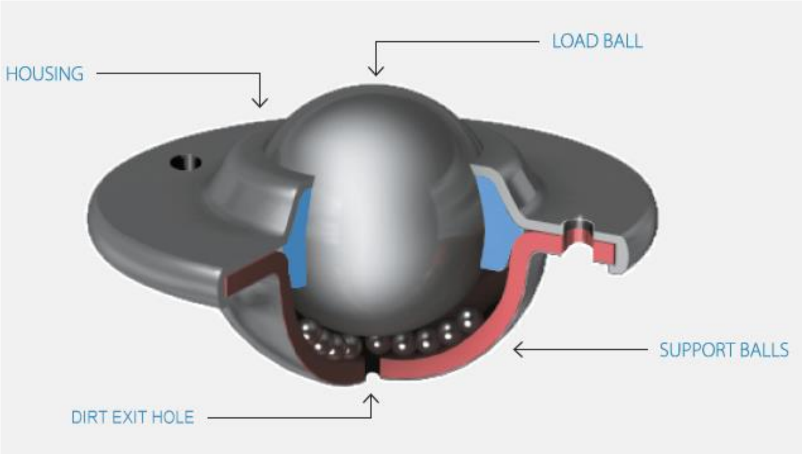
Motion Guide Styles

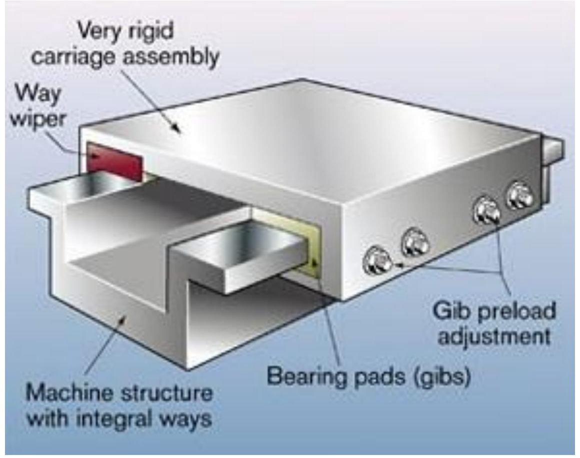
- Vee Wheel bearings
- Cam followers

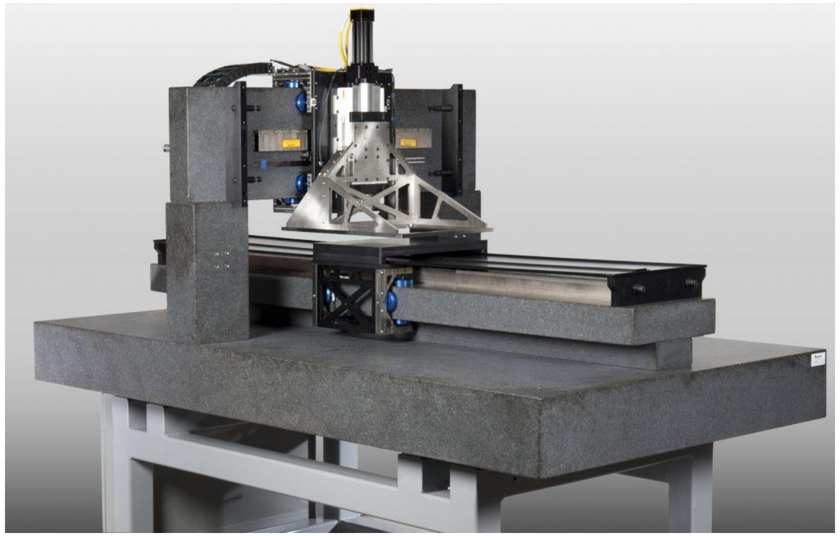


Motion Guide Styles

- Ball transfer units
- Plain linear bearing (Boxway slides)
- Air Bearings







Selecting the accuracy grade

1. Select a style of motion guide
2. **Select the accuracy grade**
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. Determine the preload and rigidity
6. Calculate the system lifetime
7. Select the type of lubrication

Most linear rails have 5 accuracy classes

- Normal grade
- High accuracy grade (H)
- Precision grade (P)
- Super precision grade (SP)
- Ultra precision grade (UP)

Selecting the accuracy class will be based on your application and your accuracy requirements.

