Title: Modern Manufacturing with Measure

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This paper is intended to discuss the Modern Manufacturing with emphasis on the measurement aspect on the manufacture of aerospace components. Rolls-Royce currently lists sixty-six locations in twenty six states. The number of locations in North America for the supply chain for the Rolls-Royce global community is significantly higher. Gas Turbine Engines have a long life span and require a regimented service schedule within the Repair and Overhaul facilities around the globe. Some of the components vital to the operation of the systems were designed and tested prior to Computer Aided Design (CAD). These components were designed by “Baby Boomers” and their pre-computer genius ability to work with master craftsmen in the manufacture of very highly refined components, as many as 20,000 in a single engine. Although historians contest the actual “Baby Boom” calendar years there is little debate over their contribution to our global society. 2011 began with the first of the baby boomers reaching retirement age and it is estimated by Mary Clarke, CEO of Cognisco as early as 2008 that we will lose over 40% of our skilled work force by the end of 2015. In addition 75% of the management was between 44 and 60 listed as having advanced degrees and been in the business between 11 and 30 years. The major issue is the timing we have to find the correct individuals and train them to carry on the business of manufacturing. Measurement of the manufactured component to meet the design intent and functionality is considered to be one of the most critical aspects of manufacturing. Modern Manufacturing is undertaking the task of assisting in the transformation from the paper and mechanical manufacturing and measurement to the digital and 3-D manufacture, validation, and retention of methods of manufacture for each component type. As we have embraced the graphics world in other industries we must also in manufacturing to maintain our ability to produce accurate dependable components.

A little bit about Rolls-Royce: Rolls-Royce Group plc (LSE: RR) is a global power systems and services company headquartered in the City of Westminster, London, United Kingdom. It is the world’s second-largest maker of aircraft engines (behind General Electric), and also has major businesses in the marine and energy sectors. Through its defense-related activities it is the world's 23rd largest defense contractor. It had an announced order book of £58.3 billion (~$ 85 billion US) at 31 December 2009. It is listed on the London Stock Exchange and is a constituent of the FTSE 100 Index. As of August 2010, it was the 32nd largest company on the FTSE, with a market capitalization of £10.24 billion (~$17 billion US) (1)
The Rolls-Royce Black label appeared in 1934 and was the first car that Henry Royce did not have input into the car. This logo was licensed to VW in 1998 and then to BMW in 2003. Autos are built by a division of BMW.
As we began to identify the tasks associated with the Modern Manufacturing methods of manufacture the criticality of the accuracy and integrity of the definition of the component part to be manufactured became painfully evident. We were in the process of transferring a critical part from a casting supplier that had succumbed to the current economic demise to another more robust supplier. All precautions were in place to transfer a component in the traditional 2D method. During the transfer it was discovered that there had been a hiccup in the current supply line and “safety stock” components were rendered unacceptable for use. This pushed the transfer into “overdrive” to move to the 3-D world. Being a casting it may seem to be very easy to measure given the standard casting tolerances. The team had discovered that “tooling points” or casting datum to finished features could play a major part of inspection and validation. If was discovered that the scrap rate from “insufficient stock” or “non clean up” was not only a high cost but a major driver in delivery timing. In most cases we found that the dimensions of the casting had “changed” over time as the tool would wear from use. Because the inspection of the parts had gone from “blue line” measurement to 2-D based hand written for state of the art, however unique, CMM equipment. Transferring these measurement programs to current systems and equipment was not possible so a 3-D alternative representation was needed.

After extensive search and setting through numerous presentations from Companies that could offer 3-D solutions we began to understand just how important having current 3-D associative data was. It is very important to mention here that Rolls-Royce is not supporting any one brand of capturing or manipulating data. It is my belief that all methods of data capture, translation, manipulation, validation, and storage are good in there own right. The manufacturing community has become a prisoner of its own created technology and many wholly owned methodologies and systems that were thought to give ones company a competitive advantage have now limited their growth and capability. Therefore we strived to look at all the viable commercially available software and hardware to assist us in our endeavor. Our goal was to find a “COT” system (Commercially Off The shelf) system that we could utilize and rely on industry to drive it to the next level. We can no longer limit our long term manufacturing viability by trying to develop systems at individual companies. Following is a listing of what we found.

