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# Measurability Characteristics Mapping for Large Volume Metrology Instruments Selection

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*Abstract*—**Measurement and verification of products and processes during the early design is attracting increasing interest from high value manufacturing industries. Measurement planning is deemed as an effective means to facilitate the integration of the metrology activity into a wider range of production processes. However, the literature reveals that there are very few research efforts in this field, especially regarding large volume metrology. This paper presents a novel approach to accomplish instruments selection, the first stage of measurement planning process, by mapping measurability characteristics between specific measurement assignments and instruments.**

## I. Introduction

A recent literature review demonstrated that process modeling contributes significantly in a variety of engineering areas especially in process planning, assembly planning and measurement planning, which are three essential parts of manufacturing planning [1]-[3]. With the help of metrology as an active element of the manufacturing process, enhanced product performance and quality can be achieved [4]. In addition, costs and assembly cycle times are significantly reduced for large and complex assemblies and fabrications with complex surfaces for the aerospace, power generation and automotive industries. Measurement planning in the large volume region is, therefore, attracting considerable research and industrial interest. Measurement instrument selection is the first stage of measurement planning and most research is carried out in relation to coordinate measuring machines (CMMs) using contact or non-contact probes [5], [6]. With the aim of mapping this to large volume metrology, this paper proposes a measurability analysis based approach for selecting the most suitable instrument(s) for multiple tasks by means of measurability characteristics (MCs) mapping.

## II. Measurability Characteristics

Over the last decade, the concept and methodologies of

Quality Characteristics (QCs) have been studied and practiced in many world-class companies, and QCs play a significant role in product lifecycle management (PLM) and in collaborative and global product development [7]. There are different levels of attributes associated with QCs including basic attributes, lifecycle attributes, interrelation attributes and measurement attributes, which are all utilized to perform global planning and resource allocation [8]. In order to apply this planning and optimization approach to specific measurement aims, measurability characteristics (MCs) are proposed which have attributes such as physical capability, accuracy capability, cost and technology readiness level (TRL). Analyzing the attributes of MCs facilitates the classification of measurement aims and measurement instruments by mapping different MCs to the appropriate measurement process.

### A. Physical Capability Attributes

It is imperative to consider the physical capability requirements of a specific measurement assignment, which normally include: measurement volume, material, stiffness and environmental conditions.

Working volumetric coverage varies significantly for different instruments. For example laser trackers have maximum measurement lengths ranging from 6m to 80m for different models, horizontal (azimuth angle) measuring envelopes ranging from ±270° to ±360° and vertical (elevation angle) envelopes ranging from -50° to +80° [9]-[11].

As far as the material properties of the target part are concerned, they may restrict the range of instruments suitable for certain applications. For instance, material with low reflectivity coefficient cannot be measured accurately by instrument employing laser scanning technology. For aluminium or plastics, magnetic targets cannot be applied, which are often used with photogrammetry systems [12]. Occasionally, the stiffness of the measurand is limited resulting in the need to only deploy non-contact systems such as laser radar or laser scanner. Another consideration is the line-of-sight access to the points of measurement and instruments' capability is usually extended by a variety of accessories such as Spherically Mounted Retroreflector (SMR) holders and adaptors for laser trackers which are able to target deep hole, corner and edge.

One issue that should be addressed is that an uncertainty budget describing the uncertainty components is mandatory for any traceable measurement which not only contains the uncertainty of the instrument but also takes into account

other effects that degrade the measurement accuracy e.g. environmental conditions, thermal expansion and SMR errors for laser trackers [13]. Both temperature variations in time and temperature gradients along the measurement volume will affect the suitability and capability of laser-based systems [14], [15]. Other environmental variables, such as humidity and barometric pressure, also have an effect on measurements. The consideration of environmental factors should first eliminate instruments whose operating limits fall outside of the expected environment and should then consider the effect of the environment on capability. Accuracy Capability Attributes

### B. Uncertainty Capability Attributes

Uncertainty capability is vital for any measurement instrument since without knowledge of the uncertainty of the instrument used to take a measurement it is not possible to draw any conclusions about part conformance from those measurements. Further more even where the uncertainty of the measurement instrument is known if it represents a significant proportion of the part tolerance there will be frequent occurrences of measurements where it is not possible to state either conformance or non-conformance.

