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Tolerance Stack-up Analysis on Pipette Tips Loader Machine Using Standard ASME Y14.5-2018

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ABSTRACT

Pipette tips are used as a research tool related to liquid chemicals. Pipette tips are produced using the injection molding manufacturing process. At PT. Promanufacture Indonesia Salatiga, the transfer of every 96 pipette tips that come out of the injection molding machine is done manually into one caddy within a range of 8-10 minutes. After transfer, the pipette tips continue the printing and filtering manufacturing process. This scientific journal discusses the analysis using the DFMA method in designing an automated machine that shortens the time to insert pipette tips into the caddy within a range of less than 5 minutes. Design for Manufacturing and Assembly (DFMA) is an engineering methodology that focuses on reducing assembly time and total production costs by prioritizing manufacturing ease for product parts and simplified assembly parts into the final product. The machine design previously carried out by the Pahl and Beitz design method. In this journal, DFMA is carried out using the Stack-up tolerance analysis method. With the DFMA analysis of the machine, it will simplify the manufacturing and assembly stages when realizing the machine design. The components analyzed are critical components of the tool referring to the ASME Y14.5-2018 standard. The DFMA analysis in this scientific journal was performed using Solidworks 2021 application accompanied by the steps using the software. The output of the DFMA analysis in this journal is the manufacturability and assembly aspects of the pipette tip refill machine.

Key Words: Pipette Tips, DFMA, GD&T, Stack-up Tolerance.

1. INTRODUCTION

Design for Manufacturing and Assembly (DFMA) is a design method that considers assembly and manufacturability during the design phase for product development. The DFMA method focuses on improving the ease of manufacturing and assembly of products and their components by simplifying them. DFMA combines the outcomes of Design for Manufacturing (DFM) and Design for Assembly (DFA). Design for Assembly (DFA) is a technique to facilitate product assembly, estimate assembly costs, and assembly time. Design for Manufacturing (DFM) is a technique to design parts that facilitate manufacturing. In short, Design for Manufacturing and Assembly is a systematic process aimed at helping industries maximize the use of current manufacturing processes for a product or assembly and reduce the number of product parts to the smallest possible quantity. Additionally, DFMA also minimizes assembly effort, assembly time, and assembly costs for future improvements [1].

Tolerance stack-up analysis is a method used to determine the cumulative effects of allocated tolerances on features of a component and to ensure that the cumulative effects are acceptable to ensure product functionality after the assembly process [2]. The tolerance stack-up analysis method is generally divided into two basic methods: worst-case (WC) analysis and statistical-based analysis, also known as the root sum of the square (RSS) method. The combination of WC and RSS methods gives rise to the modified root sum of the square (MRSS) method. The comparison of these three methods is based on the aspect of production defect risk: WC method has the lowest risk, followed by MRSS, and RSS has the highest risk. However, when considering costs, the situation is reversed, where the WC method is the most expensive, and RSS is the least expensive.

