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On-machine error compensation for right first time manufacture

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Abstract

Today, high levels of precision and accuracy are needed in manufacturing to meet the increased complexities in product designs. Most products consist of multiple assembled parts, and fitting these parts together can present a major challenge, especially for complex products. Batch production systems are severely affected by scrap especially if the raw material cost is high. Producing parts right first time is a major factor for industry with manufacturing at high precision a critical requirement. This research introduces a method for compensating the machining errors using in-process measurement with the aim to machine parts right first time providing advantages over traditional methods. The method thus improves the positional accuracy of machined features while maintaining the relationships between them, compared to traditional machining. A computational model has been developed, where an algorithm within this model can handle different types of feature relationships and is able to update feature positions based on on-machine measurements. In order to validate the system, different experimental scenarios have been designed, tested with verified results. Based on these results and analysis, the proposed system showed that it can improve the error compensation on machining features by up to 77% for feature positioning, and up to 71% for feature relationships compared to traditional machining methods.

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Keywords: CNC machining; Inspection; Machining Features, Zero defect manufacture;

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1. Introduction

Process planners use tolerance charts to validate production plans and to control tolerances in the manufacturing industries. Tolerance charts also shows the relationship between features in a graphical representation. The accumulated tolerances when a part undergoes various machining stages is defined as tolerance stacking. It is important to control the tolerance stacking to maintain the part to specification [1]. Tolerance stacking analysis is used to describe the dimension's relationships within a part or assembly, and calculate the effect of the accumulated tolerances across the part. It optimises the part or feature tolerances while maintaining its functionality, which has a direct effect on minimising the cost of the part [2].

There are various research works which deal with the stack up tolerances [3] [4]. The two most common techniques used are the Worst Case (WC) and the Statistical, popularly named the Root Sum Square (RSS) [5] [6]. Another systematic solution has been proposed using a graphical approach, in which the stack up analysis is used to verify the design of a mechanical assembly and reassign the appropriate tolerances to fulfil the part functionality [7]. The Statistical Tolerance Index (STI) is another method for solving the stack up problems. A numerical method using the Monte Carlo simulation is proposed to analyse a STI stack up problem [8]. A calculation method for the worst case tolerance analysis is proposed to maintain the relationship between the functional tolerance and the tolerances associated with the geometry. The method can define the optimal allocation of tolerances for the case of a serial assembly without clearances, and to obtain the influence coefficients that affect the geometry [9].

There have been different approaches which have tried to deal with the tolerance stack-up reduction in assembly, such as tightening the tolerance specifications of each component in order to overcome the accumulated tolerance [10] [6]. Another approach was by selecting specific components in the assembly and controlling their tolerances which tends to control the overall stack-up tolerance in the assembly process. The main disadvantage of these techniques is that they increase the production cost [11]. Another investigation to reduce the tolerance stack-up by grouped random assembly for components with uniform distributions is described by Tsai et al [12]. This method assumes that there are only two components A and B to be assembled together, in which each component set is sorted and divided into groups according to their tolerance error. The group with the higher mean dimension of component A is assembled randomly with the corresponding group of component B which has the lower mean dimension and so on. Although this method decreases the stack-up tolerance between the components, it has not been investigated on multi-components assembly.

There are various causes of machining errors described by many researches. Zhao [13] classified the cause of machining errors into two categories: Machining accuracy related and tool accuracy related, the machining accuracy is concerned with the accuracy of the tool path and consists of two types of errors: Quasi- static errors which relate to the machine structure and design, and dynamic error which relates to the machine's moving elements. Other research defined the machining errors into individual feature errors and combined feature errors [14]. The individual feature errors can result from cutting tool errors, miscellaneous errors or programming errors. The combined feature errors can result from fixture/work holding errors, miscellaneous errors or machine tool errors. Different techniques have been used to compensate for machining errors. Some use offline compensation and others uses online compensation. Offline error compensation use algorithms to develop a tool deflection estimation model and a geometric error analyser in order to generate a NC program to compensate the error of the initial tool path [15]. Wang [16] proposed an error compensation software method based on on-machine measurements of volumetric errors for a machined workpiece. A vision based measurement method with use of two CMOS cameras was used. Accordingly, an error compensated NC program was generated for the next machining job. Another error compensation method which is concerned with the static/quasi-static errors that result from thermal deformation. The proposed error compensation model by Shen [17] depends on the temperature sensors attached to the machine tool and with a volumetric error calculation taking place in order to correct the tool path at a given point. On the other hand, Wu [18] used another technique to compensate the position errors resulted from the thermal expansion. The proposed model depends on the temperature sensors attached to the machine tool and use a multiple regression model to achieve a real time compensation.

