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LARGE VOLUME METROLOGY INSTRUMENT SELECTION AND MEASURABILITY ANALYSIS

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ABSTRACT

Metrology processes used in the manufacture of large products include tool setting, product verification and flexible metrology enabled automation. The range of applications and instruments available makes the selection of the appropriate instrument for a given task highly complex. Since metrology is a key manufacturing process it should be considered in the early stages of design. This paper provides an overview of the important selection criteria for typical measurement processes and presents some novel selection strategies. Metrics which can be used to assess measurability are also discussed. A prototype instrument selection and measurability analysis application is presented with discussion of how this can be used as the basis for development of a more sophisticated measurement planning tool.

KEYWORDS

Measurability Analysis, Process Classification, Process Modelling, Large Volume Metrology

1. INTRODUCTION

Metrology is a key manufacturing process. The use of metrology begins with the setting of tools and continues through in-process measurement, metrology enabled automation, product verification and through life monitoring. Consideration of the measurability of product designs should be carried out early in the design stages.

The importance of design for manufacture is well established (Fabricius 1994 ; Maropoulos, Yao et al. 2000) and design for measurability is an important aspect of this. Process modelling has also been shown to contribute significantly to process planning in areas such as tooling technology, welding and in particular at the early stages of design (Maropoulos, Yao et al. 2000 ; Maropoulos, Bramall et al. 2003). Despite the potential value of such a structured consideration of measurement operations there has been little work to integrate metrology process models with design evaluation and assembly planning.

Previous work (Cai, Guo et al. 2008) has laid out a generic framework for measurement planning. The work in this paper details an initial instrument selection software application and details how this prototype software will serve as the basis for further development of more sophisticated measurement planning tool.

There are many competing technologies, each offering specific advantages in certain measurement tasks. Faced with a wide range of different measurement technologies the decision of how best to measure a product becomes complex as does the assessment of the measurability of a new design.

The two main tasks which require the support of process modelling techniques are product design, where an early assessment of measurability is required, and process planning where a more structured approach will allow processes to be optimized. In both cases the purpose of measurement must be specified in unambiguous and quantifiable criteria. Different measurement systems can then be assessed to determine their suitability and some selection then made.

The designer seeks to optimize the design to improve measurability, the process planner to optimize the measurement process its-self. A simple approach is to relate each measurement instrument's performance to the measurement process specification in order to generate a simple pass or fail condition. This approach, using a database filter, is the basis for the prototype software described in this paper. It is also shown that a measurability index can be easily included.

The operation of this software has three stages; specifying the measurement process requirements, modelling measurement processes and assessing the suitability of the processes for carrying out the measurement. These are discussed in turn.

2. SPECIFYING THE MEASUREMENT PROCESS REQUIREMENTS

Metrology systems may be deployed for product verification, tool setting, tracking parts into assembly positions or guiding automation systems. The same generic specification variables can be used to define the measurement process regardless of the application:-

- The dimensions of the measurements
- Physical access and visibility
- The tolerance to be verified or the level of uncertainty required
- The number of individual measurements required and the time available to take the measurements
- The environmental conditions under which the measurements are to take place
- The interface with the part; contact, non-contact, fixed targets etc.
- The degrees of freedom; distance, position, orientation.
- Portability of the instrument
- Cost
- Technology Readiness Level

The less obvious of these specification variables will now be considered in turn.

2.1.

2.1. PHYSICAL ACCESS AND VISIBILITY

With traditional mechanical measurement devices such as micrometers and height gauges physical access to the part is a clear necessity. With optical instruments the requirement is for unobstructed line-of-sight along which rays of light may propagate. There are also many other less common possibilities such as magnetic flux, x-rays, ultrasound etc which are able to propagate though solids. The measurement process requirements are specified using a three-dimensional solid model of the part and any surrounding tooling.

2.2. MEASUREMENT UNCERTAINTY AND PART TOLERANCES

Measurement uncertainty is a key performance indicator for any measurement instrument. The level of uncertainty will determine whether it can be proven that a part conforms to specifications. Additionally the uncertainty of measurements will affect the cost of forming operations and product rejection rates.

If the tolerance for a part gives a minimum and a maximum value then when the part is measured using a given instrument, allowance must be made for that instrument's uncertainty. The uncertainty of the measurement is added to the minimum value to give a minimum acceptance value. Similarly the uncertainty is subtracted from the maximum value 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 say that the part is within the tolerance. This range of acceptance values, or residue tolerance, is the tolerance required by the manufacturing process (BSI 1999).

