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Towards a definition of PLM-integrated Dimensional Measurement

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Abstract

Product Lifecycle Management (PLM) enables knowledge about products to be captured and reused. Since dimensional measurement is used to determine the size and shape of the products about which PLM is centered, we contend that it is an important process to integrate. Building on emerging industry-accepted standards, a framework was developed in an effort to define what integrating dimensional measurement with PLM involves. Following a survey of the state-of-the-art against this framework and a critical review, technology gaps are identified, and key challenges and research priorities are highlighted.

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Keywords: life cycle management ; dimensional measurement ; digital manufacturing ; verification

1. Introduction

In a bid to manage the complexity associated with high value manufacturing, many organisations have implemented Product Lifecycle Management (PLM) solutions. The scope of PLM covers all aspects of the business strategy employed to manage knowledge about products throughout their life, from conception to retirement [1]; this includes creating and managing digital models of both the product and manufacturing process.

Dimensional measurement is a part of the manufacturing process that is used to quantify the size and shape of products. Knowledge derived from measurement is needed at all stages of the lifecycle to 'close the loop' between the digital models in PLM and the reality of the built product [2]. It has been demonstrated that by integrating measurement processes at different stages of the product lifecycle, significant benefits can be achieved, for example through:

- Increased innovation [3];
- Improved manufacturability [4];
- Better optimized manufacturing processes [5];
- More pro-active maintenance [6];
- Higher quality [7].

Maropoulos and Ceglarek [8] lend weight to these findings, summarizing that PLM will allow organisations to adopt state of the art methods for verification and validation, of which measurement is an important element. However, it has also been observed that some measurement activities currently occur in relative isolation of PLM [9]. For example, considerable human intervention is sometimes required to update measurement programs in response to comparatively minor design changes [10]; at a more strategic level, one can envisage making better use of measurement data that is captured at different stages of the product lifecycle in order to improve products and processes [11].

There are a growing number of commercial products that are becoming available in this domain, yet the field is new and is not well defined. Accordingly, this research is aimed at identifying the theoretical location of PLM-integrated dimensional measurement, which we shall term 'PiDM': what does it comprise?

In the following sections, the literature is first reviewed in order to identify the topical challenges that need to be addressed. Next, a methodology is described for defining PiDM, and a framework is presented with the aid of an example. Finally, by mapping the state of art back on to the framework, technology gaps are identified.

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2. Literature Review

Unsurprisingly, given the opportunities afforded by PLM, literature about the topic is vast. Possible categorisations include:

- Functional perspective: The processes developed in PLM will vary according to the business drivers for a particular domain [12];
- Phase of life: The product lifecycle can be divided into beginning (up to realization), middle (in service), and end of life (disposal or reuse) [2];
- Industry type: PLM solutions are most mature in high value discrete manufacturing industries, such as automotive and aerospace [13].

In this paper, we have chosen to take a high value manufacturing perspective, with the aim of identifying the key elements required to embed quality in the product through the use of dimensional measurement. In order to make the scope manageable, there is a focus on the tail of the 'beginning of life', when geometry is already at a detailed level of definition, though before measurement data can be gathered about how geometry changes when a product is being used. The aerospace industry will be used as a test case for the framework, since PLM is considered to be advanced in this sector and dimensional measurement can be particularly challenging [14].

In this context, there is growing focus on the importance of geometry as the primary and authoritative source of information [15]. When geometry is represented in 3D models, with semantic links to the complete set of data that is required to define manufacturing processes, this is known as Model-based Definition (MBD).

If one is to rely on models against which manufacturing methods are associated, those models must be of exceptionally high fidelity [16]. However, one might question whether industry is fully ready for MBD since some of the key standards are only in draft form [17]. Indeed, researchers have found that the uptake of MBD has not been as fast as might have been expected [18-19]. Frechette [16] observed that there are three main technical challenges: model quality and validation; consistent interpretation by applications; and long term archiving, which is a particular problem for aerospace, where lifecycles may be decades long.

There are management challenges too, which are highlighted by Marion and Fixson [20]. By increasing effort in the development of models early in the product lifecycle, designs may appear to be more complete than they actually are, and this can also lead to 'endless tinkering' at inappropriate stages.

Within the MBD environment, it is clear that dimensional measurement has a special role to play in providing the feedback needed to improve models. If measurement models could be integrated with design models, it may even become possible for measurement to quantify how 'complete' they are. However, measurement also comes with its own challenges due to its integral place in manufacturing, both in terms of aligning capability, and in its role for decision making.

