

Design and Development of an Energy-Efficient Pneumatic Gripper for Palletizing Applications

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Abstract

Palletizing automation plays a vital role across industries, requiring the selection of suitable robotic grippers to improve product quality and cost efficiency. However, issues such as carton drops, and misalignment often caused by inconsistent air supply can compromise gripper performance. Pneumatic grippers, in particular, face limitations such as low deformation resistance, leading to bending during carton handling. To overcome these challenges, pneumatic gripper pincers were designed with an integrated pressure-feedback mechanism to enhance reliability. Anti-slip rubber pads and FlexiForce sensors were incorporated to prevent carton slippage and monitor gripping force. Simulation analyses and hardness tests validated the effectiveness of tungsten carbide pincers, confirming improved durability and grip stability. The developed pneumatic gripper system demonstrated enhanced palletizing performance, with fewer operational issues and reduced production downtime. These improvements increased system reliability and availability while also enhancing energy efficiency by minimizing idle periods, reducing wasted power during stoppages, and ensuring more consistent productive operation.

Keywords

Finite Element Analysis (FEA), Gripper, Palletizing Machine, Pressure-Feedback Mechanism and System Performance

1. Introduction

Automation in manufacturing plays a crucial role in cutting down on labor, production expenses, and process durations. The end effector gripper, essentially the hand of a robotic system positioned at the end of its arm, holds significant im-

portance. Robotic end effectors find diverse applications across various industries. Pneumatic grippers, for instance, are extensively utilized in manufacturing medical equipment, within biotech and pharmaceutical sectors, in injection and plastic molding processes, laboratory operations, and autonomous systems. These grippers come in various shapes and sizes, tailored to handle a wide array of components and materials.

Palletization is a logistics process involving the arrangement of products atop a pallet to facilitate easier transportation by handling equipment, serves as the focus of this project. The aim is to detail the design and development of a versatile gripper for palletizing machines. Through the implementation of a pressure-feedback mechanism within the gripper, control over cartons in the palletizing process has been achieved. The common cause of machine downtime, according to the problem statement, is carton box drops at the palletizing machine. Such occurrences have adverse effects on production output and efficiency, potentially lowering the overall equipment effectiveness (OEE) percentage. For large-scale implementations, Zhou *et al.* [1] proposed an integrated OEE monitoring system architecture. A case study shows how the OEE system for productivity improvement was implemented successfully. To calculate the value of OEE, three major factors must first be determined, which are availability, A , performance, P and quality, Q using the provided formula below.

$$OEE = A \times P \times Q \quad (1)$$

where:

$$A = \frac{\text{Uptime}}{\text{Planned Production Time}} \quad (2)$$

$$P = \frac{\text{Ideal Cycle Time} \times \text{Total Count}}{\text{Uptime Time}} \quad (3)$$

$$Q = \frac{\text{Good Count}}{\text{Total Count}} \quad (4)$$

Palletizing machine is a machine that stacks products onto a pallet in an automated manner. The advancement of fieldbus and robotic technologies has driven the widespread use of robotic palletizing in automated production and logistics systems, where the ability to quickly and accurately transfer, sort, and package workpieces in real time is essential for improving overall efficiency [2]. The current palletizing machine is a device that basically consists of the R-30iA robot controller's maintenance and connection parts. The maintenance section includes troubleshooting as well as settings, adjustment, and replacement of units. The connection part entails connecting the R-30iA controller to the robot mechanical unit and peripheral devices, as well as the controller's installation. In relation to the system's configuration, the palletizing machine has an electrical panel as well as an external button panel with various selectors, lights, buttons, switches, and a touch screen display.

Grippers are the mechanical devices enabling users to handle objects, often uti-

lize human-like finger mechanisms with two or three fingers possessing one degree of freedom (DOF) [3]. Available in diverse types, shapes, and sizes, grippers are designed to grasp a broad spectrum of objects. In palletizing systems, the common causes of downtime include carton drops and misaligned cartons, often attributed to intermittent air supply, which can impact the gripping strength of the end effector.

