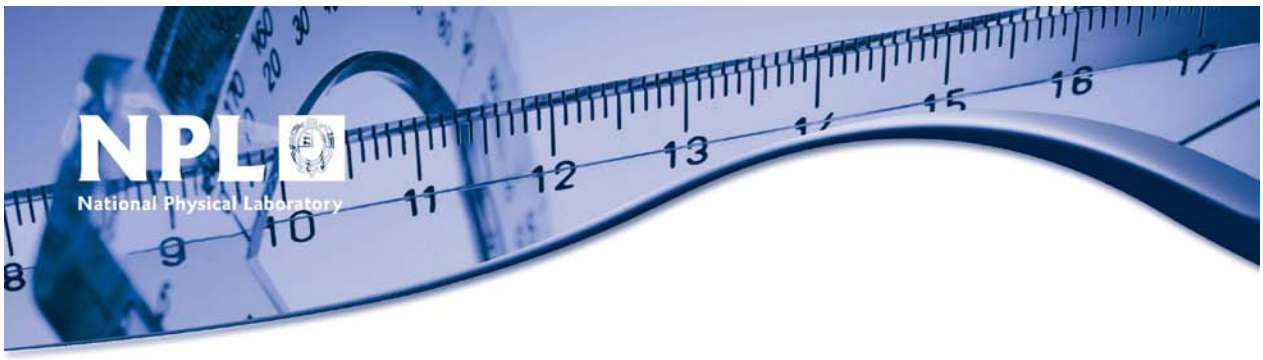

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Training for portable coordinate measurement and large volume metrology

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Abstract
The need for learning and certification of knowledge in Portable Coordinate Measurement (PCM) and Large Volume Metrology (LVM) has been recognized by professional organizations such as the Coordinate Metrology Society (CMS) and major industrial end users. Over the past year, the UK's national standards organization, the National Physical Laboratory (NPL), has been developing a training programme in PCM to complement their existing training in dimensional metrology which is designed for four levels of expertise. A programme of courses for entry Level 1 is now operational. Level 2 is currently in draft form and outlines have been proposed for Levels 3 and 4.

The programme does not endorse specific products but is intended to present the full range of measurement systems and techniques in the context of their application. Theory is complemented by practical work and participants learn how to select and handle the measurement tools relevant to their particular applications.

The programme is supported by major European users such as Airbus and course content is provided by University College London (UCL). The developers are members of the CMS committee on metrology certification and the programme has been reviewed in detail by academic and industrial users and systems manufacturers. Certificates awarded on successful completion of the courses are currently expected to receive accreditation as formal qualifications in the UK.

Background
Portable Coordinate Measurement (PCM) and Large Volume Metrology (LVM) have been developing continuously since the mid 1970s. Early optical systems applied to the measurement of large manufactured objects such as aircraft components were characterized as industrial photogrammetry (multiple camera) or industrial surveying (multiple theodolite) systems. Developments in electronic imaging and processing algorithms have turned industrial photogrammetry into a range of sophisticated vision metrology tools, for example extending the multiple imaging methods into structured light triangulation systems for detailed measurement of surface form. Surveying systems have moved from multiple theodolite intersection systems to widespread use of single instrument systems based on industrial Total Stations and the more recent developments in the 1990s of laser trackers and large volume surface scanning systems.

In a parallel strand of development in the 1970s and 1980s, portable coordinate measurement was made possible by the Articulated Arm Coordinate Measuring Machine (AACMM), often called more simply a CMM arm. The very high accuracy of conventional 3-axis Coordinate Measuring Machines (CMMs) housed in specially built, climate-controlled rooms was then complemented by the lower accuracy but more flexible CMM arm which could be taken to an operator's workbench.

Yet more choice in measuring tools is provided by systems such as the indoor Global Positioning System (iGPS) and developments to enable automation of what, until recently, has largely been a palette of manually operated systems.

These systems, and the techniques which lie behind them, therefore now encompass a very large Body of Knowledge (BoK). Unfortunately there are currently few opportunities for structured or guided learning in this field, or ready access to a convenient knowledge base of portable and large volume metrology. For more on this, see a presentation by the lead author at LVMC08[1].

This gap in the technology's development could negatively impact on the two advanced and high-value manufacturing fields where the knowledge currently has most application – aerospace and automobile. A recent survey by the CMS on users of portable and large volume metrology systems clearly shows the dominance of these two fields of application, see Figure 1.