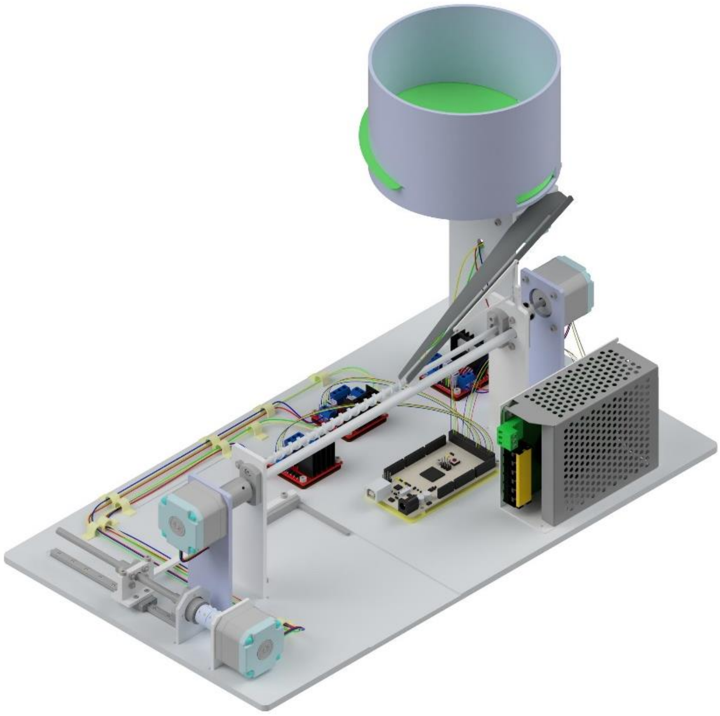

Figure 1. Pipette Tips Loader Machine

This machine utilizes a custom-made screw conveyor and gate cylinder to feed pipette tips (Figure 1). Components directly involved in the assembly process of these two components will undergo tolerance analysis of their dimensions and geometry. This is done to ensure that the worst-case manufacturing variations do not interfere with the assembly process. By conducting stack-up tolerance analysis, it will help identify suitable tolerances that do not hinder the performance of the machine.

2. MATERIAL AND METHODOLOGY

There are three functions of the components in the pipette tip refilling machine, as explained earlier. Only the components involved in the assembly function will be analyzed. The list of components from the previous design can be seen in Figure 2. The tolerance analysis process is conducted after completing the mechanical design stage and before entering the manufacturing process.

