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THE IMPLEMENTATION OF UNCERTAINTY EVALUATION MODEL IN MANUFACTURABILITY ANALYSIS SYSTEM FOR MINIATURE MACHINE TOOL

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ABSTRACT

The development of Manufacturability Analysis System for micro-machining domain (MicroMAS) is intended to address the need of the 4-axis Miniature Machine Tool (MMT) that require such system to assist the user in generating micro-component through manufacturability evaluation. One of the manufacturability aspects being assessed is the impacts from Uncertainty Evaluation Model (UEM) analysis that analyse the influence of the errors stemmed from the MMT construction on the geometrical accuracy of the machined micro-parts. The model has allowed a methodology for the errors in a custom-made MMT to be predicted and to further understand the origin of the errors on the machined micro-part. This paper reports on the implementation of UEM in the development of MicroMAS. Therefore, the results from uncertainty evaluation towards the MMT were integrated in the database which are interactively searched based on IF-THEN clauses in order to determine which rules satisfy the requirements expressed via inputs.

Keywords: manufacturability analysis system, uncertainty evaluation model, miniature machine tool.

1 INTRODUCTION

Manufacturability analysis systems (MASs) have been developed to enable the evaluation of easy to manufacture parts during the design stage, enabling the reduction of costs and time to market of the designed products. It is envisaged that MASs could enable the analysis of both manufacturability and functionality aspects such as dimensions/tolerances, surface finish, machining strategies related to material properties and part geometrical specifications; all considered at the early stages of product development with direct implications on the reduction of lead times of the product to the market (Bothroyd et al. 1994, Rao et al. 1999, Shukor et al. 2009).

MASs have been shown to be useful for macro-manufacturing processes but less attention or effort has been put for their development in the scope of micro-manufacturing (Shukor et al. 2009). In-house developed multi-axis Miniature Machine Tools (MMTs) are now becoming more popular with the demand for reduced energy consumption and workshop floor when machining small/medium batch size micro-components. As an example in watch manufacturing, due to the size of the miniature machines used, the amount of energy consumption may be reduced to approximately 30% of the conventional factory by the half-miniaturization of the production systems (Kawahara et al. 1997). The development of an in-house 4-axis MMT by the MCM Research Group at the University of Nottingham (Axinte et al. 2009) triggers a requirement for a system that can assist the user in generating micro-component using this custom-made machine. The development of MicroMAS for a custom-made 4-axis miniature machine tool (MMT) where various aspects (e.g. materials used, acceptable and suitable tolerances and dimensions) can be assessed to allow the design being compatible with the production needs that leads to improved quality of machined micro-product. In this study, MicroMAS can be defined as a system that assists the MMT user in generating micro-part based on the manufacturability analysis of a CAD model. The manufacturability aspects being considered are dimensions, tolerances, tool size, surface roughness, features interactions, impact of uncertainty in machining the recognized primitive feature and material. At the same time, it also can boost the confidence in applicability of Micro-Engineering Technologies (MET) processes such as micro-milling, micro-drilling in producing micro-component.

Although MET is adapted from conventional macro-processes, the differences generated due to 'size effect' has made it emerge as a new process which give strong grounds why MAS specifically for micro-domain is needed. This is somehow in line with the call for a system that can assist users in generating micro-component using this MMT with better judgement.

Based on this ground, it is a meaningful effort to develop MicroMAS with the MMT as its domain of application for the manufacturability aspects of the micro-parts to be evaluated. Moreover, as there are no guidelines, standards or manuals to refer to in operating the MMT, the need to evaluate its functional characteristics such as uncertainties related to the MMT construction is imperative. In this context, there is a clear need to understand the influence of the errors stemming from the MMT construction on the geometrical accuracy of the machined micropart.

