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Design of A Multi-Speed Pneumatic Linear Transfer System

Perancangan *Multi-Speed Pneumatic Linear Transfer System*

Didi Widya Utama*, Jason Waworuntu, Agus Halim, Agustinus Purna Irawan, Robin Averil, Satrio Tauladan, Kevin Raynaldo
Mechanical Engineering, Universitas Tarumanagara, Jakarta, Indonesia

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Abstract

One of the fastest-growing industries in this modern era is automation, with the goal of enhancing efficiency, productivity, and precision. In this context, production system automation is key to achieving these goals. This research reviews the use of pneumatic linear transfer systems in modern manufacturing industries that are oriented toward efficiency, productivity, and flexibility. This research uses the VDI 2221 method in conjunction with structured design approaches and pneumatic technology to design and construct a multi-speed pneumatic linear transfer system. New developments in the pick-and-place system allow it to accelerate for picking up objects and decelerate for placing them utilizing a pneumatic system. With an emphasis on enhancing production process efficiency, productivity, and flexibility, it is hoped that this research will significantly contribute to developing automation technology in the manufacturing sector. The FEA analysis results also show that this multi-speed pneumatic linear transfer system tool can safely accommodate the applied load.

Keywords: transfer system, pick-and-place, pneumatic, multispeed, VDI2221.

***SDGs*:**

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Abstrak

Salah satu industri dengan pertumbuhan tercepat di era modern ini adalah otomasi, dengan tujuan meningkatkan efisiensi, produktivitas, dan kepresisian. Dalam konteks ini, otomatisasi sistem produksi adalah kunci untuk mencapai tujuan tersebut. Penelitian ini mengulas penggunaan sistem transfer linier pneumatik pada industri manufaktur modern yang berorientasi pada efisiensi, produktivitas, dan fleksibilitas. Penelitian ini menggunakan metode VDI 2221 yang digabungkan dengan pendekatan desain terstruktur dan teknologi pneumatik untuk merancang dan membangun sistem transfer linier pneumatik multi kecepatan. Pengembangan dalam penelitian ini membahas sistem pick-and-place yang diakselerasi untuk mengambil benda dan diperlambat untuk menempatkannya menggunakan sistem pneumatik. Dengan penekanan pada peningkatan efisiensi, produktivitas, dan fleksibilitas proses produksi, penelitian ini diharapkan dapat memberikan kontribusi yang signifikan terhadap perkembangan teknologi otomasi di sektor manufaktur. Selain itu, hasil analisa elemen hingga menunjukkan bahwa multi-speed transfer system dapat secara aman mengakomodir beban yang terjadi.

Kata Kunci: sistem *transfer*, *pick-and-place*, pneumatik, multi kecepatan, VDI2221.

*Correspondence Author
email : didiu@ft.untar.ac.id

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1. INTRODUCTION

In this modern era, automation is one of the fastest-growing industries, with the aim of improving efficiency, productivity, and precision. The modern manufacturing industry demands operational excellence, high productivity, and flexibility in production processes to respond to increasingly complex and changing market demands. In this context, production system automation is key to achieving these goals.

The comparison between traditional mechanical automation systems and pneumatic systems reveals several drawbacks associated with the former, particularly in terms of efficiency, flexibility, and operational complexity. One significant drawback of mechanical automation systems is their inherent rigidity. Mechanical components can be bulky and heavy, leading to increased energy consumption and reduced speed of operation. In contrast, pneumatic systems offer a high power-to-weight ratio, allowing for faster and more efficient movement of components within automated processes (Li and Ding, 2023; Oliver *et al.*, 2023).

Pneumatic and hydraulic transfer systems are widely utilized in various industrial applications due to their efficiency and effectiveness in handling material movement and automation tasks. Pneumatic systems, which use compressed air to transmit power, are particularly prevalent in sectors such as automotive manufacturing, packaging, and robotics (Jamian *et al.*, 2020). They are favored for their lightweight components, high speed, and cleanliness, making them suitable for environments where contamination must be minimized (Cococi, Safta and Călinoiu, 2020).

In this research, the type of system that will be used is a linear transfer system with a pneumatic system. The transition from traditional relay-based automation systems to Programmable Logic Controllers (PLCs) offers significant advantages, primarily due to the inherent drawbacks of relay systems. One major limitation of relays is their lack of programmability; they function solely as switches, which restricts their ability to adapt to varying operational requirements.

In contrast, PLCs can be programmed to perform complex control tasks, allowing for greater flexibility and customization in automation processes (Christopher *et al.*, 2019; Brol, Czok and Mróz, 2020).

