Vector Based Datum Transformation Scheme for Computer Aided Measurement

Danny K. L. Lai[1] and Matthew. M. F. Yuen[2]

[1]The Hong Kong University of Science and Technology, dannylai@ust.hk
[2]The Hong Kong University of Science and Technology, meymf@ust.hk

ABSTRACT

Product geometry measurement is a critical step in the product development cycle. It provides dimensional and tolerance verification between mechanical design and measurement assuring the quality of the product. Traditional measuring strategy is based on experience rather than using a systematic approach. This paper presents a vector-based datum transformation scheme to standardize the method to define the measurement datum to improve the quality of mechanical parts. It is based on mating condition assembly models of CAD system, to identify the dimensional and tolerancing relation between a geometric feature and the measuring datum. Through Assembly Mating Map and tolerance analysis, a commonly measuring datum is defined to improve a measurement strategy with the same measuring vector of assembly features.

Keywords: computer aided measurement, datum transformation, vector base.
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1 INTRODUCTION

The quality of a product is governed by its precision which is controlled by the tolerance specification. A measuring strategy is needed to ensure satisfaction of the tolerance specification. The proper assignment of datum in the product engineering drawing is of paramount importance to guarantee effective dimensional and geometric tolerance evaluation in the measurement process. This requirement becomes even more prevalent when multiple datums are used in an assembly. Each part has its own individual datum assignment and the geometric relationship between these datums dictate the fitting of the parts and the eventual precision of the assembled unit. The fulfillment of dimensional and tolerance specification for individual parts does not guarantee the fulfillment of tolerance requirements for the assembled unit.

This research has proposed a method to enhance the current inspection strategy and to establish a link between design and inspection. Based on dimensioning and tolerancing of geometric models, "Vector Based Datum Transformation Scheme" can provide a formulized methodology to define a "Common Measuring Datum" for each assembly part. This datum is correlative to the function of final application. Inside the proposed scheme exist two major components to identify the assembly relation between each assembled parts with "Assembly Mating Map", which can define a clear assembly mating data structure between different assembly components. From the analyzed result, we can find out the "Critical Assembly Loop" for analyzing the assembly model, and then all the mating features that can be defined by "Common Measuring Datum" can be defined to verify the measuring procedure of the CAD assembly models. That is the objective of this research.

2 REVIEW

The current product geometry inspection standard is defined by international dimensioning and tolerancing standards such as ASME Y14.5M and BS308 [1,2] based on single part drawing specification. The measurement procedure depends on the experience of the inspection engineer. Fig. 1 shows the conventional measurement process flow from engineering drawing specification to product approval.

The 3D geometric modeling data in a CAD system has enhanced the quality of the product geometry data and provides an attractive platform for improving the product measurement process [3]. Elinson and Nau presented the solid modeling data structure based on manufacturing process planning [4], and Hoffmann and Kim developed an algorithm to control the dimension variant in the single solid model [5] to reduce the over-constraint problem from design to manufacture. In the data structure of solid modeling systems, tolerance is a specified attribute attached to dimensions or datum features. It is stored as information data rather than geometric data, typical of component parts. The product assembly model collates the tolerance information from the associated part models to evaluate the assembly features, the fitting conditions and related datum features.

To check fitting between assembly features, Kandikjan et al. proposed a new CAD data structure including tolerance state [6]. But it cannot completely capture the fully functional specification of a product assembly model. Dantan [7] and Latombe [8] developed a tolerance graph to represent the tolerance constraint to enhance the assembly model analysis capability of a CAD system with dimensional tolerance attributes changing to dimensional tolerance constraints. Based on this data structure change, Chen and Ostrovskv presented the parametric tolerance algorithm in calculating tolerance zone for fixture design and planar mechanical parts [9, 10]. To analyze location and orientation of the tolerance zone, Teck defined a flatness tolerance limit to verify fitting between parts in an assembly model [11].

Dimensional tolerance can present three kinds of fitting condition: clearance fit, translation fit and press fit; they are based on different tolerance specification between assembly part features. Yu [12] developed the vector-based dimensioning method for tolerance definition. Kusiak [13] applied "design of experiment" and Taguchi method approaches the deterministic tolerance synthesis to determine the cost efficient tolerance value in part manufacture. Skowronski [14] and Roy [15] presented statistical analysis methods to calculate the tolerance zone for a polyhedral object. Park [16] used a homogeneous transformation matrix to present the relationship between assembly geometric elements to determine the ability to assemble a CAD model. Teissandier [17] developed the tolerance zone proportioned assembly clearance volume and Zou [18] developed the gap-based approach as contact surface volume to calculate the tolerance zone in the assembly model.

During the measurement process, the drawing datum may not match the functional requirement of the final application. Therefore, defining the "Common Measuring Datum" is necessary to provide the same measuring vector to measure each assembly feature to minimise the measuring variation and improve the ability to assemble the final product. This paper presents a "Vector Based Datum Transformation scheme" to define the optimal measurement datum. Based on the mating conditions of a CAD assembly model and functional requirements of assembled features, an efficient measurement solution is proposed to integrate measuring strategy development tools with the CAD system to support the computer aided measurement.

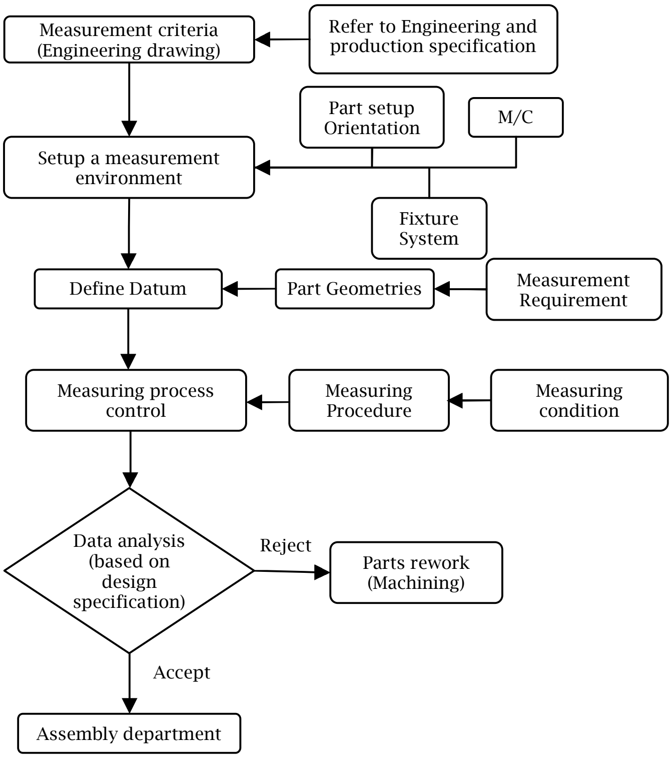

Fig. 1: Traditional measurement process flow and control.