The measurement process requirements should be specified in terms of the tolerance which must be achieved. For product verification applications the conformance conditions discussed above will be directly relevant. For metrology enabled automation the relationship between the process capability and the uncertainty of the guiding metrology system will be related in a similar way.

2.3. THE NUMBER OF MEASUREMENTS REQUIRED AND TIME AVAILABLE

Simple lengths are typically measured by locating two points while characterization of surfaces will require the measurement of a large number of discrete points.

The measurement frequency published by manufacturers, is often misleading since many instruments are capable of high frequencies but a single measurement has a low accuracy due to environmental disturbances such as vibration and turbulence. Closely related to frequency is concurrency; whether the instrument measures multiple points sequentially or concurrently. Many instruments will measure each point in sequence but multi-sensor networks may be able to measure points at multiple sensors concurrently and those based on photographic techniques will be able to image a large number of points concurrently, limited by pixel count and target size.

In specifying the measurement process requirements we must state the number of individual measurements required and the total time available to make these measurements.

2.4. ENVIRONMENTAL CONDITIONS OF MEASUREMENT

Specification of the environmental conditions in which the measurement is to be carried out should include the average temperature, temperature gradients, pressure, humidity and carbon dioxide content.

2.5. INTERFACE WITH PART

Due to physical access or health and safety constraints it may be necessary to specify that non-contact measurements should be made. It is likely that non-contact measurements will also be faster as on operator is not required to position targets. The measurement process should however not be constrained to non-contact measurement on the basis of speed since proper modelling of the measurement time is the correct way to make unbiased decisions based on process time.

2.6. DEGREES OF FREEDOM

The simple one-dimensional distance between two hole centres may be sufficient or there might be a requirement for the three-dimensional coordinates of each point. ‘Informational richness’ could be used to describe the degrees of freedom in addition to shape recognition capabilities. In actual fact shape recognition capabilities are the combined effect of the degrees of freedom, the point acquisition rate and additional software algorithms. Informational richness can therefore be represented by the degrees of freedom together with the number of individual point measurements required to adequately characterize a feature.

Six degree of freedom (6 DOF) systems are able to measure both the coordinates and the rotation of a sensor or target; these systems are particularly useful for providing feedback to automation.

3. MODELING MEASUREMENT PROCESSES

Process modelling first requires that metrology instruments and processes are classified into generic types which can be understood using common models.

Various classifications of metrology instruments are possible such as flat hierarchic structures (Huntley 2000; Maisano, Jamshidi et al. 2008; Maisano, Jamshidi et al. 2009). The classification of metrology instruments is complex and a simple flat hierarchy cannot fully characterize a group of instruments. Furthermore many instruments can operate in more than one mode and therefore fit into multiple categories for a particular property making such a classification potentially misleading. An interesting Venn diagram of the fundamental technologies used by different area scanning instruments with some illustration of the relative advantages is presented by Mermelstein (Mermelstein, Feldkhun et al. 2000). Although this approach is informative it also does not fully capture all the possible considerations that may be important in selecting an instrument for a given task.

The most important initial level of classification, with respect to modelling instrument performance, is between distributed systems and centralized systems. Distributed systems combine measurements from multiple instruments and therefore any model of a distributed system first requires an understanding of the component instruments.

A complete classification of individual instruments has not been attempted in this work but some generic instrument types which are of particular interest have been identified and are discussed in relation to specific properties. Some generic models for distributed networks are also discussed. The rational for the partial classification presented can serve as the basis for more rigorous classification in future work.

3.1. MODELLING ACCESS AND VISIBILITY

The software application presented in this paper does not allow the automatic checking of physical access and line-of-sight visibility. Checks can be carried out relatively easily using three dimensional computer aided design (3D CAD) software. A model of the measurement instrument, complete with extruded cylinders to represent any lines-of-sight, can be assembled with the product and checks for measurability thus carried out using a similar process to that normally applied to checks for assembly accessibility. It can be envisaged that a more sophisticated measurement planning tool might include such facilities. In fact the Spatial Analyzer (New River Kinematics 2007) product does include some of these features, to a limited extent, despite lacking many of the other features discussed in this work.