Additionally, relay systems are often cumbersome and complex, particularly in large-scale applications where numerous relays must be interconnected. This complexity can lead to increased installation time and difficulty in troubleshooting faults, as identifying issues within a network of relays can be time-consuming and inefficient (Miljević *et al.*, 2023). PLCs, on the other hand, simplify wiring and reduce the number of components needed, which enhances system reliability and ease of maintenance (Christopher *et al.*, 2019; Miljević *et al.*, 2023).

Pneumatic linear transfer systems rely on pneumatic principles to drive linear actuators that carry workpieces from one point to another in a production line (Kim, Yang and Kang, 2010). Used extensively in pick-and-place operations, these systems play a vital role in the process of assembling, moving, and placing workpieces (Tomokazu *et al.*, 2015; Papadakis *et al.*, 2020). While these systems have greatly contributed to improved efficiency and productivity, the challenge of achieving the ideal balance between speed, accuracy, and energy efficiency is still a major concern.

Therefore, the development of such a system requires a systematic and structured approach. Careful design and accurate calculations are required to achieve an optimal balance between speed, accuracy, and energy efficiency. In this context, the VDI 2221 method offers a reliable framework for designing and developing engineering systems holistically, considering various design and performance aspects.

This research aims to design and build a multi-speed pneumatic linear transfer system by combining pneumatic technology and a structured design approach such as the VDI 2221 method. This approach is expected to make a significant contribution to the development of automation technology in the manufacturing industry, with a focus on improving the efficiency, productivity, and flexibility of the production process.

2. METHODOLOGY

In this design, the VDI method (Verein Deutscher Ingenieure) 2221 is used to design the entire tool, and the Finite Element Analysis (FEA) simulation method to design the tool frame's structural elements.

VDI 2221 is a standard developed by a German engineering association that sets guidelines for the design of mechanical engineering systems (Jänsch and Birkhofer, 2006). This method aimed at creating a structured system. This design has the same vision and mission as the VDI 2221 method. The VDI 2221 method applied in this design is as follows (Pahl and Beitz, 2013): clarification of the task, conceptual design, embodiment design, and detail design (see Figure 1).

Figure 1. Workflow of the VDI 2221 (Pahl and Beitz, 2013).

This tool combination has several variations, so a sub-function table is needed to determine the right combination. Of course, as many combinations as possible can be made, but the solution taken is the product that produces the best quality and price. The Table 1 shown, the solution principles and combinations of solution principles from the design to be built. Based on that has been compiled in Table 1, it can be made into five variants which can be seen in Table 2.

In Table 2 there are five sub-functions and three variation options that can be combined into a particular variant. After considering the sub-functions and some of the Solution principles that have been chosen, several variants are made as shown in Table 2.

Based on Table 2, the following are the results of the variants obtained:

1. Variant 1 (V1): B1→A2→A3→A4→A5→A6→A7→A8→A9→A10 →A11
2. Variant 2 (V2): B1→B2→B3→B4→A5→A6→A7→B8→A9→A1 0→A11
3. Variant 3 (V3): A1→B2→B3→B4→A5→B6→B7→B8→B9→A10 →B11
4. Variant 4 (V4): B1→B2→B3→C4→B5→A6→A7→B8→A9→B1 0→A11
5. Variant 5 (V5): A1→A2→A3→A4→C5→B6→B7→B8→B9→B1 0→B11
6. Variant 6 (V6): C1→C2→C3→C4→B5→B6→A7→A8→A9→C1 0→C11

Table 1. Sub-function solution principle.

No	Sub-function \ Solution	A	B	C
1	Driver Type	Hydraulic	Pneumatic	Electric
2	Upper Frame Connection	Weld	Nut	Rivet
3	Lower Frame Connection	Weld	Nut	Rivet
4	Upper Frame Joint	Miter Joint	Butt Joint	Lap Joint
5	Bracket Support axis-X & axis-Z	Elbow	Plat	Anchor
6	Bracket Support for Upper & Lower Frame	Elbow	Plat	Anchor
7	Degree of Freedom	Dual-axis	3-axis	-
8	Frame Support System	One Support System	Two Support System	-
9	Gripper	2-Jaw Gripper	3-Jaw Gripper	-
10	Upper Frame Material	Mild Steel	Aluminum Profile 50x50	Stainless Steel
11	Lower Frame Material	Mild Steel	Aluminum Profile 50x50	Stainless Steel

Finite Element Analysis (FEA) simulation is a numerical method used to predict and analyze the structural response of an object to a specific load or force. There are various stages to get simulation results (Halim and Raynaldo, 2023), such as pre-processing: preparing a CAD model that has been designed and simplified, determining the material, setting boundary

Table 2. Combination principle solution sub function.

