Chasing nanometres - development of high-performance position encoders for accurate motion control in manufacturing

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Agenda

Introduction to Renishaw

Historic position encoding

Encoder types

Optical encoders

Absolute encoders

Incremental encoders

Commercial considerations

What lies ahead?

Introduction to Renishaw

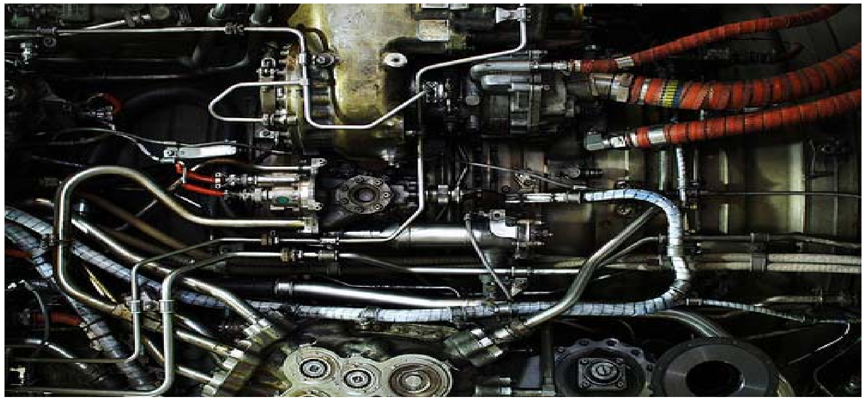
Renishaw: A technology company focused on innovation

First touch-trigger probe invented in 1973 to measure fuel pipes for the Olympus jet engine for Concorde

Organic growth sustained by patented innovations

Publicly listed company in 1983

Over 4500 staff in 70 offices in 35 countries



Sir David McMurtry
Chairman

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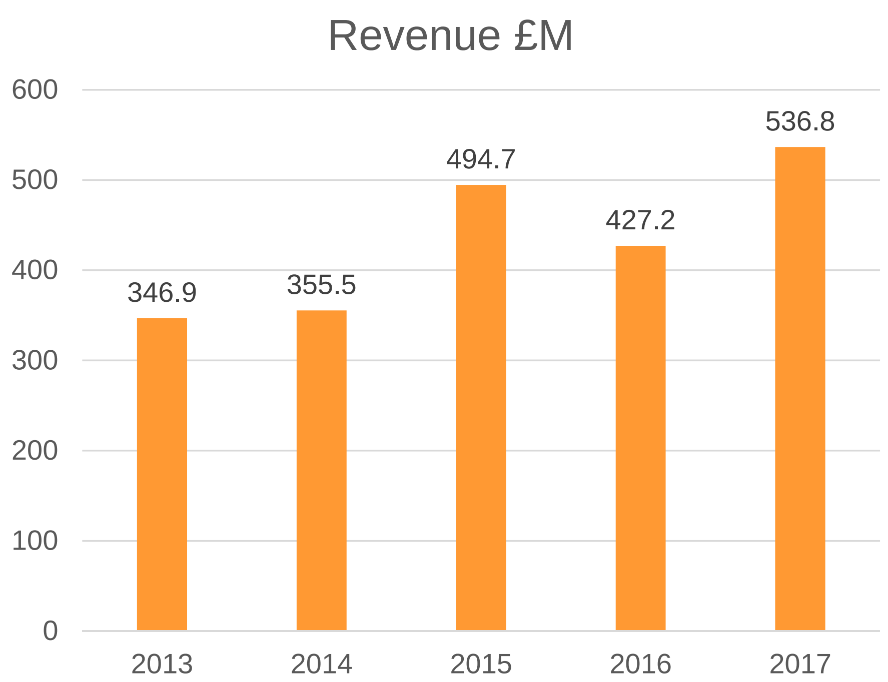
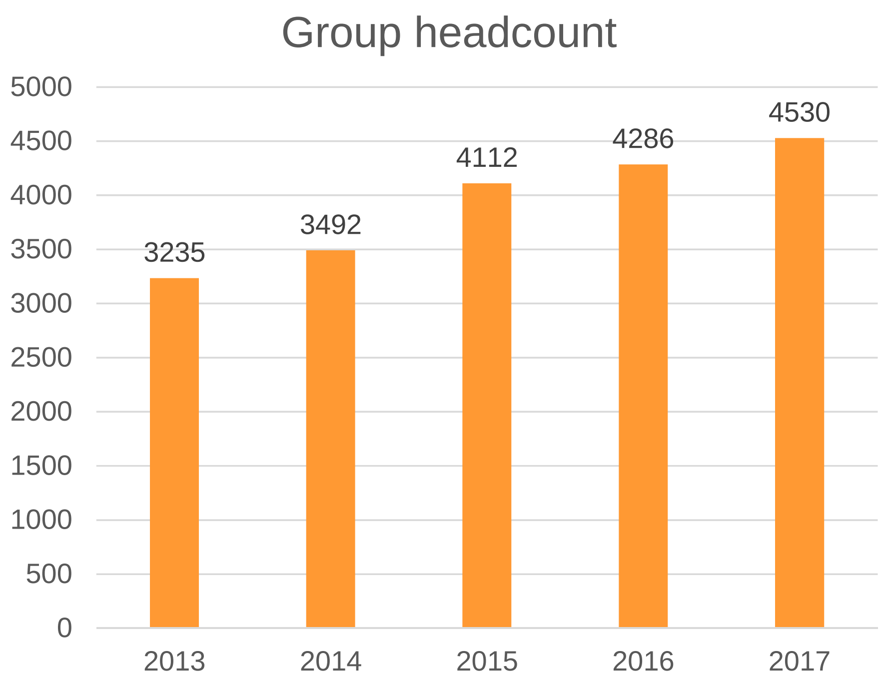
Innovation sustains margins and organic growth

Mainly Organic growth

Continual sales growth interrupted only by global recessions

Profit every year





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Renishaw is a global manufacturer

Stonehouse, UK

Woodchester, UK

Ljubljana,Slovenia

Miskin, Wales, UK

Dublin, Ireland

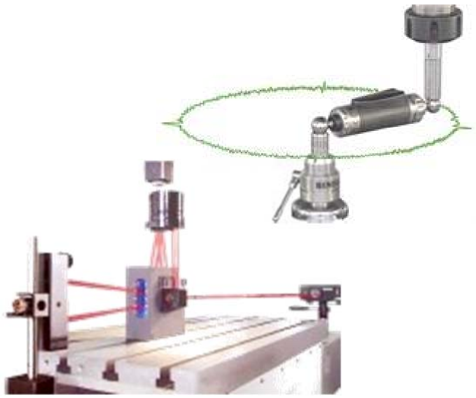
Pune, India

A diversified portfolio of industrial metrology products

CMM metrology

Position feedback encoders

Machine calibration



On-machine measurement

Metrology Gauging

What is an encoder?

An encoder is a device, circuit, transducer, software program, algorithm or person that converts information from one format or code to another, for the purposes of standardization, speed, secrecy, security or compressions.

wikipedia

An optical encoder is a device that converts optical positional information into an electrical signal and primarily consists of two components;

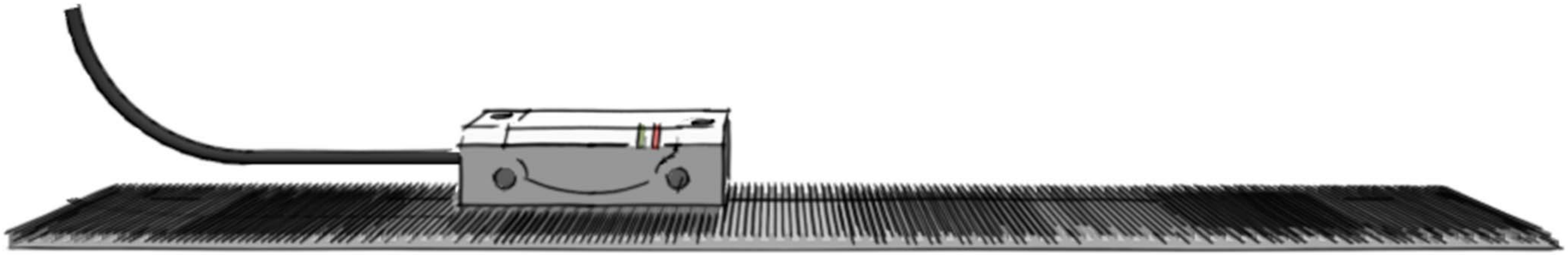
The “**Scale**” has positional (distance) information ‘encoded’ along its length

The “**Readhead**” is a transducer that reads and interprets the scale’s positional information using optical, magnetic, inductive or capacitive techniques and outputs positional data using (industry standard) electrical signals