The first major objective of this program was to develop a methodology and a system to scan the legacy parts, with prismatic features, which lack CAD models and/or detailed updated drawings, and create a fully associative 3D CAD model in a timely and efficient fashion. The conversion of these parts to the CAD environment effectively supports production of legacy components. The conversion process also helps avoid compromising competitive readiness because of the industrial base.

The project addressed the goal to preserve or expand the diminishing industrial base and enabled the companies to address the additional requirements. This was accomplished by developing the capability to re-engineer virtually any legacy part that the company or certified suppliers need to reproduce this hardware.

This methodology would eliminate 90% of the time to create a complex component from a 2D drawing to a fully associative model. CMM programming time would be reduced between 30 and 50%. Non Recurring Engineering Costs to implement change or transfer would be reduced by 75%.

In the short term, it would enable companies to reverse engineer products. This reverse engineering methodology would give the suppliers the capability of producing parts for all hardware that does not have electronic 3D models.
Long term benefits include the ability to greatly reduce the time to bring multiple suppliers up to production levels if the need should arise. This technology could also become an extremely valuable tool needed to determine the capability and dimensional tolerances of hardware and components not produced within the supply chain.

In order to properly reverse engineer a part, and not just copy a potentially bad part, it must be determined how accurate the systems measuring the part for it’s purpose. It is helpful to have access to the drawings and the drawings of the individual mating parts.

**Resolution, Repeatability and Accuracy**

**Resolution** is the smallest increment that can be seen by the scale system of the machine or measurement device

As resolution increases you improve your focus on the target

**The Metric Advantage**

.0001in or .001mm
2.5X finer resolution

**Repeatability** is how well the machine goes to a location multiple times

Repeatable errors can be easily compensated

**Accuracy** is the ability to move to a precise location

Accuracy on a single part does not guarantee continued accuracy

We know from past published papers that process capability is critical to sustainable manufacturing processes.
Different systems were looked at for creating point clouds to use in rendering models. We found that there are many point cloud methods in non contact as well as contact scanning methods. Listed below are a number of the hardware suppliers of measurement.

**Konica Minolta Scanning System**

**Description**

The Konica Minolta RANGE7 and RANGE7 & Tripod System(2) shown in Figures 4.3.1 and 4.3.2 respectively, is a non-contact 3D laser scanner that generate external profiles of various components represented by XYZ data points (Point Clouds). The digitized data can then be imported in Rapidform XOR software to be converted into a 3D CAD model. Point cloud can also be compared with a 3D CAD model generated using the 2D print, using Rapidform XOV. The Rapidform XOV software package can generate output measurement reports on overall deviations, cross-sectional deviations, wall thickness distributions, and GD&T.
For this project the RANGE7 was one of the scanners used to scan a Pump Body. This scan data was used to generate a CAD model. In addition to reverse engineering, the RANGE7 scan data can also be used to generate rapid prototyping models, machining data, and digital mockups of components.

A useful accessory for the RANGE7 scanning system is the rotary table shown in Figure 4.3.3. The rotary table has a weight capacity of approximately 30 lbs and is primarily used on smaller volume components. One key feature of the RANGE7/Rotary Table system is the ability to automatically shoot and merge sequential scans using the Konica Minolta RANGE VIEWER software.

RANGE VIEWER is the computer interface software between the RANGE7 scanner and the operator. It is used to mesh the individual scans into one complete point cloud for export into a surfacing software package such as PolyWorks or Rapidform for further detailed analysis.

The entire system including the RANGE7 scanner, mounting tripod and rotary table is shown in Figure 4.3.4.