The uncertainty of a measurement must be added to the lower tolerance band to give a minimum acceptance value. Similarly the uncertainty must be subtracted from the upper tolerance band to give a maximum acceptance value. When the part is measured the reading must be within the range of the acceptance values in order to prove conformance [16]. This range of acceptance values, or residue tolerance, is the tolerance required by the manufacturing process. Most attempts to consider uncertainty only take the uncertainty of measured points into account while integrating multi-instruments for enhanced results in terms of reduced uncertainty and measurement time [6]. An approach for assessing the accuracy against each particular measurement task is absent from the literature. A requirement therefore exists for a measurement uncertainty capability index to ensure the measuring equipment and measurement processes are suitable and capable of achieving product quality objectives. Previous definitions of this parameter are dominated by the measurement results [17]. According to the requirements of measurability analysis, an uncertainty capability index $C_m$ has been defined to indicate the instrument's measurement uncertainty capability before any measurement has been conducted, which establishes the corresponding criteria for the early evaluation of measurement uncertainty in the Large Volume Metrology Process Model [18]:

$$C_m = (USL - LSL)/U = T/U \qquad (1)$$

Where; tolerance interval $T$ is the difference between the upper tolerance limit (*USL*) and the lower tolerance limit (*LSL)* and $U$ is the *k=2* expanded uncertainty associated with the measurement results.

Simple acceptance and rejection using an n:1 rule is the most common form utilized in industry. Recently since engineering tolerances have been reduced significantly, the well-used ten-to-one ratio has been replaced by a new four-to-one ratio rule that requires:

$$C_m = T/U \geq 8 \qquad (2)$$

Other decision rules are applied under certain circumstances where different confidence levels are required such as relax acceptance rule and relax rejection rule.
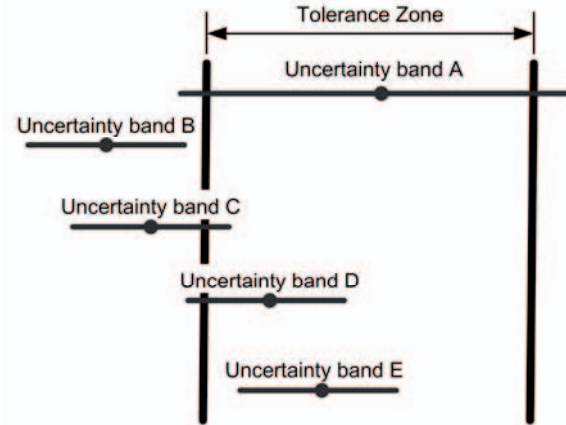


Fig. 1. An example of decision rules for part inspection

### C. Measurement Cost Attributes

As most research on measurement planning is focused on the selection of probes for CMMs or on a limited number of instruments, the measurement-induced cost has not been addressed. However, cost significantly affects the decision of choosing suitable instruments for specific tasks in most situations. Consequently, a total measurement cost $C_{total}$ is required and classified as follows:

*1) Utilization Cost of Specified Measurement System:* Utilization cost can be calculated in terms of the selected measurement system's value and activity depreciation.

$$C_u = (T_m / T_l) \times V_s \qquad (3)$$

Where; $T_l$ (hour) is the life of the selected measurement system and *Tm* is the actual engaged time of the system. $V_s$ (£) is the value of the specific measurement system including all the purchase, upgrade and maintenance charges. Then $C_u$ (£) is the cost in terms of measurement time. This activity depreciation method [19] is based on a level of activity rather than the time due to the characteristics of a large volume measurement system.

*2) Deployment cost:* This cost is caused by the setting-up and deployment of the system in real manufacturing and assembly environments. It can be calculated by estimating the deployment time.

$$C_d = CR_d \times T_d \tag{4}$$

Where; $T_d$ (hours) is the estimated deployment time of the selected measurement system, $CR_d$ (£/hour) is the corresponding cost rate for the specific measurement system. Then $C_d$ (£) is the deployment cost.

*3) Operating cost:* This cost is introduced by real measurement operations. It can be calculated in terms of the measurement time an engineer is engaged.

$$C_o = CR_o \times T_o \tag{5}$$

Where; $T_o$ (hour) is the estimated measurement time of the specific features or assembly, $CR_o$ (£/hour) is the corresponding cost rate for the specific measurement system. Then $C_o$ (£) is the cost of the measurement time.

*D. Technology Readiness Level Attributes*

Technology readiness level (TRL) is deemed to be a vital parameter for measurability analysis, which reveals the maturity of evolving measurement principles and systems that may affect the accuracy, stability and reliability of a system.