3 PROPOSED FRAMEWORK

The design intent of a product assembly is best reflected by the assignment of tolerances, dimensional or geometric, and the level of tolerances. The degree of precision associated with the tolerance assignment serves as a clear indicator of the priority of the geometric entity in the functional performance of the product assembly. "Vector Based Datum Transformation scheme" is aimed at setting up a consistent measurement requirement to ensure the performance for a product assembly to fully reflect its design intent.

Fig. 2 shows the process flow chart to select the "Common Measuring Datum"using the assembly information and the related dimension and tolerance information to create a table for selecting a mating feature of each assembly part, uses all the mating features of the assembly model to construct the "Assembly Mating Map". Referring to the analyzed results we can identify the "Critical Assembly Loop" is selected by considering the functional requirement of the product.

The assembly feature inside the "Critical Assembly Loop" is a potential "Common Measuring Datum" of each assembly part. It is a major research objective of this paper to define "Common Measuring Datum" to have a mating linkage between different assembly parts. All positioning dimensions are referenced to critical assembly loop features to measure all the dimension values.

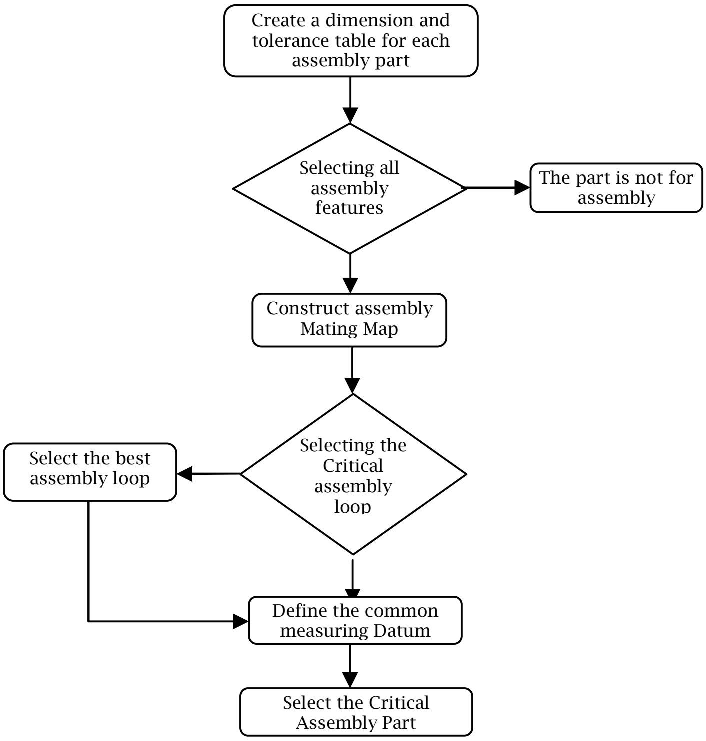

Fig. 2: Process flow chart of Vector Based Datum Transformation Scheme.

3.1 Assembly Mating Map

Before creating the "Assembly Mating Map", the first task is to construct the "Dimension and Tolerance Table". This is used for identifying each feature of the individual assembled parts. This table includes feature ID of each geometry feature, dimension, tolerance specification, design datum and mating information. Refer to the construction information, to select all related assembly geometry features to prepare data to create an "Assembly Mating Map".

To further illustrate the function of "Assembly Mating Map", a typical example is given to demonstrate the critical assembly loop selection using "Assembly Mating Map" in a mechanical assembly product. Fig. 3(a) shows a mold-base assembly model for this case study and fig. 3(b) and 4(a)~(c) shows all the assembly parts as 3D models and includes feature ID and design datum. In the case study, there is a total of twenty-two assembly features related to the assembly process and the required quantity of all assembly parts as follows:

1. Top plate X 1pc
2. Guide bush X 4pcs
3. Lower plate X 1pcs
4. Guide pin X 4pcs

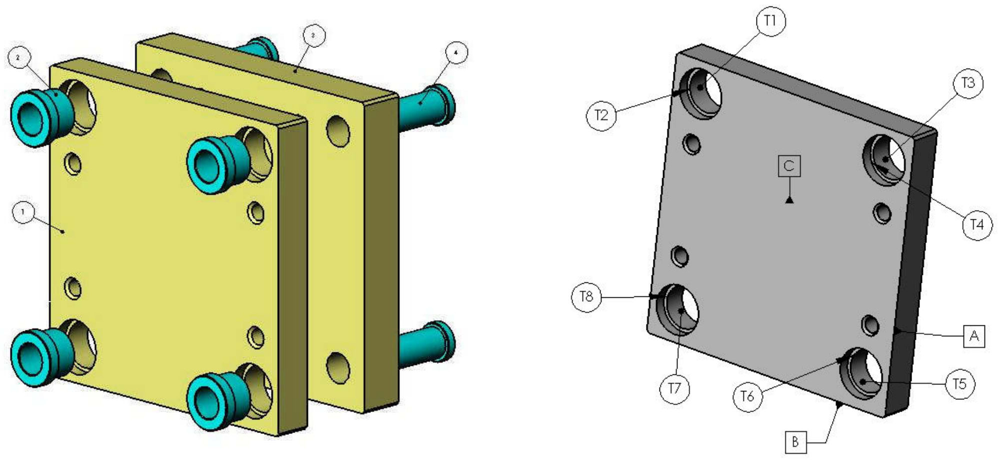

Fig. 3: (a) Mold-base assembly model, (b) Upper mold plate.