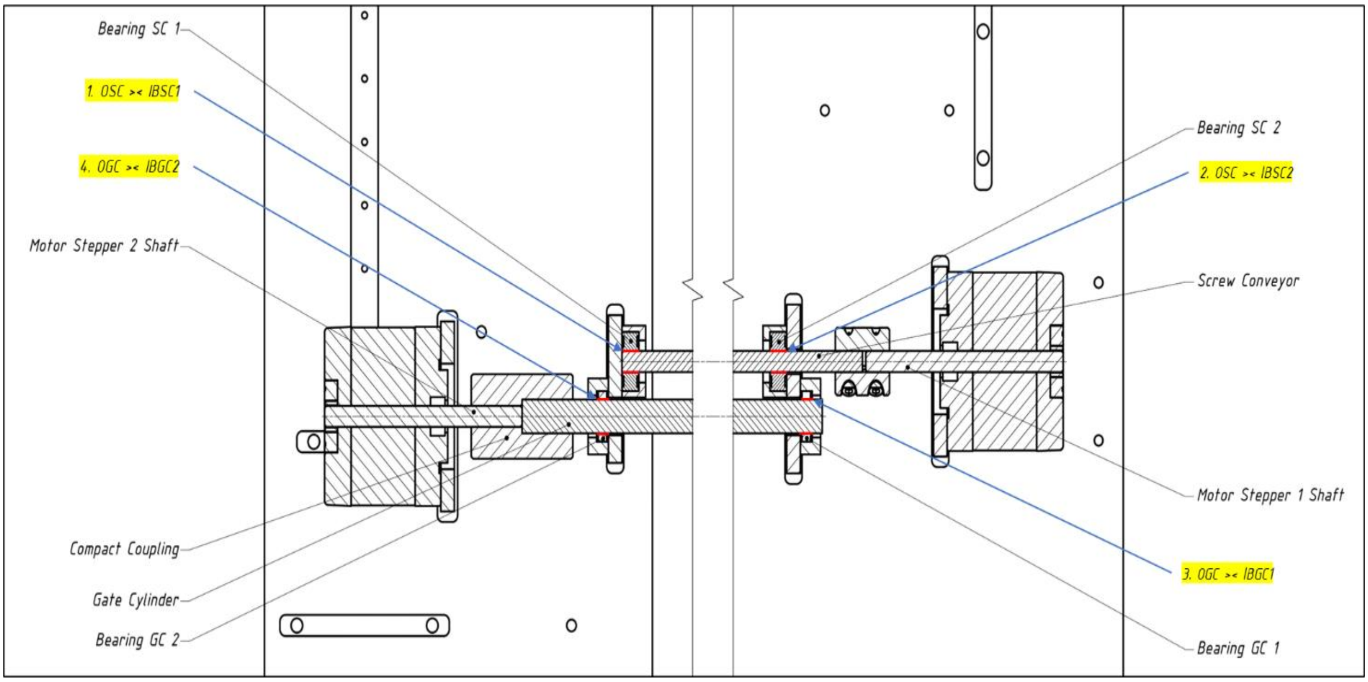

Figure 2. Component Features Identification

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The tolerance analysis of the prototype design for the pipette tip refilling machine is conducted in two stages: the identification stage and the analysis and calculation stage. The identification stage (first stage) is carried out to determine the features of the components that contribute to the main characteristics. The second stage, which is the analysis and calculation stage, is performed to ensure the cumulative effect of each allocated tolerance on the component features that contribute to the main characteristics, in accordance with the allowable requirements.

2.1 Tolerance Chain

The workpiece lane (pipette tips lane) is the main characteristic (MC) that structurally lies between the diameter of the screw conveyor shaft and the diameter of the gate cylinder shaft. The analysis of tolerance value propagation affecting the main characteristic can be identified from the relationships among the component features. The series of component features along with their interrelationships can be seen in Figure 2. The red lines in the figure represent direct interconnections between component features, while the blue line indicates the main characteristic of this analysis.

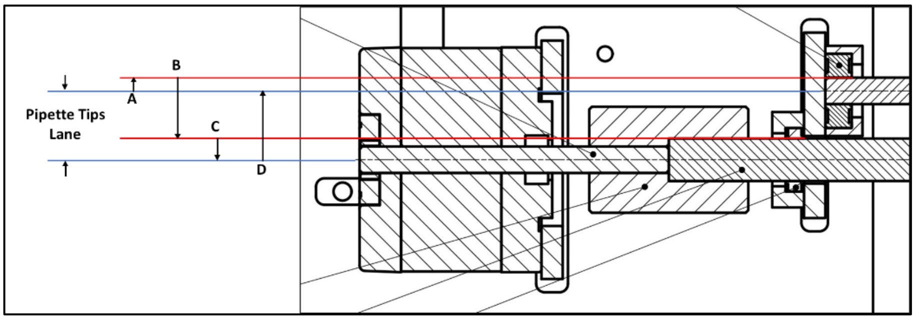

Figure 3. Loop Diagram Analysis of Pipette Tips Loader

The blue line in the figure represents the main characteristic of this analysis, which is the pipette tips lane. There are four adjustments in the assembly of the assembly function. The first adjustment is the outer surface feature of the screw conveyor (OSC) with the inner surface feature of the SC 1 bearing (BSC1). The second adjustment is the outer surface feature of the screw conveyor (OSC) with the inner surface feature of the SC 2 bearing (BSC2). The third adjustment is the outer surface feature of the gate cylinder with the GC 1 bearing. The fourth adjustment is the outer surface feature of the gate cylinder with the GC2 bearing. The features of these related components must be controlled by allocating the appropriate dimensional tolerances and geometric tolerances.

Table 1. Tolerance Analysis Input Parameter

No	Component	Component's Feature	Value (mm)
1	**Screw Conveyor**	Diameter of surface that interacts with surface of SC (OSC) bearing inner diameter	5
2	**Gate Cylinder**	Surface contact surface diameter GC bearing inner diameter (OGC)	8
3	**The distance between the SC axis and GC axis**	Allowable deviation between axles (KC)	± 0,4
4	**Tower A**	The distance between the screw conveyor holes and the horizontal side	26,5
		The distance between the screw conveyor holes and the vertical side	106
		Distance of Gate Cylinder hole to the horizontal side	13,5
		Distance of Gate Cylinder hole to the vertical side	106
5	**Tower B**	The distance between the screw conveyor holes and the horizontal side	24
		The distance between the screw conveyor holes and the vertical side	106
		Distance of Gate Cylinder hole to the horizontal side	11
		Distance of Gate Cylinder hole to the vertical side	106
6	**Bearing SC**	Inside diameter of surface interacting with screw conveyor surface (IBSC1 and IBSC2)	5
7	**Bearing GC**	Inside diameter of surface interacting with surface of Gate Cylinder (IBGC1 and IBGC2)	8