Incremental / absolute

The scale is made up of a series of equal graduations/lines

The Readhead can only output relative displacement



Must refer to a unique “Reference Mark” to find repeatable absolute position

If power is lost during an operation, so is any position information

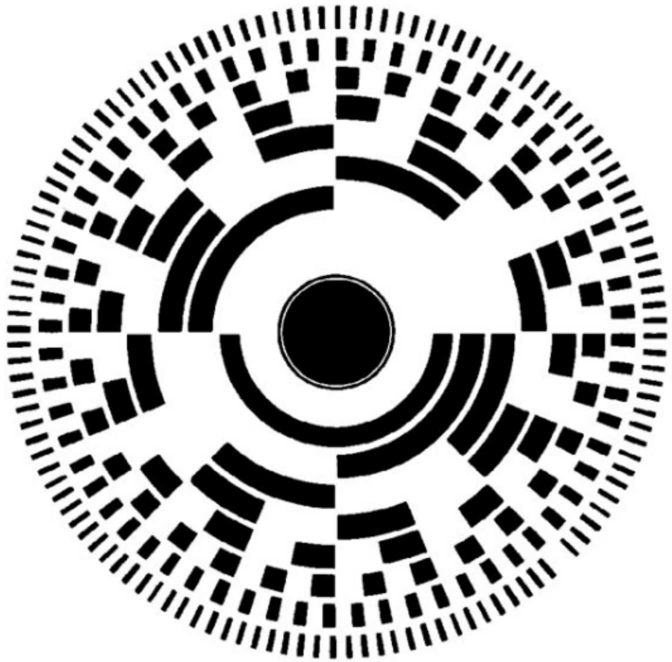
Incremental / absolute

Each position on a scale is marked uniquely

e.g. marked with a simple binary (grey) code

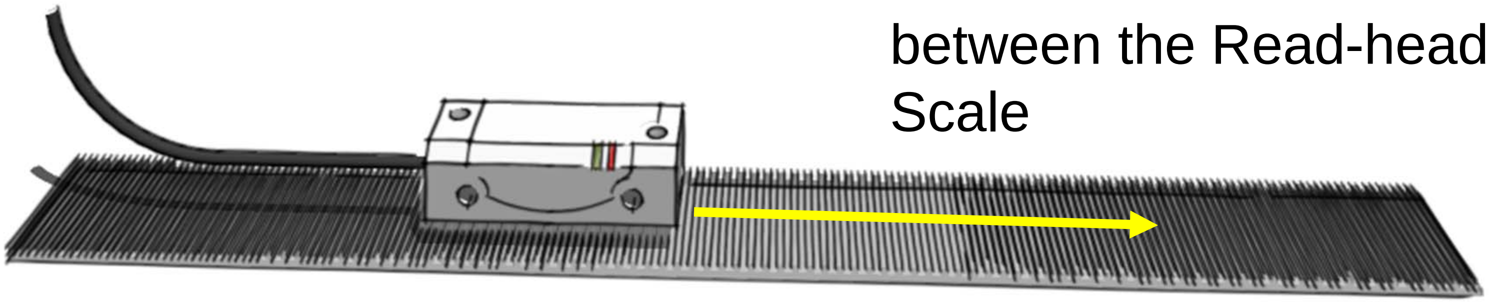
The readhead always knows its exact position

If power is lost during an operation, position information is calculated immediately upon switch on



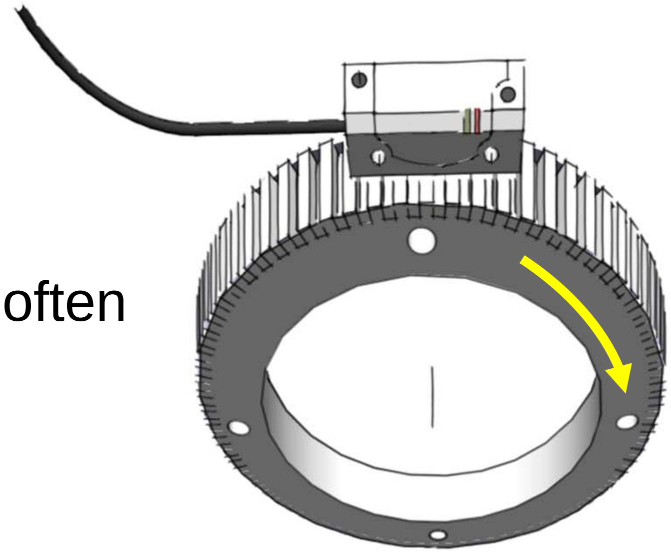
Linear / angle / rotary

Linear



Relative linear movement between the Read-head and the Scale

Rotary



Scale rotates about its own axis

Open rotary encoders often referred to as angle encoders

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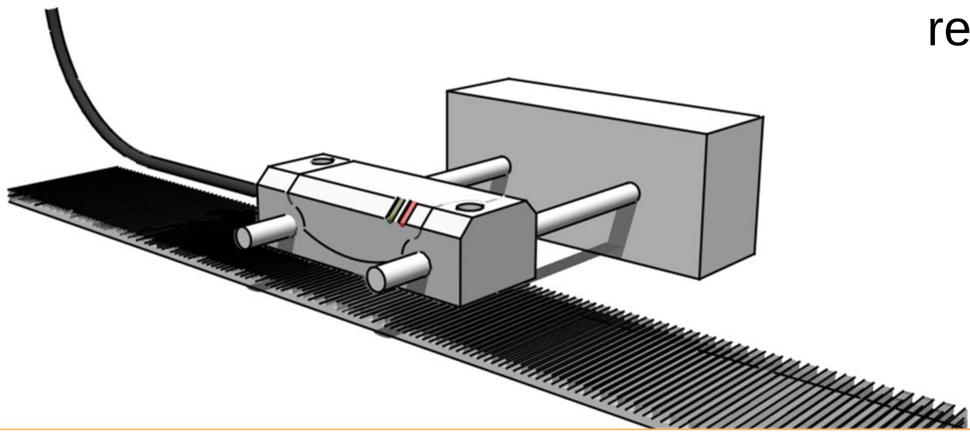
Open/Enclosed (Linear)

Open

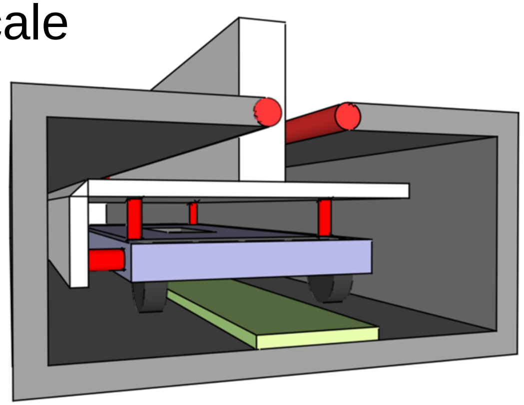
Usually:

- Scale directly mounted to stationary part of motion system
- Readhead directly mounted to moving part of motion system



Enclosed

- Scale and Readhead enclosed in a case with seals to protect them from contamination/harsh environments
- Readhead is mounted to the moving part of the motion system
- Linear enclosed systems have a compliant coupling, which ensures consistent relationship between readhead and scale



Mechanical Encoders

- The Earliest types of Encoders were all mechanical

- The **Ramsden Theodolite** was constructed in 1790 and was used to complete the first ever full geographical survey of the UK

  - It uses two mechanical encoders, one to give an angle of elevation and the other to give a directional reading, having a resolution of 1 arc second!

  - The one pictured is in the Science Museum in London

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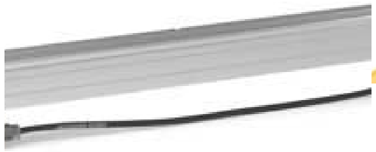
Optical encoder products



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Optical encoders pros and cons

Pros	Cons
High accuracy	Higher cost
High Resolution	Some are sensitive to contamination
Zero friction and wear	Sealing is required for many machine tool applications
Can have very good repeatability	Setup tolerances are often tight
Good positional stability	Glass scales are fragile
Overall the best dynamic performance encoder technology	

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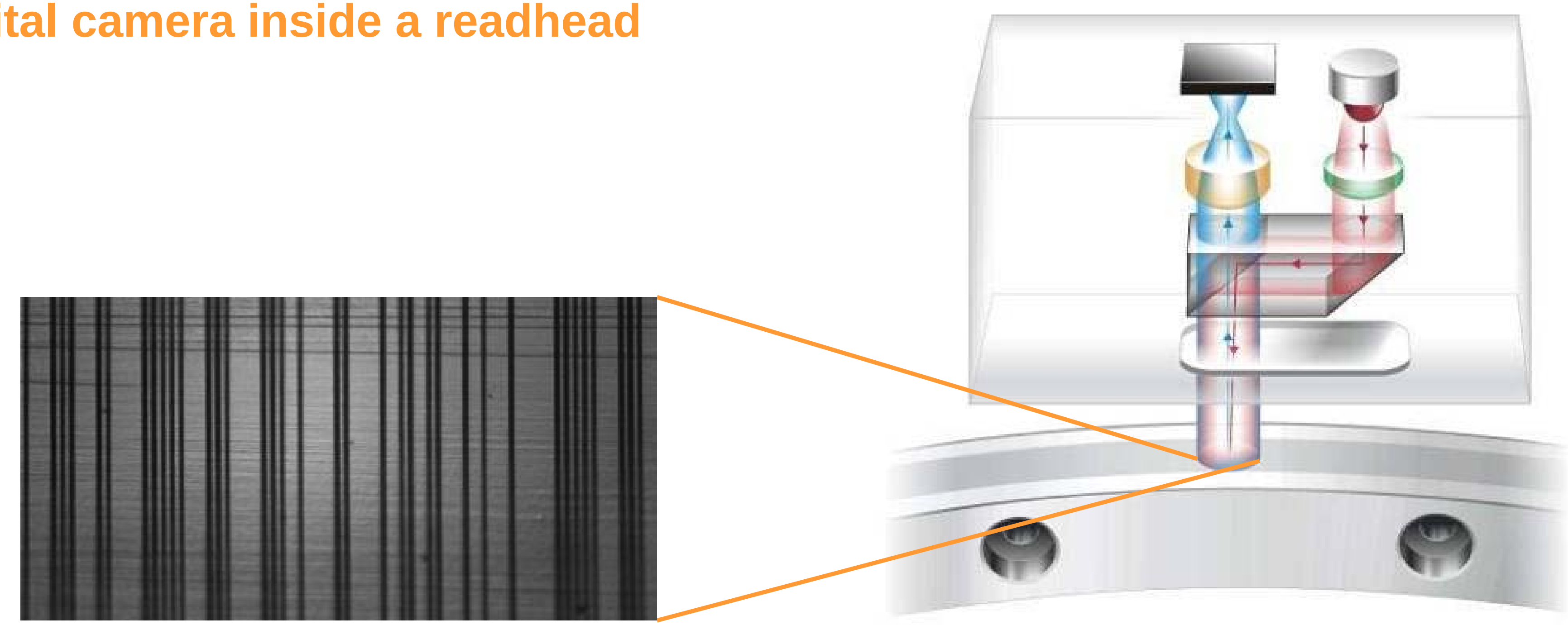
RESOLUTE™