In addition, a method to identify the kinematic errors of a three-axis machine tool is proposed by Pezeshki [19]. A volumetric error model is used to show the effects of kinematic/geometric errors of a machine component on the position and orientation of tool with respect to work piece. A virtual machining model has been applied in order to assess the proposed method using machining simulation software, in which the resulted estimated errors have been compared with the results of the laser interferometer. Another error compensation technique has been proposed by Gu [20] using a global offset method to compensate for five- axis machine tool errors. The compensation method is based on adjusting the origin and/or orientation of the machine coordinate system (MCS) which directly affects the dimensions of all features in the part. The error correction takes place through software and interfacing the NC program with macro variables without generating new NC Codes. This method provides a median correction so that the total part deviations will be minimized. On the other hand, Cui [21] developed a software system that compensates the geometric error for CNC machine tools based on NC program reconstruction. The new generated NC program considers the predicted errors; resulting from the error model; across the ideal tool path using virtual machining simulation. A methodology by Guiassa [22] has been proposed in order to machine parts right first time by compensating errors detected using on-machine probing. The method depends on intermittent probing through the multi-cut milling process. The error compensation taking place at the finishing process according to the estimated error resulting from the developed model.

2. Closed Loop Machining And Inspection System

This research proposes a closed loop error compensation entitled “CLosEd loop MAchining and inspecTIon System” (CLeMatiS). CLeMatiS achieves this goal by considering the sequence in which the features will be machined in conjunction with GD&T requirements that link the features together to accurately produce parts first time. During manufacturing, after each step in the sequence of CLeMatiS, data is gathered about features that are already machined via On-Machine Measurement (OMM). CLeMatiS then updates coordinates of subsequent features that are yet to be machined to meet GD&T requirements. CLeMatiS thereby aims to produce each part right first time. In order to validate the system, different machining and inspection scenarios are proposed to assess the capability of the system in the manufacture.

3. Methodology For Right First Time Manufacturing

First, the material to be machined is fixtured on a Dugard Eagle 850 vertical CNC machine, and its dimensions are measured using an on machine touch trigger probe. This measurement process (Node A3) is shown in the node tree for the proposed framework in Figure 1. The measurement values are assessed at the analyze data process (Node A1) in which the measured data, in addition to the part design data, will be evaluated and the deviation calculated (Node A11) in Figure 2. Following these calculations, the error compensation process takes place in order to define the updated values for all of the feature co-ordinates (Node A12). All feature positioning co-ordinates and their tolerances are updated by the value defined earlier by the error compensation process, resulting in new feature co-ordinates and new tolerances (Node A13). According to the new feature tolerances, the next feature to be machined will be identified. The feature specified for machining is selected based on the tightest tolerance band (Node A14).

3.1. Tolerance band sorting

This technique is extracted logically where the tolerances may have an effect on machining a feature. Since all machines have a limit to their accuracy, tolerance stacking as outlined in Section 1 may eventually result in a tolerance band that is too narrow to be machined with confidence. As tolerance bands approach the limit of the machine’s accuracy, the narrowest tolerance band has the lowest probability of being machined accurately. Conversely, the feature with a large tolerance band has the highest probability.

As the features are sorted according to their tolerance band and the feature with the smallest tolerance is machined first, this increases the probability of machining all features within the required precision. This is due to the tolerance stacking affecting the rest of the features, and since they have a larger tolerance band, this increases the opportunity to machine all features correctly.

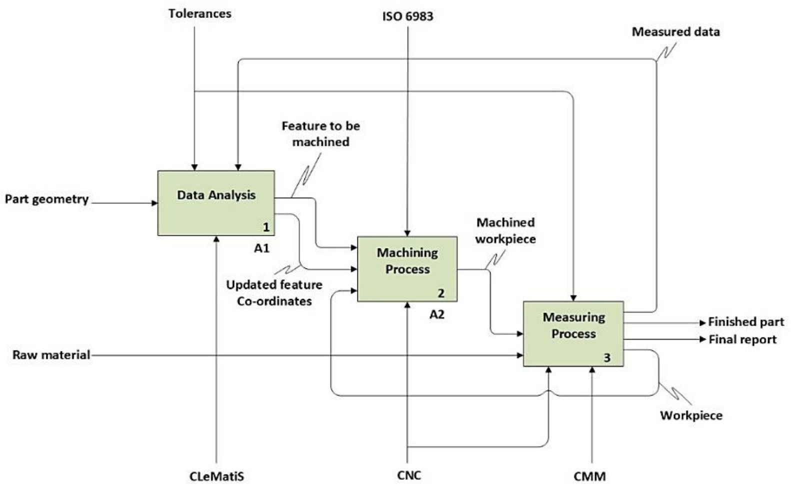

Figure 1. The main activities of the closed loop machining and inspection framework