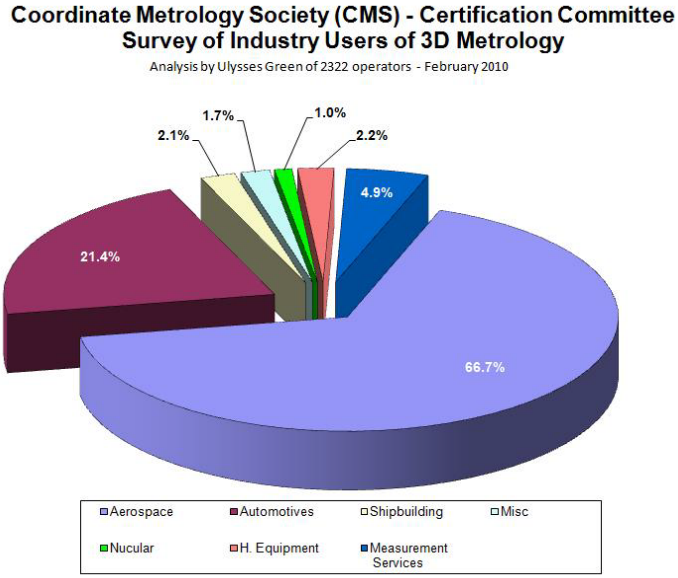

Figure 1 Technology usage by industry sector

To use a technology properly and efficiently you need to understand it. Even a simple measurement tool such as a micrometer needs to be treated with respect and used intelligently. More complex instruments such as CMM arms or laser trackers place higher demands on those who physically use them or make decisions on how best to apply them.

In-depth knowledge will be required for a number of reasons such as:

- Choosing the best instruments and techniques for a given task
- Performance checking to prove a chosen system does what it says on the box
- Confirming measurement traceability to national standards in order to re-assure clients
- Understanding, and dealing with, the sources of uncertainty in measurement
- Designing an optimal measurement strategy with multi-instrument setups
- Locating the problem when things go wrong

With the acquisition of knowledge comes an associated need for certification so that individuals and companies with the knowledge can be identified as having the competence and skills necessary to solve a client's measurement problems with confidence.

For some time the CMS has had a committee to define the body of knowledge relevant to PCM and LVM and to put in place a system of certification. In a parallel development, the UK's National Physical Laboratory (NPL), which has a presence on the CMS certification committee, has decided to expand its existing training courses in basic dimensional metrology with additional courses relevant to portable and large volume metrology. Initial proposals were presented at LVMC09[2]. Course development, trialling and review has since continued and a programme of courses is now operational. This presentation reviews the current state of the development and places it in context with other developments.

This development has the support of major end users such as Airbus UK and Rolls-Royce.

Why portable and large volume metrology?
The current term "large volume metrology" is a more recent variant of "large scale metrology". Both imply application to 3-dimensional objects, typically with maximum dimensions of a few metres or more, and a requirement for on-site measurement. This is not so descriptive of systems such as CMM arms or surface patch scanners which may be applied to the measurement of relatively small objects. However, all the systems have portability in common and portability enables large volume measurement. Arms and patch scanners can be moved around much larger volumes than they can sense from a single location, so NPL's courses address themselves to "Portable coordinate measurement systems (PCMS) and large volume metrology (LVM)".

NPL's general training structure
NPL develops training courses in metrology, both dimensional and non-dimensional, at 4 levels:

- **Level 1**, the entry level, is aimed at **users** of metrology and aims to develop in these users a questioning culture which ensures solutions are appropriate and correct
- **Level 2** is for **appliers** of metrology who should develop a planning culture appropriate for those who select and implement solutions from a wide choice of options
- **Level 3** is for metrology **developers** with the depth of knowledge to champion and take ownership of new solutions to their application problems
- **Level 4** is for metrology **definers** who will create new measurement solutions and methods

Basic or "core" dimensional metrology at levels 1 and 2 covers areas such as:

- Geometric product specification
- Coordinate systems
- Understanding measurement uncertainty, standards and traceability
- Usage of simple measurement instruments such as micrometers

The concept for PCMS and LVM is that these are treated as extensions or supplementary modules to the core material, i.e. course participants must first study core principles before studying the details relevant to PCMS and LVM. At Levels 1 and 2 the course material for portable metrology is intended to introduce participants to the full range of systems and measurement techniques which lie behind them. This does not endorse specific products but uses them to illustrate the very different operational techniques, and associated applications, relevant to portable metrology.