According to Zaytran Automation [4], jaw style, jaw length, and acceleration are the three most important factors that influence the specification of a robotic gripper. In a gripper application, the force required is determined by the jaw style. Friction grips and encompassing grips are two types of grips. To hold the part, friction grip jaws simply rely on the gripper's force. While encompassing grip is like driving the jaws open for a part to be dropped. The different jaw gripper styles are shown in **Figure 1**.

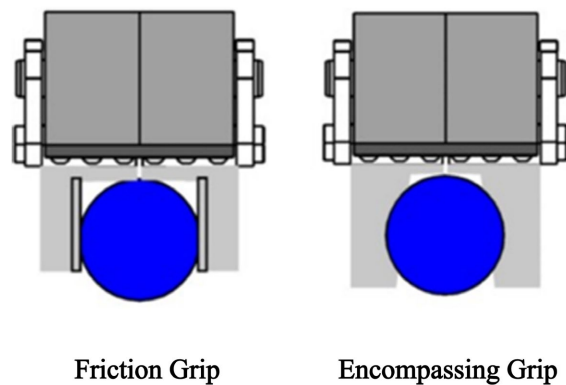


Figure 1. The styles of jaws gripper [4].

The jaw factor is the rule of thumb that when handling the same part with a friction grip, four times the force is required. The Friction grip jaw factor is 4 and encompassing grip jaw factors is 1. Next, the weight of the object must be considered in determining the required gripper force, where the gripper experiences both gravity and acceleration. Equation (5) can be used to approximate the gripping force for any type of product is:

$$\text{Grip force} = \text{Part weight} \times [1 + \text{Acceleration} (Gs)] \times \text{Jaw style factor} \quad (5)$$

where G_s is the earth gravity (9.75 meters/sec²)

Adaptive gripper is an industrial robotic hand that is both efficient and simple. It has a three-finger mechanism that conforms to the shape of various objects and secures them. Cheng *et al.* [5] introduced a soft-rigid gripper that operates using a linear-extension soft pneumatic actuator, which incorporates a steel spring wound around the outer wall of a cylindrical silicone cavity. This type of gripper can achieve low damage gripping of objects in a static gripping system.

Meanwhile, the pneumatic grippers are run on compressed air and controlled by pneumatic valves and pressure cylinders to operate gripper jaws. A compressed air supply network is connected to the gripper. The gripper jaws close while air

pressure is applied to the pistons and opens while the pressure is released. Romeo *et al.* [6] proposed a pneumatic system comprising a gripper and two pressure regulators. The piston's upward movement corresponds to an increase in pressure within the opening chamber, and conversely, as the pressure decreases, the piston moves downward. The gripper's jaws are operated by two levers that translate the motion of the piston, with a pin joint connecting these levers to the gripper's main body. On the other hand, Gurav *et al.* [7] proposed a vacuum system consisting of a suction pad, mounting elements, a vacuum generator, valves, switches, filters, and connectors. Like a mechanical gripper, in a pneumatic gripper, the fingers lack independent movement. Currently, the fingers maintain contact with the object to stabilize it while the gripper is in motion. Ensuring that fingers and suction pads are positioned at the appropriate angle enhances the gripper's flexibility.

2. Gripper Design

The research consists of two main systems integrated together: a pneumatic gripper's design, and a pressure-feedback mechanism. It is necessary to thoroughly understand the existing pneumatic gripper system to ensure that all important specifications are considered of the new end effector while removing the failure properties that can cause machine downtime to occur again. The existing pneumatic gripper system is illustrated in **Figure 2**. As the pincers are simple in design, consisting of a rectangle with a round shape at the end of the side to locate the screw. The pincer then has rubber pads to grip the objects securely.