No	Solution / Sub-function	A	B	C
1	Driver Type	Hydraulic	Pneumatic	Electric
2	Upper Frame Connection	Weld	Nut	Rivet
3	Lower Frame Connection	Weld	Nut	Rivet
4	Upper Frame Joint	Miter Joint	Butt Joint	Lap Joint
5	Bracket Support axis-X & axis-Z	Elbow	Plat	Anchor
6	Bracket Support for Upper & Lower Frame	Elbow	Plat	Anchor
7	Degree of Freedom	Dual-axis	3-axis	-
8	Frame Support System	One Support System	Two Support System	-
9	Gripper	2-Jaw Gripper	3-Jaw Gripper	-
10	Upper Frame Material	Mild Steel	Aluminum Profile 50x50	Stainless Steel
11	Lower Frame Material	Mild Steel	Aluminum Profile 50x50	Stainless Steel

V1 V2 V3 V4 V5 V6

conditions, loads received, contact conditions on the component geometry, performing constraints, and meshing (mesh setting is general mesh due to iteration time); then processing: run the simulation to obtain simulation results and solutions; and post-processing: analyze the simulation results, verify, and get the conclusion of the simulation results.

In the research method, there is a research flow chart of the "Design of Multi-Speed Pneumatic Linear Transfer System", as Figure 2. The flowchart is an overview of the activities that will be carried out during the research. Research on this "Design of Multi-Speed Pneumatic Linear Transfer System" starts with conducting a literature study. After studying the existing literature, the process of identifying existing problems is carried out.

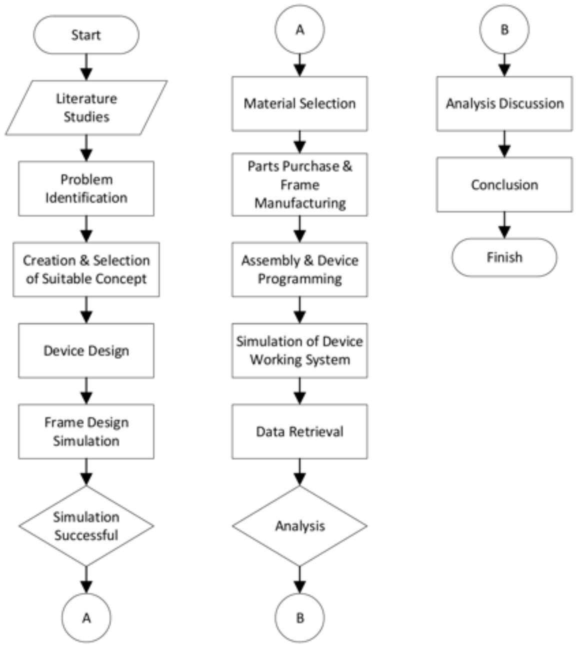

Figure 2. Research flowchart.

After that, the concept is made first, and after the concept is appropriate, the design of the tool is carried out using Autodesk Fusion 360 software. Then the selection of frame material and the determination of the type of components are carried out. Then purchase the components and make the frame. This is followed by the tool assembly process and tool programming, and then data collection is carried out related to the work system and tool functionality.

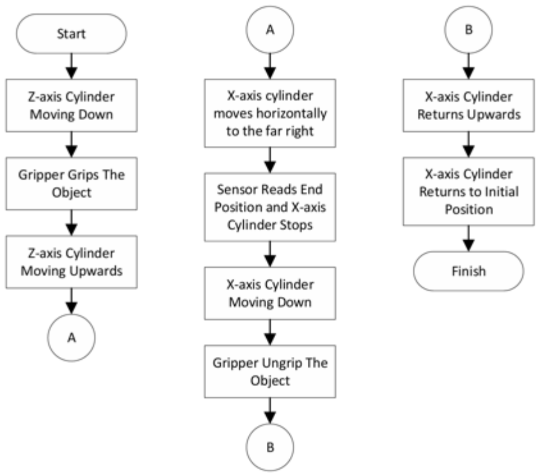

Figure 3. Flowchart of the tool's working system.