System Calibration
Prior to scanning an object, the Konica Minolta RANGE7 system needs to be calibrated to insure its accuracy. The system calibration standard setup is illustrated in the sketch shown in Figure 4.3.4.1. It is also shown pictorially in Figure 4.3.5.

![Figure 4.3.4.1 - RANGE7 Calibration Setup (3D Data)](image)

**Figure 4.3.4.1 - RANGE7 Calibration Setup (3D Data)**

The operator positions the RANGE7 on top of the appropriate illustration on the calibration sheet. Once the scanner is positioned the operator aligns the calibration chart,

![Figure 4.3.5 - Calibration of RANGE7](image)

**Figure 4.3.5 - Calibration of RANGE7: The scanner body is leveled to and aligned with the dots on the rollout calibration map. The Calibration Chart is placed on the rollout map according to the software instructions.**
Figure 4.3.6, on the appropriate position markers shown on the calibration sheet. There are two sets of position markers on the calibration sheet, one for calibrating the wide angle lens and the other for the telephoto lens, respectively.

After setting up the system as illustrated in Figure 4.3.4, the operator uses the RANGE VIEWER software and its built-in calibration application, “Calibration Wizard” shown in Figure 4.3.7. The Calibration Wizard application will prompt the operator through a series of repositioning exercises using the color-coded markers on the calibration sheet to complete the process. This system calibration is to be performed when the lens is changed or the ambient room temperature changes relative to the previous calibration temperature.

Calibration instructions are integral to the RANGE VIEWER software and have step-by-step pictorials for each calibration scan. Outlines of chart positions are on the map so that placement and repositioning are easily accomplished.

In the first calibration window, the software detects the type of lens being used and directs the operator in the calibration procedure. The next seven positions of the calibration chart are comparisons of a sample image shown on the right as the chart is moved from one scan position to another.

Defining Axis of Rotation

When smaller objects are to be processed, the RANGE7 system can use an integrated rotary indexing table and controller, shown previously in Figure 4.3.3. This provides angular rotational measurement capability, aiding in the alignment of individual scanned sections automatically as discussed below.

To define the axis of rotation the operator mounts the calibration charts, fitting two alignment pegs into the two corresponding calibration holes on the rotary table as shown in Figures 4.3.8 and 4.3.9 below. The RANGE VIEWER software can then determine the axis of rotation by taking indexed scans of the calibration chart and automatically calculating the center.
Figure 4.3.8 - Calibration Chart: The center vertical black stripe is used to establish a common axis.

Figure 4.3.9 - RANGE7 Calibration Chart setup for acquiring axis of rotation (3D Data)

Scanning Aids

**Targets:** Some parts with large freeform or cylindrical shapes can benefit from the use of self-adhesive circular paper markers (targets) to aid in manually “stitching” the individual scans together. Each scan will need to have at least three targets common in adjacent scans to ensure proper alignment to each other. The scanning software automatically recognizes the targets and aligns the individual scans. Examples of this technique are displayed in Figures 4.3.10 and 4.3.11. Figure 4.3.10 shows what a large part looks like with targets applied to its surface geometry.

Figure 4.3.10 - Part with Paper Targets Applied

Figure 4.3.11 - Scanner Recognition of Targets and Scan Alignment. A: Live view from camera on scanner; B: Current data cloud from scan; C: Previous data cloud scanned, and D: Combined scan aligned using paper targets
Figure 4.3.11 includes screen shots of the alignment process between two scanned images. Section A is a real-time image from the camera located on the RANGE7 scanner to help the operator position a shot. Section B is a current view of the data cloud generated from the scan. Section C is the data cloud image from the operator’s previous scan. Finally, section D is the image of the merged data clouds utilizing the target alignment method. The overlapped images show at least three targets common to both shots.

**Clay Markers:** When it is impractical to move a large part or if a part has no defining geometric features to use in alignment, clay markers can also be applied to a part to help in scan alignments. An example of this technique is shown in Figure 4.3.12. Including the clay markers in adjacent shots provides unique features to help in the alignment process, similar to using targets.