Consulting the most common definitions of TRL published by the Department of Defence [20] and the National Aeronautics and Space Administration [21], the TRL for large volume measurement technologies is

TABLE1- TECHNOLOGY READINESS LEVEL IN LVM

| Technology Readiness Level | Description |
|---|---|
| Level 1 Basic measurement principles observed and reported | Lowest level of technology maturity. At this level, scientific research of the measurement principles starts to be translated into applied research and development. |
| Level 2 Measurement system or subsystem model or prototype demonstration | Practical demonstration of the measurement principle using a representative model or prototype system must be carried out in order to demonstrate the fidelity of the measurement technology either in a company or the laboratory. |
| Level 3 Actual system completed and sold in the commercial market | Entire measurement system must be supplied with essential peripherals and support devices as well as adequate operation and control software. |
| Level 4 Actual system qualified by international standard | Verification approach for measurement accuracy capability, stability and reliability must be demonstrated and standardised by a National Measurement international standard. |

composed of four generic levels that classify all measurement principles and instruments shown in Table 1.

An initial coefficient *Cr* is estimated for each measurement instrument and this information is being upgraded continuously according to the rapid technology development nowadays.

*E. Matrix Presentation of MCs*

The relationship between measurement aims and MCs can be presented as a matrix MA-A, as shown in Fig.2. The relations can either be presented as numbers or as symbols. In this paper, uxy is used to denote the relationship between measurement aim MAx and attribute Ay.

Each element is a numerical subjective estimate of the requirement of the measurement aim in the form of attributes of MCs. The ranking scale of each element usually ranges from 1 to 10, with the higher numbers representing the higher requirements with regard to these attributes of MCs.

Accordingly, measurement instruments have standardized MCs, as stated previously. The relationship between measurement systems and attributes of MCs is shown in Fig.3. $v_{yz}$ is used in this paper to present the correlations between measurement instrument $MI_z$ and attribute $A_y$. Each element is a numerical subjective estimate of the capability of a measurement instrument in the form of attributes. The ranking scale of each element usually ranges from 1 to 10, with the higher number representing the higher measurement capability with regards to those attributes.
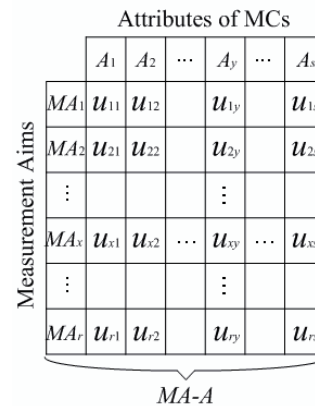


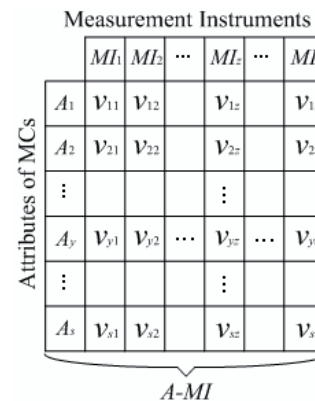Fig. 2. The relation between measurement aims and MCs.



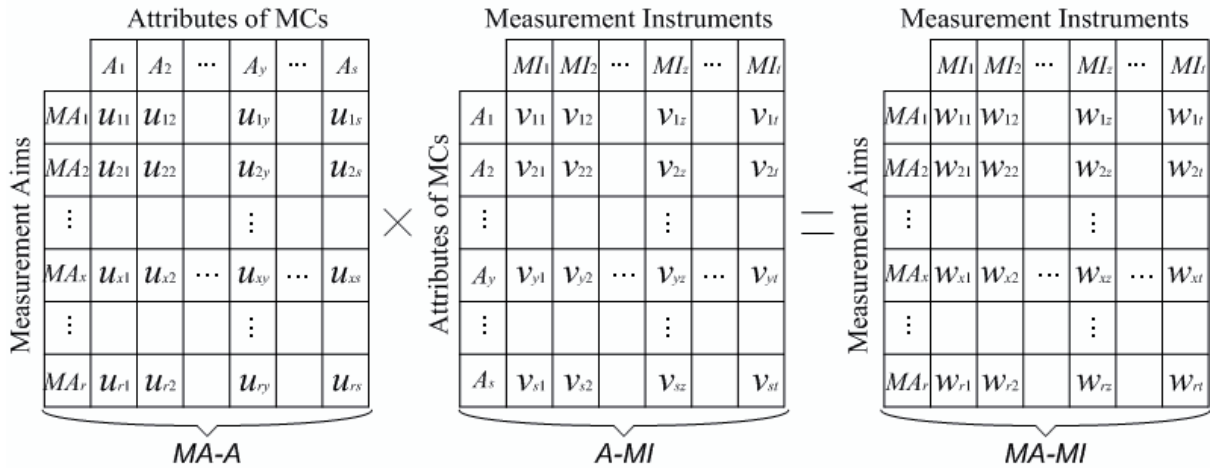Fig. 3. Measurement instruments classification based on MCs.