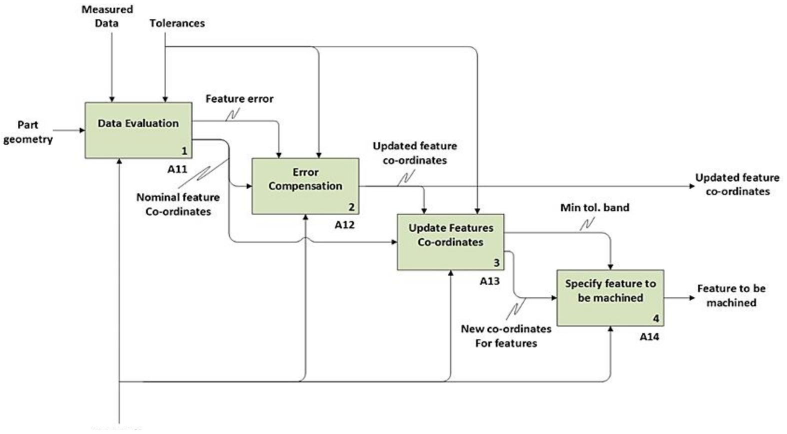

Figure 2. Graphical representation of the data analysis in CLeMatiS

3.2. Machining by using sacrificial features

Another technique being used in industry is machining by sacrificial features. Smaller versions of the final features, termed sacrificial features, are machined and then measured. Based on the measurements, the feature co-ordinates are updated and the final features are then machined to their final dimensions. It should be noted that there can be more than one sacrificial feature for the same feature, but the authors have found no literature to date to support the precision achieved against the number of sacrificial features machined.

4. Realization of Right First Time Manufacturing

The proposed framework outlined in Section 3 combines both techniques of tolerance band sorting and machining by sacrificial features in order to assess the performance and their interactions. Hence, the framework sorts the features according to their tolerances, specifies the feature to be machined and then machines one or more sacrificial features for the specified feature with the minimum tolerance band. When the first feature is machined, all the other feature co-ordinates are updated and then sorted again according to the width of their new tolerance band. The same steps are repeated until the last feature is completed.

Based on the selected sacrificial feature percentage, a G&M code file for feature machining is generated using CAM software with the CNC machine executing this file. After finishing the machining process, the machined sacrificial feature is measured. The measured data is evaluated, with error compensation taking place. Lastly, the machined feature co-ordinates and tolerances are updated. If there is another sacrificial feature to be machined for the same feature, then the process of defining the sacrificial feature will be repeated again, and a new G&M code file generated and executed on the CNC machine. Finally, the G&M code file for the finished geometry of the feature will be generated and this feature machined.

5. Mechanism for Right First Time Manufacturing

The proposed methodology comprises of systematic procedures to compensate machining errors for interlinked manufacturing features. In this research, the feature parameters are updated manually. First, all parameters for the workpiece and features must be defined, such as: coordinates, datums, dimensions, tolerances, positioning and feature relationship constraints. These definitions can be defined by the operator or extracted directly from the CAD or CAM file.

5.1. Defining the predecessor feature

The chosen mechanism for defining the feature relationships and how measured deviations affect the other manufacturing features is a critical decision process within the proposed methodology. Figure 3a shows an example of how the system differentiates between the feature deviations and which deviation affects which feature. Inspired by the critical path method used in operations research [23] to define the predecessor task, this adaptation identifies the predecessor feature instead. The example shows that there are four features to be machined on the workpiece, presented in circles, together with the tolerance relationships between these features denoted by the arrows. The example shows that all features are dependent on the workpiece co-ordinates datum (WP), which means that any deviation in the dimensions of the workpiece will affect all features directly. Also it shows that Feature F3 for example has three constraints as it depends on features F1, F2, and WP together. This means that a combined deviation from feature F1, F2, and WP has to be considered and calculated in order to update the machining co-ordinates for feature F3. Figure 3b shows the test part to be machined consists of a block with four pockets.