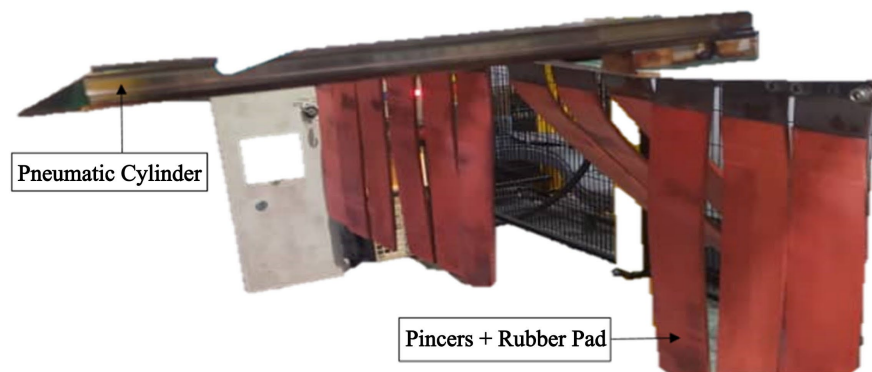


Figure 2. Existing pneumatic gripper system.

2.1. Mechanical Properties of the Pneumatic Gripper

The mechanical properties of the existing pneumatic gripper system include mechanical properties such as air pressure, gripper grip pressure, coefficient of friction and safety factors. The pneumatic device integrates a filter, regulator, and lubricator into a single unit, and the air pressure is derived from the pneumatic gripper system. Gripper grip pressure refers to the pressure data of the pneumatic gripper system that is collected and analyzed, providing crucial information for the design and fabrication of the pneumatic gripper pincer. The coefficient of friction measures the friction between two surfaces, such as the pneumatic gripper's

pincer and the carton box, and experiment that determine the force required to overcome this friction. The safety factor is the ratio of the component material's ultimate stress to its working stress and applying Finite Element Analysis (FEA) simulation to the pneumatic gripper's pincer helps identify design failures and improvements.

The hardness test is used to determine a pincer's resistance to penetration by the carton box. This will be the first experiment to determine the appropriate deformation resistance that will prevent the pincers from bending when gripping multiple cartons. The hardness of the pincers has been tested at one point.

The Rockwell hardness test was carried out by inserting the C-diameter diamond indenter into the machine's ball holder and cleaning the surface of the tungsten carbide specimen to remove dust. The jack adjusting wheel was rotated until the indenter contacted the specimen, after which the appropriate button was pressed to apply the preliminary load. The load release lever was then pulled to allow the load to be applied gradually and maintained for at least 15 seconds. Once completed, the specimen was removed from the support table, and the indentation point was marked. This process was repeated three to four times, and the average value was taken as the final Rockwell hardness result.

Rubber pads for the pneumatic gripper pincers are important because they assist the gripper in securely moving the carton box from one position to another, causing friction between the pneumatic gripper pincer and the carton box. **Figure 3** illustrates the location of the rubber pad, which is located between the carton box and the pincer.

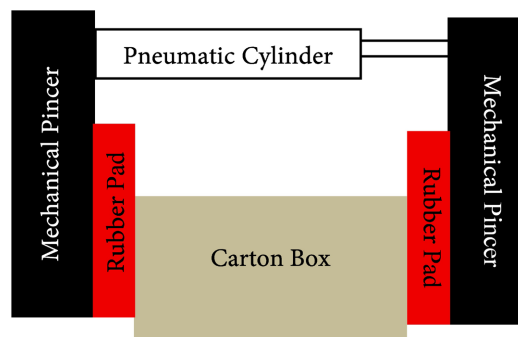


Figure 3. Rubber pad layered between the carton box and mechanical pincer.

Based on the existing system data obtained through the first method, the hardness test data is used to design the pincer of the pneumatic gripper with rubber pad to fulfil the first objectives. The pincer is analyzed using a Finite Element Analysis (FEA) simulation, however the material properties and applied force to the pincer and carton box are different. The pincer design is divided into two parts which are the pincer itself and a rubber pad for anti-slip purposes. The pincer is both made of a simple rectangle shape; however the pincer has round shape for the hole, which consists of three holes. The focus of the second part of the design is the rubber pad itself.