true-absolute optical encoder

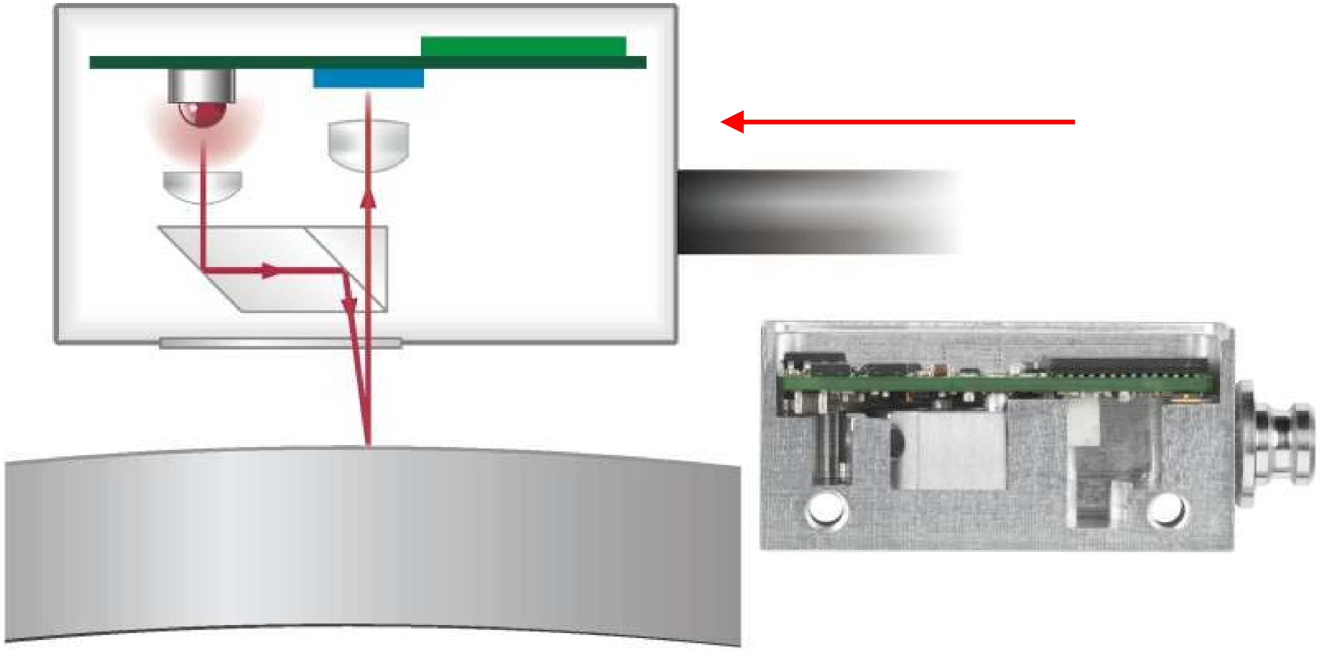
How does RESOLUTE work?

A digital camera inside a readhead



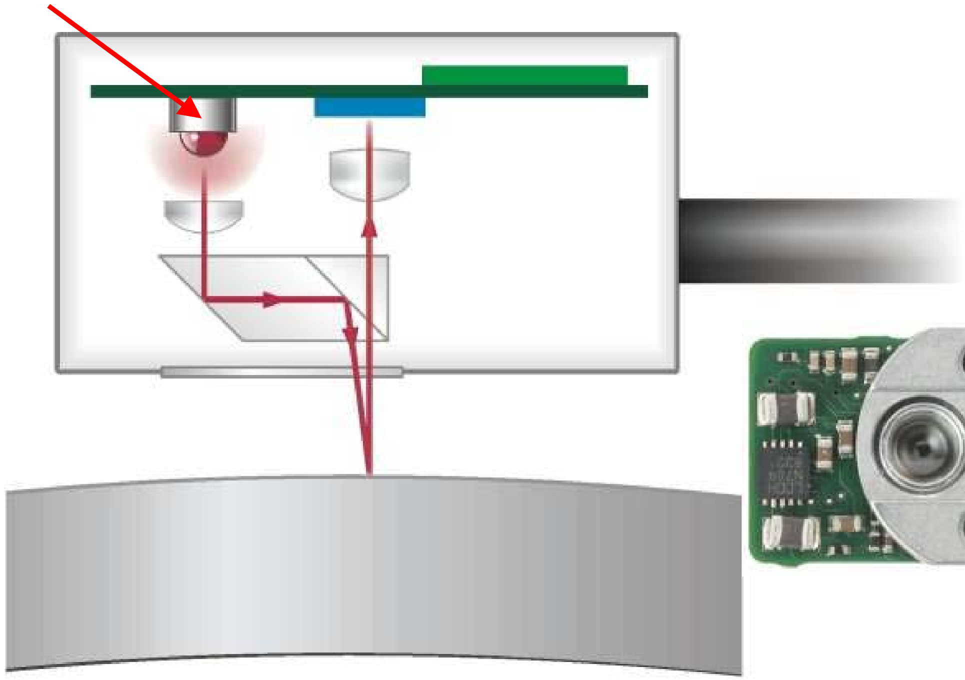
How does RESOLUTE work?

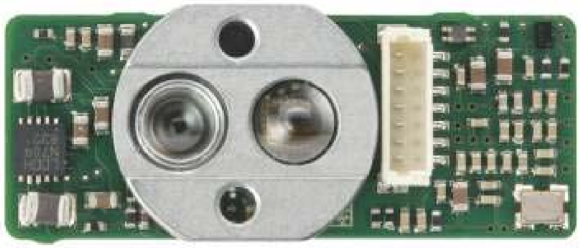
Controller sends request for position data



How does RESOLUTE work?

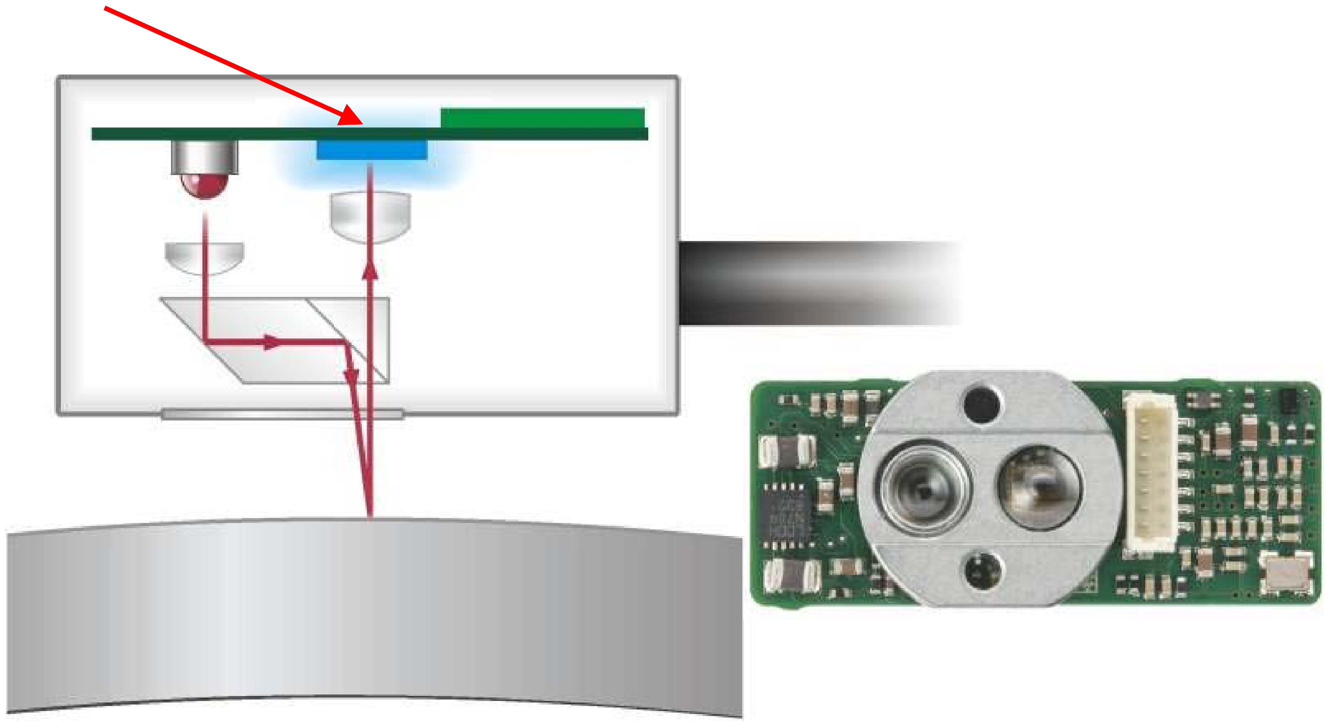
Light source is flashed and photo is taken





How does RESOLUTE work?

Custom detector captures light and dark lines



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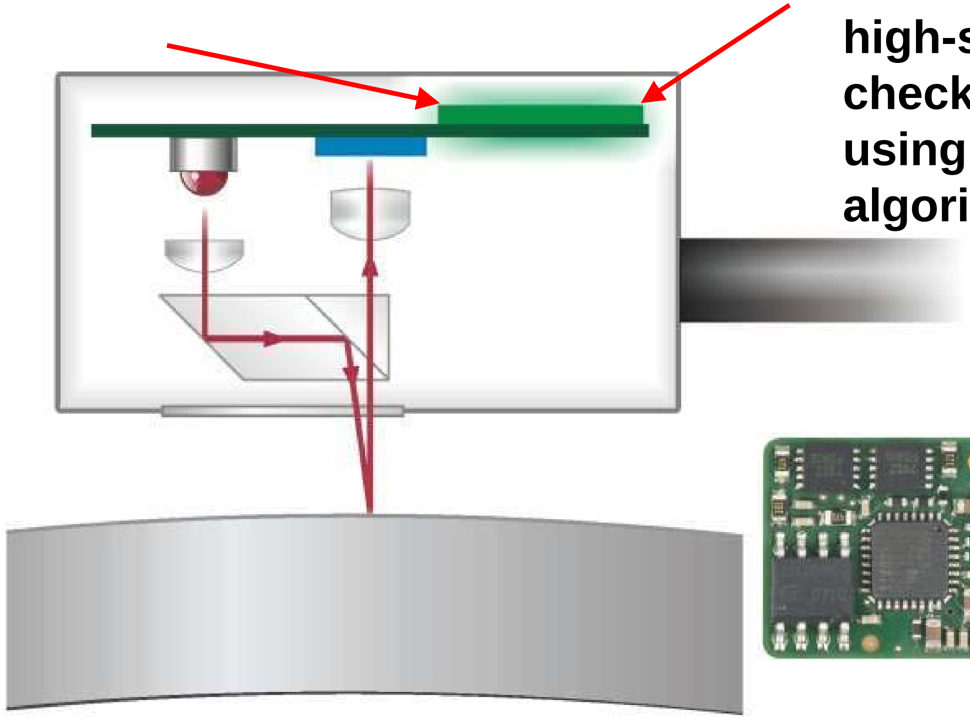
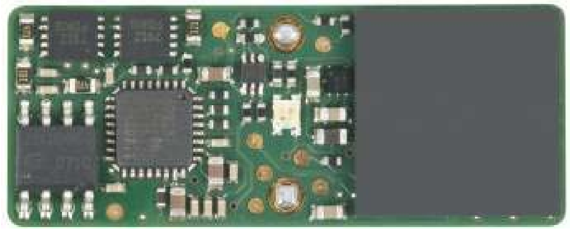
How does RESOLUTE work?