The result of identifying the features of the components that contribute to the formation of the key characteristic (KC)is the establishment of an inter-component relationship scheme to create a loop diagram of the pipette tip gap. Figure 3 illustrates the loop diagram, which represents the closed graph of the propagation of each contribution from the components that make up the key characteristic (KC), which will be accumulated to obtain the value of the gap. In the diagram, it can be observed that there are

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four variables from A to D, which will be influenced by the tolerance values of the geometries and dimensions assigned to each related component feature.

2.2 Tolerance Allocation

The tolerance allocation process involves specifying the allowed requirements for the key characteristic (KC), in this case, the distance between the screw conveyor axis and the gate cylinder (pipette tip lane) for each affected component. The established tolerance consists of dimensional tolerance and geometric tolerance. According to Table 1, the permissible deviation of the axis distance (Δptl) is ± 0.4 mm. This value was obtained from previous design experiments. Based on previous research, with a pipette tip lane deviation of ± 0.4 mm, it ensures that the pipette tips will remain in a perfect position. If the allowable pipette tip lane requirement is 13 ± 0.4 mm, the overall dimensions and geometric tolerances associated with each additional component feature should be greater than 12.6 mm and less than 13.4 mm.

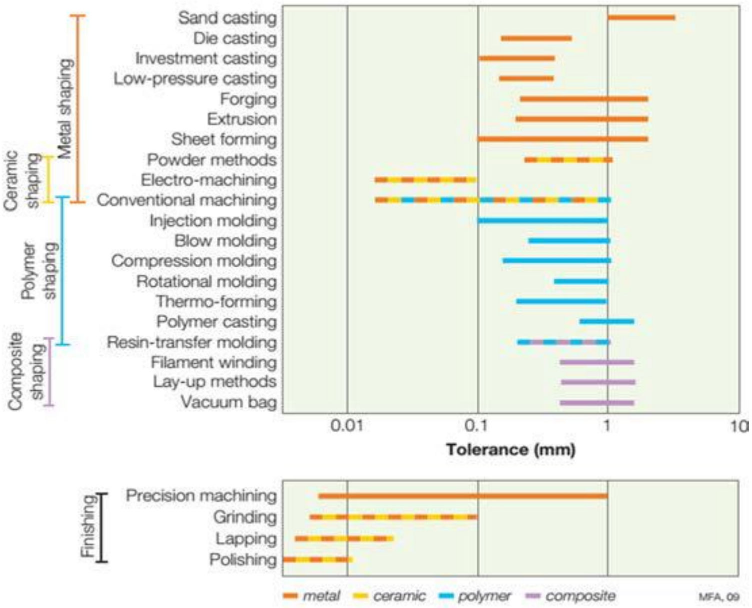

Figure 4. Tolerance Chart in Manufacturing Process Selection

The first step in establishing tolerance allocation is considering the production machine capability, particularly the machine's ability to meet the specified tolerance levels. Figure 4 illustrates a graph of the achievable tolerance values by several common manufacturing/machining processes. The gate cylinder is produced using lathe and milling machines, which have a minimum allocated tolerance value of 0.02 mm. The screw conveyor manufacturing process utilizes a lathe machine with precision up to 0.02 mm. Tower A and Tower B components are produced using CNC milling machines with precision up to 0.02 mm.