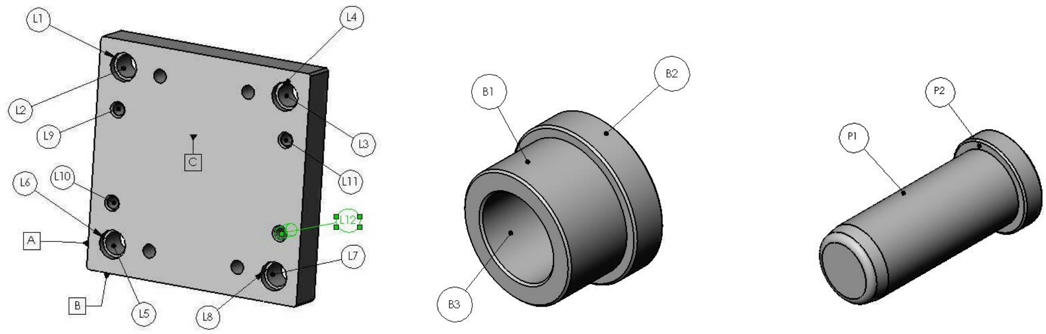

Fig. 4: (a) Lower plate, (b) Guide Bush, (c) Guide pin.

3.1.1 Dimension and Tolerance Specification Table

Tab. 5 and 10 shows dimension and tolerance specification table for the all assembly parts. It consists of all dimensions and tolerance specification of each assembly feature. For example, in the first cell of column one is a feature ID. Feature T1 is the first assembly feature in the top plate, the hole diameter of T1 is Ø19.99mm. The feature tolerance is USL=-0.01mm, LSL=-0.02 and positioning tolerance = 0.01mm with drawing datum's A and B. In the second cell is the dimension and tolerance specification of T2. Basically, this is a shoulder hole with 5mm depth from datum C.

With the dimension and tolerance table of all assembly parts complete, we can now discuss the detail of the functional requirement of the mold-base. It provides the precision parallel movement between top and lower plate. Figure 14 shows the movement detail, Fig. 10(a) shows the mold-base in the open condition, Fig. 10(b), top and lower plate are close together to Fig. 10(c) condition. All position accuracy is controlled by guide pins and guide bushes.

Referring to the assembly structure of mold-base, we can classify the top plate and four guides as a sub-assembly model and the other sub-assembly model is the lower plate and guide pins to create the final assembly model. Below is the detail assembly tolerance specification of the mold-base:

1. The guide bush cylindrical face B11 transition fit 0.03mm to T1 hole of top plate.
2. The guide bush shoulder face B12 press fit to T2 hole bottom face.
3. The guide pin cylindrical face P11 transition fit 0.03mm to L1 hole of lower plate.
4. The guide bush shoulder face P12 press fit to L2 hole shoulder face.

Feature No.	Positioning Specification									Geometry Spec	
	Datum	Dimension	Tol	Datum	Dimension	Tol	Datum	Dimension	Tol	Dimension	Tol
T1	A	175.0mm	+0.01 -0.01	B	175.0mm	+0.01 -0.01				Ø19.99mm	-0.01 -0.02
T2	A	175.0mm	+0.1 -0.1	B	175.0mm	+0.1 -0.1	C	5.0mm	+0.05 -0.05	Ø23.00mm	+0.2 +0.1
T3	A	25.0mm	+0.01 -0.01	B	175.0mm	+0.01 -0.01				Ø19.99mm	-0.01 -0.02
T4	A	25.0mm	+0.1 -0.1	B	175.0mm	+0.1 -0.1	C	5.0mm	+0.05 -0.05	Ø23.00mm	+0.2 +0.1
T5	A	25.0mm	+0.01 -0.01	B	25.0mm	+0.01 -0.01				Ø19.99mm	-0.01 -0.02
T6	A	25.0mm	+0.1 -0.1	B	25.0mm	+0.1 -0.1	C	5.0mm	+0.05 -0.05	Ø23.00mm	+0.2 +0.1
T7	A	175.0mm	+0.01 -0.01	B	25.0mm	+0.01 -0.01				Ø19.99mm	-0.01 -0.02
T8	A	175.0mm	+0.1 -0.1	B	25.0mm	+0.1 -0.1	C	5.0mm	+0.05 -0.05	Ø23.00mm	+0.2 +0.1

Tab. 5: Dimension and Tolerance Specification of Top Plate.

Feature No.	Positioning Specification									Geometry Spec	
	Datum	Dimension	Tol	Datum	Dimension	Tol	Datum	Dimension	Tol	Dimension	Tol
L1	A	25.0mm	+0.01 -0.01	B	175.0mm	+0.01 -0.01				Ø15.98mm	+0.01 -0.01
L2	A	25.0mm	+0.1 -0.1	B	175.0mm	+0.1 -0.1	C	3.1mm	+0.05 -0.05	Ø19.20mm	+0.2 -0.2
L3	A	175.0mm	+0.01 -0.01	B	175.0mm	+0.01 -0.01				Ø15.98mm	+0.01 -0.01
L4	A	175.0mm	+0.1 -0.1	B	175.0mm	+0.1 -0.1	C	3.1mm	+0.05 -0.05	Ø19.20mm	+0.2 -0.2
L5	A	175.0mm	+0.01 -0.01	B	25.0mm	+0.01 -0.01				Ø15.98mm	+0.01 -0.01
L6	A	175.0mm	+0.1 -0.1	B	25.0mm	+0.1 -0.1	C	3.1mm	+0.05 -0.05	Ø19.20mm	+0.2 -0.2
L7	A	25.0mm	+0.01 -0.01	B	25.0mm	+0.01 -0.01				Ø15.98mm	+0.01 -0.01
L8	A	25.0mm	+0.1 -0.1	B	25.0mm	+0.1 -0.1	C	3.1mm	+0.05 -0.05	Ø19.20mm	+0.2 -0.2
L9	A	20.0mm	+0.05 -0.05	B	180.0mm					Ø10.05mm	+0.02 -0.02
L10	A	20.0mm	+0.05 -0.05	B	180.0mm					Ø10.05mm	+0.02 -0.02
L11	A	20.0mm	+0.05 -0.05	B	180.0mm					Ø10.05mm	+0.02 -0.02
L12	A	20.0mm	+0.05 -0.05	B	180.0mm					Ø10.05mm	+0.02 -0.02

Tab. 6: Dimension and Tolerance Specification of Lower Plate.