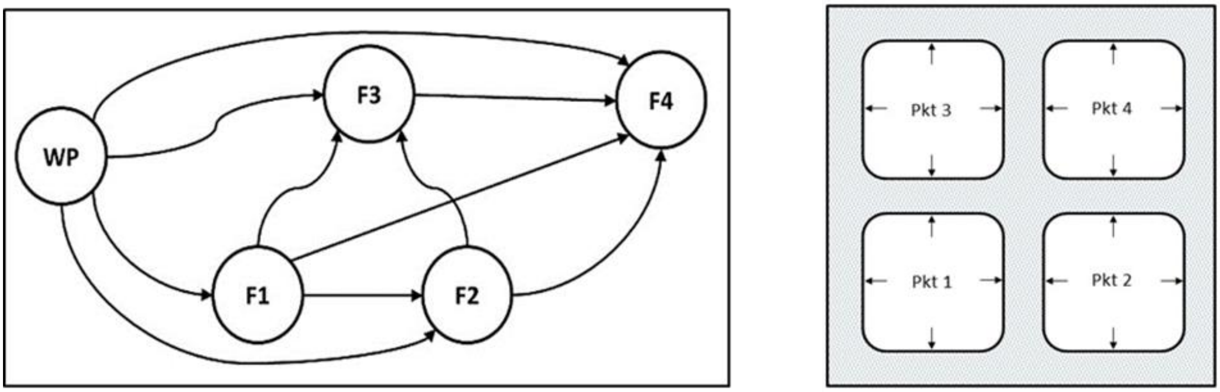

Figure 3. (a) A diagram shows the relationship between features, (b) The test part consists of a block with 4 pockets

5.2. Calculation of feature tolerance

Formulae based on mathematical equations have been developed using an Excel spreadsheet to update features with respect to their predecessors. The following parameters have been defined: “μi” is the mean for a specific feature’s dimension where “i” represents the number of the updated constraints; “UTL” and “LTL” are the upper and lower tolerance limits for a specific dimension respectively. Figure 4 shows the tolerance zones for a specific feature dimension in which µ1, UTL1, LTL1 represent the nominal geometric tolerance zone, while µ2, UTL2, LTL2 represent the updated geometric tolerance zone after adding the deviation error. When adding both zones to each other, there is a common area between them which is the new tolerance zone for the required feature in which µ3, UTL3 and LTL3 are the mean, upper, and lower control limits, respectively. To calculate the new dimension and tolerance, the following equations have been used:

$$LTL_3 = \max(LTL_1, LTL_2)$$

$$\mu_3 = (\mu_1 + \mu_2) \div 2 \ \text{ OR } \ \mu_3 = (UTL_3 + LTL_3) \div 2$$

So, the general equation will be as follow:

$$UTL_{new} = \min(UTL_1, UTL_2, \dots, UTL_i)$$

$$LTL_{new} = \max(LTL_1, LTL_2, \dots, LTL_i)$$

$$\mu_3 = (UTL_{new} + LTL_{new}) \div 2$$

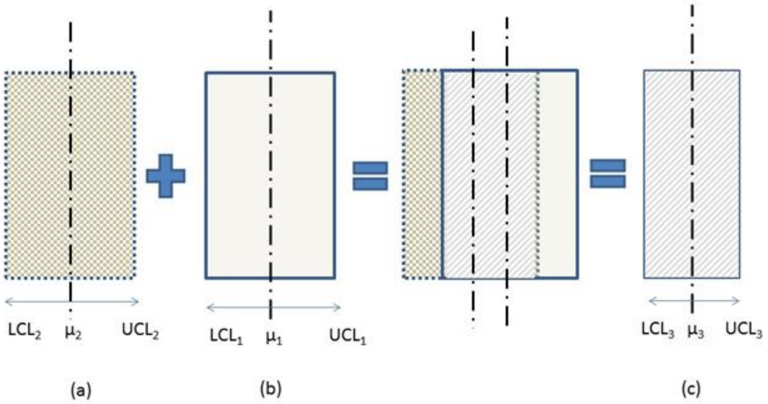

Figure 4. Adapted schematic drawing shows different tolerance zones and their common area
(a) tolerance zone with deviation error, (b) nominal tolerance zone, (c) the new updated tolerance zone

6. Machining and inspection scenarios

To identify the factors that affect machining whilst using the framework outlined in section 3, a preparation experiment was developed. The preparation experiment contains 10 scenarios, namely S1 to S10 that are compared to a traditional machining and inspection scenario, namely S0. Each of the 10 scenarios are concerned with a specific factor namely: i) *the percentage of the sacrificial feature*, ii) *the type of feature relationship constraints* or iii*) the number of feature constraints*. Figure 5 shows a schematic representation for the different factors to be tested within the 10 scenarios S1- S10. The first factor has been tested by applying three percentages for the sacrificial feature. The 50% sacrificial feature size is applicable for small features where it is not advisable to machine less than 50% of its nominal dimension (e.g. poor chip formation or delicate tool geometries) as shown in Figure 6a. On the other hand, a 90% sacrificial feature size is a closer representation of the final feature geometry as shown in Figure 6b, perhaps giving more relevance to the measured coordinates and increasing productivity. Finally, the 100% sacrificial feature in scenarios S3 and S6 means that it considers the effect of ignorance of the sacrificial feature, in which each feature will be machined on one step. The second factor to be tested has been classified into four strategies. First strategy is "Center to Center" relationship which means that the relationship between features is depending on the center of these features. The second strategy "Side to Side" relationship which means that the relationship between features is depending on feature side position as shown in Figure 6c. The third strategy considers the effect of ignoring the features relationships in updating the features coordinates, and the measuring process takes place on the machine tool using the installed touch trigger probe. The fourth strategy is the same as the third category, but this time the measuring process takes place on the CMM machine. The third factor depends on number of relationships between features.