High-speed DSP processes data to determine absolute position



At the same time, the high-speed DSP checks the position using a separate algorithm



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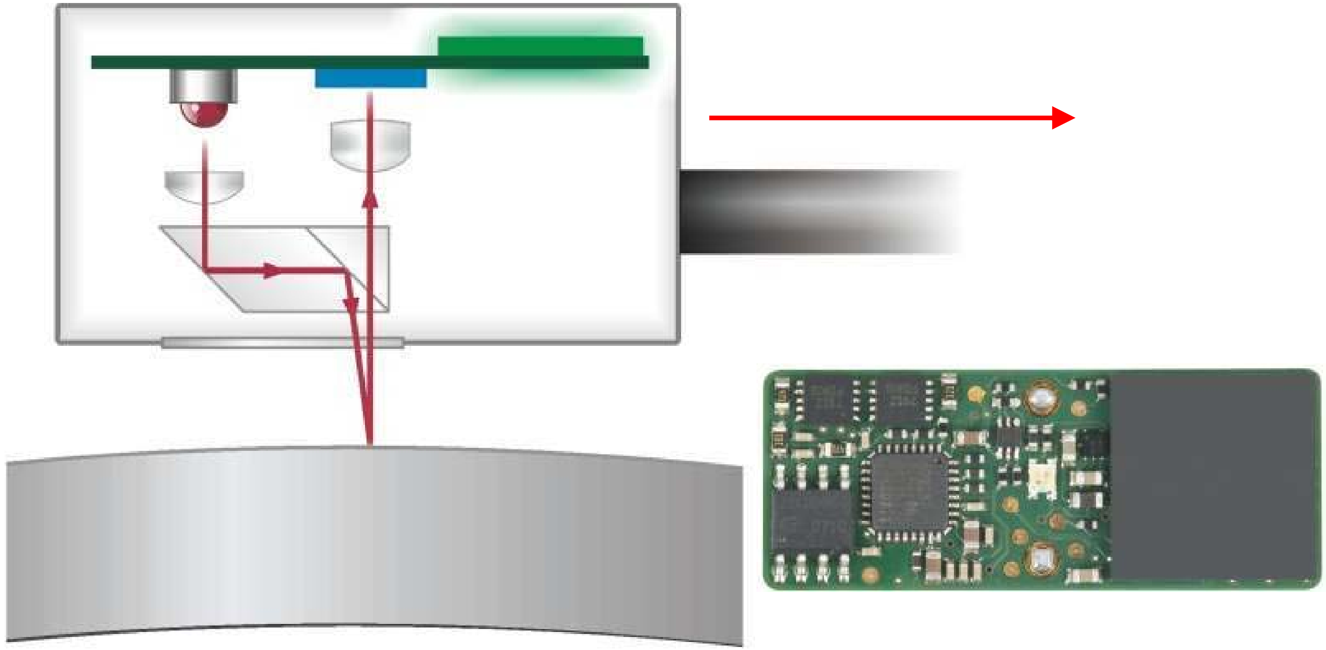
How does RESOLUTE work?

Absolute position data is sent to the controller using a serial comms protocol



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How does RESOLUTE calculate position?

Resolute calculates position using a combination of "coarse position" and "fine position"

Coarse position

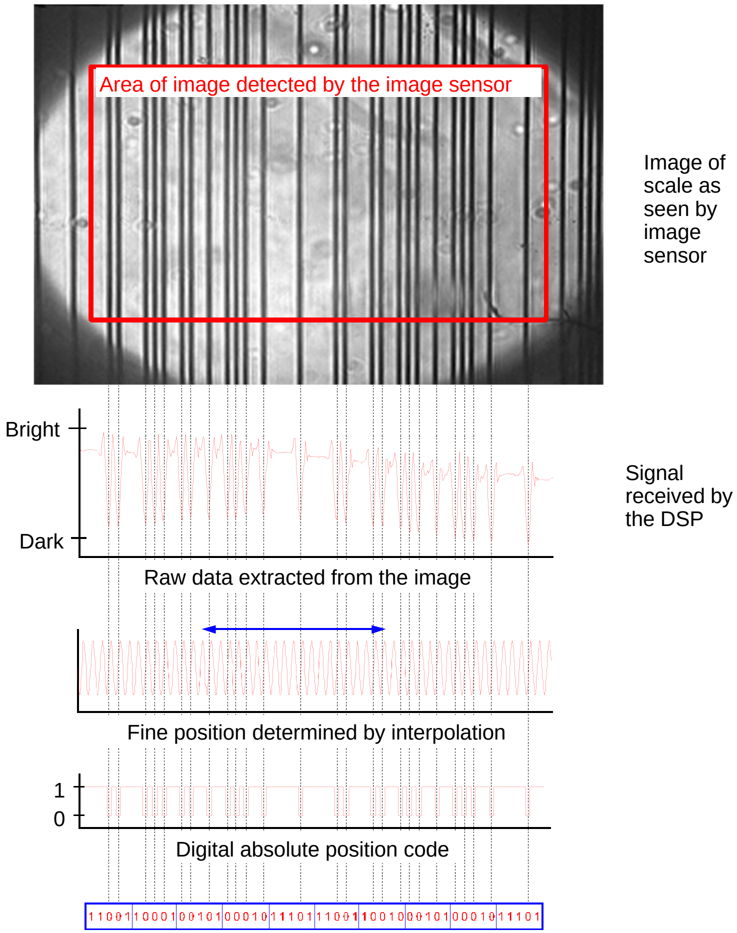
\+ Fine position

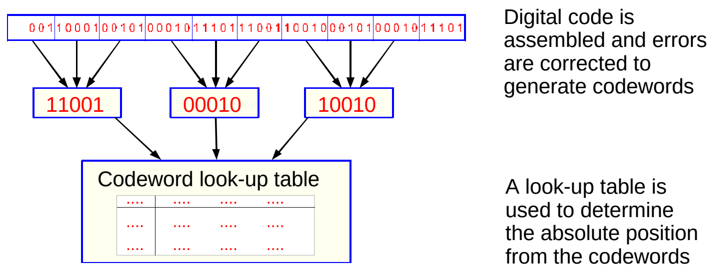
= Absolute position to 1 nm

Coarse position is calculated to "1 scale pitch"

Position within that scale pitch is calculated by interpolation

How does RESOLUTE calculate position?





Coarse pos

+

Fine pos

=

1 nm Absolute

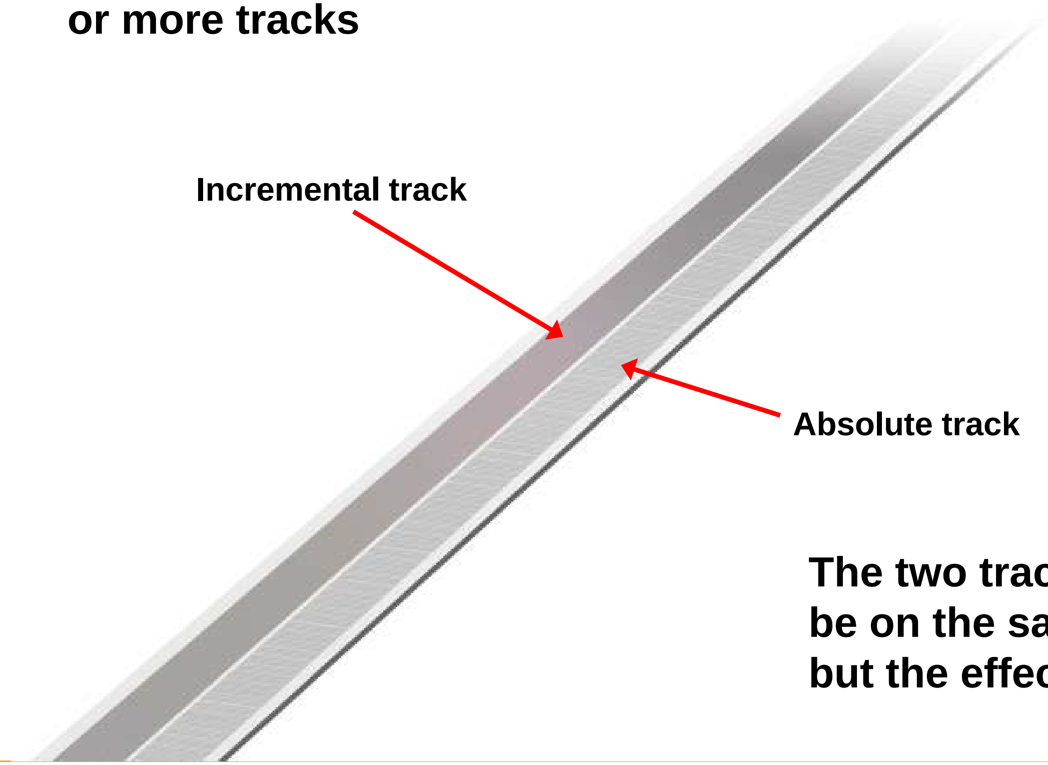
Absolute scale for RESOLUTE

Nominally 30 µm period, but lines missing to encode absolute position

Code repeat length is 21 m

Why is a single track of code so important?