Feature No.	Positioning Specification									Geometry Spec	
	Datum	Dimension	Tol	Datum	Dimension	Tol	Datum	Dimension	Tol	Dimension	Tol
B11	A	0.0mm	+0.005 -0.005	A	0.0mm	+0.005 -0.005				Ø20.01mm	+0.01 -0.01
B12	A	0.0mm	+0.1 -0.1	A	0.0mm	+0.1 -0.1				Ø22.5mm	+0.2 -0.2
B13	A	0.0mm	+0.005 -0.005	A	0.0mm	+0.005 -0.005				Ø17.00mm	+0.01 -0.01

Tab. 7: Dimension and Tolerance Specification of Guide Bush (1).

Feature No.	Positioning Specification									Geometry Spec	
	Datum	Dimension	Tol	Datum	Dimension	Tol	Datum	Dimension	Tol	Dimension	Tol
P11	A	0.0mm	+0.002 -0.002	A	0.0mm	+0.002 -0.002				Ø16.97mm	+0.01 -0.01
P12	A	0.0mm	+0.1 -0.1	A	0.0mm	+0.1 -0.1				Ø19.0mm	+0.1 -0.1

Tab. 8: Dimension and Tolerance Specification of Guide Pin (1).

Feature No.	*Positioning Specification*									*Geometry Spec*	
	Datum	*Dimension*	*Tol*	*Datum*	*Dimension*	*Tol*	*Datum*	*Dimension*	*Tol*	*Dimension*	*Tol*
B21	A	0.0mm	+0.005 -0.005	A	0.0mm	+0.005 -0.005				Ø20.01mm	+0.01 -0.01
B22	A	0.0mm	+0.1 -0.1	A	0.0mm	+0.1 -0.1				Ø22.5mm	+0.2 -0.2
B23	A	0.0mm	+0.005 -0.005	A	0.0mm	+0.005 -0.005				Ø16.00mm	+0.01 -0.01

Tab. 9: Dimension and Tolerance Specification of Guide Bush (2~4).

Feature No.	*Positioning Specification*									*Geometry Spec*	
	Datum	Dimension	Tol	Datum	Dimension	Tol	Datum	Dimension	Tol	Dimension	Tol
P21	A	0.0mm	+0.002 -0.002	A	0.0mm	+0.002 -0.002				Ø15.97mm	+0.01 -0.01
P22	A	0.0mm	+0.1 -0.1	A	0.0mm	+0.1 -0.1				Ø19.0mm	+0.1 -0.1

Tab. 10: Dimension and Tolerance Specification of Guide Pin (2~4).

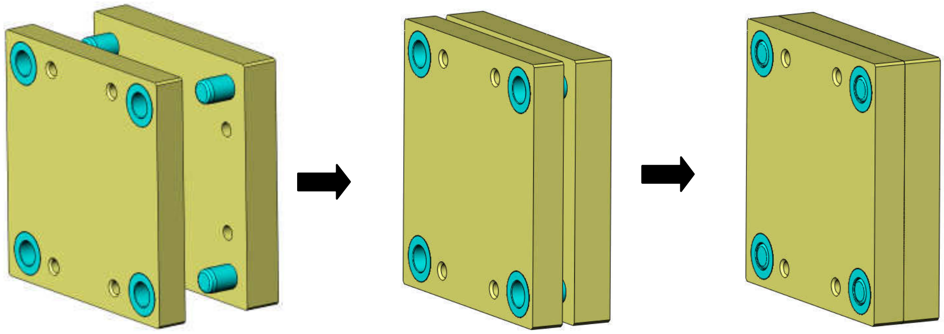

Fig. 10: Functional Flow Chart for Mold-base: Mold open (a), Mold closing (b), Mold Closed (c).

As the functional requirement of the mold-base assembly, the running clearance between the hole of the gauge bush and gauge pin cannot be more the 0.01mm. The positioning tolerance of the top plate and lower plate cannot be more than 0.02mm, with the top plate moving up and down.

The Assembly Mating Map presents the assembled parts mating relationship and the associated parts features assembly mating requirements. This lays the foundation for the selection of the critical features and the critical assembly path. Fig. 11 shows the geometric characteristic symbol of "Feature Control Frame" and the method of representing the fitting condition of the assembly.

All symbols of Feature Control Frame are created based on adaptation from ASME Y14.5M [1] and a detail description follows:

a : Geometric Characteristic Symbol:

This is based on ASME Y14.5M dimensioning and tolerancing standard, geometric tolerance symbol to represent the geometric characteristic symbol of the assembled feature. The clear representation structure shows the geometric requirement of each assembly feature.

b : Positioning requirement Symbol:

It shows the positioning tolerance between design datum and assembly feature. It is designed so that, if the drawing datum is identical to this feature, we use symbol "D" to represent. However, if the position tolerance is not specified on this feature, we use symbol "N" to represent.

c : First Positioning tolerance limit for mating feature:

The first positioning tolerance limit of the relevant feature.

d : Second position tolerance limit for mating feature:
The second positioning tolerance limit of the relevant feature.

e : Feature Number:
An assigned number to identify each assembly feature for each assembled part.

f : First Positioning tolerance limit for mating feature:
The first positioning tolerance limit of the relevant feature.

g : Second position tolerance limit for mating feature:
The second positioning tolerance limit of the relevant feature.

h : Mating part name:
The part name for the assembled feature.

i : Mating Feature ID:
The feature ID for assembled feature.

j : Fitting requirement:
The fit requirement for the assembly feature; we use letter "C" to represent clearance fit, "P" to represent press fit and "T" to present transition fit.