The three main dimensions used to measure the pincer and carton box are length, width, and height, followed by the diameter, which measures the round circle used to locate the screw. All dimensions are in millimeters (mm). The pincer has dimensions of 380 mm in length, 3 mm in width, and 70 mm in height, with a hole diameter of 10.13 mm.

2.2. Pressure-Feedback Mechanism

This subsection covers the design and implements pressure-feedback mechanism for the pneumatic gripper system, components selection and physics of the design. **Figure 4** shows the pneumatic gripper system. A FlexiForce sensor and a digital SMC pressure switch are included in the system. The FlexiForce sensor is tapped on the pincer's surface. The FlexiForce sensor is connected directly to an Arduino UNO and programmed using the Arduino.

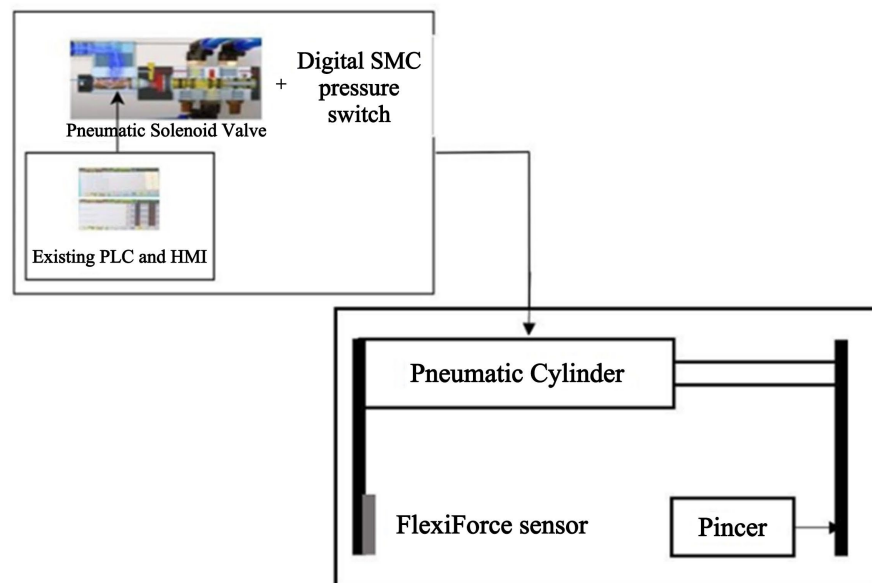


Figure 4. Pneumatic gripper system.

A FlexiForce sensor is selected and tapped on the pincer's surface. When the pneumatic gripper grips the carton box, the force applied to the FlexiForce sensor is 160 Newton. The applied force is still within the FlexiForce sensor's standard force ranges. The FlexiForce sensor is programmed with the Arduino UNO. A digital SMC pressure switch is selected and connected to the pneumatic gripper system. The minimum pressure on the digital SMC pressure switch is set to 5 bar, while the maximum pressure is set to 7 bar.

The FlexiForce sensor was mounted on the pincer surface to measure the applied gripping force. During operation, the pneumatic gripper exerted a force of approximately 160Newton on the sensor, which remained within the standard measurement range of the FlexiForce device. The sensor was interfaced with an Arduino UNO for data acquisition and processing. In parallel, a digital SMC pres-

sure switch was incorporated into the pneumatic gripper system, with the operating pressure range configured between 5 bar (minimum) and 7 bar (maximum). The pressure could not be set to 8 bar, as the pneumatic system was limited by an air supply capacity of 7 bar, representing the maximum deliverable pressure within the system constraints.

The second experiment was designed to evaluate the grip force of the pneumatic gripper system, with a focus on the friction grip jaws incorporated in the existing configuration. The carton box weight was first determined using a calibrated scale, and the gravitational force was subsequently derived using a constant of 9.75 m/s^2 . The jaw type was identified as friction grip, corresponding to a jaw style factor of 4, and the grip force was then calculated. Throughout the experiment, the system pressure was continuously monitored via the digital display of the SMC pressure switch to ensure accuracy and consistency in measurement.