Fig. 4. Matrix mapping approach for measurement instruments selection.

### III. INSTRUMENTS SELECTION FOR MULTIPLE MEASUREMENT ASSIGNMENTS

#### A. Matrix Matching

Given the attributes of MCs for each measurement assignment, a mathematical mapping approach generates a matrix which matches the measurement aims to the attributes of MCs (MA-A), and another matrix which links the attributes of MCs with the measurement instruments (A-MI). The result is the matching degree matrix (MA-MI) between measurement aims and measurement instruments. Fig.4 illustrates the matrix multiplication process.

As shown in Fig.4, the first matrix (MA-A) is composed of all measurement assignments with required attributes of MCs while the second matrix (A-MI) is composed of vectors $v_{iz}$ that represent capability attributes of all measurement instruments relative to the matrix MA-A.

An element $w_{xz}$ of the result matrix MA-MI can be obtained as follows:

$$w_{xz} = \sum_{i=1}^{s} u_{xi} v_{iz} \tag{6}$$

The element $w_{xz}$ indicates a matching degree of a measurement aim with respect to a certain measurement instrument in terms of a particular associated attribute. A vertical column of matrix SA indicates the requirements of measurement assignments while a horizontal row of matrix MA-MI indicates a vector of matching degrees of measurement instruments with respect to a measurement aim. By adding corresponding weights that vary with the real situation of the measurement assignments to each attribute, the selection result enables the integrated design and manufacturing team to define different values based on the priorities among different attributes of MCs e.g. accuracy, total measurement cost and the reliability of the measurement system.

After arranging the numerical elements of this vector in a descending order, the suitability of each measurement instrument with respect to all measurement assignments is indicated by the appropriate matching degrees.

#### B. Multiple Assignments Optimization

Weighted zero-one goal programming (WZOGP) is a feasible method to optimize the matching process for multiple measurement processes [22] and the general mathematical model is presented as follows.

$$\min \sum_{x=1}^{r} \left( \omega_x \cdot \left( \sum_{z=1}^{t} d_{xz} \cdot \left( 1 - \frac{w_{xz}}{W} \right) \right) \right) \tag{7}$$

wherein:
$$W = \max_{\substack{1 < x < r \\ 1 < z < t}} (w_{xz}),$$

$$d_{xz} = 0 \quad or \quad 1$$

$$\sum_{x=1}^{r} d_{xz} = 1, z = 1, 2, \dots \dots t. \quad and$$

$$\sum_{x=1}^{r} \sum_{z=1}^{t} r_{xz}^{k} \cdot d_{xz} \le R_k, k = 1, 2, \dots m.$$

In (7), $\omega_x$ is the weight of measurement aim $MA_x$ (i =1,2, …, r), $w_{xz}$ is the matching degree between measurement aim $MA_x$ and measurement instrument $MI_z$. $d_{xz}$ is the 0-1 variable, wherein $d_{ij}$ =1 means the measurement operation $MI_j$ ( j =1,2, …, n ) is selected to implement measurement aim $MA_i$. $R_k$ represents the $k$th resource restriction. $r_{xz}^{k}$ is the amount by which resource $R_k$ will be needed when utilizing measurement instrument $MS_z$ to implement measurement aim $MA_x$. The matching between measurement instruments and measurement aims can be obtained by employing WZOGP. Further modification of the planning result can be made by the designers and engineers based on the result of simulation and evaluation.

## IV. CONCLUSION

This paper proposes a measurability analysis based methodology for matching metrology instruments to specific measurement aims. Four elements of measurement characteristics (MCs) have been discussed in detail explaining the means to define and estimate these attributes including physical capability, uncertainty capability, cost and TRL. A matrix mapping approach for measurement instruments selection is outlined together with an optimization algorithm for solving the combination of multiple measurement aims and measurement instruments. However, the optimization process requires more flexibility for different situations such as real shop floor environments. Additionally, more attributes of MCs such as measurement time will be taken into account for the comprehensive selection process in the subsequent stages of the research.

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