Precision Manufacturing
current status and future development

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Some things have got bigger!
Some things have got faster!

Some things have got “smarter”!
One critical thing has got smaller!

0.01mm  0.006mm  0.003mm  0.001mm

0.0001mm  0.00006mm  0.00003mm  0.00002mm

So we might ask the following questions

1) How do product development paths influence manufacturing?

2) What key developments secure successful manufacturing capability?

Looking forward,

3) What future manufacturing developments are critical to human-kind’s long term prosperity?
Presentation structure

1. Some observations and questions
2. Enabling our future?
3. Drivers of accuracy improvement
4. Power of metrology innovations
5. Precision manufacturing
   i. Current examples
   ii. Future developments
6. Summary
Energy = enabling our future

- Wind turbine market will increase and mature
- Solar energy generation will increase and mature
  (government drive/environmental pressure)
- People in “developing countries” will want lots more energy, and soon

German government announced the country’s nuclear power plants phased out by 2022
Environment = enabling our future

- Flooding seems to be a growing problem
- Drought continues to plague many despite huge technical advancements
- Fires rage in locations near wealthy human dwellings
- Consumption of earth's natural resources is not slowing
- Lots of bright / credible scientists say the earth is warming up

Medical / aging population = enabling our future

- People live longer
- People want to be active longer & will spend money on doing so
- People are more conscious of their appearance
- Younger people are familiar (trust) computer based technologies
- Lots of bright / credible scientists say the protective layers of the earth are waning
Consumer devices = enabling our future

- Display based products will increase and they will become 2.5D / 3D capable
- Plastic WiFi enabled “newspapers” will emerge
- Hand held communications devices present major opportunities

Computing speeds will need to continue to increase

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Drivers of manufacturing accuracy capability

- Astronomy
- Particle physics
- Gravity/space
- Environment
- Defence
- Trains
- Automotive, aerospace
- Micro-electronics
- Renewable energy
- Wind & water mills

Year:
- 1600
- 1800
- 1900
- 1930
- 1960
- 1980
- 2000
- 2010
- 2020

Ref: Shore, Morantz, Phil. Trans. Royal Society 2011

Enabling technology that swept away 2000 years consideration given to an "earth-centred" universe

Emerging manufacturing technology of the 1600's

1. Grinding and polishing of glass lenses
2. Optical imaging "stopping down" the aperture
“measure what is measurable
make measurable what is not”

Maxim ascribed to Galileo Galilei

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CE Johansson 1864–1943

inventor and metrologist

Carl Edvard Johansson worked for the Swedish Carl Gustaf arms factory.
Johansson was concerned that components of their rifles were not “interchangeable”.
His combination gauge block set, which he patented, enabled effective calibration of inspection gauges and testers.
Cadillac Model T

Henry Martyn Leland 1843 – 1932
a machinist, inventor, engineer and automotive entrepreneur
Founded Cadillac and Lincoln

Henry Ford employed CE Johansson

Ford realised the concept of “inter-changeability” proposed by Leland at Cadillac to produce high quality cars would allow others to employ a new production concept to make affordable automobiles.

Production-line assembly

Mass production assembly is enabled through effective inspection of components prior to assembly.

Johansson Slip gauges were in practice the mechanism by which inspection could be achieved in factories.
Soichiro Honda

Honda transformed the motorcycle industry by a combination of innovation and detail attention to quality.

Attention to tolerance band reduction

Honda had concern for not only dimensional tolerances but also geometric tolerances.

Honda motorcycles reliability on the race track rapidly turned into huge sales of their commercial motorcycles.

Honda out sold both Triumph in England and Harley Davidson in the US in just 5 years.

Power of metrology innovation

From top left counter clockwise:
Some things got BOTH faster and bigger..............

..............but only for a while!

On the Basic Concept of ‘Nano-Technology’
There’s plenty of room at the bottom
—an invitation to enter a new field of physics

by Richard P Feynman

Talk given on the 20th December 1959 at annual meeting of the American Physical Society. Published in the February 1960 issue of Caltech’s Engineering and Science Journal.

Discussed:

- Nanometre scale information storage by electron writing
- Integrated circuits for computing
- Machines for manipulation of atoms and molecules


Electron beam writing
Encyclopaedia Britannica on the head of a pin

Each letter is made of holes approximately 4nm diameter

C. Humphreys, 1992, Cambridge University
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One critical thing has got smaller!

Minimum feature size/areal density
Development of transistors

Minimum feature size (mm)

Transistor density (TPM)

Year


10^2 10^3 10^4 10^5 10^6 10^7

All manufacturers

AMD

IBM

Intel

Motorola
Adherence to Moore’s law

2000: Twinscan, Resolution: 100 to 38 nm, overlay: 20 to 4 nm

Silicon wafer development trend

1 part in 10⁶ relative precision of accuracy to size
Adherence to Moore’s law

2 parts in 10^9 relative precision of accuracy to size

ASML 2010: NXE EUV systems, Resolution: 32 < 20 nm, overlay: 2 nm

Laser produced plasma light source

30 micrometre Tin droplets

Many kW laser

Near normal Multilayer collector

Sn droplets
Large ultra precision optic demands

Astronomy mirror fabrication and space mirror coating technologies are now to be found in the next generation of EUV microlithography systems.