2.3. System Performance

The integration of the two developed designs was subjected to testing and evaluation within the pneumatic system. Throughout the testing process, the system was monitored to verify that the pneumatic gripper was capable of securely handling carton boxes for the palletizing operation. Performance-based adjustments were implemented to enhance the system and achieve the intended outcomes. As reliability is inherently dependent on maintenance, systematic measurement is essential. Effective reliability management and improvement require comprehensive data collection, analysis, and interpretation. Machine availability is determined by the total operational time of the facility, with planned shutdown periods in which production is intentionally suspended, subtracted from the total uptime. The remaining duration is defined as the planned production time. Overall Equipment Effectiveness (OEE) is subsequently quantified as the product of equipment availability, process efficiency, and product quality. The corresponding OEE values are calculated using Equations (1)-(4).

3. Result and Analysis for Gripper Design

3.1. Hardness Test

The Rockwell hardness test is performed on original single plate. The original single plate specimens are designed, fabricated, and analyzed. The first experiment's Rockwell hardness test results are shown in **Table 1** below.

Table 1. Rockwell hardness test.

Specimen	Rockwell hardness value	Hardness scale	Test force (N)	Material type
Originated single plate	44.8	HRC	1471	Tungsten carbide or aged hardening steel
Fabricated single plate	88.9	HRB	980.7	Soft mild steel
Carbon fiber	49.5	HRB	980.7	Carbon fiber

3.2. HRB and HRC Hardness Test of the Pincer Test

The Rockwell hardness scale is used for the HRC and HRB hardness testing. The main difference between HRC and HRB hardness testing is that the HRC hardness test employs a spheroconical diamond as its indenter, whereas the HRB hardness test employs a 1/16-inch ball on the pincer of the pneumatic gripper. The Rockwell hardness test for various types of specimens or pincers is shown in **Figure 5**.

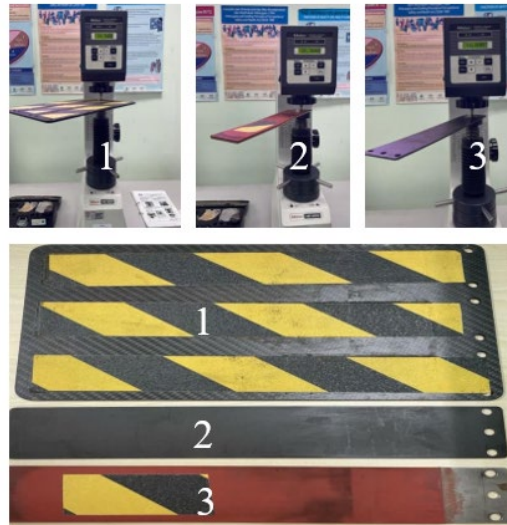


Figure 5. Rockwell hardness test.

HRB and HRC hardness tests are performed on the pincers. The results of the Rockwell hardness test for various types of specimens or pincers are shown in **Table 1**. The specimen, which is a fabricated single plate made of soft mild steel and carbon fiber, is subjected to HRB hardness testing with the same force applied to the pincer, which is 980.7 Newton. While the original single plate, which is made of tungsten carbide, is undergoing an HRC hardness test with a proposed Rockwell hardness value of 60.

The original single plate or pincer has a Rockwell hardness of 44.8 and a 1471 Newton test force on the pincer. When the test force on the pincer is 1485 Newton, the Rockwell hardness value is 46.1, refers to hardness conversion table for unalloyed and low alloy steels and cast iron. The value falls within the range of the proposed Rockwell hardness value of 60.

3.3. Finite Element Analysis (FEA) of the Pincer

Significant stress, displacement, and strain distribution can be seen in **Figures 6-8**. The deformation appeared at the front end of the pincer's hole, as shown in **Figure 10**, with stress 6.509×10^8 Von Mises of (N/m²). This is due to the presence of the hole and stress concentration can easily occur at the gripper's front end. **Table 2** below shows the distribution stress, displacement and strain values for the pincer.