In this paper, the development of the UEM was considered to analyse the influence of the occurred errors in constructing the MMT on the geometrical accuracy of the machined micro-parts. Furthermore, it also allowed on understanding of how these errors are transferred into kinematic (tool path generation) flaws. However, the errors occurring/generated during machining (e.g. tool deflections, tool wear, vibrations) are not considered in this study. Besides developing a model/method that can predict errors of a (custom-made) machine tool, the results from this analysis is proposed to be integrated into the MicroMAS. The integration can portray the real condition of the MMT in the developed MicroMAS. For this reason, the effect of flaws in the MMT construction is taken into consideration in determining the MIs.

2 UNCERTAINTY EVALUATION ANALYSIS

Uncertainty of measurement (UEM) is defined by VIM (1993) as a parameter associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand. There are various procedures and concepts of uncertainty evaluation were proposed and discussed, but in 1993 the publication of Guide to the Expression of Uncertainty in Measurement (GUM) (Ridler et al. 2007) offered a unified method for the evaluation and expression of measurement uncertainties that has been accepted by almost all calibration services worldwide and has become a standard in the field of metrology (von Martens 2002, Kessel 2002). The basic approach of GUM is to describe a measurement using a model in the form of functional relationship between input and output quantities (Ridler et al. 2007). The input quantities are defined as the aspect that actually determined during measurement process while output quantities describe the result of the measurement.

UEM has been developed to understand the influence of the errors in constructing the MMT on the geometrical accuracy of the machined micro-parts. In any micro-machining domain, there are many aspects (e.g. machining parameters, machine tool characteristics, materials, and tooling) to be taken into consideration, which might not be important in the macro-machining area. Therefore, it is important to analyse any errors related to the construction of the MMT; these errors might not be of high importance in the case of using a conventional macro-machine tool but in this case it can significantly affect the quality of the machined micro-parts. The results from this analysis are proposed to be integrated into the MicroMAS. The integration can portray the real condition of the MMT in the developed MicroMAS. For this reason, the effect of flaws in the construction is taken into consideration in determining the Manufacturability Indexes (MIs) which is the major output of MicroMAS. MIs reflect the relative ease of machining of the component based on associated ratings of various aspects such as PF characteristics, surface roughness, tool dimension, tolerances, machinability of selected materials and also uncertainty effect in machining the micro-feature using the custom-made 4-axis MMT.

The analysis of the UEM is carried out in GUM Workbench which is a software tool for evaluation of uncertainties in measurements. Basically, the approach taken to develop the UEM is divided into three main phases: model development, model analysis and finally simulation and validation which are based on the ISO GUM (GUM 1993, Choi et al. 2003).

From the analysis, four sources of main errors have been identified which are: errors due to the MMT construction; errors related to evaluation of workpiece reference point; errors related to temperature variations and errors originating from positioning inaccuracies of each table. In order to evaluate the uncertainties stemming from the identified errors, the uncertainty model/equations are generated based on the spiral milling tool path in machining a cylinder. The model and methodology developed in analysing the errors above provide a proof that uncertainty analysis is able to understand the sources of errors from a custom-made machine tool that affect the quality of the final machined part. Moreover, once this model/methodology is developed, the geometrical errors can be evaluated in any situation when other (more) complex surfaces are generated.

Furthermore, in order for the developed MicroMAS to mirror the real condition of the MMT in the system, the impact of UEM analysis is taken into consideration for calculating the Manufacturability Index for Single Feature Analysis (MI_{SFA}). The Manufacturability Index for Uncertainty Evaluation Model (MI_{UEM}) is introduced and being considered in the MI_{SFA} formula for each identified primitive feature (PF). With this scheme, the manufacturability analysis in MicroMAS is more significant as it consider the uncertainty effect in machining the shape/form of the PF.