Helping to hold “Moores law” density packing of transistors on integrated circuits.

2010: NXE EUV systems
Resolution: 32 < 20 nm, overlay: 2 nm

Enabling technology that swept away 2000 years consideration given to an “earth-centred” universe

Emerging manufacturing technology of the 1600’s
1. Grinding and polishing of glass lenses
2. Optical imaging “stopping down” the aperture
Astronomy: driver of Precision Manufacture

Next generation ground-based telescope
E ELT
~1000 segments
Reqd. Production rate: 1 per day

ESO ELT mirror segment
Mass production chain for \( \sim 2 \) metre scale optics

1 mm form accuracy

Stage 1
Fixed abrasive grinding

1 \( \mu \)m form accuracy

Stage 2
Computer control polishing

0.01-0.3 \( \mu \)m form accuracy

Stage 3
Reactive atom Plasma

10 nm form accuracy

1 metre square per 10 hours having form accuracy of lambda / 20 (30nm RMS)

Rapid Process Chain

1 mm form accuracy

Stage 1
Fixed abrasive grinding

1 \( \mu \)m form accuracy

Stage 2
Computer control polishing

0.5-1 \( \mu \)m form accuracy

Stage 3
Ion beam figuring

10 nm form accuracy

Surface Figuring Rate [mm\(^2\)/second]
BoX® Ultra Precision Machine 1600

Rapid grinding and measuring system for free-form optics

BoX® 1600 performance

Work-piece quality
Form accuracy: < 1 um RMS
Sub-surface damage: < 5 um
Roughness: 100 - 200 nm
(Zerodur data)

Processing rate
Grind time: 20 hours
(10 hours per m²)
Measurement time: ~ 4 hours
Load time: 1 hour

BoX® Grinding Motion
BoX® Ultra Precision Machine 1600
Rapid grinding and measuring system for free-form optics

BoX® In machine metrology
Workpiece metrology has full system accuracy ~ 0.25 μm
In-situ post grinding measurement using laser based metrology frame
BoX® Ultra Precision 1600
Freeform grinding & measuring machine

Deterministic ultra precision production technology to rapidly grind large optics of complex shape

- Proven freeform surface generation
- Unrivalled form accuracy capability
- Rapid processing rates
- Reduced levels of sub-surface damage
- Low cost of ownership

www.loxhamprecision.com

Growth in size of typical commercial wind turbines (height in metres)

IPCC (2011), “Special report on renewable energy”
Wind turbine bearing fabrication

KMT Lidköping Vertical
Hard turning/Grinding machine

- Grinding and hard turning in the same setup.
- Machine designed for bearing rings.
- Dedicated Man-Machine-Interface.
- Linear motors – ultra precision.
- Short cycle time.
- Hydrostatic slides and workhead.

Machine weight 145 000 kg
Working range, OD 1 300 – 4 000 mm
Max workpiece weight 10 000 kg
Complex shape component processing
Technology Strand to Develop Effective Manufacturing.
Ref, Rolls Royce

High Performance Disc Machining
A system of technology strands for a modern and competitive Method of Manufacture – technology demonstration for the Washington Disc Facility

- Operations down 40%
- Hours down 50%
- Productivity up 100%
- Quality up 15% (RFT)
- Underpins new factory investment

HPDM will halve the current value added time, double the productivity at zero consumable cost difference and achieve 6-sigma process capability

© 2013 Rolls-Royce plc
Robotic based machining technologies

Image credit: http://www.insu.cnrs.fr

Ref, SAGEM - REOSC

Marine Robotised Propeller Finishing
A robotised approach to replace a time-served, manual process

<table>
<thead>
<tr>
<th>Current Method</th>
<th>KPV &amp; Development</th>
<th>System Validation</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture process</td>
<td>Force control &amp; CLP</td>
<td>Auto tool changer</td>
<td>Automated Polishing</td>
</tr>
</tbody>
</table>

- 50% cycle time reduction
- Improved productivity
- Consistent quality
- Product configurable
- HSE benefits

In production and winner of the 2012 Manufacturing Excellence ‘Sir Henry Royce Award’

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Energy = enabling our future

Ref: HiPER, RAL
Nuclear Fusion

Focusing the high power laser beams

Use similar approach to the large area optical telescope community

Ref, HiPer project
Focusing lens “wedge” optic
(700mm with form accuracy < 30nm RMS)

Today’s main “wear” component in
Fusion Energy Research

2 parts in 10° relative precision of form accuracy to size

RAP state-of-the-art

Helios 1200 machine featuring reactive atom plasma
technology for figuring of large optics up to 1.2m.
RAP process technology

Rapid nanometer dexterity surface process for figure correction of ultra precision metre-scale optics. Technology employs inductively Coupled Plasma Torch.