A <u>traditional</u> absolute has two or more tracks



The two tracks will normally be on the same piece of scale, but the effect is the same…

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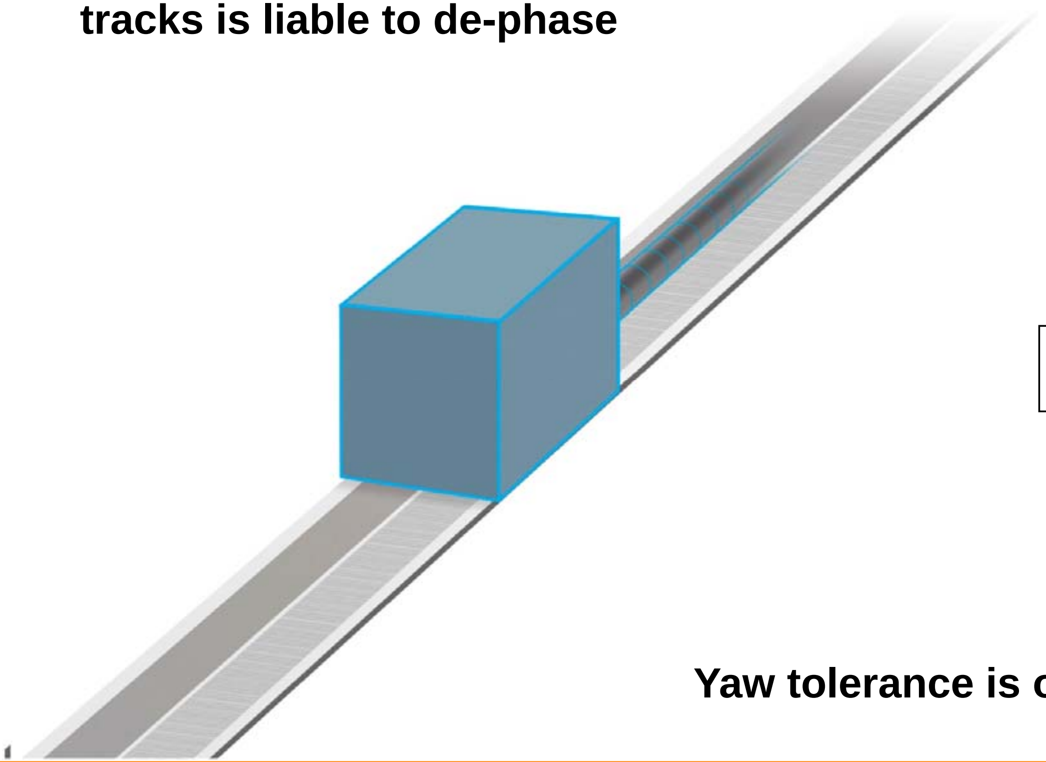
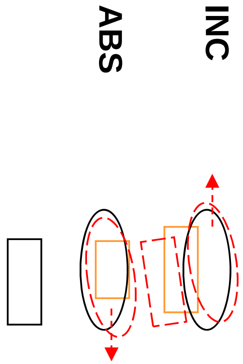
Yaw problems with traditional absolute encoders…

An absolute encoder with two tracks is liable to de-phase

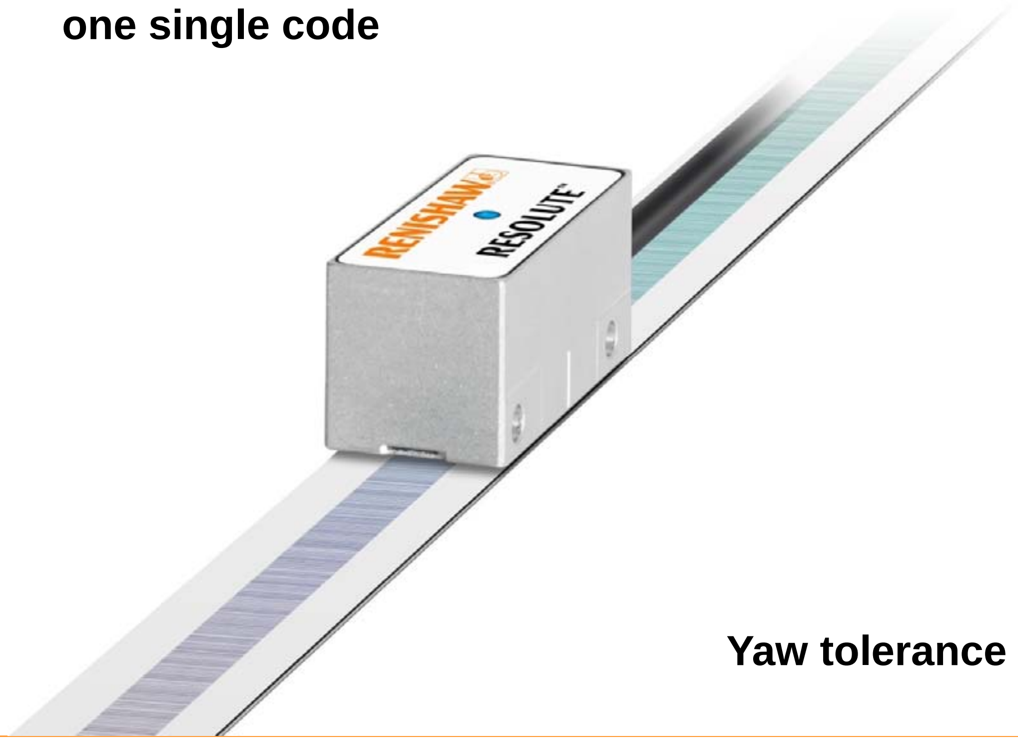


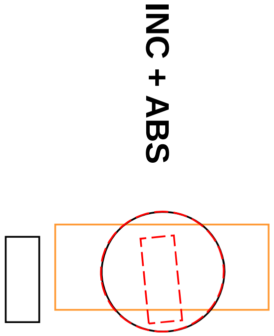


Yaw tolerance is only ±0.02°

The single-track advantage…

Single track contains absolute and incremental information in one single code





Yaw tolerance is ±0.5°

Resolution

RESOLUTE’s smallest unit of measurement is ~465 pm

Allows any resolution 1 nm or greater

- 1 nm is below the noise floor, but useful for holding position as noise averages over several readings

Rotary RESOLUTE

Protocols send a certain ‘word length’ which defines resolution (because all rings have 360 degrees)

Various resolutions available as standard (18 – 32 bits/revolution)

Readheads are ring size specific

Linear RESOLUTE

1 nm, 5 nm, 50 nm resolutions available as standard

Others available as specials

Position checking – SAFETY

Readhead continuously keeps track of position

Checks position using the coarse position, by extrapolating previous position measurements

Already knows where it *expects* to be, before the next position is output

Allows it to be certain whether the position it sends out is correct or not → if the checking algorithm shows a discrepancy then an error flag is raised

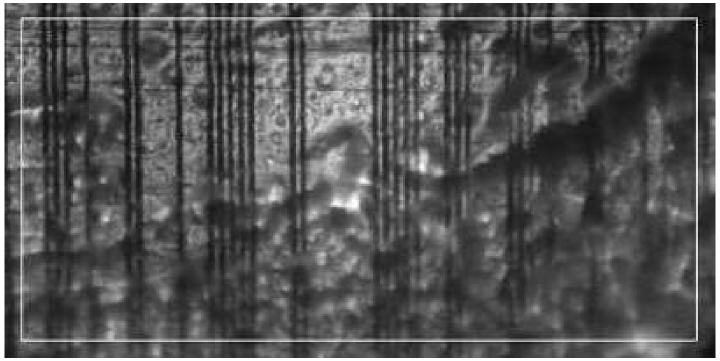
Side effect is limitation on readhead acceleration

Most encoders provide an error flag based on signal size, which does not necessarily reflect the validity of the position data.

RESOLUTE provides confidence that if the error flag is not set then the position will be correct.

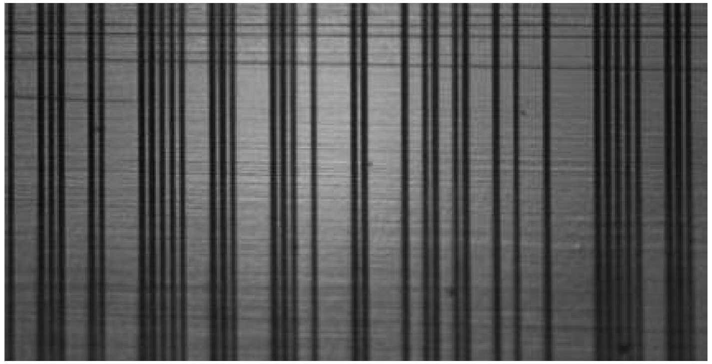
Dirt immunity

CCD images showing tolerable contamination



Thick grease smear

Particle contamination



Clean scale

Dirt immunity

How does RESOLUTE provide such good dirt immunity?

Detector

Array of 1 mm long × 8 µm wide pixels

Long length 'averages' image over large footprint for each pixel, aiding dirt immunity