3.2. MODELLING UNCERTAINTY

Process models are required which describe the uncertainty of different metrology systems as a function of the measurement process specification variables. Much work has already been carried out in this area (Peggs, Maropoulos et al. 2009). The uncertainties associated with optical disturbances due to environmental factors are described by models created for laser-lased spherical coordinate measurement systems, such as laser trackers and laser radar (ASME 2006). These models can be applied to any optical instrument if the refractive index is calculated for the environmental conditions and the wavelength of light used by the instrument (Ciddor 1996 ; Stone and Zimmerman 2000).

A simple process model for the range dependent uncertainty of laser-based spherical coordinate measurement systems is described in the ASME standard for these instruments (ASME 2006), this is summarized below.

$$U_r = A + B \cdot r \qquad (1)$$

$$U_a = C + D \cdot r \qquad (1)$$

Equation (1) gives the uncertainty for measurements in the radial direction from the laser tracker where *r* is the radial distance at which the measurement is taken. Equation (2) gives the uncertainty for measurements in the tangential direction. *A, B, C* and *D* are constants which characterize the uncertainty of a given laser tracker.

Pin-hole camera models (Brown 1971), which are a well established method of modelling the uncertainty of the individual cameras used in photogrammetry systems, are unnecessarily complex for the purposes of this work. A simple model for individual cameras using equations of the form of equation (2) would be more appropriate. This simplified approach to specifying uncertainty as a function of range is used by manufacturers (Geodetic Systems 2005).

Coordinate measurements may be calculated from a number of angular measurements obtained using cameras, theodolites, iGPS (Muelaner, Wang et al. 2008) etc. The uncertainty of measurements made by such a network can be determined using bundle adjustment algorithms (Triggs, Mclauchlan et al. 1999). Similar techniques have also been used to estimate the uncertainty of coordinate measurements made by combining measurements of range; a technique known as multilateration (Cox, Forbes et al. 2003).

The Monte Carlo method also provides a general technique which can be used to propagate the uncertainties of multiple instruments through to coordinate measurements made by the network as a whole (Calkins 2002). This technique is useful as it can readily be applied to virtually any instrument model, although it is somewhat computationally intensive.

3.3. MODELLING MEASUREMENT TIME

The process specification will state the number of individual measurements required. It is then necessary to calculate the total time which each metrology system will require to carry out this task. This may be stated as the composite time (T_P) required to take a number of measurements using a given system. In order to define this performance characteristic as a function of the measurement process specification it is necessary to define a number of variables.

The actual number of points which can potentially be measured concurrently (N_a) must be specified as part of the measurement process specification. The other variables are all performance characteristics of the instrument configuration. Examples of N_a include the number of points to be measured on a part before it is moved to a different position or the number of points to be measured from one view point before the instrument is moved to a different position. The number of points the instrument is able to measure concurrently is denoted by N_I.

The typical time required to take a single measurement (t_m) is generally not simply the reciprocal of the measurement frequency but rather includes the whole measurement process; positioning the target and taking repeated measurements for averaging etc. For example, a Laser Tracker requires time for the instrument to actually measure and for the operator to move the SMR to the next nest, for sequential multi-lateration this time is multiplied by the number of station positions. For a Laser Scanner t_m will simply be the reciprocal of the instruments' measurement frequency.

The positioning time (t_P) is the setup time required each time either the part or the instrument is moved. For example when using sequential multi-lateration, where the part is measured using a single instrument from multiple view point stations, this will be the total time for all the station moves.

Equation (1) defines the composite time (T_P) in terms of the variables defined above. It is important to note that this is an approximation making the assumption that N_a is a multiple of N_I for the case where $N_a > N_I$. It never-the-less provides a useful way to compare instruments as has been demonstrated through case study based use of the prototype system.

$$\begin{aligned} &\text{if} \quad N_a \le N_I \\ &T_P = t_m + t_P \\ &\text{if} \quad N_a > N_I \qquad (1) \\ &T_P = \frac{t_m \cdot N_a}{N_I} + t_P \end{aligned}$$

This process model is entirely generic and does not require any process classification.

3.4. ENVIRONMENTAL CONDITIONS FOR OPERATION OF INSTRUMENTS

There are two aspects to consider concerning the environmental conditions. Firstly, is the instrument able to function within the operating environment, and secondly, what effect will the environmental conditions have on the performance of the instrument? In particular, how will temperature gradients affect the measurement uncertainty?