Although some things to consider before selecting very high accuracy classes are:

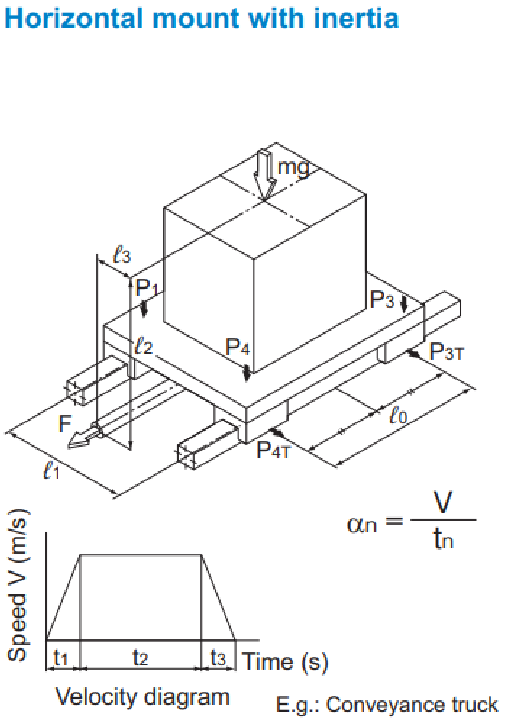
- Is the structure the rail is mounted onto rigid and stable enough for this level of accuracy? i.e don’t put high accuracy rails on a thin or flexible structure
- What is your budget and time scales, as most high accuracy rails are custom made in Japan or other countries so have long delivery times

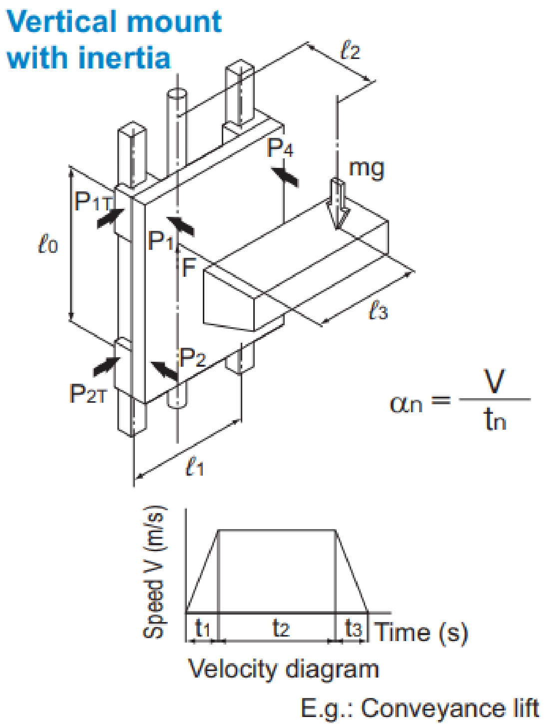
Selecting guide configuration

1. Select a style of motion guide
2. Select the accuracy grade
3. **Define the size and number of blocks on the rail**
4. **Calculate the maximum load of the selected blocks**
5. Determine the preload and rigidity
6. Calculate the system lifetime
7. Select the type of lubrication

Guide Configurations

- There are lots of different guide configurations but the 2 most common are:
  - Horizontal mount with inertia
  - Vertical mount with inertia
- The inertia doesn't always have a large impact on systems, especially if they are slow moving, but it's always best practice to take it into account

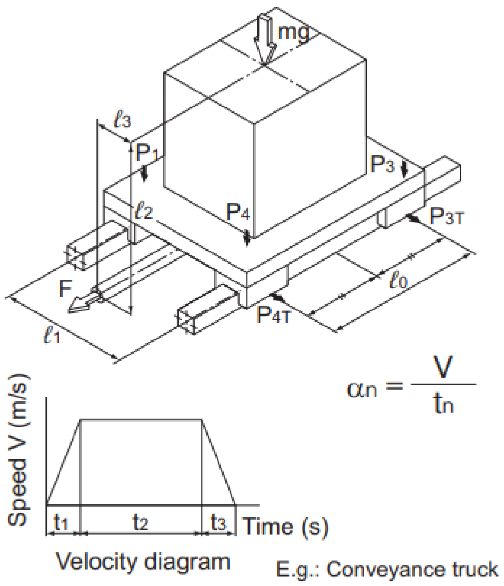




Guide Configurations

- For a horizontal mount with inertia, the load calculations can be seen below. The equations are specific to each guide configuration but most manufactures provide equations for each guide configuration