Data redundancy

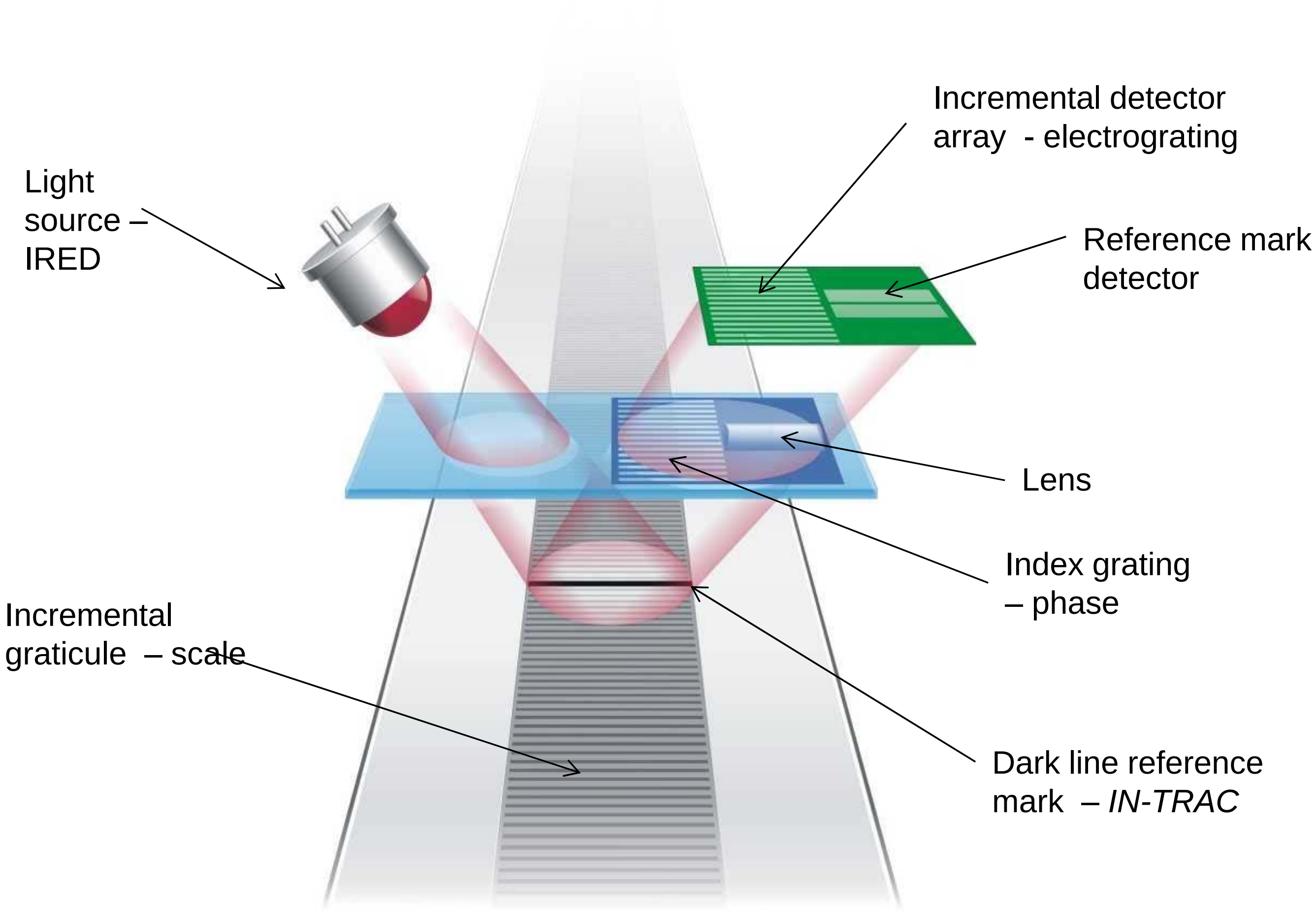
Readhead image contains 64 bits of information but only 16 are required to define a unique position

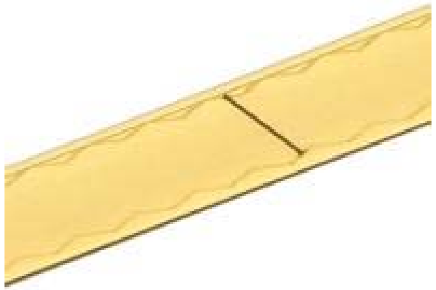
Remaining bits are used for error checking and correction

Position checking algorithm

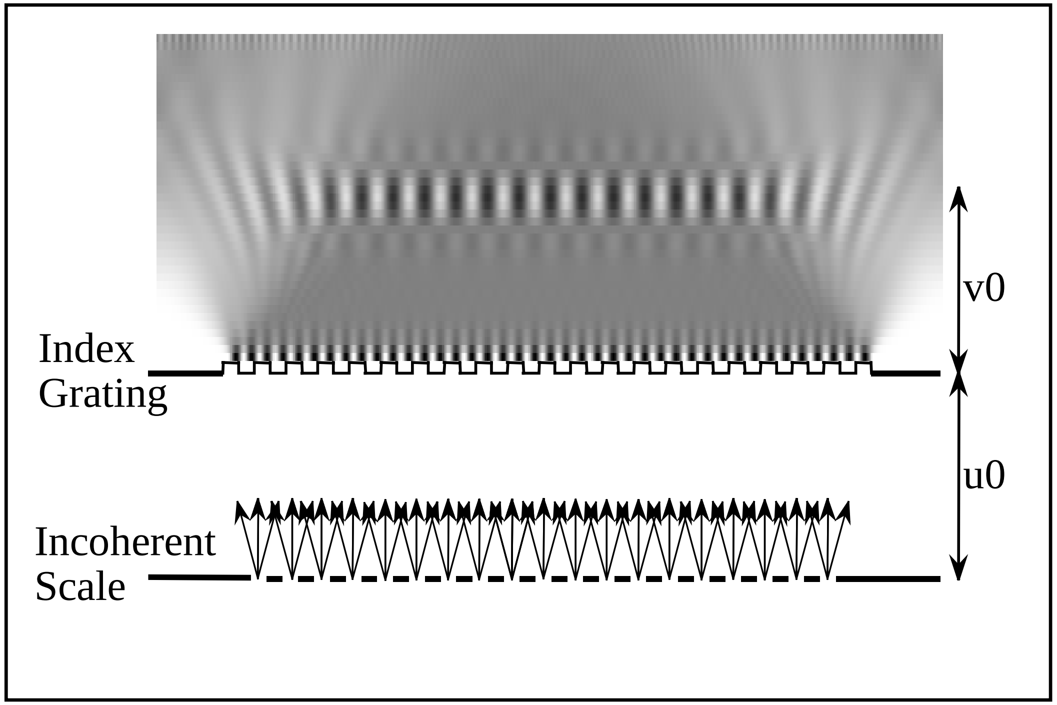
Ensures that RESOLUTE cannot output an incorrect position without flagging an error