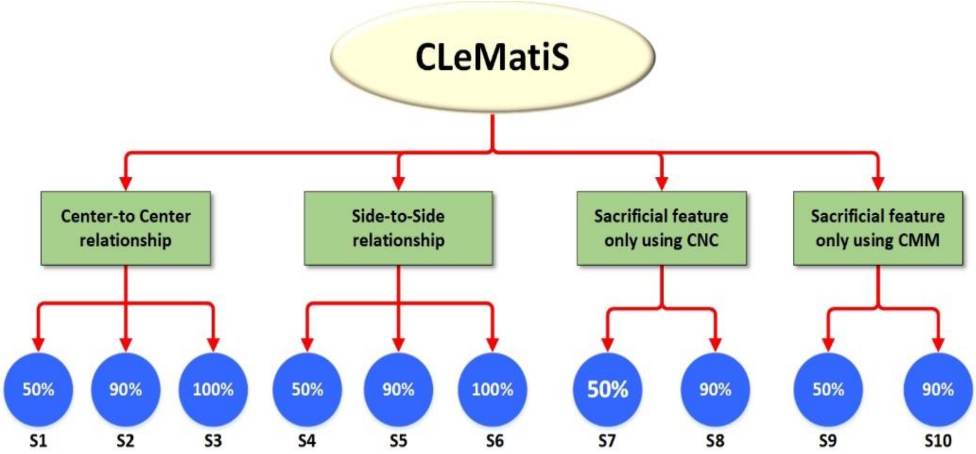

Figure 5. Schematic representation of CLeMatiS for the 10 machining and inspection scenarios

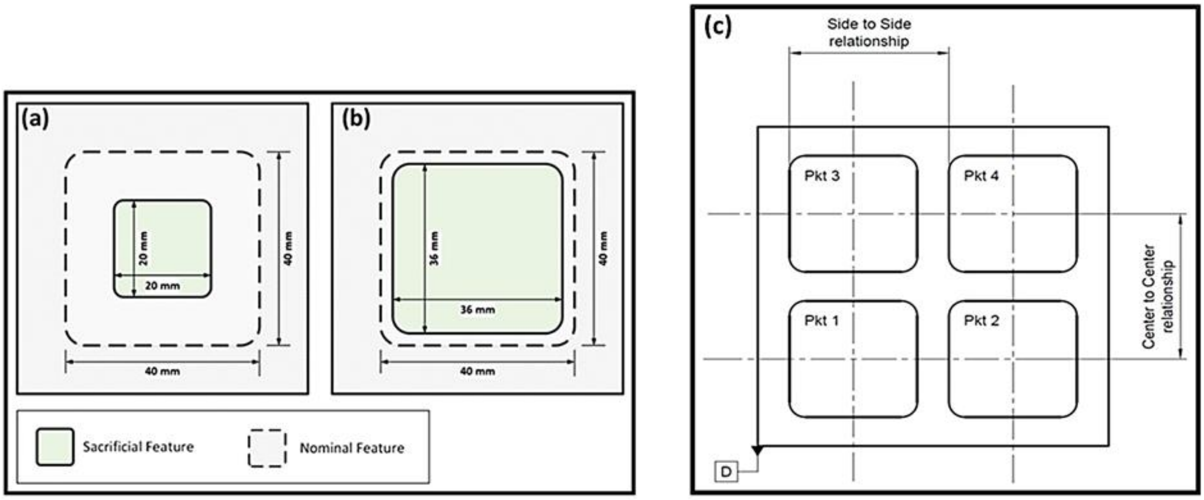

Figure 6. (a) 50% sacrificial feature (b) 90% sacrificial feature (c) Different types of relationships

Three test parts were machined, based on the part shown in figure 3b, for each of the 11 scenarios, with 33 parts in total. After the machining process for all the scenarios, the 33 parts were measured using the CMM machine in a metrology laboratory with the data gathered in an Excel spread sheet for analysis. This analysis of the data considers the relationship error for each feature in each of the X & Y directions, which is the difference between the actual and the nominal distance between each of the features. An ANOVA test has been applied to the data in order to determine which factors are significant and affect the CLeMatiS. From this statistical analysis it has been concluded that there is an improvement when machining sacrificial features in the feature positions and feature relationships relative to the traditional machining scenario S0. However, the percentage of the sacrificial feature machined does not play a major role in the results. This has been observed using the graphical representations and proved using the ANOVA test. The difference in the mean error and the range of variation between the various strategies used shows that the type of the strategy can play a major role on the results, mainly on the feature relationship. Finally, 4 scenarios have been selected for the second set of experiments.