Horizontal mount with inertia



During acceleration

$$P_1 = P_4 = \frac{mg}{4} - \frac{m \cdot \alpha_1 \cdot \ell_2}{2 \cdot \ell_0}$$

$$P_2 = P_3 = \frac{mg}{4} + \frac{m \cdot \alpha_1 \cdot \ell_2}{2 \cdot \ell_0}$$

$$P_{1T} = P_{4T} = \frac{m \cdot \alpha_1 \cdot \ell_3}{2 \cdot \ell_0}$$

$$P_{2T} = P_{3T} = -\frac{m \cdot \alpha_1 \cdot \ell_3}{2 \cdot \ell_0}$$

During uniform motion

$$P_1 \text{ to } P_4 = \frac{mg}{4}$$

During deceleration

$$P_1 = P_4 = \frac{mg}{4} + \frac{m \cdot \alpha_3 \cdot \ell_2}{2 \cdot \ell_0}$$

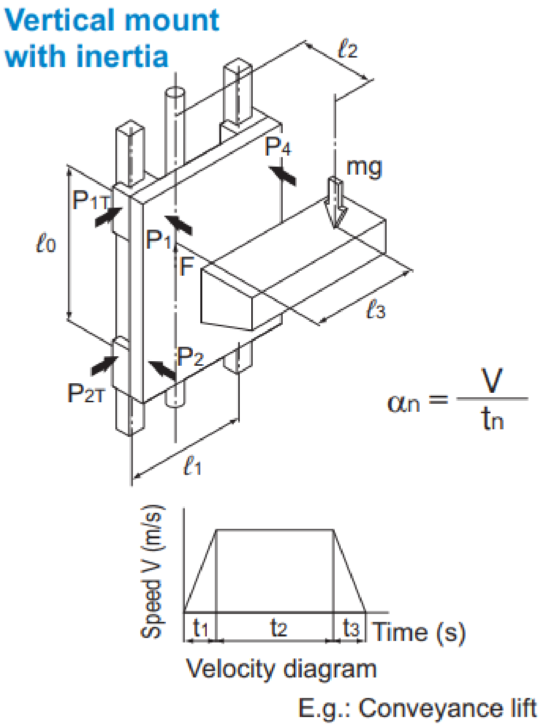
$$P_2 = P_3 = \frac{mg}{4} - \frac{m \cdot \alpha_3 \cdot \ell_2}{2 \cdot \ell_0}$$

$$P_{1T} = P_{4T} = -\frac{m \cdot \alpha_3 \cdot \ell_3}{2 \cdot \ell_0}$$

$$P_{2T} = P_{3T} = \frac{m \cdot \alpha_3 \cdot \ell_3}{2 \cdot \ell_0}$$

Guide Configurations

- For a Vertical mount with inertia, the load calculations can be seen below. The equations are specific to each guide configuration but most manufactures provide equations for each guide configuration