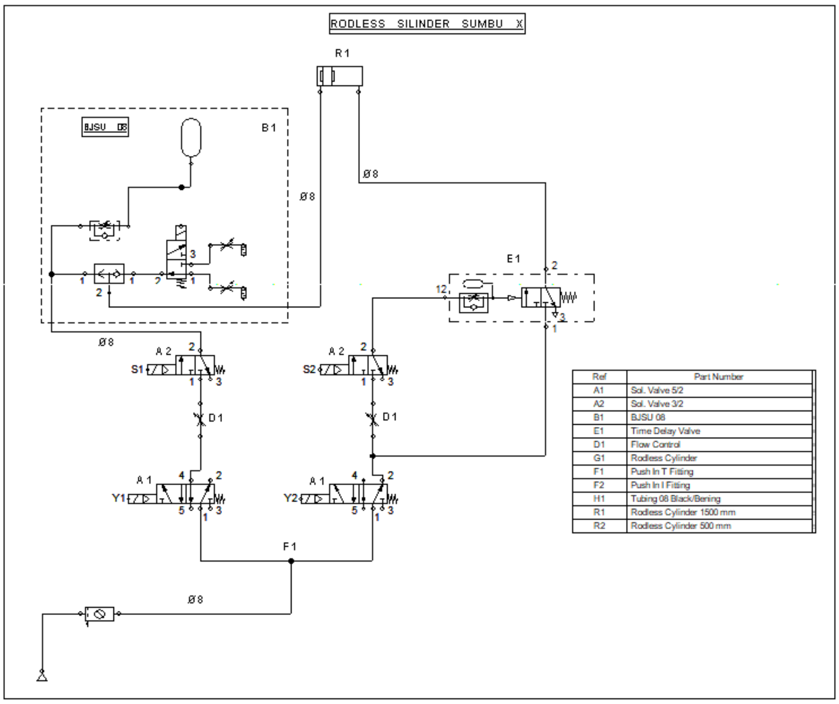

Figure 4. X-axis drive pneumatic diagram.

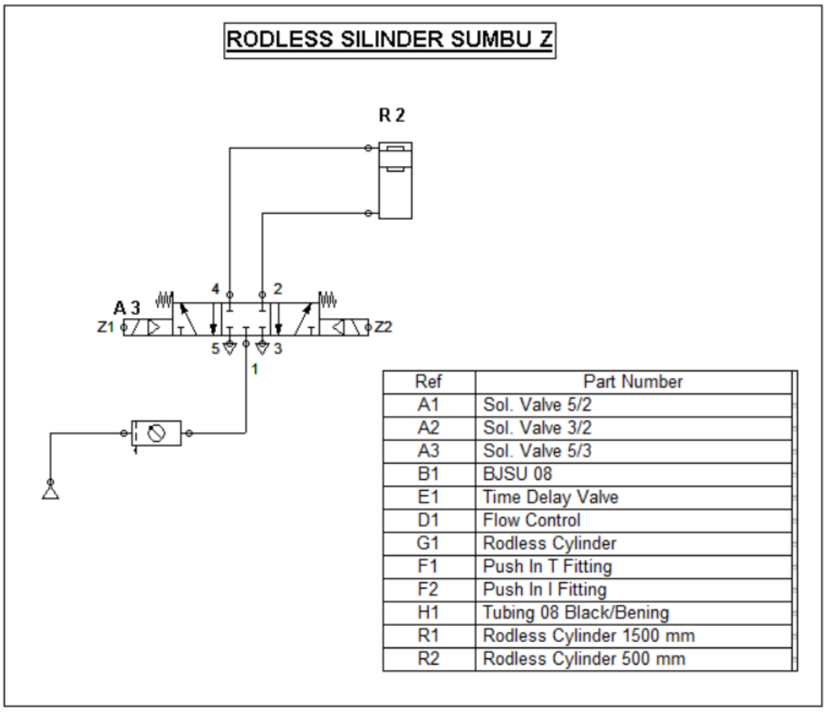

Figure 5. Y-axis drive pneumatic diagram.

If the work system's results are found to be unsatisfactory, the work will be returned to the assembly and programming processes. If the analysis's results are considered good, the process will continue with the discussion, documentation, and conclusion. This research can be declared complete by reaching the documentation and conclusion stages.

The following is a flow chart of the working system of the multi-speed pneumatic linear transfer system tool, as shown in Figure 3. The Figure 4 and Figure 5 as shown the X-axis drive pneumatic system diagram and Z-axis drive pneumatic system diagram.

3. RESULTS AND DISCUSSION

After several combinations of variants have been found, the study will continue by determining which combination of variants meets the best quality. Choosing a combination of several variants can use forms as shown in Figure 6.