The three scenarios S2, S8, and S10 have been selected for the case study of this research with further analysis been applied in order to assess them relatively to the traditional machining S0. According to the National Institute of Standards and Technology (NIST) (NIST, 2017), the minimum sample size, N, for two sided test of hypothesis with standard deviation (σ) assumed to be known can be calculated using the following equation:

$$N = \left(z_{1-\alpha/2} + z_{1-\beta}\right)^2 \left(\frac{\sigma}{\delta}\right)^2$$

By calculating the sample size using $\alpha = 0.05$, $\beta = 0.10$ which are the most common values used, and to get δ equal to the standard deviation, the sample size N is going to be 11 parts. Thus, each scenario needs at least 11 parts to be machined, which means that the total number of parts to be machined are 44 parts.

7. Results

The assessment of the proposed scenarios is due to the calculation of the improvement percentage in errors relatively to the traditional scenario. Data analysis shows the effect of the different scenarios on the machining errors. Table 1 shows the improvement percentage in the feature relationship for each scenario compared to the traditional scenario (S0). In Table 1 the pink shaded results show the worst results compared to the traditional scenario (S0), while the green shaded results show an improved results performance relative to traditional scenario. From this table it can be concluded that scenarios S8 and S10 do not show any consistent improvement neither in X nor Y directions. It also shows that these scenarios have worst results than the traditional scenario results. The improvement is only by 18% for two of the feature relationships in both scenarios S8 and S10. On the other hand, scenario S2 is capable to improve the relationship between features compared to traditional scenario (S0), however, this scenario has further limitations for its improvement due to the capability of the CNC machine. The capability of the CNC machine defines the precision that cannot be reached by CLeMatiS, which is the pink shaded area in Figure 7a and Figure 7b, in which any error in the X direction has a value more than 26 microns can be improved, while any error in the Y direction has a value more than 16 microns can be improved.

Table 1. Tabulated improvement percentage in the features relationship for scenarios S2, S8, and S10 compared to the traditional scenario (S0) (Green: Improvement & Red: No Improvement)

Relationship	Traditional (S0)		C-C 90% (S2)		CNC 90% (S8)		CMM 90% (S10)	
	X	Y	X	Y	X	Y	X	Y
Pkt1-Pkt2	12.45	15.82	-320%	-3%	-142%	6%	-799%	-55%
Pkt1-Pkt3	29.18	34.36	17%	51%	-43%	-28%	-306%	18%
Pkt1-Pkt4	13.27	26.27	-42%	65%	-190%	-113%	-668%	-84%
Pkt2-Pkt3	26.00	47.82	-91%	35%	-20%	-8%	-149%	18%
Pkt2-Pkt4	19.00	34.27	-187%	71%	-122%	-100%	-251%	-65%
Pkt3-Pkt4	35.36	48.82	59%	52%	-1%	18%	3%	-21%