3 MICRO-MANUFACTURABILITY ANALYSIS SYSTEM

The development of the system is based on the three-step unidirectional which was divided into three modules/components: i) data input module; ii) manufacturability assessment module; iii) output generation module. The data **input module** is where all the relevant and related data were feed into the system. In this study two approaches were selected and combined which were *the user-system interaction* and *collection of related manufacturing information*. In the *user-system interaction* method the system prompts user with enquiry leading towards the collection of related information. While for the second method, the users are allowed to choose related data and parameters from the manufacturing information in the system's database.

The *Ruled-Based System (RBS)* was implemented to assist the decision making in the **manufacturability assessment** through the IF-THEN clauses. It helps to control the analysis of MicroMAS and represents the systems' knowledge base via logical combinations. RBS has been applied in manufacturing based inference engines because the IF-THEN rules are similar to common sense logic (Kusiak et al. 1988). Moreover, the concept of RBS and IF-THEN clauses can be implemented in any programming language or software packages including VB. In this study, the related rules and conditions correlated to micro-milling and primitive features elements are saved in the form of IF-THEN clauses. All the rules and conditions stored in database are interactively being searched based on IF-THEN clauses in order to determine which rules satisfy the inputs.

Finally in the third module which is the **output generation**, it provides the outputs from the manufacturability assessment such as redesign suggestion, overall MI and selection of materials. This result was displayed in various type of interface (e.g. pop-up window, reports, forms) generated using VB. The database is the medium where all the data and information needed for the analysis is stored; it was developed using Microsoft Access (MS ACCESS) and linked to the VB. Figure 2 illustrated the relationship between the software (VB.NET, MS ACCESS, GUM Workbench) and machining experiments. All related manufacturing information and rules are embedded in the database to be used as guide for assessing the manufacturability of the proposed design.

4 IMPLEMENTING UEM IN MICRO-MAS

In order to enhance the capacity of MicroMAS in assessing manufacturability aspects, the results from uncertainty evaluation towards the MMT will be integrated in the system's database. This is to fully understand the capabilities of the MMT which is the main scope of the developed MicroMAS. This analysis provides the opportunity to partly portray the real condition of the MMT in the developed MicroMAS. For this purpose, it is proposed to integrate the results from the UEM analysis in the MicroMAS by taking into consideration the uncertainty effect in machining the particular form/shape of PF in calculating the manufacturability indexes (MI) in MicroMAS. As the analysed micro-part in MicroMAS is being decomposed to primitive features (e.g. box, cylinder, sphere), in order for its manufacturability aspect to be assessed, the uncertainty effect is suggested to be integrated in the Single Feature Analysis (SFA) phase.

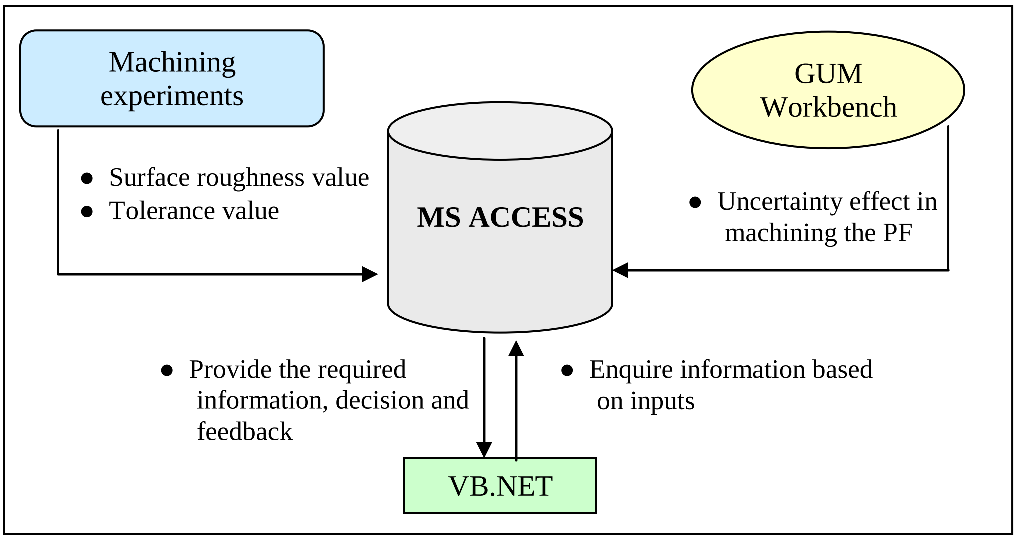

Figure 2: Schematic of relationship between the VB.NET, MS ACCESS, GUM Workbench and Machining experiments