FRAME VARIANTS SELECTION TABLE

SELECTION

(+) Yes
(-) No
(?) Lack of Information
(!) Check the Specification

A: Suitable for all needs
B: Fulfill the requirements of wishlist
C: Secara prinsip dapat direalisasikan
D: Affordable
E: Safe to use
F: Operator's favorite
G: Fulfill safety requirements

VARIANTS	A	B	C	D	E	F	G	NOTES	RESULT
V1	+	-	+	+	-	-	+	No	-
V2	+	+	+	+	+	+	+	Yes	+
V3	-	-	+	-	+	-	+	No	-
V4	+	+	+	+	+	+	+	Yes	+
V5	-	-	+	-	+	-	+	No	-
V6	-	-	+	-	+	-	+	No	-

Figure 6. Sub-function solution principle.

Based on the concept selection table of frame variants, variant 2 and variant 4 were selected as concept variants by the needs and desires. Of the two variants, there are significant differences, namely in the x and z-axis connection support brackets and upper and lower frame connection support brackets. Although they do not look much different, these two things greatly affect the frame's strength.

The next stage is the evaluation of concept variants. At this stage, the weighted values of each evaluation criterion can be calculated. Each evaluation criterion and weight is converted into a table from the objective tree that has been created. After that, the value of each pre-selected variant is determined in the truss variant selection table.

Then, multiplication and calculation of the sum of all value weights on each evaluation criterion are used to determine which variant is following the criteria. The total value of the largest value weight variant indicates the most ideal variant and is following the criteria based on the VDI 2221 value scale instructions as shown in Figure 7 (Arifiansah and Anwar, 2024). The Table 3 is an evaluation table of concept variants that have been made, Variant 4: $OVW_1 = 7.3175$, Variant 2: $OVW_1 = 6.5075$.

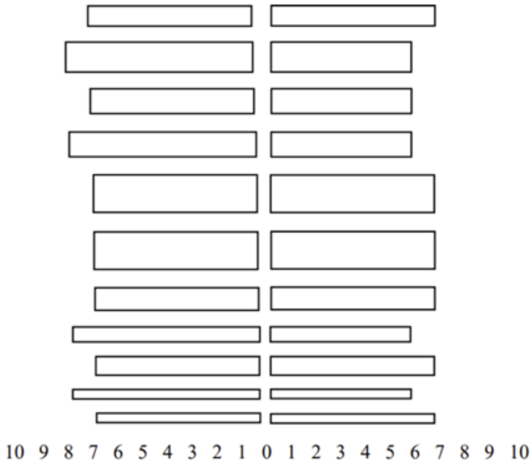

Figure 7. Value profile for detecting weak points.

Based on the calculation in Tabel 3 of the concept variant evaluation, variant 4 has a significant value weight of 7.3175, which is in the good—very good value range on the VDI 2221 value scale instructions. From Figure 6, It can also be seen that variant 4 qualifies for the design concept. After getting a variant that matches the criteria, proceed to the next stage, namely implementing the concept of variant 4 in designing a dual-speed linear transfer system. The system designed based on the VDI 2221 method is in the form of variant 4, which shown in Table 4.

The basic concept of the tool is designed using Autodesk Fusion 360 software. The height of this tool will be adjusted to the visibility of the human eye, which is 1200 mm, consisting of a table bottom frame with a height of 550 mm and a top frame of 600 mm. The total length of the tool is 2000 mm, the size of the rodless cylinder axis x, which has a stroke length of 1500 mm, and the length of the rodless cylinder axis z is 400 mm. Figure 8 and Figure 9 follow the multi-speed pneumatic linear transfer system's tool design, components, and dimensions.

Table 5 as shown the tool system component pointer base on Bill of Material (BoM) in Figure 9.

Table 3. Concept variant evaluation table.