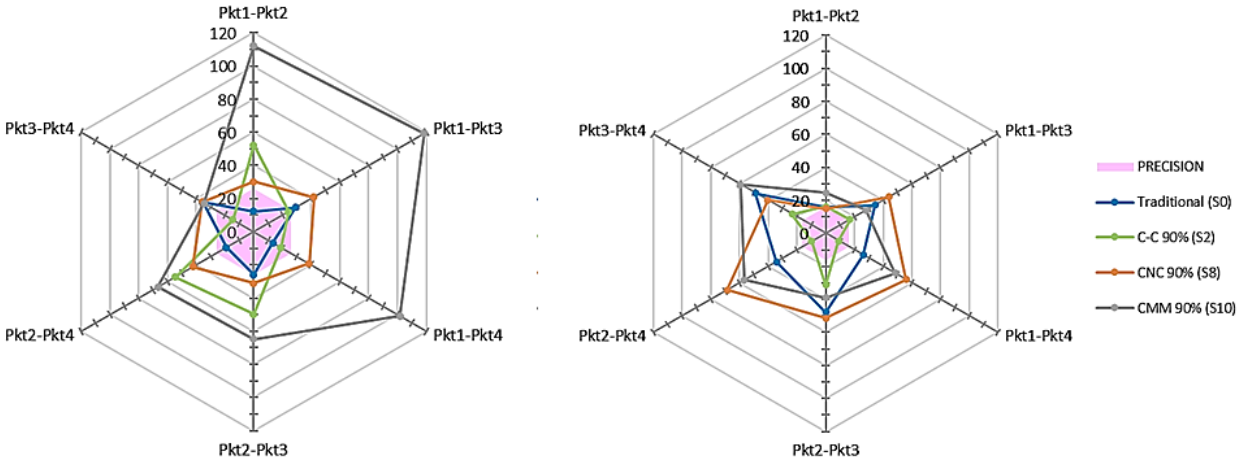

Figure 7. Comparison of the effect of the different scenarios for each feature relationship (a) X direction (µm) (b) Y direction (µm)

Another set of analysis has been applied for the feature positioning. The results show the improvement percentage for the feature positions across the different scenarios S2, S8 and S10 compared to the traditional scenario S0. It can be seen that scenarios S8 and S10 are not able to improve the positioning error, and even the resulted improvement is not significant or consistent. Unlike scenarios S8 and S10, S2 shows a significant improvement in X and Y directions. It is also recognised that C-C 90% scenario (S2) is capable to improve errors in the X direction that have values more than 15 microns, and errors in Y direction that have values more than 6 microns. Any trial to compensate an error has a value less than these limitations tends to be a worst deviation either in X or Y directions as shown in Figure 8a and Figure 8b.

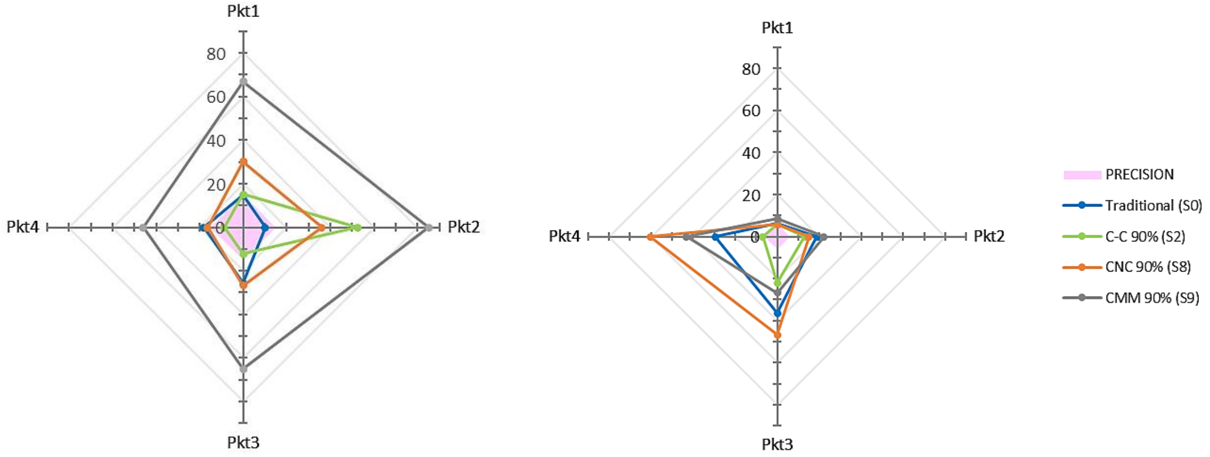

Figure 8. Comparison of the effect of the different scenarios for each feature relationship (a) X direction (µm) (b) Y direction (µm)

8. CONCLUSIONS

CLeMatiS can be considered as an effective and cost effective solution for increasing the machining accuracy in CNC manufacture. This is achieved by decreasing scrap through predicting the defective parts at an early stage of production, saving time and money. Online machining error compensation is considered as an ideal solution for minimizing cost and time, as there is no need to machine a part then measure it, and then compensate for the error in future production. This was highly significant when raw material costs are high and machine degradation occurs over time to minimize scrap.

The experiments and its analysis have demonstrated the advantages and the limitations of the in-process measurement on a CNC machine tool. The main advantage is the capability of measuring the part features dimensions' errors through the machining process, without the need to move the part. Accordingly, compensating errors can take place on the machine tool for the current part to avoid scrapping it. Though the approach does not guarantee right first time manufacture, the case studies showed that CLeMatiS can improve the positional accuracy of the machined features relatively to traditional machining. However, CLeMatiS limitations depend on the machine tools precision. CLeMatiS has been shown to improve the accuracy of the feature positions and feature relationships in both X and Y axes. This has been achieved through compensation of any errors that are larger than the accuracy limit of each axis.

References

[1] B. Ngoi and K. Tan, "Tolerance stack analysis for assembly," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 210, no. 3, pp. 279-288, 1996.