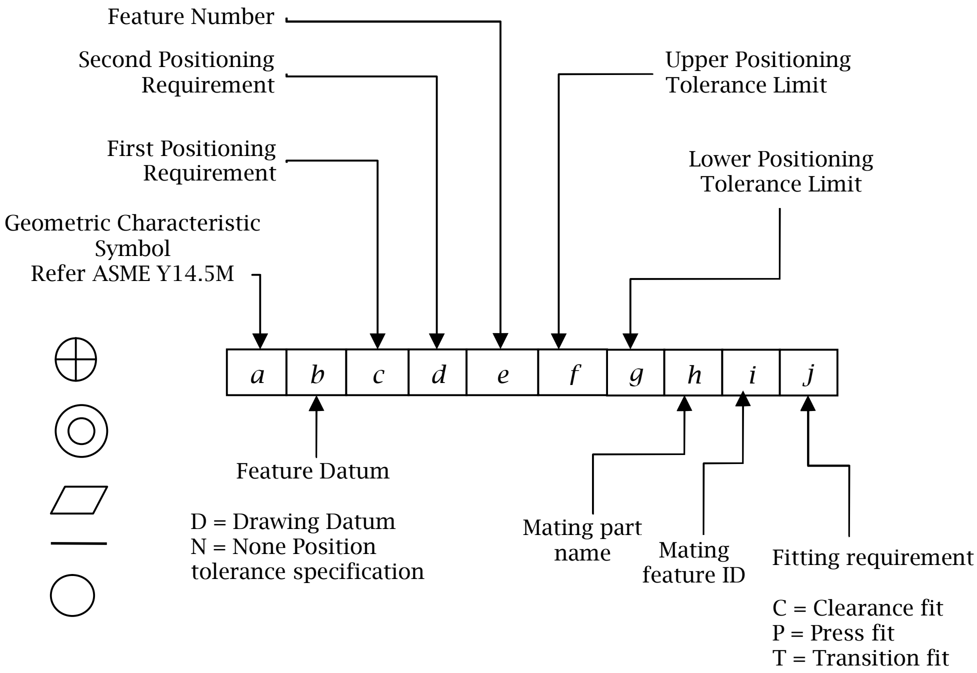

Fig. 11: Symbol for Assembly Mating Map to represent assembly mating relationship.

3.1.2 Construct Assembly Mating Map

To construct "Assembly Mating Map", we need to be clear about the assembled structure of all the assembled parts. Fig. 12 shows the assembly flow chart for case study, which basically includes two sub-assemblies; "Top plate sub-assembly and Lower plate sub-assembly". Each sub-assembly includes four guide bushes for the upper plate and four guide pins for the lower plate. Finally to assemble the two plates together, guide pin and guide bushes are used to maintain the movement position within the design specification.

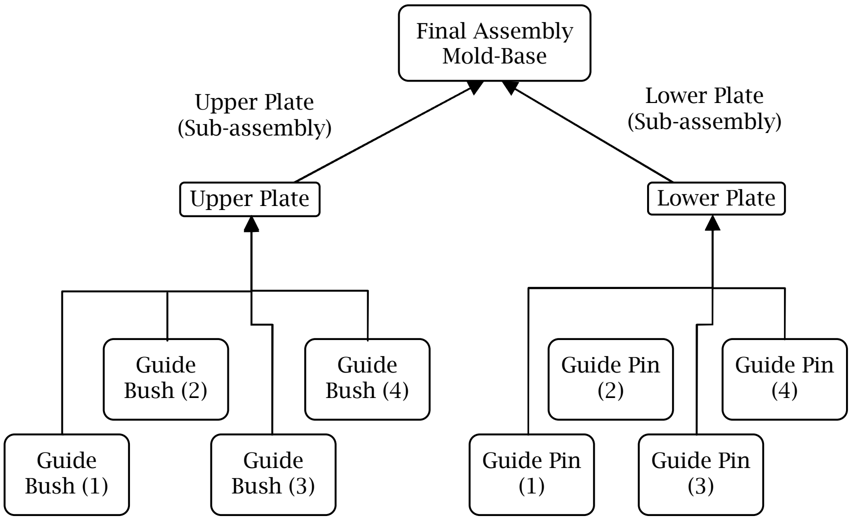

Fig.12: Assembly flow chart for mold-base.

1. The first step is input all the part tolerance specification values to "Feature Control Frame". Fig. 13 shows the example of the Top Plate. This refers to Tab. 5 dimension and tolerance values for construction. The first row shows the feature ID T1 values to represent the tolerance requirement in this mold-base assembly. The first column represents positioning requirement of "T1", the second column represents T1 having the design datum requirement. The third and forth columns represent positioning tolerances ±0.01mm of first position and ±0.01mm of second positioning tolerance based on the design datum A and B. The fifth column represents the given feature ID and sixth and seventh columns represent the geometric tolerance +0.01mm and -0.02mm. The eighth to tenth columns represent the information of the mating feature and included part names, feature ID and fitting requirement with transition fit.

Top Plate									
⊕	D	0.01	0.01	T1	+0.01	-0.02	G-bush(1)	B11	T
⊕	D	0.1	0.1	T2	+0.2	+0.1	G-bush(1)	B12	C
⊕	D	0.01	0.01	T3	+0.01	-0.02	G-bush(2)	B21	T
⊕	D	0.1	0.1	T4	+0.2	+0.1	G-bush(2)	B22	C
⊕	D	0.01	0.01	T5	+0.01	+0.02	G-bush(3)	B31	T
⊕	D	0.1	0.1	T6	+0.2	+0.1	G-bush(3)	B32	C
⊕	D	0.01	0.01	T7	+0.01	+0.02	G-bush(4)	B41	T
⊕	D	0.1	0.1	T8	+0.2	+0.1	G-bush(4)	B42	C

Fig.13: Construct feature control frame for Top plate.