Process models which describe the uncertainties associated with optical disturbances due to environmental factors are covered in section 0.

The operational limits for instruments should be specified as simple maximum and minimum conditions for properties such as temperature, pressure and humidity. The decision as to whether the instrument specification is within the operating conditions should then be based on the average temperature specified, the product of the temperature gradient and the maximum range, and an additional safety margin should also be added.

3.5. INTERFACE WITH PART

Whether a particular instrument makes contact with the part can be described as a simple Yes/No condition.

3.6. DEGREES OF FREEDOM

Provided that the assumption made in section 0, that a 1 DOF instrument measures length etc, then the degrees of freedom of an instrument can be given a simple numerical value. This will allow a straightforward filtering for instruments with at least the required degrees of freedom.

3.7. PORTABILITY OF THE INSTRUMENT

Two performance characteristics can be used to describe the portability of an instrument; the packed volume and the set-up time.

3.8. MODELLING MEASUREMENT COST

The simplest approach to modelling the cost associated with measurement operations is to ignore the impact which measurement uncertainty has on part rejection and other process requirements. The cost of the measurement can then be considered to derive from the capital costs of the measurement equipment, the utilization rate of the equipment and the labour costs of carrying out the measurement as described by Cai (Cai, Guo et al. 2008) and summarized below. The total measurement cost which is directly attributable to the measurement activity (C_c) is then given by

$$C_c = C_U + C_d + C_O \tag{2}$$

where C_U is the utilization cost, C_d is the deployment cost and C_O is the operating cost.

The utilization cost is related to the depreciation cost of the instrumentation, based on the activity depreciation method (Wikipedia 2008), and is given by

$$C_U = \frac{T_m}{T_l} V_s \tag{3}$$

where T_m is the time for which the instrumentation is occupied by the operation, T_l is the expected life of the instrument and V_s is the total value of the instrumentation.

The deployment cost is the labour related cost of instrument set-up given by

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

where CR_d is the cost per unit time for labour related deployment costs and T_d is the estimated deployment time for the selected measurement system.

The operating cost is the labour related cost of operating the instrument given by

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

where CR_o is the cost per unit time for labour related operating costs and T_o is the time required to carry out measurement.

The simplified cost model described above ignores the affect of measurement uncertainty on part rejection rates and on the accuracy requirements for other processes.

The cost of part rejection due to measurement uncertainty can be calculated given the following variables which are illustrated in Figure 1:-

The cost of the component	(C)
The component tolerance being measured	(T)
The measurement uncertainty	(U)
The manufacturing uncertainty (does the required tolerance represent +/- 2 or 3 sigma)	(M)

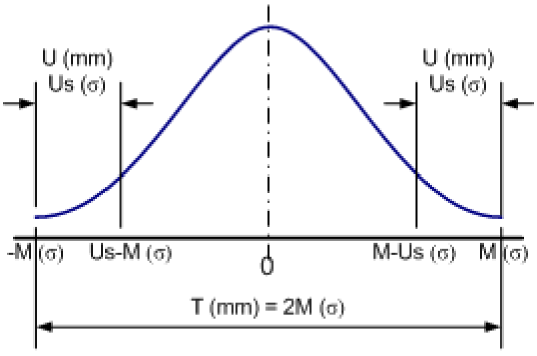


Figure 1 : Part Rejection due to Measurement Uncertainty

The component tolerance and the measurement uncertainty both have units of length. The measurement uncertainty can be converted into standard deviations of the part by:-

$$Us = \frac{U}{T} 2M \qquad (6)$$

We can then say that the percentage of parts, which are within tolerance, and that are rejected due to measurement uncertainty (R) is given by equation (7) which uses Microsoft Excel syntax.

R=2*(NORMSDIST(M+Us)-NORMSDIST(M)) (7)

The cost of this rejection is then simply R*C per part. This model assumes that a strict conformance condition is applied (BSI 1999) and that the process is under statistical control.

In order to achieve a reasonable rejection rate with a given level of measurement uncertainty it may be necessary to improve the accuracy of the manufacturing process. This will also have an associated cost which will be highly dependent of the manufacturing processes used. The consideration of these costs would require a holistic approach to process planning which is beyond the scope of this paper.