[2] D. Indra, K. Suherman and P. Oken, "Tolerance Stack Analysis in Francis Turbine Design," vol. 42, no. 1, pp. 73-90, 2010.

[3] G. Cogorno, Geometric dimensioning and tolerancing for mechanical design, McGraw-Hll, 2006.

[4] J. Meadows, "Geometric Dimensioning and Tolerancing Handbook: Applications, Analysis & Measurement," 2009.

[5] F. Scholz, "Tolerance stack analysis methods," 1995.

[6] K. G. Swift, M. Raines and J. D. Booker, "Tolerance optimization in assembly stacks based on capable design," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture,* vol. 213, no. 7, pp. 677-693, 1999.

[7] A. Sahani, P. Jain, S. C. Sharma and J. Bajpai, "Design Verification through Tolerance Stack up Analysis of Mechanical Assembly and Least Cost Tolerance Allocation," *Procedia Materials Science,* vol. 6, pp. 284-295, 2014.

[8] A. Otsuka and F. Nagata, "Stack-Up Analysis of Statistical Tolerance Indices for Linear Function Model Using Monte," no. July, pp. 1-10, 2015.

[9] M. Mansuy, M. Giordano and P. Hernandez, "A new calculation method for the worst case tolerance analysis and synthesis in stack-type assemblies," *CAD Computer Aided Design,* vol. 43, no. 9, pp. 1118-1125, 2011.

[10] A. Asha, S. Kannan, V. Jayabalan and M. Kannan, "Optimization of clearance variation in selective assembly for components with multiple characteristics," *International Journal of Advanced Manufacturing Technology,* vol. 38, pp. 1026-1044, 2008.

[11] S. Kannan, V. Jayabalan and K. Jeevanantham, "International Journal of Production Research Genetic algorithm for minimizing assembly variation in selective assembly Genetic algorithm for minimizing assembly variation in selective assembly," *International Journal of Production Research int. j. prod. res,* vol. 4114, no. 14, pp. 3301-3313, 2003.

[12] J. C. Tsai, F. Chen and J. H. Dai, "Reduction of tolerance stack-up by grouped random assembly for components with uniform distributions," *Procedia CIRP,* vol. 27, pp. 260-263, 2015.

[13] F. Zhao, "An integrated process planning system for machining and inspection," 2009.

[14] R. Bagshaw and S. Newman, "Manufacturing data analysis of machine tool errors within a contemporary small manufacturing enterprise," Pergamon, 2002.

[15] M. Vahebi Nojedeh, M. Habibi and B. Arezoo, "Tool deflection and geometrical error compensation by tool path modification," *International Journal of Machine Tools and Manufacture,* vol. 51, no. 6, pp. 439-449, 2011.

[16] S. M. Wang and J. J. Lin, "On-machine volumetric-error measurement and compensation methods for micro machine tools," *International Journal of Precision Engineering and Manufacturing,* vol. 14, no. 6, pp. 989-994, 2013.

[17] H. Shen, J. Fu, Y. He and X. Yao, "On-line asynchronous compensation methods for static/quasi-static error implemented on CNC machine tools," *International Journal of Machine Tools and Manufacture,* vol. 60, pp. 14-26, 2012.

[18] C. W. Wu, C. H. Tang, C. F. Chang and Y. S. Shiao, "Thermal error compensation method for machine center," *International Journal of Advanced Manufacturing Technology,* vol. 59, no. 5-8, pp. 681-689, 2012.

[19] M. Pezeshki and B. Arezoo, "Kinematic errors identification of three-axis machine tools based on machined work pieces," *Precision Engineering,* vol. 43, pp. 493-504, 2016.

[20] J. Gu, J. S. Agapiou and S. Kurgin, "Error compensation and accuracy improvements in 5-axis machine tools using the global offset method," *Journal of Manufacturing Systems,* vol. 44, pp. 324-331, 2017.

[21] G. Cui, Y. Lu, J. Li, D. Gao and Y. Yao, "Geometric error compensation software system for CNC machine tools based on NC program reconstructing," *International Journal of Advanced Manufacturing Technology,* vol. 63, no. 1-4, pp. 169-180, 2012.

[22] R. Guiassa, J. R. Mayer, M. Balazinski, S. Engin and F. E. Delorme, "Closed door machining error compensation of complex surfaces using the cutting compliance coefficient and on-machine measurement for a milling process," *International Journal of Computer Integrated Manufacturing,* vol. 27, no. 11, pp. 1022-1030, 2014.

[23] J. E. Kelley, "Critical-path planning and scheduling: Mathematical basis," *Operations research,* vol. 9, no. 3, pp. 296-320, 1961.