The difficulty of aligning capability was articulated thirty years ago by Taniguchi [21], who extrapolated probable future machining accuracies. The extrapolation has proved to be a useful guide – for example, in the 1980s, accuracy to one micron could only be achieved through a precision machining process, but now this is possible through normal machining in a well-controlled environment. Taniguchi also listed the then available measuring instruments for each level of accuracy, which made the point that there is continual pressure for dimensional measurement techniques to improve over time. The challenge for manufacturers is to ensure that their measurement systems are capable of quantifying size and shape to a level of accuracy and repeatability that is commensurate with the manufacturing process, whilst not over specifying [22]. This is also confounded by new materials, such as composites, and innovative technologies, such as additive manufacture, which will require new measurement systems to be developed.

Measurement data is used to make decisions. In manufacturing, decisions are made as to whether to pass or reject a part. Additionally, data is used to keep track of processes, and measurement is singled out within the Six Sigma DMAIC (define-*measure*-analyze-improve-control) improvement methodology [23]. In order to make better decisions, the level of uncertainty associated with measurement data needs to be quantified. In some circumstances, this may be enforced through regulation. For example, ISO14253-1 [24] states that measurement uncertainty should be used in conformance decisions.

In summary, PLM solutions are being built on increasingly comprehensive models. These models are based on 3D geometry. As products progress through their lifecycle, the models should be associated with all the data needed to define the manufacturing process, of which measurement is a part. Challenges include ensuring the model is valid and that data is used consistently and appropriately. Additionally, manufacturing and measurement techniques change over time. For industries such as aerospace, where products may have lifecycles of several decades, there must be a means of managing changes in the method of manufacture. Finally, in recognition of measurement's role in providing data for decision-making, a complete PiDM solution should consider measurement uncertainty.

Whilst many proprietary solutions exist to one or more elements of these challenges, the authors have been unable to locate an independent, comprehensive, and generic framework that allows users to locate the boundaries, functionalities, and critical interfaces of these solutions from a PLM perspective. The following section discusses the methodology followed in order to derive such a framework.

3. Methodology

Having identified the critical issues, an action case approach was taken [25]. The action case began at Rolls-Royce plc in the UK in the summer of 2011, and was later broadened out to the participants of a related research project at the Manufacturing Technology Centre (MTC). Action case is a combination of action research and case study, in which the researcher is part of the case. Literature, state of the art, and company documents were consulted to derive an initial model for the measurement programming process, and key aspects of PLM. Current practice was then identified through a number of focus group meetings within Rolls-Royce plc in order to improve the workflow. An initial framework was produced which was then described and reviewed through debate with a broader audience which included leading practitioners in the field (representing both users and suppliers). Feedback was collated and used to improve the framework. As of writing, the case is still ongoing and the definition of PiDM will be refined.

4. PiDM Framework Development

4.1. PiDM framework objectives

Since our interest is in high value manufacturing, the telecommunications industry may seem like an eccentric place to look for literature. Yet it is here that one can find a good exemplar of a business process framework, in the shape of the enhanced Telecom Operations Map™ (eTOM) [26]. Telecom operators 'make' products, such as mobile phone or internet services, through a mixture of physical activities (e.g. installing new cables) and software activities (e.g. activating email accounts). eTOM attempts to describe all the activities that are needed by Telecom operators to run their business, and locate these activities on a layered map. For example, to complete an order for a new mobile phone service, a service fulfillment process will be enacted. The fulfillment process will interact with functions relating to customer relationship management, service management, resource management, and supplier management. At each stage, the required processes are named, and solution vendors can indicate which of these eTOM processes they cover. eTOM thus provides a standard means of communication; business process professionals within telecoms need to be conversant in eTOM in much the same way as manufacturing engineers should be familiar with the language of geometrical dimensioning and tolerancing (GD&T).

The lesson from eTOM is that it is valid and useful to generically map organizational capabilities through a simple, prescriptive, matrix of processes. Accordingly, an eTOM-inspired framework will be developed to describe the necessary processes in PLM-integrated dimensional measurement. The framework will initially take the form of a simple grid showing PLM functions against a dimensional measurement workflow. In this initial phase, there will be a focus on coordinate measurement machines (CMM) since dimensional measurement is most mature in this area, and CMMs are a dominant measurement instrument within aerospace.