The extended module structure looks like this (Figure 2):

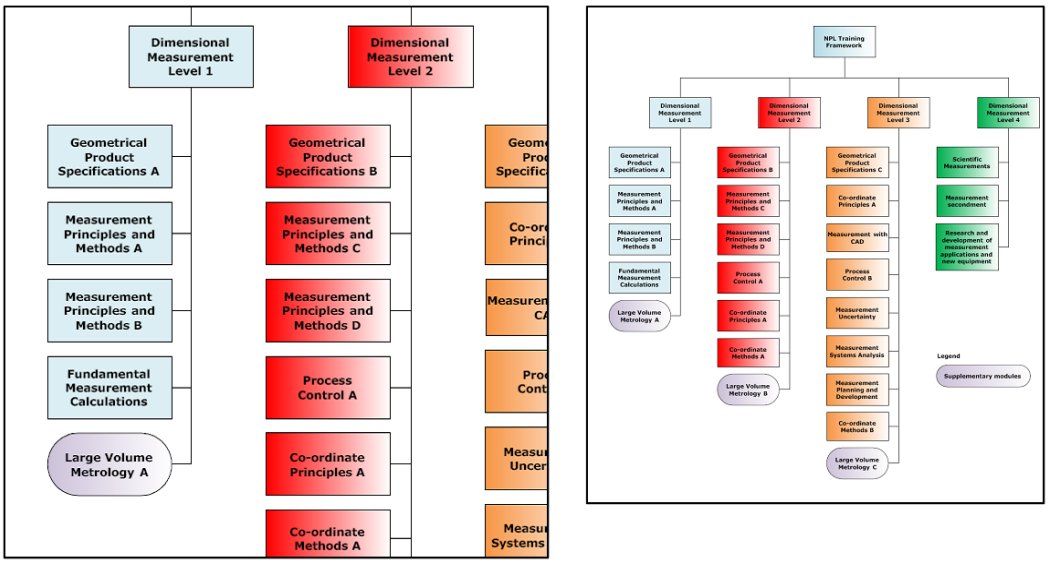

Figure 2 Training module structure

Level 1 course design

Level 1 has been designed as a 2-day course:

- Day 1 is for presentations, interspersed with system demonstrations or videos
- Day 2 concentrates on practical tasks

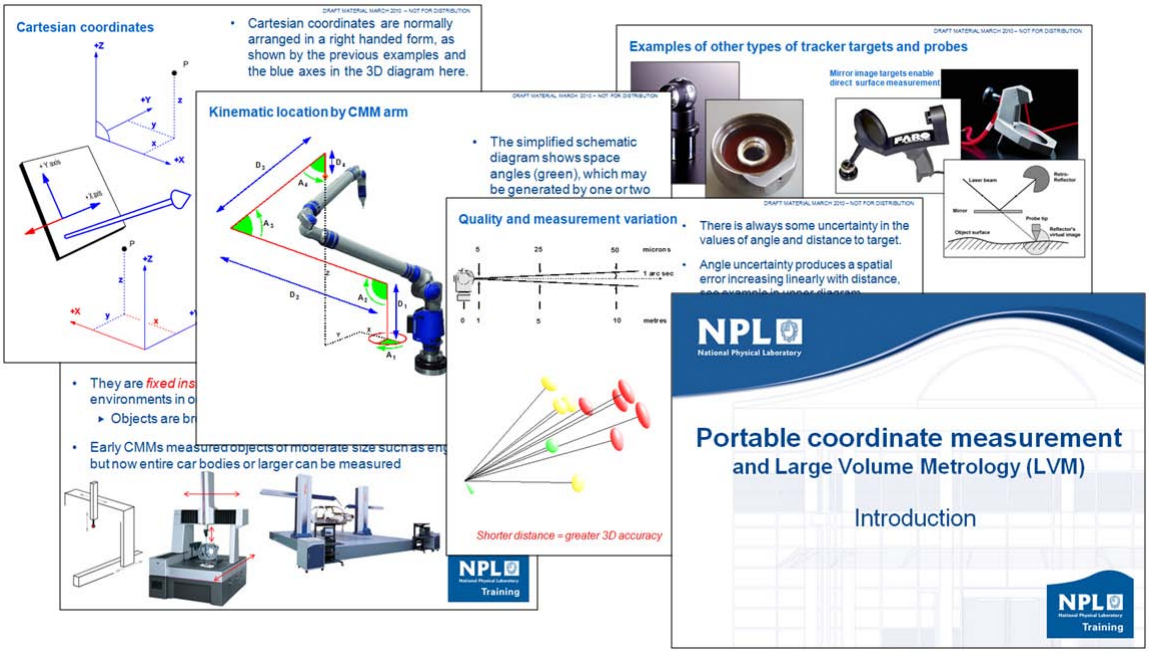

Figure 3 Sample presentation content

The material on day 1 is delivered in PowerPoint format (see sample illustration of content in Figure 3) and contains the following elements (with some sample details):