Table 2. Fits Types Between Component Features

No.	Fits		Function
	Feature	Type	
1.	OSC >< IBSC1	Transition fit	The screw conveyor shall be securely attached to Tower A via bearing SC1, with easy disassembly for maintenance purposes
2.	OSC >< IBSC2	Transition fit	The screw conveyor shall be securely attached to Tower B via the SC2 bearings, with easy disassembly for maintenance purposes
3.	OGC >< IBGC1	Transition fit	The gate cylinder shall be securely attached to Tower A via bearing GC1, easily removed for maintenance purposes
4.	OGC>< IBGC2	Transition fit	The gate cylinder shall be securely attached to Tower B via the GC2 bearings, easily removable for maintenance purposes

The second step in tolerance allocation involves determining the type of compatibility between the involved component characteristics based on their functions. Each type of assembly between the features of the affected components is specified in Table 2. Once each type of adjustment is known, the dimensional tolerance values for the corresponding features can be determined using the base hole system principle. All features are designated using transitional fits to ensure that the shaft can be securely fitted into the respective bearing holes, while considering ease of maintenance.

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The third step in tolerance allocation is allocating geometric tolerances to each component feature that contributes to the accumulation of tolerance in the key characteristics. When determining the type of geometric tolerance, two factors need to be considered: the pipette tip lane requirement and the assembly requirement between components in terms of geometry. Considering the pipette tip lane requirement, the rotational axis of the screw conveyor with the SC bearing should be aligned/coaxial. Similarly, the rotational axis of the gate cylinder with the GC bearing should be aligned/coaxial as well. From the perspective of component assembly, attention should be given to the tolerance of the shape, position, or location of the features that need to fit together.

2.3 Component Feature Deviation Analysis

The deviation analysis process is conducted by simulating the deviation of the contributing component features after dimensional and geometric tolerances have been allocated. Simulation is useful in facilitating calculations to determine variable values. The simulation process can be performed using any CAD (Computer Aided Design) software, but in this study, SolidWorks software is used. The TolAnalyst feature in SolidWorks is utilized to conduct the simulation. The simulation is performed only on the assembly of functional components. The success of the simulation relies on ensuring that the required steps align with the actual assembly process. The flowchart of the simulation process using TolAnalyst can be seen in Figure 5.