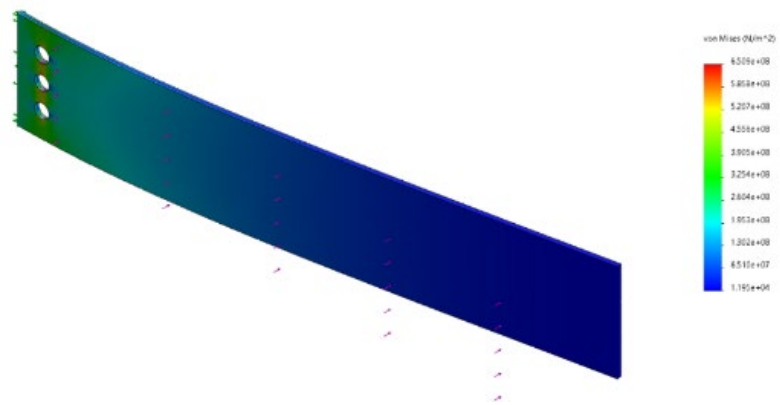


Figure 6. Stress distribution of the pincer.

The pincer has a displacement of 0.5872 URES of (m), which are related to the mechanical structure of the gripper, is better than pincer that undergoes HRB hardness test, as shown in **Figure 7**.

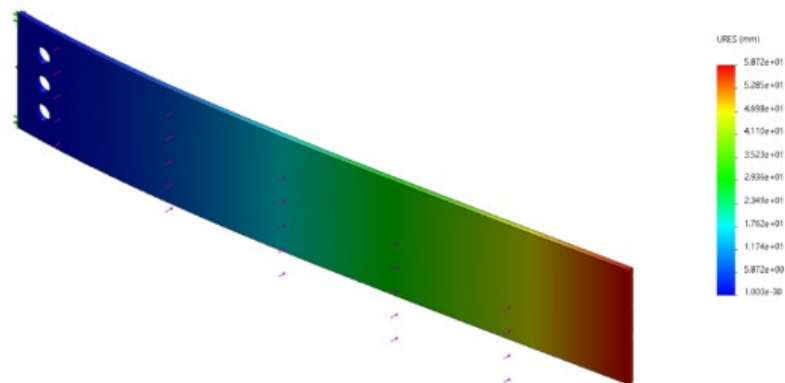


Figure 7. Displacement distribution of the pincer.

The strain distribution of the pincer is 2009 ESTRN, as shown in **Figure 8**. The analysis' findings are consistent with gripper deformation observed during production, which is forced to 160 N.

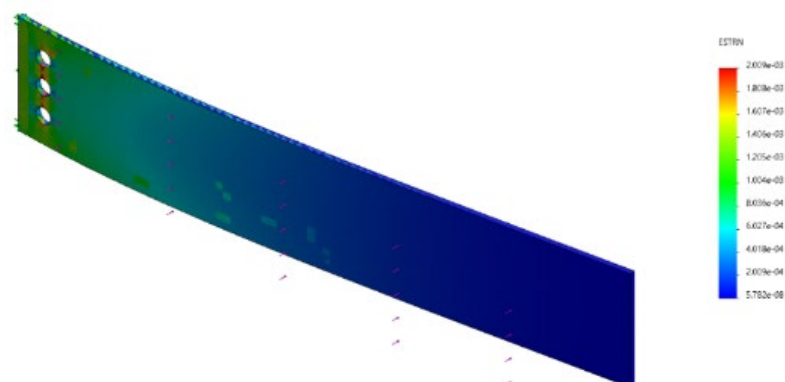


Figure 8. Strain distribution of the pincer.