During acceleration

$$P_1 = P_4 = -\frac{m(g+\alpha_1)\ell_2}{2\cdot \ell_0}$$

$$P_2 = P_3 = \frac{m(g+\alpha_1)\ell_2}{2\cdot \ell_0}$$

$$P_{1T} = P_{4T} = \frac{m(g+\alpha_1)\ell_3}{2\cdot \ell_0}$$

$$P_{2T} = P_{3T} = -\frac{m(g+\alpha_1)\ell_3}{2\cdot \ell_0}$$

During uniform motion

$$P_1 = P_4 = -\frac{mg\cdot \ell_2}{2\cdot \ell_0}$$

$$P_2 = P_3 = \frac{mg\cdot \ell_2}{2\cdot \ell_0}$$

$$P_{1T} = P_{4T} = \frac{mg\cdot \ell_3}{2\cdot \ell_0}$$

$$P_{2T} = P_{3T} = -\frac{mg\cdot \ell_3}{2\cdot \ell_0}$$

During deceleration

$$P_1 = P_4 = -\frac{m(g-\alpha_3)\ell_2}{2\cdot \ell_0}$$

$$P_2 = P_3 = \frac{m(g-\alpha_3)\ell_2}{2\cdot \ell_0}$$

$$P_{1T} = P_{4T} = \frac{m(g-\alpha_3)\ell_3}{2\cdot \ell_0}$$

$$P_{2T} = P_{3T} = -\frac{m(g-\alpha_3)\ell_3}{2\cdot \ell_0}$$

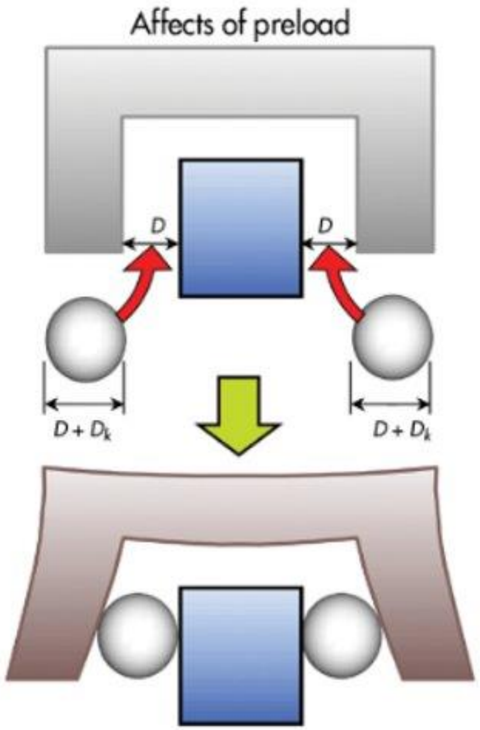
Determine the preload and rigidity

1. Select a style of motion guide
2. Select the accuracy grade
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. **Determine the preload and rigidity**
6. Calculate the system lifetime
7. Select the type of lubrication

Determine the preload

- The preload is usually application specific and some applications can be seen below:

	Normal Clearance	Clearance C1 (Light Preload)	Clearance C0 (Medium Preload)
Condition	• The loading direction is fixed, impact and vibrations are minimal and 2 rails are installed in parallel. • Very high precision is not required, and the sliding resistance must be as low as possible.	• An overhang load or moment load is applied. • LM Guide is used in a single-rail configuration. • Light load and high accuracy are required.	• High rigidity is required and vibrations and impact are applied. • Heavy-cutting machine tool
Examples of applications	• Beam-welding machine • Book-binding machin • Automatic packaging machine • XY axes of general industrial machinery • Automatic sash-manufacturing machine • Welding machine • Flame cutting machine • Tool changer • Various kinds of material feeder	• Grinding machine table feed axis • Automatic coating machine • Industrial robot • various kinds of material high speed feeder • NC drilling machine • Vertical axis of general industrial machinery • Printed circuit board drilling machine • Electric discharge machine • Measuring instrument • Precision XY table	• Machining center • NC lathe • Grinding stone feed axis of grinding machine • Milling machine • Vertical/horizontal boring machine • Tool rest guide • Vertical axis of machine tool



Determine the rigidity

- The rigidity is dependant on the preload and size of the linear rail selected. The rigidity value for each rail type and preload is normally looked up from a table and then the deflection can be calculated using the calculated load.

$$\delta = \frac{P}{K}$$

K	: Rigidity value	(N/μm)
δ	: Deflection	(μm)
P	: Calculated load	(N)

Selecting guide configuration

1. Select a style of motion guide
2. Select the accuracy grade
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. Determine the preload and rigidity
6. **Calculate the system lifetime**
7. Select the type of lubrication

Calculate the system lifetime

- The system lifetime can be calculated, although for most neutron applications this is often not very important as most positioning systems have very low duty cycles compared to factory or automation equipment.
- The equations are again found in the suppliers catalogue. This example below is for a THK LM guide
- LM Guide with balls (Using a basic dynamic load rating based on a nominal life of 50 km):

$$L_{10} = \left(\frac{C}{P_C}\right)^3 \times 50 \quad \cdots\cdots\cdots\cdots (1)$$

L_{10}	: Nominal life	(km)
C	: Basic dynamic load rating	(N)
P_C	: Calculated load	(N)

Selecting guide configuration

1. Select a style of motion guide
2. Select the accuracy grade
3. Define the size and number of blocks on the rail
4. Calculate the maximum load of the selected blocks
5. Determine the preload and rigidity
6. Calculate the system lifetime
7. **Select the type of lubrication**

Select the type of lubrication

- There are 2 main lubrication methods: oil or grease. Here are a few factors to consider when selecting a lubrication method:
  - The speed of the axis; oil is better for higher speed applications as it allows quicker recirculation
  - The frequency of lubrication; thinner lubricants need to be applied more regularly
  - The environment is also important; for example, in high radiation areas grease will often stiffen up

Selection Tools

- Most Linear rail catalogues have step by step instructions for selecting and designing linear rails (for Example THK, IKO, Hiwin, SKF, Hepco, Schaeffler, Schneeberger)
- Also ask Linear rail suppliers to help specify rails for systems. Most have application engineers that are experts and can help specify an appropriate rail.
- THK have a linear rail online selection tool as well as a lifespan calculator