Incremental encoder optics





Computer model of fringe formation

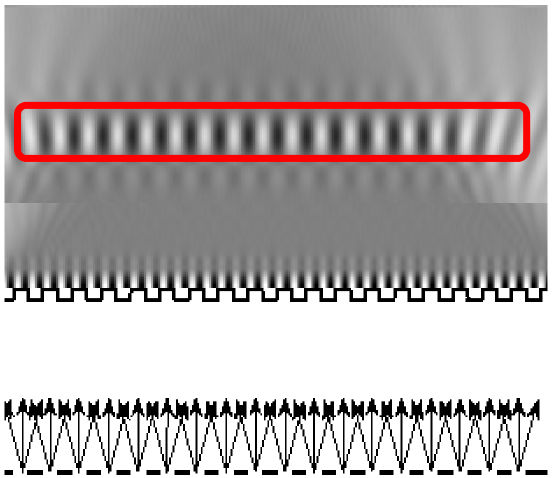


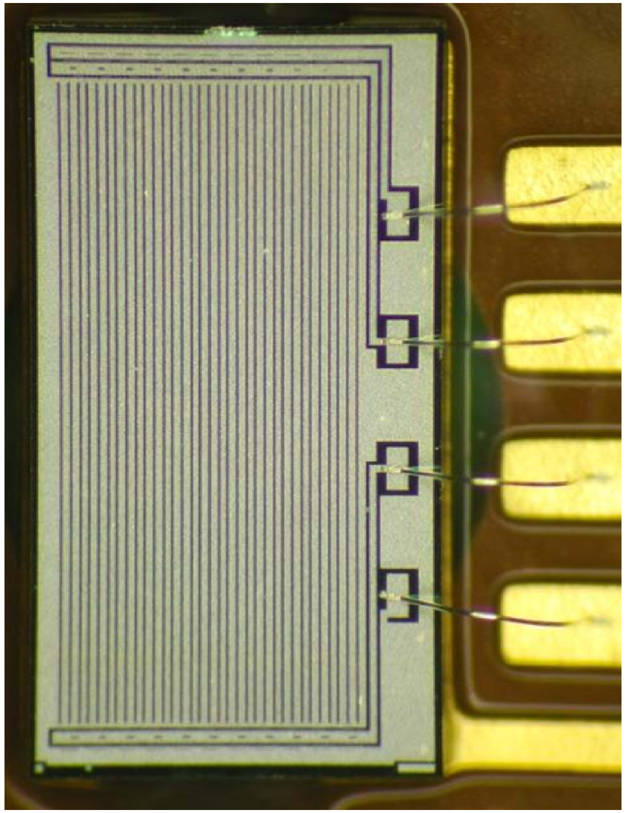
Electrograting

Window

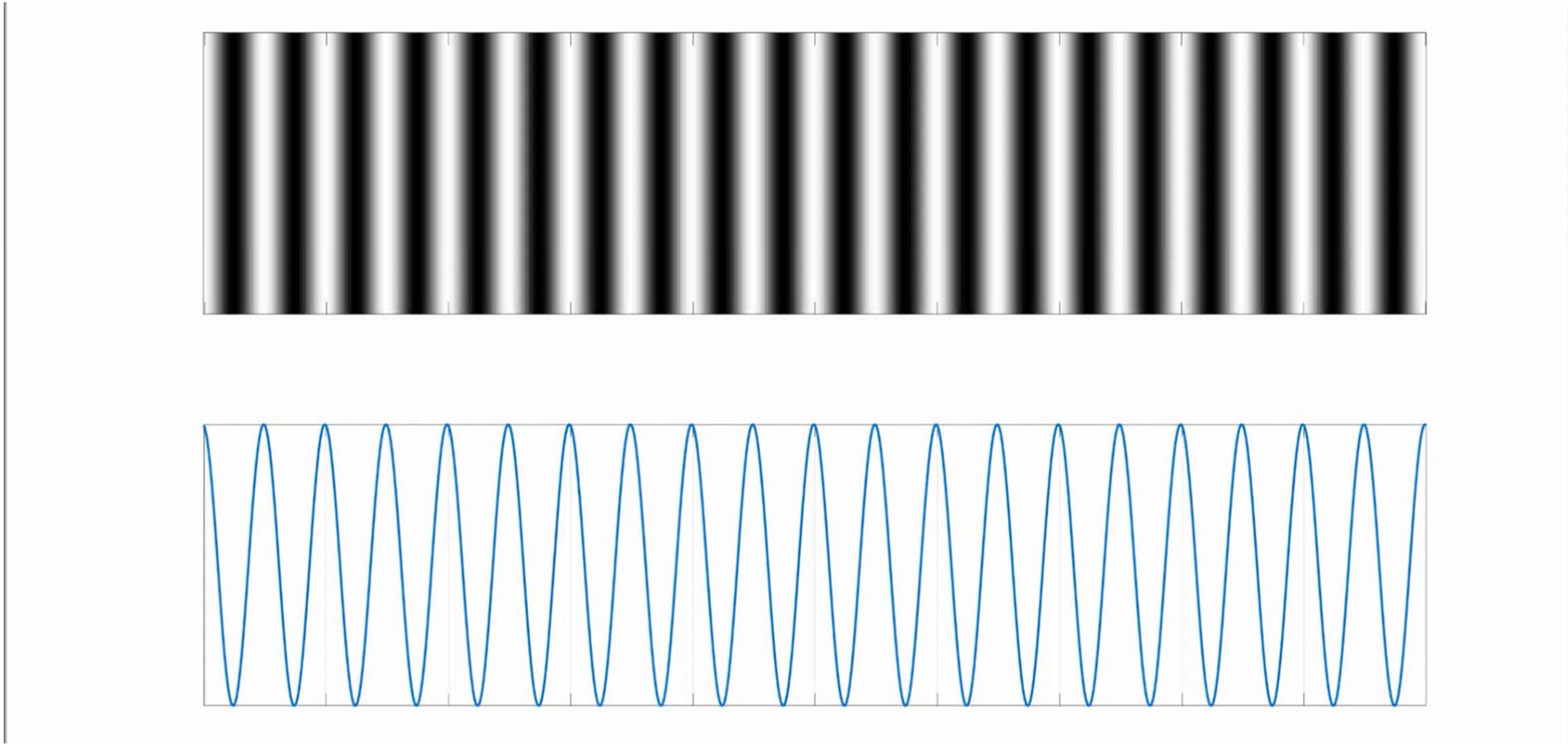
Scale

Fringe movement with scale displacement

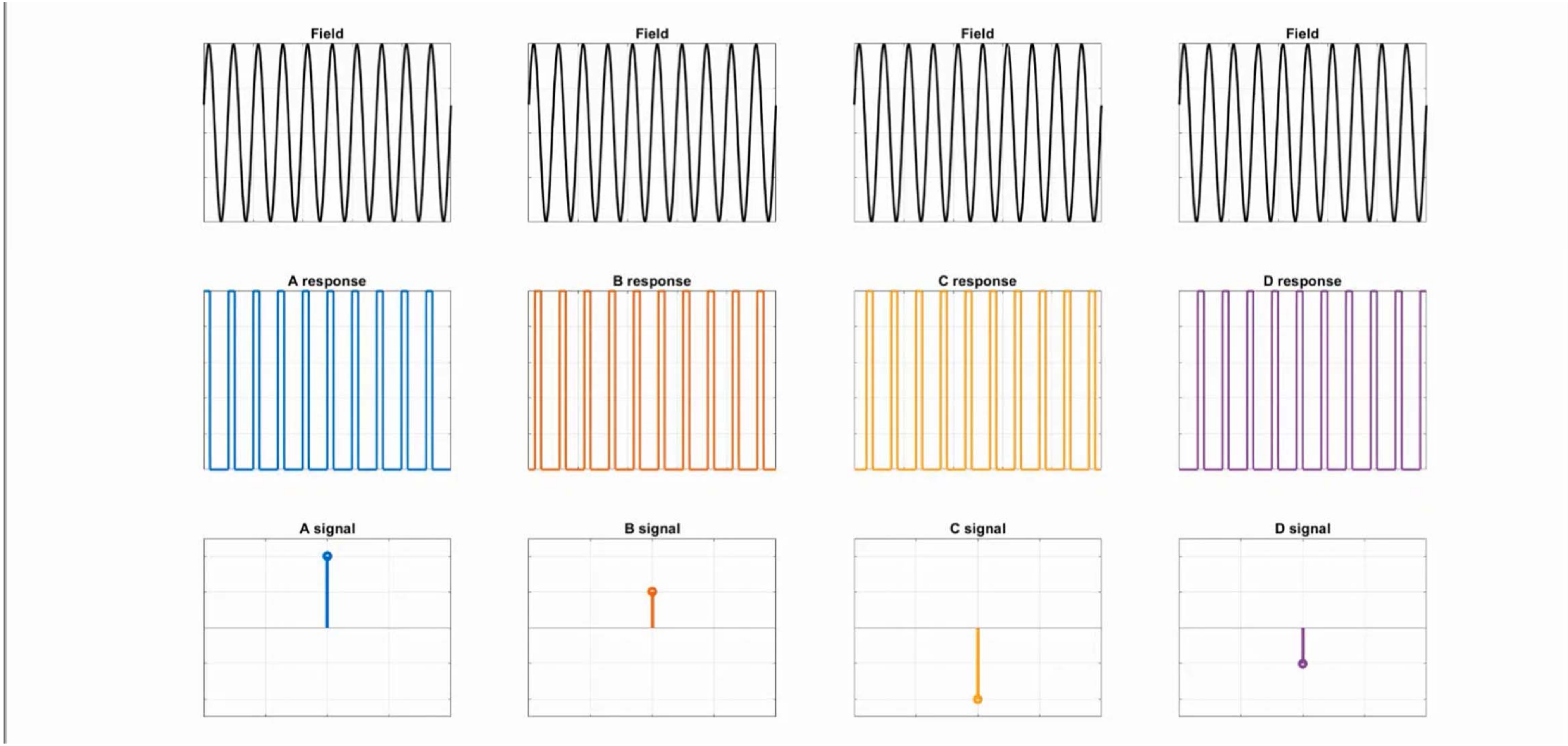




Fringes



Channel Detection



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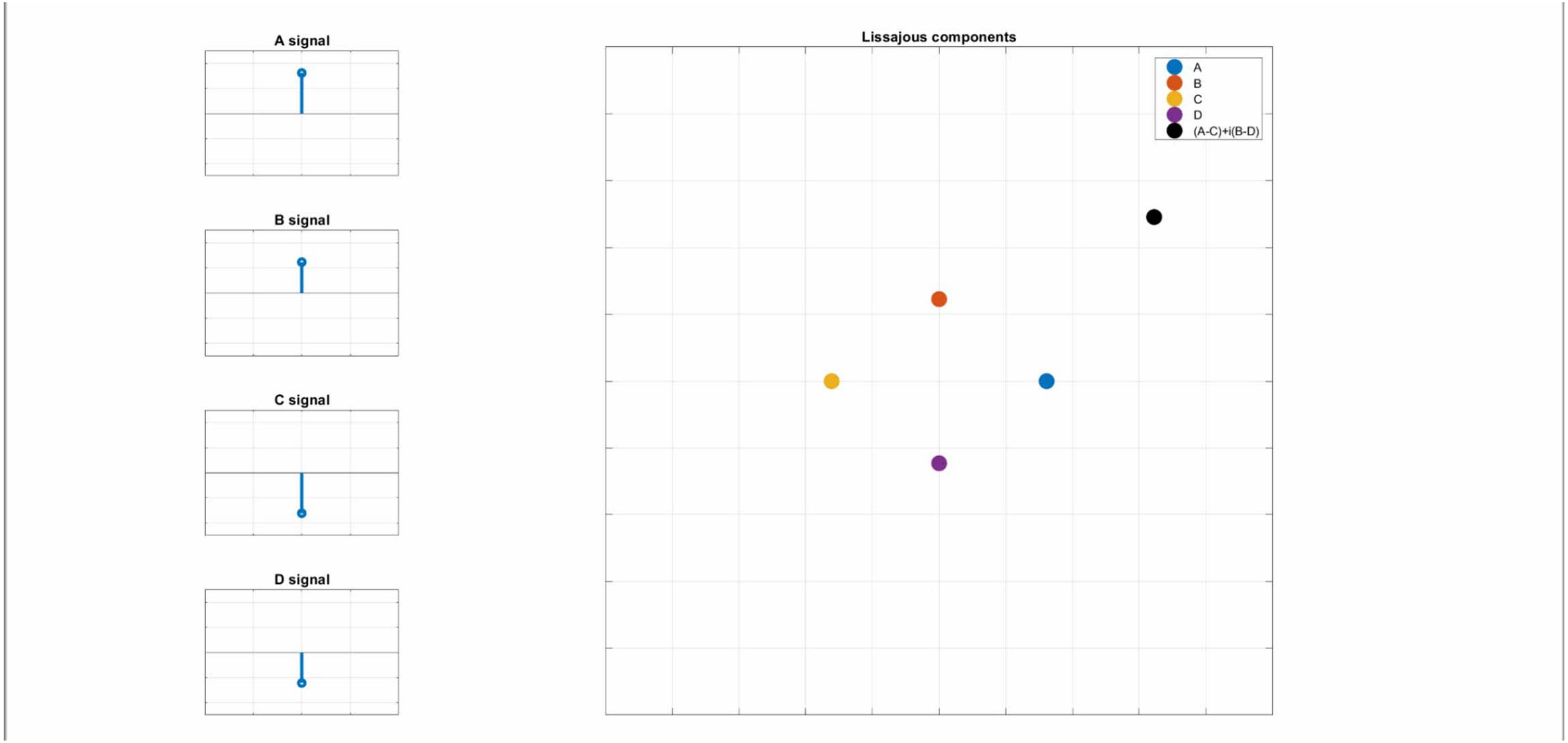
Lissajous Generation



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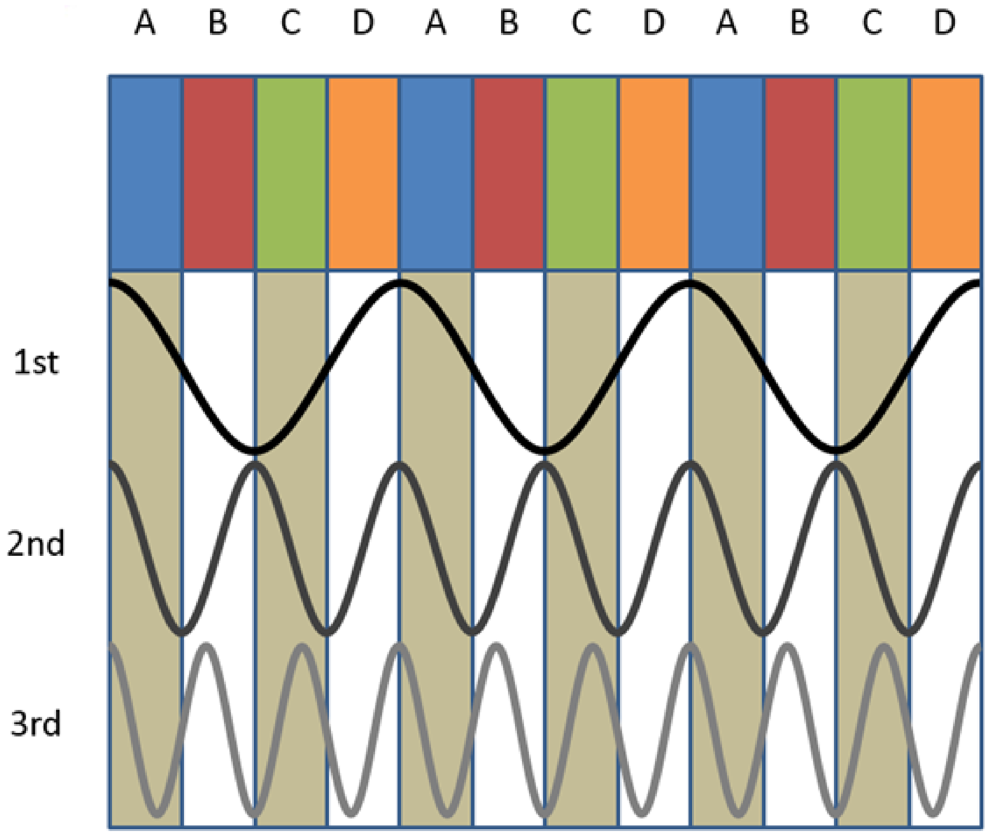
The Combination Scheme (A-C and B-D)



1st harmonic: Each phase sees a **different** part of the fringe field.