4. INSTRUMENT SELECTION AND MEASURABILITY ANALYSIS

Instrument selection, measurability analysis and measurement process planning should be carried out numerous times as a product progresses from concept though to the design of the manufacturing process. This is required since the initial assessment of the measurability of concept designs will necessarily be carried out using incomplete information. For example the lines of sight available to measure a product will depend on the exact design of jigs and tooling which will not be decided until relatively late in the design of the production process.

A number of possible strategies for instrument selection and measurability analysis have been identified and these are discussed below.

4.1. INSTRUMENT SELECTION BY DATA FILTERING

A pragmatic approach which has already been applied to the selection of instruments for industrial processes involves a database containing two tables. The first table is used to specify certain aspects of the measurement process requirements and the second to store the performance characteristics of the instrument configurations. The performance characteristics in the second table may be dynamically generated as functions of the variables in the first table. The remaining aspects of the measurement process specification not specified in the first table are then stated as database queries, such as filters and sorts, applied to the second table.

This approach allows the efficient selection of instruments and multiple instrument networks with minimal development costs. A similar approach, described by Cuypers (Cuypers, Gestel et al. 2008), involves specifying the task requirements, environment restrictions and part restrictions before selecting instruments manually. The creation of databases and the use of data filtering to aid selection is a logical progression of these ideas.

The measurement process definition table details the range and distance between points to be measured, the number of points on the part and the temperature gradients present in the working volume.

The instrument specification table has three classes; instrument type, instrument and configuration. Each instrument type can have multiple instruments and each instrument can have multiple configurations. Each configuration has a number of performance characteristics such as measurement uncertainty and measurement time which may be defined as functions of the measurement process specification variables.

This database approach, detailed fully in the appendices, allows the measurement process requirements to be first specified and then for appropriate instruments to be selected using standard data filtering techniques.

4.2. INDEX BASED ASSESSMENT

A straightforward extension of the data filtering and sorting application discussed above is the addition of capability index calculation. The capability indices can be added to the instrument specification table as performance characteristics defined, for each instrument configuration, as a function of the measurement process specification variables and/or other performance characteristics of the instrument configuration. When the operator is filtering and sorting to select instruments it then becomes possible to filter for instruments which have a particular range of values of a given capability index or to sort to find the instrument with the best value.

The use of capability indices also facilitates the use of automated data filtering. For example a traditional ‘rule of thumb’ has been that a measurement system should have an accuracy (or uncertainty in modern terms) ten times less than the tolerance of the dimension being measured. Due to significantly reduced tolerances this rule is often now relaxed to four times (Department of Defence 1988). An automatic filter could remove all instruments which do not meet this condition. This measurement accuracy capability index (Cai, Guo et al. 2008) (C_m) is defined as

$$C_m = \frac{T}{U} \qquad (8)$$

where T is the tolerance of the dimension being measured and U is the expanded uncertainty of the measurement instrument.

This measurement accuracy capability index can be converted to a dimensionless comparative value. For the *ith* measurement system in a database which contains n measurement systems, the dimensionless measurement accuracy capability index is given by

$$C'_{mi} = C_{mi} \Big/ \sum_{i=1}^{n} C_{mi} \qquad (9)$$

Similarly the measurement cost and the technology readiness level can be converted to dimensionless indices. The dimensionless cost index is given by

$$C'_{ci} = C_{ci} \Big/ \sum_{i=1}^{n} C_{ci} \qquad (10)$$

where C_{ci} is the cost for the *ith* measurement system calculated using equation (2).

The dimensionless technology readiness index is given by

$$C'_{ri} = C_{ri} \Big/ \sum_{i=1}^{n} C_{ri} \qquad (11)$$

where the technology readiness index C_r is simply equal to the integer value of the technology readiness level.

The calculation of these dimensionless indices should be carried out after data filtering. This will ensure that the comparison is between only those instruments which are able to meet the basic requirements such as having access to the measurement and being able to operate within the specified environment.

Cai et al(Cai, Guo et al. 2008) have proposed that these dimensionless capability indices can be combined to give an overall measurement capability index using equation (12).

$$I_i = w_1 C'_{mi} + w_2 C'_{ci} + w_3 C'_{ri} \qquad (12)$$

where w_1, w_2 and w_3 are weights corresponding to each individual capability index.

Considering equation (12), C_m is the ratio of measurement uncertainty to the part tolerance and as such larger values are preferable, C_c is an estimation of the cost of the measurements and so smaller values are preferable, and C_r is a the technology readiness level with larger values preferred. Therefore w_1 and w_3 will take positive values while w_2 will take a negative value.