Evaluation Criteria		Parameter		Var. 4			Var. 2		
Des.	**W**	**Des.**	**Unit**	**lvl**	**V**	**W**	**lvl**	**V**	**W**
Slight component movement	0,08	number of moving parts	-	few	7	0,56	few	7	0,56
little disturbance factor	0,12	confounding factors	-	low	8	0,96	mid	6	0,72
low replacement frequency	0,1	number of components per year	Unit/year	1	7	0,7	2	6	0,6
easy-to-replace components	0,1	-	-	easy	8	0,8	Mid	6	0,6
Safe in operation	0,15	preferred mechanical safety	-	high	7	1,05	High	7	1,05
safe for construction	0,15	preferred construction safety	-	high	7	1,05	High	7	1,05
easy to manufacture	0,09	complexity of the component shape	-	mid	7	0,63	Mid	7	0,63
easy to assemble	0,06	simplicity of assembly	-	easy	8	0,48	Mid	6	0,36
small number of components	0,075	a number of components	-	Mid	7	0,525	Mid	6	0,45
attractive appearance	0,0375	eye-catching appearance	-	high	8	0,3	Mid	6	0,225
easy to carry	0,0375	portability	-	easy	7	0,2625	easy	7	0,2625
Description: V = Value W = Weight		$\Sigma W_1=1$			$\Sigma V1$ = **81**	$\Sigma WV1$ = **7,3175**		$\Sigma V2$ = **71**	$\Sigma WV2$ = **6,5075**

Table 4. VDI 2221 design system variant number 4.

No	Function	Component
1	Drive Type	Pneumatic
2	Tool frame connection type	Bolt
3	Rod connection type	Lap joint
4	Bracket support rod connection	Plate
5	Degree of freedom of movement	Dual-axis
6	Construction form of truss	Two support system
7	Clamp type	Two jaw gripper
8	Frame material	Aluminum Profile

Figure 8. Frame 3D design of isometric, side, and front views of the device.

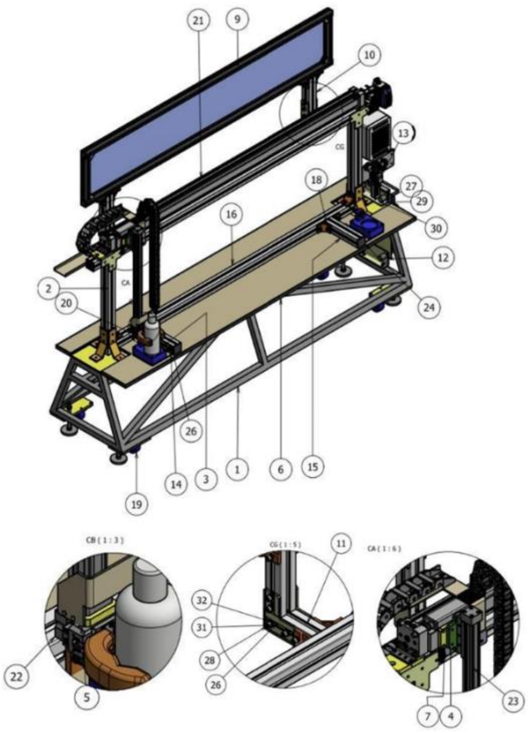

Figure 9. Final 3D design of device.

The static simulation results are divided into four variables: safety factor, stress Von Mises, displacement, and strain (Muhammad, Ali and Shanono, 2020). The simulation results are carried out on the machine frame with 2 (two) conditions, namely first, when the Z-axis rodless cylinder is in the initial position (the force acting on the Z-axis rodless cylinder in the final position is the same as when it is in the initial position so that only one data collection simulation is carried out and the second when the Z-axis rodless cylinder is in the middle position. The static simulation was carried out in Autodesk Fusion 360 software.

$$FOS = \frac{\delta_y}{\delta_a} \quad (1)$$

The structural design must provide adequate safety according to the accepted working conditions (using Equation 1). Since the yield strength of the aluminum profile is 110 MPa and mild steel is 250 MPa, and the safety factor set is 2, the maximum allowable stress in the construction is 55 MPa for the aluminum profile and 125 MPa for mild steel.

Figure 10 until Figure 17 is the simulation results of the machine frame when the Z-axis rodless cylinder is in the center position of the frame and in the first-last position.

Table 5. Tool system component pointer.