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**GOM 3D Digitizer/Scanner**

**Description**

Rolls-Royce has been involved with white-light scanning since the mid-1990s. Entry into this field started with an EOIS (Electro-Optical Inspection Systems) sensor mounted on a Coordinate Measuring Machine (CMM). The technology has matured considerably since then. A GOM system was purchased and implemented in 1996 and a second one was purchased in 2009. GOM is a German acronym (Gesellschaft für Optische Meßtechnik) that translates to “Association for Optical Instrumentation.” The company was developed as a spin-off of the Technical University of Braunshweig and has offices in several European countries.

Early applications of optical scanning technology at Rolls-Royce primarily involved engineering analysis of part deformation and full-surface comparison of manufactured parts. Reverse engineering applications have continued to grow. They are currently being used or are being considered in CAD model generation, repair, and adaptive machining. As the technology becomes more pervasive, there is concerted effort directed at implementing the technology in the production process, including final approval of completed parts. The EOIS system is still used occasionally at Rolls-Royce, but has limited application due to its very small field of view. GOM systems, and more recently, Konica Minolta systems, are currently being used for larger parts. The high-resolution GOM systems are used to capture fine details on extremely complex parts, while the Konica Minolta system is more practical for parts that have larger features.

Two GOM products, TRITOP and ATOS, are used at Rolls-Royce as a system for dimensional evaluation of manufactured parts. Each product is composed of a hardware component and a software component for capturing and analyzing data.

**TRITOP system**
The TRITOP system consists of a Digital Single Lens Reflex (DSLR) camera, calibrated scale bars, barcode targets, and target dots, along with analysis software.

Figure 4.6.1 illustrates a camera and computer used with the TRITOP system. Notebook or desktop computers may be used and camera shots may be transferred to the computer by wireless network or direct transfer.

**Calibration**

Reference, or “target,” dots are applied to a “reference frame” that is constructed to surround the part. (The use of a reference frame is more convenient than putting dots on actual small parts and can be used with multiple similar parts without adding and removing targets to/from the parts themselves.)

Then, scale bars and bar-coded targets are arranged around the reference frame (Figure 4.6.2). The target dots themselves are too small to be visible in the picture.

Each target dot consists of a .4mm diameter white dot on a black background. The camera is used to capture an “umbrella” of shots of this setup. (Figure 4.6.3)

The pictures are analyzed with the TRITOP software and the target dot positions are noted and recorded in a file. These known reference (target) points are included in ATOS scans and used to establish an absolute, traceable reference system for the ATOS scans.

**ATOS System (3)**

**Description**

The ATOS 3D Digitizer is a white-light scanner that delivers three-dimensional measurement data for industrial components such as sheet metal parts, tools and dies, turbine blades, prototypes, injection molded and cast parts. Instead of measuring single points as is the case with CMM technology, full part
geometry is captured in a dense point cloud that describes the object's surface and primitives precisely. The sensor consists of a projector that projects a pattern of parallel fringes on the part to be inspected. The two cameras, also incorporated in the sensor, record this pattern, which contains displacements or distortions because of the shape of the part. The ATOS software calculates the displacement of fringes projected on the surface of the object to determine the position of individual points (pixels) in 3D space.

The ATOS 3D is able to scan objects of different sizes and complexities, delivering:
- Highly accurate 3D coordinates
- Full-field deviation to CAD
- Section-based analysis
- Complete measuring reports

The ATOS 3D Digitizer is a flexible, adaptable optical measuring machine. With more than 2500 installations in measurement and analysis rooms as well as factory and production halls worldwide, the ATOS has been for a long time an accepted measurement method beside the mechanical measurement machines.