4.2. Dimensional measurement workflow

One major attempt to define the full set of activities required for dimensional measurement was reported in Evans *et al.* [27] in 2001. The activities were grouped into four types of systems: Computer-Aided Design (CAD); programming; execution; and reporting/analysis. Evans *et al.* found that there was a lack of standardisation of interfaces both between and within these systems – for example, the interface for planning data within inspection programming was considered to be immature. This systems-based workflow was later refined and documented by Zhao *et al.* [28] as a multi-layered IDEF-0 model. In our action case, we conducted a number of interviews with practitioners based around the completeness of this model. The interviews highlighted a number of issues that required special attention (for details, see [29]):

- Efficient use of GD&T to communicate requirements;
- Integral nature of measurement in manufacturing;
- Formal identification of measurement objectives;
- Prevalence of feedback.

These issues are made explicit in the workflow shown in Fig. 1. The workflow begins with component design, in which CAD is used to create a 3D model of nominal geometry. The permitted variation of shape and size is then defined by assigning GD&T callouts to features on the model. Verification and process planning is carried out to determine the strategy for verifying GD&T requirements and the sequence of manufacture. In some cases, it may be found that verification can take place with minimal dimensional measurement – for example, a feature might be verified through the control of process inputs during manufacturing. Following the identification of measurement objectives, measurement planning determines the measurement tasks, instruments, probing strategy, and probe path. Programming and execution is carried out to create and run a CMM program. Finally, the results are analysed, and trends may be reviewed during component variation analysis.

By arranging these steps in a 'V', one can see how measurement enables feedback, answering questions like: Did the execution go to plan? How closely was the specification met? How did reality differ from design?

Throughout the workflow, the interfaces can be described using the Quality Information Framework (QIF) [30]. QIF is an emerging ontology which is both vendor-independent and open. It is also gradually finding its way into commercial products, which shows that it is gaining acceptance in industry.

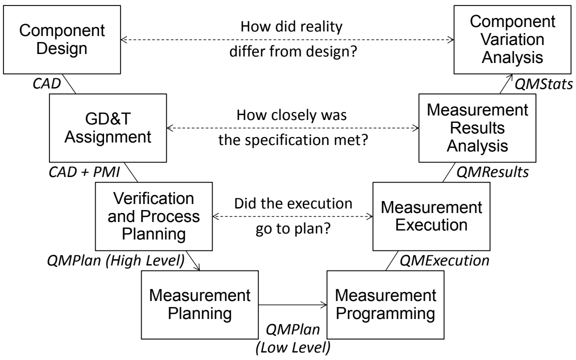

Fig. 1. Dimensional measurement workflow

4.3. PLM operational context

Campbell *et al.* [31] discuss the need for customers to describe the operational context in which a system will be used that is *independent* of vendor capabilities. Whilst such context will by definition be customer-specific, we have attempted to create a superset of functionality that should be evaluated.

PLM was conceived to manage product data, so we have taken the view that this should be a central element for the PiDM framework. The literature review in Section 2 found that there is a need to (a) align measurement and manufacturing capability, (b) account for the decision-making role of measurement, and (c) use measurement to provide feedback in order to improve models. These issues will therefore be used to derive the other main aspects, as shown in Table 1.

Table 1. PLM operational context

PLM Aspect	Responsibilities
Data Management	Capture and organisation of data needed to support the dimensional measurement workflows
Resource Management	Allocation and optimisation of measurement resources, allowing for measurement capability.
Verification and Validation	Verification that activities are done right. Validation that the right activities are done. Providing information for decision-making.
Feedback	Enable communication of changes to Design, Manufacturing, and back to Measurement.

4.4. Example: A more stringent tolerance

Imagine a component is in the early stages of detailed design. In order to support a concurrent engineering methodology, measurement plans and programs have been generated, even though the model has not yet been bought off. Now imagine that a review has taken place and the tightest tolerance on the drawing became tighter. What might one expect from a PLM-integrated dimensional measurement solution?

We can work through this scenario by following the dimensional measurement workflow considering the PLM functions of data management, resource management, verification and validation, and feedback. Initial questions may be raised, as shown below and as referenced in Table 2:

1. Can we record the reason for the changed tolerance? [Q1]
2. Will this have an impact of the feasibility of measuring the feature? [Q2]
3. How will this information be fed back so that the measurement strategy can be reviewed? [Q3]
4. Is the currently selected measurement instrument capable? [Q4]

Table 2. Applying PiDM to the case of a more stringent tolerance

	GD&T Assignment	Verification & Process Plan	Measurement Planning
Data Management	[Q1]		
Resource Management			[Q4]
Verification and Validation		[Q2]	
Feedback		[Q3]	

Even though Table 2 only shows three of eight steps described for the dimensional measurement workflow, and none of the interfaces, the framework now prompts additional questions. For example, reflecting on just the GD&T assignment step, one might wish to know the cost of the change on the manufacturing process (a Verification and Validation question), and how this information should be best relayed to design (a Feedback question).