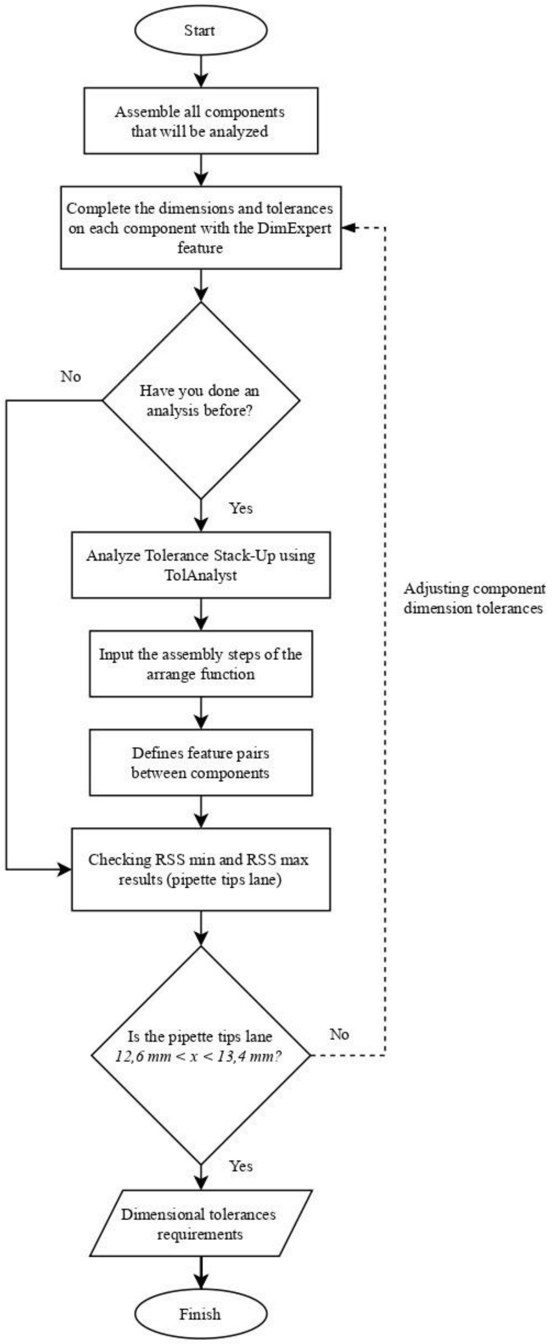

Figure 5. Flow chart of simulation work

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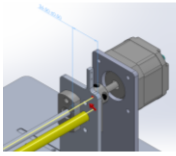
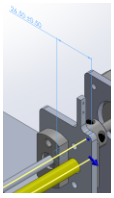
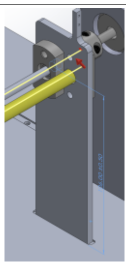
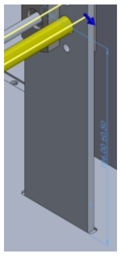
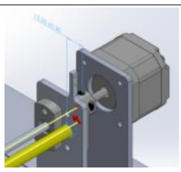
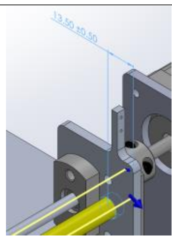
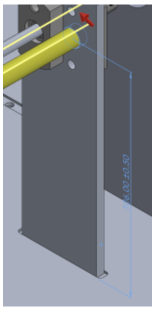
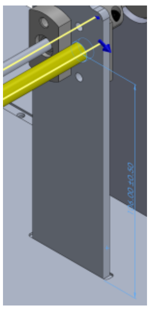
The first step in this simulation is to input the dimensions that affect the pipette tip lanes. Each component in the assembly goes through this stage. The second step is to assemble all the components by inserting suitable mates for the assembly process. Appropriate and sufficient mates are required to ensure that the simulation results are not interfered with. The third step is to use the TolAnalyst feature. In this step, the first thing to input is the values of key characteristics that need to be maintained. In this case, it is the center of the screw conveyor and the center of the gate cylinder. The fourth step is to input the assembly process in the order of the components that are assembled first. The fifth step is to establish the related features during the assembly process. Each component requires only one identification of the feature relationship between components (primary constraint). If two features are needed, the next feature is set as a secondary constraint or primary constraint 2. The sixth step is to check the minimum RSS (Root Sum of Squares) and maximum RSS values on the result page. If the minimum RSS is not above 12.6 mm and/or the maximum RSS is not below 13.4 mm, then it is necessary to make tolerance position changes on specific components. The result page provides information on the contribution of various features that affect the main characteristics. If the minimum RSS and maximum RSS are within the desired range, then the simulation can be considered complete.

3. RESULT AND DISCUSSION

The initial simulation yielded an RSS min value of 12.293 mm and an RSS max value of 13.707 mm (Table 3). Since the results are still not in line with the key characteristics, the positional tolerances of the components that contribute the most to the KC value are modified. A second simulation experiment is conducted to achieve the desired KC value by adjusting certain features.

Table 3. First simulation results

Minimum Contributor; RSS min 12,293			**Maximum Contributor; RSS maks 13,707**		
Feature	**Location**	**Tolerance**	**Feature**	**Location**	**Tolerance**
DistanceBetween16@Simple Hole10(26.5)@2C Tower 1-1		0,2	DistanceBetween16@Simple Hole10(26.5)@2C Tower 1-1		0,5
DistanceBetween17@Simple Hole10(106)@2C Tower 1-1		0,5	DistanceBetween17@Simple Hole10(106)@2C Tower 1-1		0,5
DistanceBetween18@Simple Hole11(13.5)@2C Tower 1-1		0,1	DistanceBetween18@Simple Hole11(13.5)@2C Tower 1-1		0,5
DistanceBetween19@Simple Hole11(106)@2C Tower 1-1		0,5	DistanceBetween19@Simple Hole11(106)@2C Tower 1-1		0,5

The second simulation resulted in an RSS min value of 12.776 mm and an RSS max value of 13.224 mm (Table 4). The RSS min value is already greater than 12.6 mm, and the RSS max value is smaller than 13.4 mm. In the second simulation, the tolerance for the feature "DistanceBetween16@Simple Hole10(26.5)@2C Tower 1-1" was changed from 0.5 mm to 0.2 mm. Additionally, the tolerance for the feature "DistanceBetween18@Simple Hole11(13.5)@2C Tower 1-1" was changed from 0.5 mm to 0.1 mm.