- *Introducing portable coordinate measurement and large volume metrology*
  Articulated arms, photogrammetric and laser tracking systems are briefly introduced as portable systems and contrasted with 3-axis coordinate measuring machines
- *The World in 3D*
  An introduction to 3-dimensional measurement, coordinate systems and alignment
- *Articulated arm coordinate measuring machines* (AACMMs or CMM arms)
  Concept of operation, how to use in large volumes, good practice tips
- *Laser trackers*
  Concept of operations, simple distance measurement, refraction effects, good practice tips
- *Total Stations*
  A brief introduction with comparison to trackers
- *Camera networks*
  Basic photogrammetry using multiple camera stations, quality issues and good practice tips.
- *Fixed-base cameras*
  A brief introduction to the packaged photogrammetric solution - stereo and triplanar systems

Participants have a workbook in which they answer questions at intervals about the material presented. Examples of questions are:

- Next to an image of an instrument, state what the instrument is
- Name the type of coordinates collected by a Total Station

Practical work is essential in a technology which is primarily a process of manual measurement. It is important that newcomers get direct, hands-on experience and that all users appreciate the need to evaluate the working conditions and environment and plan the measurement properly.

A “recipe book” series of exercises is not prescribed. Instead, key aspects of a physical measurement process are defined as a sequence of checks or best practices which relate to:

- Measurement planning
- Measurement execution
- Reporting of results

Up to 3 measurement tasks will be defined by the course deliverer and these will be used to guide the course participants through the sequence of issues to be addressed, such as:

- The temperature of the environment
- The information source which specifies the measurements to be made, e.g. CAD file
- The probing strategy best suited to the task, e.g. touch probe or surface scanner
- The best way of presenting the results, e.g. graphically or as a list

In an ideal situation there would be time and resources to offer 3 tasks covering the main portable metrology systems of CMM arm, laser tracker and camera. However, the delivery team can be flexible on how the practical work is implemented. The primary objective is that course participants should understand the practical aspects of the measurement process and if their intention is only to adopt CMM arms then the course can be tailored exclusively to arm usage.

Level 1 training has be subject to a full review process (see later comments) and a programme of course dates will start in July 2010.

Levels 2, 3, 4 and supporting material

Higher level courses are not yet complete, although level 2 has been extensively drafted and also subjected to a review by expert users. It will be obvious from the detailed description (above) that Level 1 does not cover the full spectrum of portable metrology systems and methods. Practicalities dictate that courses have limited duration and so the next course at level 2 also completes the overview. Level 2 is expected to be a 3-day course which provisionally has the following content:

- *Theodolite networks* – manual triangulation and intersection systems
  Although of more historical interest, theodolite triangulation systems are very instructive of measurement techniques which are relevant to photogrammetric and iGPS networks and theodolite operation offers a simple calibration model relevant to laser trackers
- *iGPS* – automated triangulation networks
- *Singe camera systems and the space resection technique*
- *6DOF laser tracking*
- *Hybrid LVM*
  Nikon’s iSPACE CMM arm and the Metronor/Breuckmann naviScan system are examples
- *Automated LVM*
  Nikon’s robot CMM arm and Leica’s T-Mac are illustrative here
- *Introduction to range measurement and surface scanning*
  Triangulation, time-of-flight and phase measurement methods would be introduced here

Other material could be added to this list and it is not yet clear how much could be covered in a maximum 3-day course. One major addition, which could be delivered at level 2 or level 3 as a stand-alone course, is a detailed presentation of technologies for surface form measurement. The different concepts for short, mid and long range surface scanning, structured light techniques, the effects of surface properties such as texture and the undeveloped area of performance evaluation of systems together indicate the wide range of knowledge needed to fully understand this field.

Once into Level 3, further courses are possible such as:

- LVM analysis and quality evaluation
    - General mathematical techniques such as least squares
    - LVM techniques such as bundle adjustment and analysis of rotations
    - Statistics for measurement quality
- LVM calibration and testing
    - System modelling and error compensation, e.g. for cameras and laser trackers
    - LVM standards and performance testing
    - LaserTRACER and CMM calibration

Level 4 is very possibly no longer a conventional training course but might appear as follows:

- A module in a university master's course, e.g. LVM system concept design
- Part of a technology seminar, e.g. a State-of-the-Art review of LVM technology

Back at the introductory end of the spectrum, there is currently an initial draft of a Good Practice Guide which would accompany the course materials at Levels 1 and 2.

Finally, a need has been provisionally identified for a Foundation Level course which would be appropriate for a company's senior managers and non-technical staff. Giving these individuals a good understanding of the scope and power of portable metrology would help to support decision making in what is now a key technology area in aerospace and automobile manufacture.