5. Discussion

In this section, the state of the art for PiDM is explored. Following a brief overview of the CMM software and PLM market, each aspect of the framework is discussed in order to identify technology gaps, and highlight key challenges and research priorities.

Although there has recently been considerable consolidation of CMM hardware vendors, much of the associated software is current. In fact, all of the 31 example software packages that Zhao *et al* [28] referred to in an article written in 2009 are still being developed as we write at the start of 2013, even if a few now have different names. This presumably reflects the long life of CMM hardware, the need to continue to support new probing technology, and an entrenched user base.

There are also a plethora of PLM solutions (45 are listed in [32]), however these are dominated by just three large vendors who support mechanical engineering design: Dassault Systemes, Siemens PLM, and PTC [33]. In each case, these organisations are attempting to expand their support for dimensional measurement, whether by opening up interfaces, allying themselves with metrology software vendors, or through acquisition.

5.1. Data Management

In their mission to develop an ontology for the QIF (see Section 4.3), the Dimensional Metrology Systems Consortium (DMSC) are researching data requirements for the entire manufacturing metrology system, and have arrived at the following classification [34]:

- Part geometry and its permitted variation;
- Quality management information, such as feature criticality and traceability;
- Measurement resource availability and capability;
- Measurement rules.

They have found that much of the data required is only available within individual applications; that is to say, there is a gap in the interfaces. For example, a complete semantic representation of GD&T has long been absent from open non-proprietary standards. This is a major obstacle for PLM integration, since other PLM functions need to be built around such data.

5.2. Resource Management

A resource management function within PLM should allow measurement plans to be implemented that make best use of available resources. Most metrology software allows for some kind of probe or machine library that may include data relating to the capability of the equipment, such as the contribution to measurement uncertainty. However, it is known that measurement uncertainty is highly dependent on the task at hand [35]. Although a number of tools have been developed to evaluate task-specific uncertainty when using CMMs, the authors could not identify any software that makes recommendations based on such an evaluation.

5.3. Verification and Validation

One of the purposes of dimensional measurement is to inform decisions about the onward processing of a component - e.g. whether one should progress to the next manufacturing stage, or how a machining operation should be adjusted. Verification and validation of the measurement process itself is therefore critical; however, this can be complex and expensive. For instance, CMM program validation typically involves finding an independent person to create a second program, running both, and then comparing the results. By integrating measurement programming in PLM with other processes like resource management, there may be opportunities to cut down on such duplicated effort – for example, one might validate the process of creating the program, rather than validating the program itself.

Another technology gap is the ability to simulate against non-nominal geometry. Whilst most metrology software will simulate a measurement probe path, these are typically on nominal geometry. Measurement differs from many other manufacturing processes in that the probe is not actively driven to a precise position; rather it records the position at which it detects an object, which may not have been produced to its nominal size.

Finally, determining appropriate measurement rules for a given task is particularly complex on CMMs, not least because measurement rules are dependent on the criticality of a feature [36]. Tools are needed to deal with this, yet there are few available solutions.

5.4. Feedback

Contrasting design with manufacturing, Busby [37] found that feedback in design is difficult since it is often negative and only compelling after a major failure; in manufacturing, Busby argues that feedback is often more positive, or at least reinforcing, and is thus acted upon more frequently. Measurement is more like design in this regard, and we should therefore pay special attention to enabling feedback. This is a particular strength that integration with PLM can bring, and the degree of associativity between measurement, manufacturing, and design models should be the target of further research.

6. Concluding Remarks

The presented PiDM framework is deliberately theoretical since we did not want to be influenced by existing solutions prior to testing against real products. We found gaps relating to the provision of standardised interfaces, the use of uncertainty evaluation, the validation of CMM programs, the simulation of non-nominal geometry, and criticality-based measurement rules. Driven by both the metrology and PLM vendors, increasing levels of automation are now being claimed in some of these areas. Accordingly, further research should be carried out to investigate these claims, and more fully define and populate the PiDM landscape.

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