4.1 Uncertainty effect in machining the primitive feature (MI_{UEM})

MI_{UEM} is implemented to partly reflect the real condition of the MMT which is the main domain of the MicroMAS implementation. It considers the uncertainty effects in machining the PF based on the UEM analysis on the occurred errors stemming from the construction of the MMT which affects the accuracy of the forms/shapes of the machined micro-features (e.g. PF). From the analysis and the generated UEM results (that gives the expected uncertainties in form/shape machining), it can be concluded that the smaller the size or dimension of the PF, the bigger the impact of this uncertainty impact towards the machined forms/shapes.

The foundation of MI_{UEM} index range is divided into a series of different features size intervals according to the size of the proposed micro-slots and thin walls. The index range for the MI_{UEM} is generated based on the expanded uncertainty value obtained from the UEM analysis in machining the cylinder using the spiral milling tool path. The nominal value(s) for MI_{UEM} for each interval is determined based on the average value of the obtained expanded uncertainty. As an example, for feature sizes between 0.5 and 1.0 mm, the nominal value selected *(S)* is 0.0055µm. Based on the approach in determining the MIs (Equation 1), if the uncertainty effect selected by the user for the particular PF *(N)* is 0.0085 µm, then the MI_{UEM} is equal to 1.55. This is derived from the calculations of 0.0085 divided by 0.0055 and the level of manufacturability in this case is *Easy to Manufacture*.

$$MI_{UEM} = N/S \qquad \text{Equation 1}$$

In calculating the MI_{SFA}, MI_{UEM} is incorporated for each identified primitive feature (PF) as presented in the formula below (Equation 2).

$$MI_{SFA} = \frac{\sum K_i . MI_i}{5}, \qquad \text{(Equation 2)}$$

Where *i*= PF, Ra, TOL, DIM, **UEM**

In this paper, the UEM development was analysed based on the machining of a cylinder in the MMT using a spiral milling tool path. Even though the impact of the generated error can be considered small and insignificant towards the geometrical accuracy of the machined micro-part, it is a value added approach to take this effect into consideration as it provides a better judgement towards the determination of the MIs. Assumption has been made that the smaller the size or dimensions of the PF, the bigger the impact of the uncertainty. Furthermore, the average of the expanded uncertainty from the 30 repetitions of cutting time is considered as the nominal value for the MI_{UEM}. Therefore, as a conclusion, the calculation of MI_{SFA} has taken into consideration the uncertainty effect by introducing it into the formula (Equation 1) and the details of the MI_{UEM} range value was presented in Table 1.

Table 1: Index ratings for MI_{UEM}

Feature size (mm)	≤ 0.5	1.0	>1.0
	← Harder to manufacture		Easier to manufacture →
	Uncertainty effect (μm)		
0.0 – 0.5	0.0035	0.0065	0.0095
0.5 – 1.0	0.0025	0.0055	0.0085
1.0 – 1.5	0.0020	0.0045	0.0075
1.5 – 2.0	0.0015	0.0035	0.0065
> 2.0	0.0010	0.0030	0.0045