Component	Material	Amount
Table Underframe	Mild Steel	1
Rodless Cylinder Frame	Aluminum Profile	1
Bottle Jig	PLA Plastic	2
Bracket Rodless Vertical 2	Aluminum	1
Bracket Rodless Gripper Schunk	Aluminum	1
Plywood	Wood	1
Vertical Rodless Bracket	Aluminum	1
Reinforce Aluminum Profile 2	Mild Steel	4
Poster Spot	Acrylic	1
Aluminum Profile 50x50 - 6	Aluminum	2
Aluminum Profile 50x50 - 5	Aluminum	2
Mounting Pneumatic Panel 2	Mild Steel	1
Mounting Pneumatic Panel	Mild Steel	1
Mounting Jig	Mild Steel	2
Aluminum Profile 50x50-4	Aluminum	2
Aluminum Profile 50x50 - 3	Aluminum	1
Angle Bracket	Aluminum	14
Misumi Table Bottom Frame Wheel	Mild Steel	4
Proximity Sensor Capacitive CR 18-8DN		2
Rodless Cylinder Festo DGC-32-1500-GF-YSR-A	Aluminum	1
Gripper Schunk-0371092 PGN-plus 64-1-AS	Aluminum	1
Rodless Cylinder Axis Z Norgren	Aluminum	1
End Cap Rodless Cylinder	Plastic	4
Subsequent Nut M8	Steel	48
Baut L - M6 x 16	Steel	8
Baut L - M8 x 20	Steel	44
Ring Per - M6	Steel	8
Ring Plat - M6	Steel	8
Ring Per - M8	Steel	44
Ring Plat - M8	Steel	44

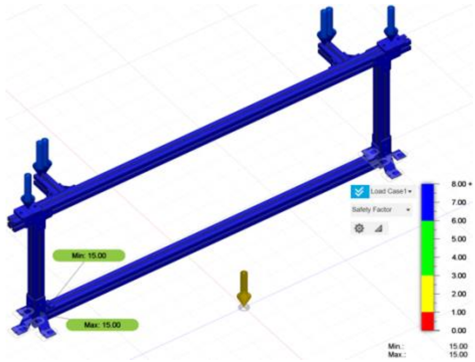

Figure 10. Simulation results of safety factor on rodless cylinder in the center position.

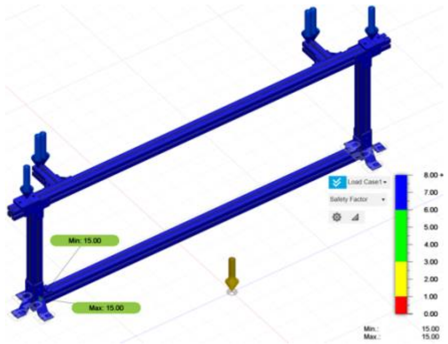

Figure 11. Simulation results of safety factor on rodless cylinder in first-last position.

Based on the simulation results in Figure 10 and Figure 11, the maximum safety factor is 8 for the Z-axis rodless cylinder in the middle position and 8 for the first-last position.

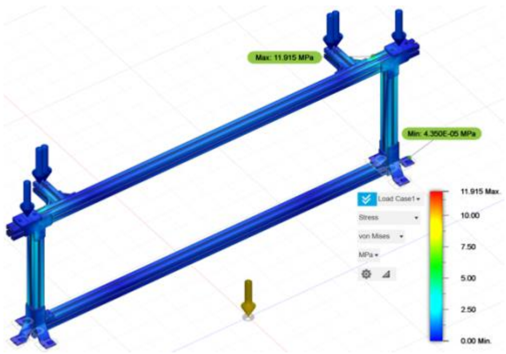

Figure 12. Simulation results of stress on rodless cylinder in center position.

Based on the simulation results Figure 12 and Figure 13, the maximum von Mises stress of 11.915 MPa and the minimum stress of 4.350E-05 MPa were obtained in the simulation of the Z-axis rodless cylinder in the middle position, while in the simulation of the Z-axis rodless cylinder in the first-last positions, the maximum von Mises stress of 11.783 MPa and the minimum von Mises stress of 3.948E-05 MPa were obtained.

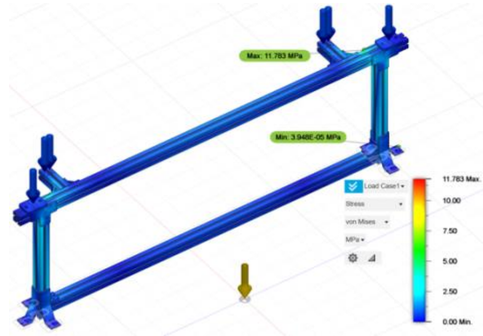

Figure 13. Simulation results of stress on rodless cylinder in the first-last position.

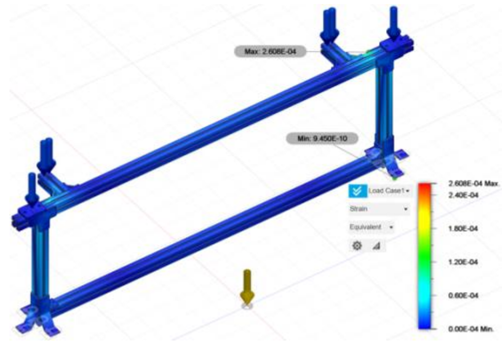

Figure 14. Simulation results of strain on rodless cylinder in center position.