2. After finishing the ”Feature Control Frame” for each assembled part, the second step is to group the “Feature Control Frame” for each sub-assembly parts together and use a solid-line to link each mating feature. Fig. 14 shows the construction result of “Feature Control Frame” for top plate and four guide bushes Sub-Assembly. Inside the “Feature Control Frame” is shown some of the assembly features using a solid-line to link the mating feature of other assembled parts. For example: the guide bush feature ID B11 is mating to the top plate T1 feature with transition fit. The benefit of this is that we clearly see the assembly data structure of each sub-assembly parts, included the fitting condition and tolerance specification of each assembly feature.

3. The final step to construct “Assembly Mating Map” integrate all “Feature Control Frame” together and use a solid-line to link the relating mating features. Then evaluate the “Critical Assembly Loop” before moving forward to establish the common measuring datum. Fig. 15 shows the “Assembly Mating Map” for mold-base case study. Basically, this contains two sub-assembly parts and four important mating features shown with a red solid-line. It should be a potential “Critical Assembly Loop” feature for the next step evaluation.

Guide Bush (2)									
◎	D	0.005	0.005	B21	+0.01	-0.01	Up-plate	T3	T
◎	D	0.1	0.1	B22	+0.2	-0.2	Up-plate	T4	C
◎	D	0.005	0.005	B23	+0.01	-0.01			C
Guide Bush (1)									
◎	D	0.005	0.005	B11	+0.01	-0.01	Up-plate	T1	T
◎	D	0.1	0.1	B12	+0.2	-0.2	Up-plate	T2	C
◎	D	0.005	0.005	B13	+0.01	-0.01			C
Top Plate									
⊕	D	0.01	0.01	T1	+0.01	-0.02	G-bush(1)	B11	T
⊕	D	0.1	0.1	T2	+0.2	+0.1	G-bush(1)	B12	C
⊕	D	0.01	0.01	T3	+0.01	-0.02	G-bush(2)	B21	T
⊕	D	0.1	0.1	T4	+0.2	+0.1	G-bush(2)	B22	C
⊕	D	0.01	0.01	T5	+0.01	+0.02	G-bush(3)	B31	T
⊕	D	0.1	0.1	T6	+0.2	+0.1	G-bush(3)	B32	C
⊕	D	0.01	0.01	T7	+0.01	+0.02	G-bush(4)	B41	T
⊕	D	0.1	0.1	T8	+0.2	+0.1	G-bush(4)	B42	C
Guide Bush (3)									
◎	D	0.005	0.005	B31	+0.01	-0.01	Up-plate	T5	T
◎	D	0.1	0.1	B32	+0.2	-0.2	Up-plate	T6	C
◎	D	0.005	0.005	B33	+0.01	-0.01			C
Guide Bush (4)									
◎	D	0.005	0.005	B41	+0.01	-0.01	Up-plate	T7	T
◎	D	0.1	0.1	B42	+0.2	-0.2	Up-plate	T8	C
◎	D	0.005	0.005	B43	+0.01	-0.01			C

Fig. 14: Feature Control Frame for Top Plate and four guide bushes Sub-Assembly.

Guide Pin(2)									
◎	D	0.002	0.002	P21	+0.01	-0.01	L-plate	L3	T
◎	D	0.1	0.1	P22	+0.1	-0.1	L-plate	L4	C
Guide Pin(1)									
◎	D	0.002	0.002	P11	+0.01	-0.01	L-plate	L1	T
◎	D	0.1	0.1	P12	+0.1	-0.1	L-plate	L2	C
Lower Plate									
⊕	D	0.01	0.01	L1	+0.01	-0.01	G-pin(1)	P11	T
⊕	D	0.1	0.1	L2	+0.2	-0.2	G-pin(1)	P12	C
⊕	D	0.01	0.01	L3	+0.01	-0.01	G-pin(2)	P21	T
⊕	D	0.1	0.1	L4	+0.2	-0.2	G-pin(2)	P22	C
⊕	D	0.01	0.01	L5	+0.01	+0.01	G-pin(3)	P31	T
⊕	D	0.1	0.1	L6	+0.2	-0.2	G-pin(3)	P32	C
⊕	D	0.01	0.01	L7	+0.01	+0.01	G-pin(4)	P41	T
⊕	D	0.1	0.1	L8	+0.2	-0.2	G-pin(4)	P42	C
Guide Pin(3)									
◎	D	0.002	0.002	P31	+0.01	-0.01	L-plate	L5	T
◎	D	0.1	0.1	P32	+0.1	-0.1	L-plate	L6	C
Guide Pin(4)									
◎	D	0.002	0.002	P41	+0.01	-0.01	L-plate	L7	T
◎	D	0.1	0.1	P42	+0.1	-0.1	L-plate	L8	C

Guide Bush (2)									
◎	D	0.005	0.005	B21	+0.01	-0.01	Up-plate	T3	T
◎	D	0.1	0.1	B22	+0.2	-0.2	Up-plate	T4	C
◎	D	0.005	0.005	B23	+0.01	-0.01	G-pin(2)	P21	C
Guide Bush (1)									
◎	D	0.005	0.005	B11	+0.01	-0.01	Up-plate	T1	T
◎	D	0.1	0.1	B12	+0.2	-0.2	Up-plate	T2	C
◎	D	0.005	0.005	B13	+0.01	-0.01	G-pin(1)	P11	C
Top Plate									
⊕	D	0.01	0.01	T1	+0.01	-0.02	G-bush(1)	B11	T
⊕	D	0.1	0.1	T2	+0.2	+0.1	G-bush(1)	B12	C
⊕	D	0.01	0.01	T3	+0.01	-0.02	G-bush(2)	B21	T
⊕	D	0.1	0.1	T4	+0.2	+0.1	G-bush(2)	B22	C
⊕	D	0.01	0.01	T5	+0.01	+0.02	G-bush(3)	B31	T
⊕	D	0.1	0.1	T6	+0.2	+0.1	G-bush(3)	B32	C
⊕	D	0.01	0.01	T7	+0.01	+0.02	G-bush(4)	B41	T
⊕	D	0.1	0.1	T8	+0.2	+0.1	G-bush(4)	B42	C
Guide Bush (3)									
◎	D	0.005	0.005	B31	+0.01	-0.01	Up-plate	T5	T
◎	D	0.1	0.1	B32	+0.2	-0.2	Up-plate	T6	C
◎	D	0.005	0.005	B33	+0.01	-0.01	G-pin(3)	P31	C
Guide Bush (4)									
◎	D	0.005	0.005	B41	+0.01	-0.01	Up-plate	T7	T
◎	D	0.1	0.1	B42	+0.2	-0.2	Up-plate	T8	C
◎	D	0.005	0.005	B43	+0.01	-0.01	G-pin(4)	P41	C