Trialling and review

Prior to the imminent roll-out of the courses in summer 2010, the draft material for Levels1 and 2 were reviewed at the beginning of February. This took the form of a 2-day pilot course for Level 1, followed by a 1½ day in-depth review of the presentation material for Level 2. The review was held at the West Midlands Manufacturing Measurement Centre (www.wmmmc.co.uk), located at the University of Coventry's TechnoCentre in central England. The WMMMC was launched in September 2006 and has a range of portable metrology systems to support course delivery.

A number of course supporters generously gave staff time to participate in the review. These were Airbus UK, Boeing (including the CMS certification committee chairman, Talion Edwards), Rolls-Royce, BAE, Astrium, Jaguar Land Rover, Diamond Light Source (particle physics laboratory), Hexagon, API and Mitutoyo. Interest in participation was very strong and the development team had to switch to a bigger lecture room to accommodate larger numbers than originally estimated.

Participation was positive and enthusiastic and the feedback has been directly incorporated in many aspects of the revised material and course concept.

Training delivery and monitoring training quality

The NPL Training framework has been based on ISO17024.

NPL does not itself deliver courses but operates through third parties. These organizations must have access to facilities where courses can be presented and must be able to provide some of the portable metrology systems to enable hands-on demonstrations and testing.

Trainers are themselves trained by NPL. The first two courses delivered by trainers are directly monitored by NPL and, subject to approval, trainers are then with a 12 monthly certificate to deliverer. There is then an on-going monitoring process, such as checking of participants' workbooks or further on-site visits.

Trainers can be independent organizations like WMMMC or systems manufacturers such as Hexagon. NPL's strict policy of no bias in the presentations must be accepted by all deliverers, including systems manufacturers, but course participants can make their own choice of provider. Currently courses are available in the UK and to a more limited extent in other European countries.

Accreditation of training

To achieve a national impact and provide a standard for comparison, training courses should be able to award recognized certificates to successful participants. A number of "awarding bodies" exist in the UK and these nationally recognized organizations are themselves subject to monitoring by Sector Skills Councils. One aspect to this is the division of learning into individual units which can be combined, within a set of rules, to achieve a complete qualification. These units are held within the UK's Qualifications and Credit Framework (QCF) to ensure they meet standards.

NPL has been working with one of the awarding bodies, EMTA* Awards Limited (EAL) which awards 70% of the UK's qualifications in the general fields of Engineering and Manufacturing.

Currently the sector skills council responsible for Metrology has accepted the need for vocational qualifications in measurement, including portable coordinate measurement. Once these vocational qualifications have been through the required approval process, the NPL Training modules will become a nationally recognized award in metrology contained within the QCF. For more information on EAL and the QCF, visit the EAL website at www.eal.org.uk.

Related learning opportunities

Figure 4 Quality on Tour - sample content

In a related development which underscores the importance of learning about portable coordinate measurement, systems manufacturer Faro Europe have designed their own 2-day seminar, "Quality on Tour". This was originally delivered in Barcelona in 2008 and is currently under comprehensive revision for presentation at various European locations from September 2010. A sample of current revision material is shown in Figure 4.

* Engineering and Marine Training Authority, a merger of two previously existing training authorities in the UK.

Faro's course concentrates on the CMM arm and laser tracker. Although demonstrated using Faro's own products, the presentations themselves acknowledge the wider spectrum of portable metrology systems, including rival products. Faro not only want users to appreciate the tools of portable metrology but also the quality aspects relevant to good measurement practice.

"Quality on Tour" does not duplicate NPL's comprehensive training structure or offer formal certification. However, it will certainly contribute to a user's understanding and help promote quality in portable coordinate metrology for the industry's general benefit.

Conclusions

The strong interest from the end users of PCMS is clear evidence that training in the field of portable coordinate metrology is valued and required. Together with additional indicators such as Faro's independent promotion of knowledge transfer in PCM, this should further encourage the efforts of the CMS to define the body of knowledge and further develop metrology certification.

Knowledge transfer is in demand and we can expect further developments in this aspect of portable coordinate metrology.

Acknowledgements

The support of the review teams on the pilot course in February is particularly valued.
Initial review of course material by LVM experts at the University of Bath was very helpful.

REFERENCES

[1] Kyle, Stephen, Accessing the LVM knowledge base, Large Volume Metrology Conference, Liverpool, 4/5 November 2008 (accessible at www.lvmc.org.uk)

[2] Kyle, Stephen and Bevan, Keith, Developments in LVM training, Large Volume Metrology Conference, Chester, 3/4 November 2009 (accessible at www.lvmc.org.uk)