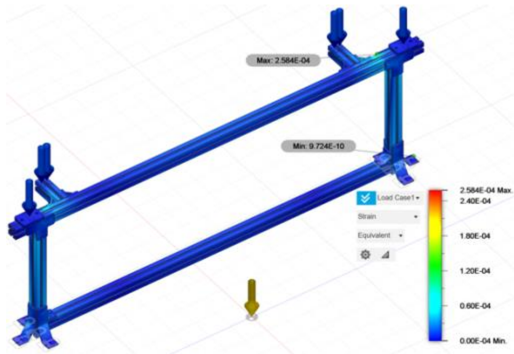

Figure 15. Simulation results of strain on rodless cylinder in the first-last position.

Based on the simulation results in Figure 14 and Figure 15, the maximum strain of the rodless cylinder in the middle position is 2.608E-04 MPa, and the minimum strain is 9.450E-10 MPa. In the simulation of the rodless cylinder in the first-last position, the maximum strain is 2.584E-04 MPa, and the minimum strain is 9.724E-10 MPa.

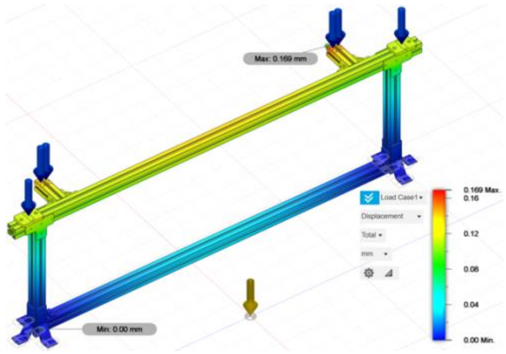

Figure 16. Simulation results of displacement on rodless cylinder in center position.

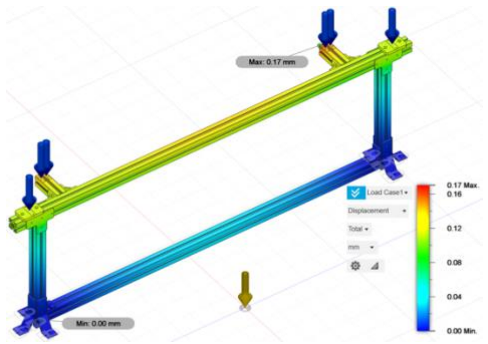

Figure 17. Simulation results of strain on rodless cylinder in the first-last position.

Based on the simulation results in Figure 16 and Figure 17, the highest displacement data of 0.169 mm is obtained in the middle of the frame for the rodless cylinder in the middle position. In comparison, the highest displacement data of 0.017 mm is obtained in the first-last position.

4. CONCLUSION

The design of the dual-speed linear transfer system frame is concluded to be successful in terms of safety and function. This tool was designed using the VDI 2221 method. The VDI 2221 method aims to create tools that can be applied to the industrial world, such as designing this linear transfer system using rodless cylinder brands FESTO and Norgren. The rodless cylinder FESTO is 1760 mm long with a stroke of 1500 mm, while the rodless cylinder Norgren has a length of 470 mm with a stroke of 400 mm. The machine is 1246 mm high, 2000 mm long, and 525 mm wide, while the panel control table is 998 mm high, 695 mm long, and 35 mm wide.

After analyzing the simulation of the frame structure in a static state, there are two simulations, namely when the Z-axis rodless cylinder is in the initial-end and center positions. The upper frame of the machine with the specified material can withstand a load of 122 N and 80 N when the Z-axis rodless cylinder is in the initial-end position and a load of 100.75 N when in the middle position. The results of the safety factor simulation obtained the maximum safety factor at the number 8 when in the initial-end and middle positions. The maximum Von Mises stress simulation result is 11.783 MPa and a minimum of 3.948E-05 MPa when the Z-axis rodless cylinder is in the initial-end position, while the Von Mises stress simulation result when the Z-axis rodless cylinder is in the middle position obtained a maximum von mises stress of 11.915 MPa and a minimum von mises stress of 4.350E-05 MPa. From the simulation results of the tool frame structure in a static state, it can be concluded that the material used, namely aluminum 6061 on the aluminum profile, angle bracket 50-EB-50-90, and extruded angle foot and mild steel material on the reinforced aluminum profile and bracket rodless cylinder X is strong enough and sturdy for the machine frame structure when supporting loads in static conditions.

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