2nd harmonic: A and C see the **same** part, same for B and D.

3rd harmonic: Each phase sees a **different** part of the fringe field.

Performing A-C and B-D removes even harmonics but not odd harmonics.

AGC, AOC and ABC

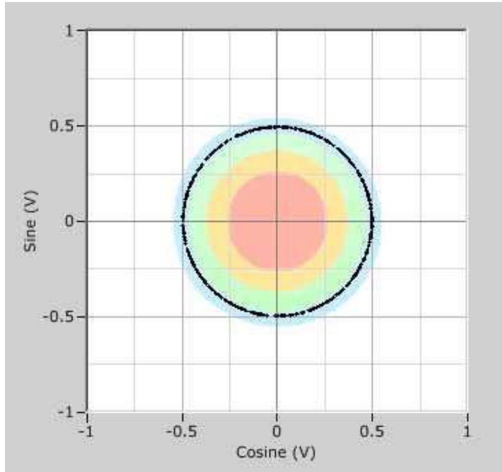
AGC: Automatic Gain Control

Readhead servos the IRED current to maintain 100% signal strength

AOC: Automatic Offset Control

Calculates mean of sinewaves and uses DACs to offset signals

Measures peak of sine on the zero-crossing of cos (and vice versa)



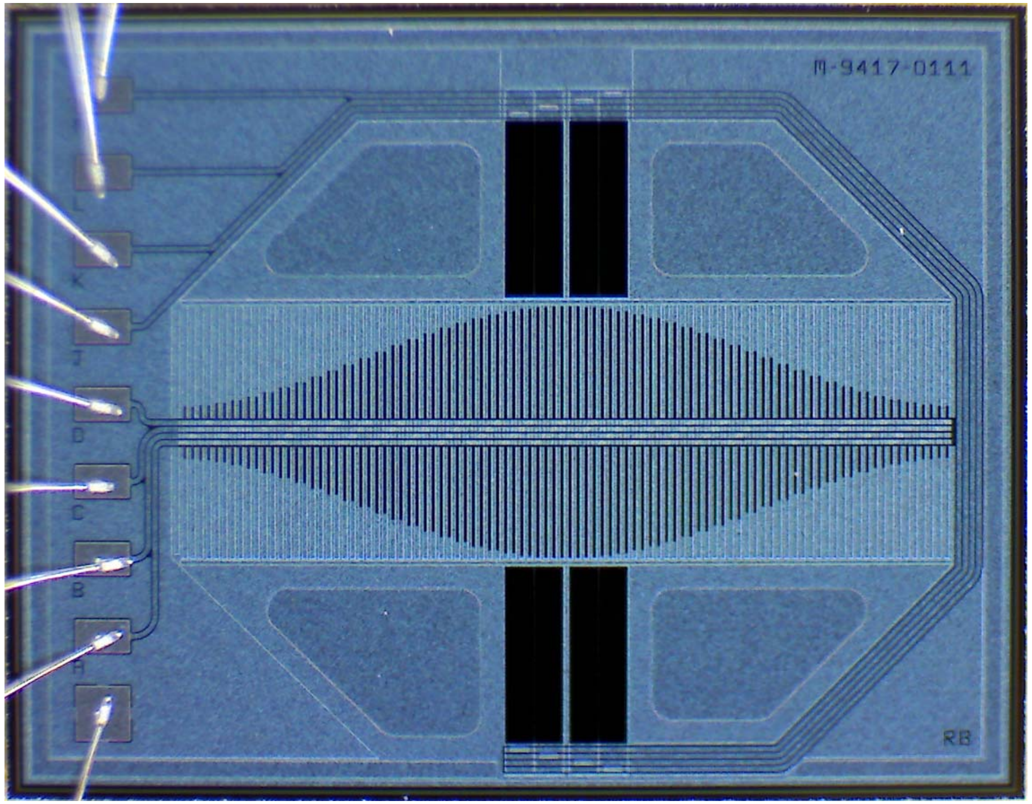
ABC: Automatic Balance Control

Adjusts sine and cosine signal amplitudes making them the same

For all corrections, movement of at least two scale periods needed to take measurements and apply corrections

Sub-harmonic suppression by windowing

- **Sub-harmonics in fringe field impair signal purity**
- Impure sin/cos signals produce measurement errors when interpolated
- **Metal window over detector fingers**
- Similar technique to Kaiser window filtering in signal processing
- **Sub-harmonics are suppressed**
- Signal interpolation is more accurate
- Overall signal level is reduced – like sunglasses!



Commercial requirements for encoders

- **High performance metrology**
- Appropriate accuracy, repeatability and stability
- **Small space envelope**
- Renishaw's ATOM™ encoder readhead is
- **High reliability and long working life**
- A failed encoder can easily stop a process line or production machine
- **Low price**
- Encoders often sell for £150 - £750

What lies ahead?

Industrial Internet of Things (IIoT)

- High speed internet
- Increase connectivity
- More devices have wi-fi
- Cloud storage
- Streaming

Big Data

- IoT companies data volume grew by 30% in the past year
- Smaller more powerful sensors
- Digitisation of assets and infrastructure
- <0.5% of all data is analysed

Industry 4.0

Analytics

- Rise in computational power
- Cloud analytics
- Edge computing
- Real time monitoring dashboards

IBM Watson Analytics

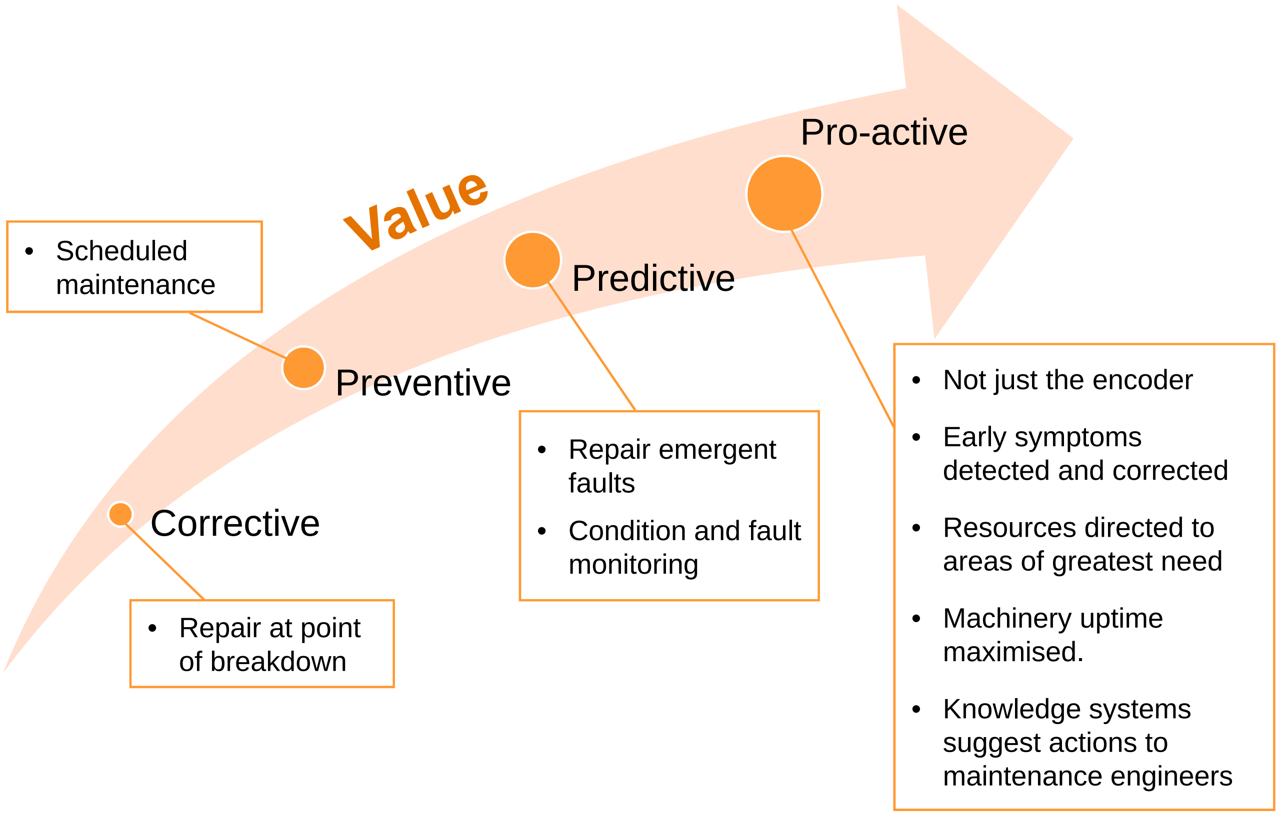
Microsoft Azure

Added value

- Artificial intelligence and machine learning
- Automatic decision making
- Maximise asset utilisation
- Early symptoms detected and corrected
- Augmented reality and guided maintenance

Industry 4.0 for encoders

- Mounted on machine guideway or spindle
- Monitor machine vibration
- Monitor environmental and operating conditions
- Bearing and machine wear
- In process monitoring and control



Renishaw's set-up LED

- Signal strength indicator
- Quicker installation
- Error reporting