4.2 Interface of MicroMAS

Figure 3 demonstrates the main interface where the input from user is collected. A guideline for entering and using this interface is provided by selecting the button 'TO DO'. A pop-up window showing the guidance to fill in the form and assess the preliminary result of the input is also presented. Figure 3 shows the data input for PF_8 of the micro-component. Fundamentally, there are five important steps involved in the input mechanism and SFA analysis as pictured in Figure 3. Manufacturing related details such as the process involved (micro-milling), diameter of the tools and part quality measures (tolerance, surface finish and **uncertainty)** in generating the PF are required at Step 4. For the part quality measures, in order to assist the user in determining the suitable and appropriate MI_{Ra}, MI_{TOL} and MI_{UEM}, each button provides a related guideline. A pop-up guideline for MI_{UEM} is to guide the user with value for harder, medium and easy to manufacture and calculating the MI_{UEM} based on Equation 1. The MI_{Ra}, MI_{TOL} and MI_{UEM} are determined based on the related input in each guideline window and the indices scheme described in Table 1.

5 CONCLUSION

From here, it can be concluded that the implementation of the results from the UEM analysis mirrored the real condition of the MMT in the developed MicroMAS. This is done through the consideration of calculating MI_{UEM} in MI_{SFA} for each identified PF in the selected micro-component. The implementation provides user with assistant in analysing the generated micro-component based on the impacts of UEM towards machining the micro-component on the MMT. It offers user facility to generate the manufacturability index (MIs) of the micro-component to portray the level of its manufacturability. In the future, it is proposed for the affected identified errors in the UEM to be also implemented in the MicroMAS to provide more accurate MI_{UEM} value.

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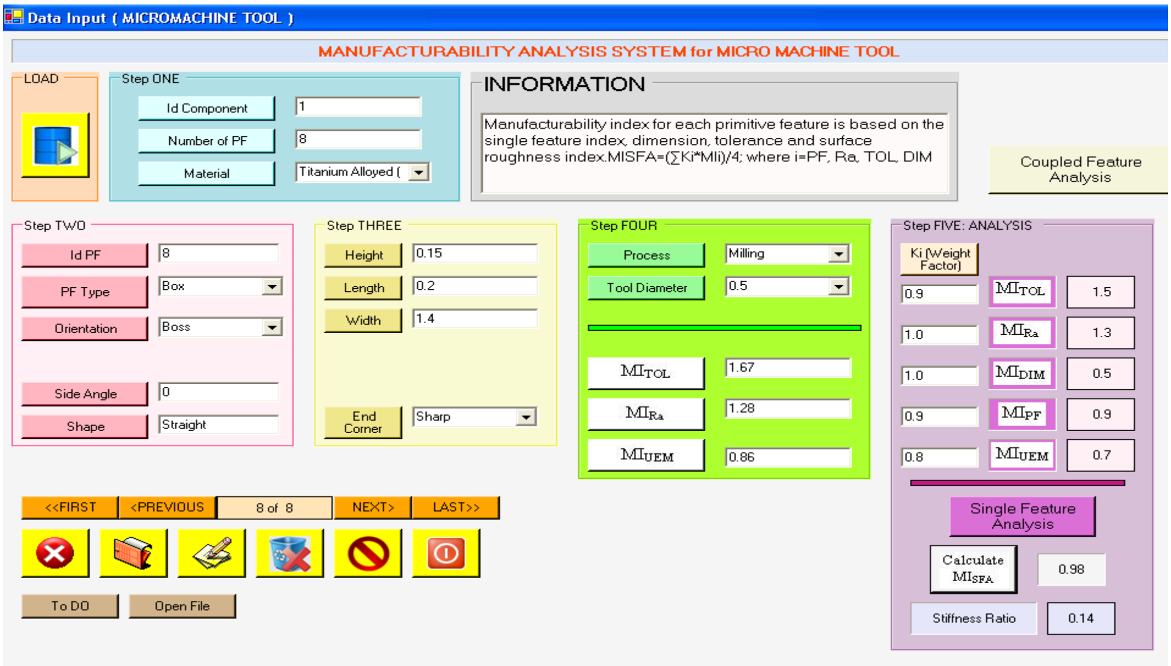

Figure 3: Main interface of MicroMAS

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