Figure 4.6.4 depicts an unmounted ATOS scanner. The scanner that is mounted on a robot arm in Figure 4.6.5 is used for flexibility in scanning larger parts. The scanner in Figure 4.6.6 is mounted on a multi-axis linear and rotary system and is used for scanning medium-sized parts. Automated motion control of the sensor and part is the most effective way to implement a scanner in a production system.
Figure 4.6.7 shows an object with the fringe lines of the scanner projected onto it. A scanner mounted in a production motion control (small object) system is shown in figure 4.6.8. This is the unit that was used to generate the white-light point cloud used in this program.

**Calibration**

Calibration of the ATOS system is accomplished using a ceramic plate (Figure 4.6.9) with a pattern of white dots with known (gage-certified) locations. This plate is positioned at various angles and locations in the Field of View and Depth of Field of the sensor. Camera shots are taken at each of these locations and the positions of the dots are used to adjust the system to the certified dimensional locations.

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**Rapid Reverse Engineering of a Part for Casting Production**

A specific application involved emergency re-creation of casting tooling. The newly-developed process was put to the test when production of an air inlet casting was being transferred to another vendor. The original vendor went out of business. In the process of transferring the only tooling to a new vendor, the tooling was destroyed. There were prints, but no CAD model with which to rapidly generate tooling to meet production demands. Only one example of the casting remained in stock. Following the reverse engineering methodology process,

1. The casting was scanned.
2. The scan data was used as a template to build a model.
3. Nominal dimensions were applied to the model using the existing prints.
4. Any ambiguities in the prints were resolved using design intent.
5. Updated prints were generated and casting tolerances were applied.
6. New tooling was generated directly from the model.
7. Castings were produced and verified against the updated prints.

Modelers worked around the clock and were able to shorten the model generation process considerably. Conventional methods of creating a model from older prints would have taken approximately three months. The new process took approximately two weeks. (Figure 7.1.1).

Once the model was created it could now be used to program the Coordinate Measurement Machines (CMM) that were used to validate the component throughout the manufacturing processes.
Reverse Engineering via Laser Scanning and Associated Methodology

Here are some examples of savings obtained from having models to produce or transfer parts:

*Figure 7.1.1 Air Inlet casting*

Model construction reduced from 3 months (from conventional drawings), to 10 days

*Figure 8.1 Possible increases from digital data*
Next Steps

Rolls-Royce has extensively investigated the use of non contact methodology to better create a 3-D accurate representation of the components manufactured for its product offerings. One of the key points of this work was to validate additional tools to assist and raise the level of available systems capability to insure the best product for our customers. As measurement hardware and software advance in capability it has become critical to increase the richness of raw data. In the past we have relied on the skill and experience of the CMM programmer to understand the “what and how” to interoperate the 2-D method of communication with their developed 3-D skill set. This amazing group with this unique skill is now being augmented with computer skill sets that have to be fed specific scientific diets of information in order to perform at the needed levels for today’s environment.

As the complexity and capability of manufacturing equipment has continued to develop we are now seeing an advantage to have data rich models for multiple axis capability machines. One area that is still contested heatedly is the ability to infinitely control 5 axis movements of machine tools. Although it has been around for many years and perhaps has as many explanations as industry competitors find resources to fund the unique mind set it is beginning to mature to a level of competency and repeatability that is going to demand the same understanding in the measurement communities. The standards for validating machine tools and classifying them with regards to capability and accuracy are deemed inadequate by some as they were written for a 3 axis world with mechanical / electrical microswitch technology. Most of these standards appear to be heavily concerned with the accuracy and control of the movement of the machine parts (tables, columns, ball screws, glass scales…) and the math that calculates and interprets the distances and movements of the number of axis moving.

As the richness of the 3-D model continues to allow us to imbed more information within the model how will we be able to take advantage of this technological development to increase our understanding of the 5 axis world? As we discuss the “full 5 axis” issues and debate the technology to cope with it I sometimes think about what would happen if we began to discuss the 6th or 7th axis movements that are whispered to be coming.

References


Figures

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