Fig. 15: Assembly Mating Map for Mold-Base.

3.1.3 Critical Assembly Loop Selection

As a result of the “Assembly Mating Map”, all assembled components have features mating to another assembled component. Some mating structures are closed loops in the “Assembly Mating Map”. This is a potentially Critical Assembly Loop in this assembly model, identifying the critical assembly loop of this assembly model. “Total Tolerance Differential Variation Algorithm” is proposed to identify the selection of the “Critical Assembly Loop”.

In selection of the Critical Assembly Loop of the assembled model, we use “Total Tolerance Differential Variation algorithm” to calculate the total tolerance variation of each assembly loop features. The “Critical Assembly loop” would be the minimum value of $Tdf_{(n)}$.

The equation structure “Total Tolerance Differential Variation Algorithm” is calculated from the feature radial ”$Df_{(n)}$” of between tolerance range “$Tq_{(n)}$” and feature dimension “$Df_{(n)}$”, then sum all feature radial “$TDf_{(n)}$” with equation (3). The minimum value of “$TDf_{(n)}$” is the “Critical Assembly Loop”.

$Tq_{(n)}$ = Feature tolerance variation
USL = Upper size limit
LSL = Lower size limit
$Fd_{(n)}$ = Feature Dimension
$Df_{(n)}$ = Differential variation of features
$TDf_{(n)}$ = Tolerance differential variation of features

The tolerance variation follows:

$$Tq_{(n)} = |USL - LSL| \tag{1}$$

The Tolerance Differential Variation of feature:

$$Df_{(n)} = \frac{Tq_{(n)}}{Fd_{(n)}} \tag{2}$$

The Total Tolerance Differential Variation of Critical Assembly Loop:

$$TDf_{(n)} = \sum_{n=1}^{n=x} \frac{Tq_{(n)}}{Fd_{(n)}} \tag{3}$$

In this case study, there are four potential "Critical Assembly Loops". The detail assembly structure (feature) of each potential assembly loop is as follows:

Feature ID T1 + Feature ID B11 + Feature ID B13 + Feature ID P11 + Feature ID L1

Potential critical assembly loop (1).

Feature ID T3 + Feature ID B21 + Feature ID B23 + Feature ID P21 + Feature ID L3

Potential critical assembly loop (2).

Feature ID T5 + Feature ID B31 + Feature ID B33 + Feature ID P31 + Feature ID L5

Potential critical assembly loop (3).

Feature ID T7 + Feature ID B41 + Feature ID B43 + Feature ID P41 + Feature ID L7

Potential critical assembly loop (4).

Refer to required features dimensioning and tolerancing values of four potential "Critical Assembly Loops". We substitute those data to equation (3) "Total Tolerance Differential Variation Algorithm" to calculate each TDF value and select the minimum value of "Critical Assembly Loop".

Calculating the result and comparing with the result of all the TDF values, Critical Assembly Loop (1) is minimum value "0.04977" (Tab. 16), therefore the feature ID "T1" for top plate, "B11" or "B13" for Guide Bush, "P11" for Guide pin and "L1" for lower plate is the "Common Measuring Datum" of each assembled part.

Feature ID	*USL*	*LSL*	*Tq*	*Fd*	*TDf*
T1	-0.01	-0.02	0.01	19.99	0.0005
B11	0.01	-0.01	0.02	16.97	0.001252
B13	0.01	-0.01	0.02	17.00	0.00125
P11	0.01	-0.01	0.02	15.97	0.001252
L1	0.01	-0.01	0.02	23	0.00087
				TDf(n)	***0.004977***

Tab. 16: *TDf* calculated result of Potential Critical Assembly Loop (1).

Feature ID	*USL*	*LSL*	*Tq*	*Fd*	*TDf*
T3	-0.01	-0.02	0.01	19.99	0.0005
B21	0.01	-0.01	0.02	15.97	0.001252
B23	0.01	-0.01	0.02	16.00	0.00125
P21	0.01	-0.01	0.02	15.97	0.001252
L3	0.01	-0.01	0.02	23	0.00087
				TDf(n)	***0.005125***

Tab. 17: *TDf* calculated result of Potential Critical Assembly Loop (2).

Feature ID	*USL*	*LSL*	*Tq*	*Fd*	*TDf*
T5	-0.01	-0.02	0.01	19.99	0.0005
B31	0.01	-0.01	0.02	15.97	0.001252
B33	0.01	-0.01	0.02	16.00	0.00125
P31	0.01	-0.01	0.02	15.97	0.001252
L5	0.01	-0.01	0.02	23	0.00087
				TDf(n)	***0.005125***

Tab. 18: *TDf* calculated result of Potential Critical Assembly Loop (3).

Feature ID	*USL*	*LSL*	*Tq*	*Fd*	*TDf*
T5	-0.01	-0.02	0.01	19.99	0.0005
B31	0.01	-0.01	0.02	15.97	0.001252
B33	0.01	-0.01	0.02	16.00	0.00125
P31	0.01	-0.01	0.02	15.97	0.001252
L5	0.01	-0.01	0.02	23	0.00087
				TDf(n)	***0.005125***

Tab. 19: *TDf* calculated result of Potential Critical Assembly Loop (4).