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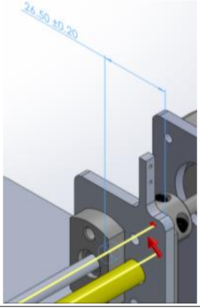
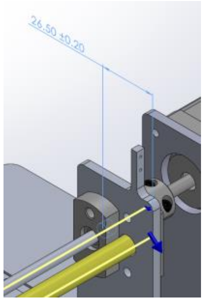
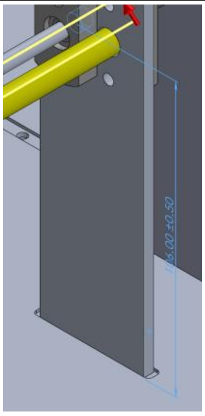
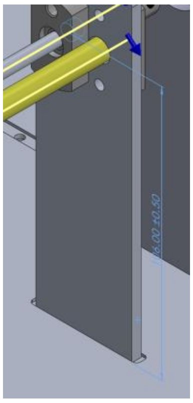
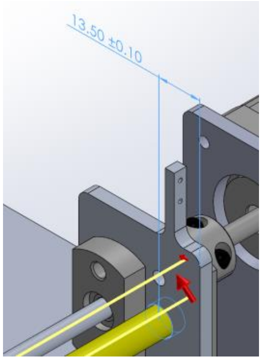
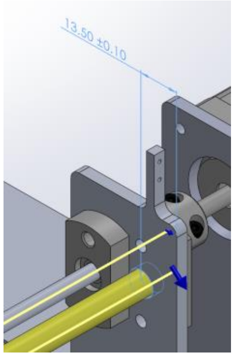
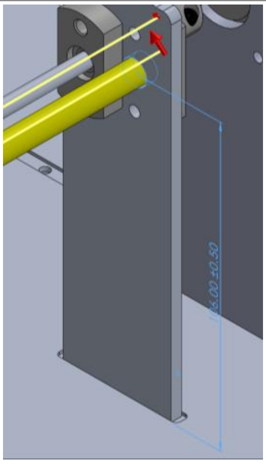
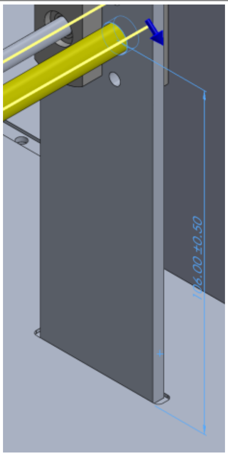
Table 4. Second simulation results

Minimum Contributor; RSS min 12,776			Maximum Contributor; RSS mkas 13,224		
Feature	**Location**	**Tolerance**	**Feature**	**Location**	**Tolerance**
DistanceBetween16@ Simple Hole10(26.5)@2C Tower 1-1		0,2	DistanceBetween16@ Simple Hole10(26.5)@2C Tower 1-1		0,2
DistanceBetween17@ Simple Hole10(106)@2C Tower 1-1		0,5	DistanceBetween17@ Simple Hole10(106)@2C Tower 1-1		0,5
DistanceBetween18@ Simple Hole11(13.5)@2C Tower 1-1		0,1	DistanceBetween18@ Simple Hole11(13.5)@2C Tower 1-1		0,1
DistanceBetween19@ Simple Hole11(106)@2C Tower 1-1		0,5	DistanceBetween19@ Simple Hole11(106)@2C Tower 1-1		0,5

The changes in tolerances during the tolerance stack-up analysis simulation were not significantly impactful. All custom components in the assembly of functional parts had a tolerance value of ±0.5 mm. From the simulation, only the Tower A component required tolerance adjustments in two different features, as mentioned earlier. However, these adjustments do not have a significant impact on the manufacturing process. One of the features in Tower A, with a positional tolerance of up to ±0.1 mm, can be manufactured using a CNC milling machine. To inspect the manufacturing results, a caliper capable of measuring up to 0.01 mm is sufficient.