An alternative form for the combined capability index might be

$$I_i = e^{w_1} C'_{mi} - e^{w_2} C'_{ci} + e^{w_3} C'_{ri} \qquad (13)$$

Further work should investigate the optimum method of combining the capability indices. Feedback to the user may be a simple numerical readout or preferably a graduated Red - Amber – Green colouring could be used to vividly represent the suitability of each measurement system.

The inclusion of the measurement accuracy capability index, reflecting the measurement uncertainty, is largely required because the simplified cost term does not reflect the cost of measurement uncertainty. In a fully developed solution it may be possible to accurately model the full cost implications of measurement uncertainty. At that stage it may no longer be deemed necessary to include a separate term reflecting uncertainty or alternatively that term may assume a greatly reduced weighting.

5. PROTOTYPE SOFTWARE

The prototype software has been created using a database management system (DBMS) and consists of two tables; a measurement process specification table and an instrument performance table. These tables are detailed in the appendices. An overview of the flow of information within the prototype software application is given in Figure 2.

The measurement process specification table contains the user inputs which specify the process requirements and are used as variables by the instrument process models. This table has a single record and each field therefore occurs only once.

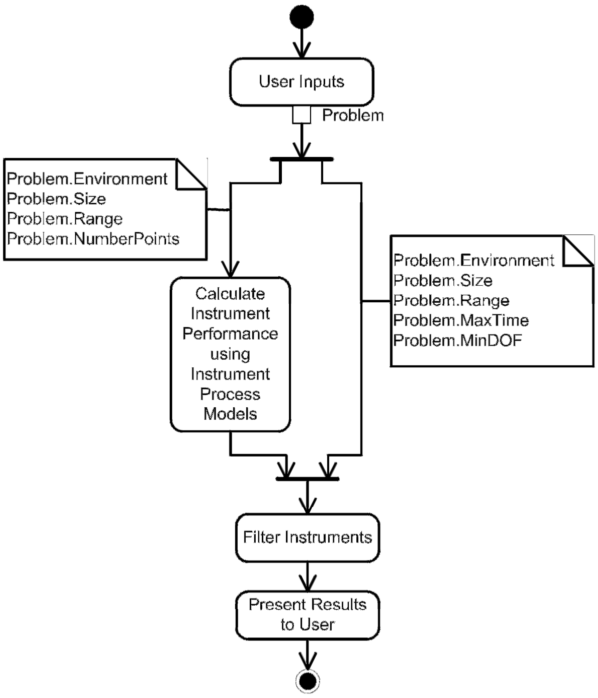


Figure 2: UML Activity Diagram of Instrument Selection and Measurability Analysis Software Function

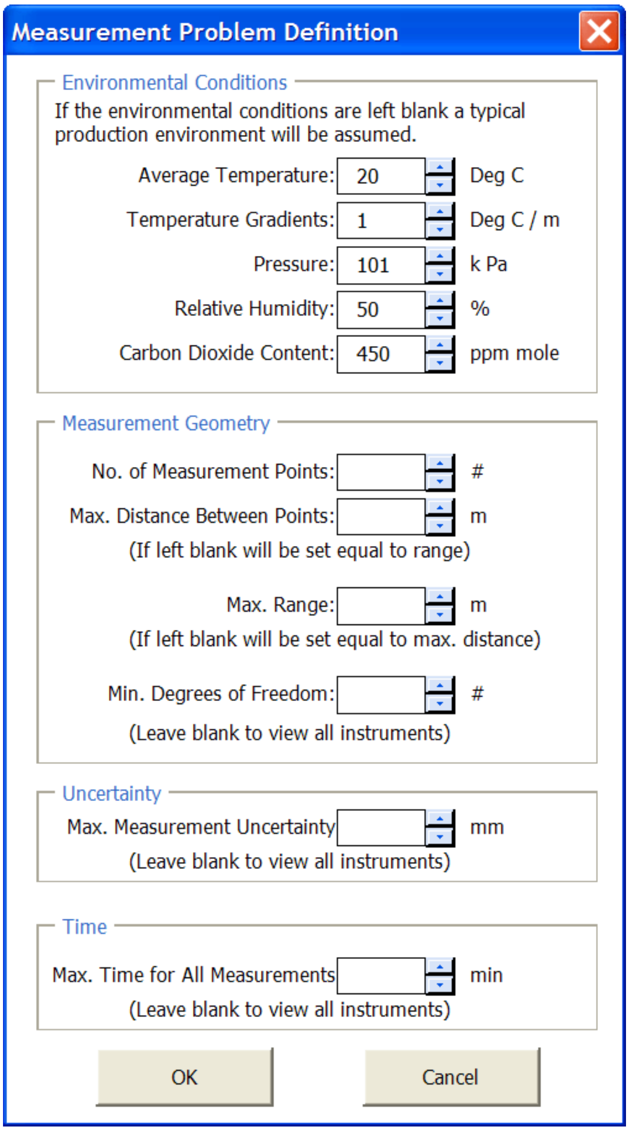
In the instrument properties table there is a record for each instrument configuration. For example a laser tracker may be used as a one-dimensional range measurement device, as a centralized three-dimensional coordinate measurement machine or as a distributed network of, for example, four laser trackers forming a three-dimensional coordinate measurement machine etc. Each of these configurations has a separate record in the database. Many of the values in the instrument table are dynamically generated using variables stored in the measurement process specification table.