4 CRITICAL ASSEMBLY PART SELECTION

Normally in a mechanical product, some components have impact on the functional result. Different precision areas can be devised to represent this. But, not all the assembled components have impact on the final result, which is the critical component of this product and is important to the manufacturing decision making of industry. The final part of "Vector Based Datum Transformation scheme" uses a calculating method to find the "Critical Assembly Part" to define a measurement strategy in the manufacturing process.

Inside the "Critical Assembly Loop", one assembly component would be the "Critical Assembly Part", therefore we consider all related assembly features of each assembly part of the dimensioning and feature tolerance to calculate the "Critical Assembly Part". Equation (7) $TDpxy_{(n)}$ and (8) $TDfxy_{(n)}$ calculate the Total of position tolerance rate and feature tolerance rate of each assembly part. After that, we use equation (9) to find out the total rate of *"CAP"*.

Finally, selection of the assembly part with minimum *"CAP"* value is a "Critical Assembly Part" of the study assembly model. In this case study, the top and lower plate are potentially the "Critical Assembly Part" and through equation (9) we calculate which parts have minimum *"CAP"* value with details shown in tab. 24 and 25.

$Pq_{(n)}$ = Positioning tolerance variation

$Pqx_{(n)}$ = Feature tolerance variation of X-axis

$Pqy_{(n)}$ = Feature tolerance variation of Y-axis

$Pd_{(n)}$ = Positioning Dimension

$Pdx_{(n)}$ = Positioning Dimension of X-axis

$Pdy_{(n)}$ = Positioning Dimension of Y-axis

$TDf_{(n)}$ = Total tolerance differential variation of feature

$TDp_{(n)}$ = Total position tolerance differential variation

$TDpx_{(n)}$ = Total position tolerance differential variation of X-axis

$TDpy_{(n)}$ = Total position tolerance differential variation of Y-axis

$TDpxy_{(n)}$ = Total positioning tolerance differential variation of two-dimension

$TDfxy_{(n)}$ = Total features tolerance differential variation of two-dimension

Fn = Number of feature in the assembled component

CAP = Critical Assembly Part

The Tolerance Differential Variation of position:

$$TDp_{(n)} = \frac{Pq_{(n)}}{Pd_{(n)}} \tag{4}$$

Position tolerance Differential Variation of X-axis:

$$TDpx_{(n)} = \frac{Pqx_{(n)}}{Pdx_{(n)}} \tag{5}$$

Position tolerance Differential Variation of Y-axis:

$$TDpy_{(n)} = \frac{Pqy_{(n)}}{Pdy_{(n)}} \tag{6}$$

Total positioning tolerance Differential Variation of two-dimension:

$$TDpxy_{(n)} = \left(\frac{Pqx_{(n)}}{Pdx_{(n)}}\right) + \left(\frac{Pqy_{(n)}}{Pdy_{(n)}}\right) \tag{7}$$

Total features tolerance Differential Variation of two-dimension:

$$TDfxy_{(n)} = \left(\frac{Tqx_{(n)}}{Fdx_{(n)}}\right) + \left(\frac{Tqy_{(n)}}{Fdy_{(n)}}\right) \tag{8}$$

The “Critical Assembly Part” is defined by:

$$CAP = \frac{\sum_{n=1}^{n=x} TDpxy_{(n)} + \sum_{n=1}^{n=x} TDfxy_{(n)}}{Fn} \tag{9}$$

Tab. 20 and 21 use “Vector Based Differential Tolerance Variation algorithm” to find out “Critical Assembly Part” in this study. Referring to the calculated result, the Top Plate is minimum *CAP* value 0.0002013 compared with the Lower Plate *CAP* 0.0002284. Therefore, the Top Plate is the “Critical Assembly Part” in this case study.

Feature No.	*TDfxy*	*TDpxy*
T1	2.5025E-07	1.30612E-08
T2	1.89036E-05	1.30612E-08
T3	2.5025E-07	9.14286E-08
T4	1.89036E-05	9.14286E-08
T5	2.5025E-07	0.00000064
T6	1.89036E-05	0.000064
T7	2.5025E-07	9.14286E-08
T8	1.89036E-05	9.14286E-08
Sum	7.66154E-05	8.44278E-05
CAP		**0.0002013**

Tab. 20: Calculate the Critical Assembly Part for Top Plate.

Feature No.	*TDfxy*	*TDpxy*
T1	1.56641E-06	9.14286E-08
T2	0.000434028	9.14286E-08
T3	1.56641E-06	1.30612E-08
T4	0.000434028	1.30612E-08
T5	1.56641E-06	9.14286E-08
T6	0.000434028	9.14286E-08
T7	1.56641E-06	0.00000064
T8	0.000434028	0.000064
Sum	0.001742377	8.44278E-05
CAP		**0.0002284**

Tab. 21: Calculate the Critical Assembly Part value of Lower plate.

5 CONCLUSION

In a common product development cycle, design, manufacturing, inspection and assembly are the critical functional activities. The current research focuses on establishing the data communication linkage between different stages. Therefore, CAD/CAM/CAE systems can be used to support product design and manufacturing. In this proposal, "Vector Based Differential Tolerance Variation scheme" is proposed to develop an enhanced measuring and manufacturing strategy in order to improve the tolerancing control and ability to assemble a final product. The following are the major contributions of this research:

- Standardized methodology in defining the measuring strategy to stabilize quality control procedures and minimize human mistakes is proposed. The defined common datum relates to the function of product application.
- An efficient assembly data structure representation scheme to include the fitting and dimensioning and tolerancing requirement of assembled parts is proposed.
- Using "Assembly Mating Map" and "Vector Based Differential Tolerance Variation Scheme" can define the "Critical Assembly Loop" and "Critical Assembly Part" systematically, which is based on the dimensioning and tolerancing functional applications to develop measuring and production process planning in order to increase the ability to assemble a final product.
- Proposed scheme is sutable for regular object in define the measuring strategy. The non-regular feature, such as freeform object would be for development in future research.

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