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4. CONCLUSION

One of the efforts to ensure the functionality of the pipette tip refilling machine is through tolerance stack-up analysis. The analysis aims to maintain the distance between the screw conveyor shaft and the gate cylinder (pipette tip lane) as the key characteristic. The analysis is performed using SolidWorks software for simulation purposes. From the simulation, it is determined that the feature "DistanceBetween16@Simple Hole10(26.5)@2C Tower 1-1" was changed from 0.5 mm to 0.2 mm, and the feature "DistanceBetween18@Simple Hole11(13.5)@2C Tower 1-1" was changed from 0.5 mm to 0.1 mm (Figure 6). By adjusting the dimensional tolerances of these two features, a minimum RSS value of 12.776 mm and a maximum RSS value of 13.224 mm were obtained. With the assistance of the software, the assembly process can maintain the shaft distance within ±0.3 mm, which is 0.1 mm smaller than the expected value. Furthermore, the cost and time required to produce Tower A are not significantly affected.

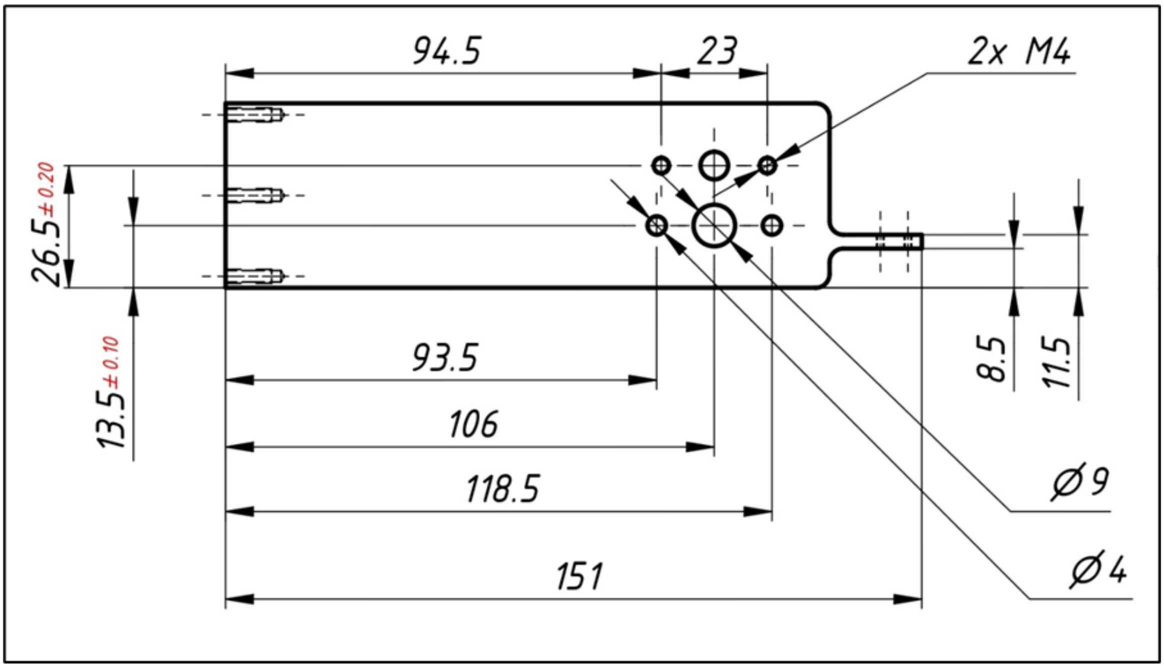

Figure 6. Dimensional tolerances requirements on component [4]

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