- Dry etch process – fluorine based gas
- Atmospheric pressure processing
- Gaussian beam distribution
- Dwell time based raster figuring algorithm
- No induced SSD

RAP figuring process

Fused Silica
RAP figuring process

Expected processing time for NIF focussing lens (1 um correction)

- Removal depth of 1um
- 420 mm x 420mm surface
- 2 iteration process
- Average MMR 1.5 mm3/min
- Figuring time ~ 3 hours
- Accuracy < 10 nm RMS
- At least 10 times faster than IBFI
Fusion energy fuel

1mm radius sized pellet
0.1mm thick shells
1 um shell thickness control
25 nm hemispherical accuracy
25nm RMS roughness

Micro-milling and diamond turning machines are presently employed for laser target / fusion fuel pellet manufacture
Translating microelectronics production technology to fusion energy programmes

Rapid “Fusion target” fabrication system

μfour - 6 axis micro-machining
Ultra Precision 6 Axes Micro-Machining System

- Wafer stepper accuracy compact machine tool
- Air bearings, mass comp.
- In situ metrology with error compensation
- 370,000 rpm speeds
- CAD/CAM/metrology integration

Ref: FP7 Integ micro / UPS2. IKC

Automating Ultra Precision

Compact 6 axes Ultra Precision Diamond Machining System

The μ-4
- Extremely compact 6-axes machine
- Highly dynamic control
- Single phase energy
- Integrated tool changer
- Integrated part loading
- Integrated tool and part metrology
- Integrated controller and drives
- Integrated control of thermal stability
- Multi-process capable within one cycle
  - Diamond turning
  - Micro-milling, turn-milling, drilling etc.

info@loxhamprecision.com

www.loxhamprecision.com
Diamond machining of multi-mirror arrays
Diamond turning of mirrors 10 nm RMS form
5 nm roughness (Cranfield)

Undeformed chip thickness of 1nm on amorphous copper
Ref, Ikawa & Donaldson, circa. 1990
www.cranfield.ac.uk
Surface Structuring of mould tools for Reel to Reel fabrication of light handling – emitting films

Purpose built facility
Clean room class 10,000
Lab temperature control +/- 1°C
Enclosure temperature control +/- 0.1°C
Active vibration isolation

Replicating film from a structured drum
Micro-textured cylindrical mould
Cutting a varying included angle: corner sharpness

Emerging products – film based products
Plastic film based products

Toppan and Plastic Logic unveiled a 42-inch flexible E-ink display in March 2013

Emerging production
Shifting from processing stable silicon substrates to films
Shifting from “step and repeat” operations to “reel to reel” continuous processing
Emerging products – glass/plastic film based

Image showing Corning Willow glass substrate at 0.1 mm thickness

Summary

1) How do product development paths influence manufacturing?
   generally they demand higher levels of measurement accuracy to be performed …………and often closer to production processing itself

2) What key developments secure successful manufacturing capability?
   those which are demonstrably deterministic (repeatable) in their application

Looking forward,

3) What future manufacturing developments are critical to human-kind’s long term prosperity?
   those that enable sustainable energy generation…..whatever form that may take
Acknowledgements

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- EPSRC Cranfield IMRC
- EPSRC UPS$^2$ IKC Programme
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www.euspen.eu
**Energy = enabling our future**

- Wind turbine market will increase and mature
- Solar energy generation will increase and mature
  
  (government drive/environmental pressure)
- People in "developing countries" want energy
- Fission energy will continue to be used
- A "free" energy source would be nice for everyone so fusion programmes will advance
Micro-textured retro-reflecting surfaces

Replicating film from a structured drum

- Application
- Optical design
- Drum diamond turning
- UV curing
- Film production
- Assembly
Diffuser film moulds for high brightness LED lighting applications

Solar Power technologies

Solar Power
- Photovoltaic
  - Thin Film
  - Flat Panel
- Concentrated
  - Lenses
  - Mirrors
- Thermal
Concentrating Solar PV demands

- 1.5GW capacity will be installed in 2014
- Equates to 7 million m² of solar units

Ref: Microsharp Ltd.

Presentation structure

1. What will enable the future of our society?
2. Historical drivers of accuracy improvement
3. Importance of measuring system innovation
4. Developments to enabling future needs
5. My thinking of our ultimate priority
6. Closing remarks
To save the earth we need to concentrate on environmentally safe energy generation methods.

We need to focus on this precision engineering challenge with the same level of engineering concentration seen in the space race of the 1960’s.

Free abrasive polishing technology

Ref, UCL/Glyndwr/Zeeko
In-situ measuring over polishing system

μfour ultra precision machine system
Devised for

Automation
In situ metrology
Dynamic response
Motional accuracy
Compact
Low energy demand

Platform base for numerous processes:

Diamond machining
Emboss/Imprint / print
Laser / plasma beams
Axes - Strokes - Capacity

Strokes
X=190mm
Y=190mm
Z=100mm
A= 180 deg
D=180 deg

'C' = 0-3,000 rpm
'S' = 0-160,000 rpm

Max Work Capacity
50 x 50 x 50 mm

Commercial exploitation

Ultra precision machine technology developed for astronomy programmes are applied in machines for fabrication of
reflective clothing, solar concentrators, advanced displays, plastic electronics, animated packaging.