The process specification table does not contain all of the variables defining the measurement process requirements. Instead the process specification table contains only those variables which are used to generate the instrument performance characteristics stored in the instrument database. The final process specification variables used to filter and sort the data contained in the instrument table are input directly as filter and sort constraints using the database management system's default interface.

6. CONCLUSION

A comprehensive measurement planning methodology has been specified. Existing process models have been combined with newly created process models and a prototype instrument selection and measurability analysis application has been created.

The current prototype application uses generic database filters to specify the measurement process requirements which may be confusing for some users. A more refined solution would be to input the entire user input using a dialogue box interface such as the one illustrated in Figure 3. Although it appears from the image that this work has been completed in reality the creation of the graphical user interface is relatively strait forward. The challenges in implementing this approach will include incorporating the database queries required to filter and sort the instrument database. Additionally maintaining the flexibility of a filtering and sorting will be a particular challenge.



Measurement Problem Definition

Environmental Conditions

If the environmental conditions are left blank a typical production environment will be assumed.

Average Temperature: 20 Deg C

Temperature Gradients: 1 Deg C / m

Pressure: 101 k Pa

Relative Humidity: 50 %

Carbon Dioxide Content: 450 ppm mole

Measurement Geometry

No. of Measurement Points: #

Max. Distance Between Points: m

(If left blank will be set equal to range)

Max. Range: m

(If left blank will be set equal to max. distance)

Min. Degrees of Freedom: #

(Leave blank to view all instruments)

Uncertainty

Max. Measurement Uncertainty mm

(Leave blank to view all instruments)

Time

Max. Time for All Measurements min

(Leave blank to view all instruments)

Figure 3: Example of User Input Form

The aspects of the process which cannot be easily modelled within this database approach are the aspects where process models are least developed. Specifically the modelling of access and visibility will require significant work to develop models within a three-dimensional environment. Once these models are developed it will be possible to integrate them into the database orientated application.

Integration with a measurement network simulation algorithm, whether based on a Monte Carlo approach (Calkins 2002), on Finite Difference (Boudjemaa, Cox et al. 2003) or some other method, could be used to quantify the performance of actual instruments in the particular measurement process. Such networks could be optimized based on constraints such as line of sight or the physical location of the instrument.

In summary there are three phases of development required to fully realise the potential of this software. The first phase is to streamline the user interface and rationalize the process models used while maintaining essentially the same functionality as the prototype system. The second stage of development, which is likely to prove considerably more challenging, is to develop new process models for access and visibility. This second stage will require integration with a three-dimensional digital environment such as CATIA/DELMIA. Additional tasks, which may be completed at either of these stages, are the integration of process models describing the combined uncertainty for distributed measurement networks and more detailed cost models.

The third and final stage in the development of the measurement planning software is to incorporate optimization algorithms. This could allow networks of instruments to be automatically created and positioned within a production tooling environment. Constraints to this optimization would include the user specified inputs and the physical access and visibility constraints defined by the three-dimensional solid model. Optimization of multiple requirements such as uncertainty and cost minimization may be carried out using the measurability index as an objective function.

Use of the system to solve real industrial problems should occur at each stage in the development to ensure the application remains relevant to the end users.

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