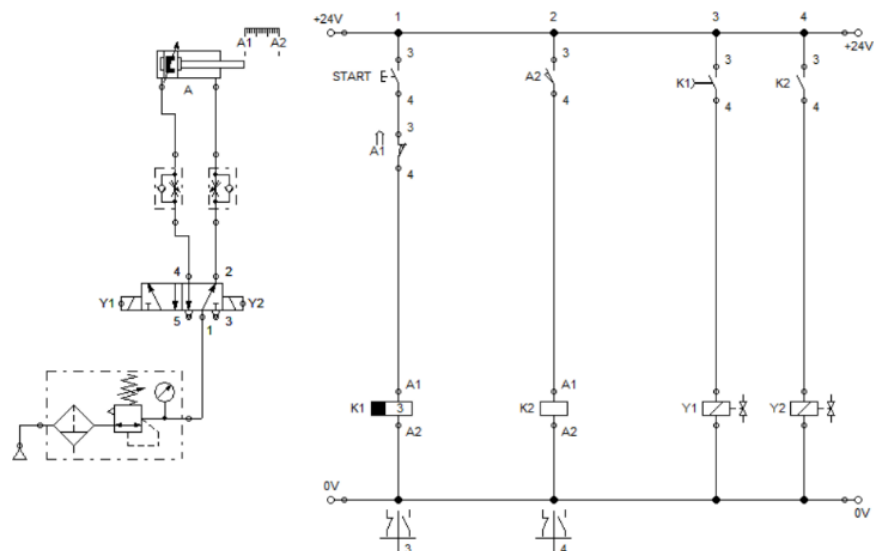
Table 2. Distribution for stress, displacement and strain values.

	Distribution		
	Stress (N/m ²)	Displacement (m)	Strain
Values	6.509×10^8	0.5872	2009

4. Result and Analysis for Pneumatic Gripper's Pressure Feedback System

4.1. System Works of the Pneumatic Gripper in FluidSIM

Three major circuits must be identified in an electro-pneumatics control system: pneumatic circuit, control circuit (electric), and power circuit (electric). According to an electro-pneumatic circuit with the use of a push button is shown in **Figure 9**.

**Figure 9.** Control and power circuit with OFF delay timer.

Lines 1 and 2 in **Figure 9** are control circuits, while lines 3 and 4 are power circuits. The cylinder is extended until the rod reaches the sensor A2 when the push button start is pushed. When sensor A2 is activated, the cylinder remains stationary for 3 seconds before retracting. The electro-pneumatic circuit follows the motion sequence structure for each line of the circuit. A push button is a button that ON when it is activated. As a result, the system will come to a complete stop when the cylinder retracts.

In FluidSIM, **Figure 10** depicts the pneumatic circuit diagram for one double acting cylinder of the electro-pneumatics control system mentioned earlier. The carton box is fed into the system, where it is placed at the back end of the pneumatic cylinder. The rod of the pneumatic cylinder extends when the push button is pushed ON. It is retracted after sensor A2 activates the signal to the end of the process. The carton box is clamped by the pincer, as shown in **Figure 11**. The

pincer is attached to the end of the pneumatic cylinder as well as the pneumatic cylinder's rod.

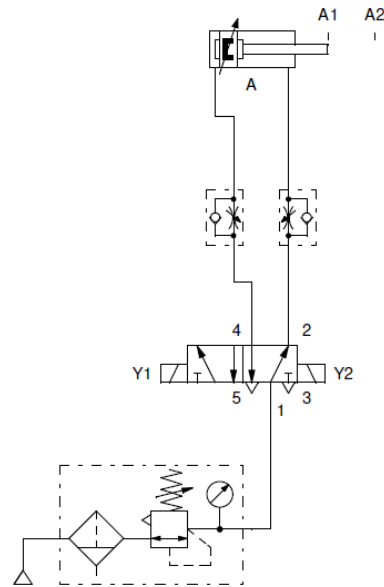


Figure 10. Pneumatic circuit diagram for one double acting cylinder.



Figure 11. Pincer grips the carton box.

4.2. FlexiForce Sensor and SMC Pressure Switch Data

The second experiment is conducted to accomplish the second objective. The experiment involves measuring the force between any two surfaces that resulted in the pneumatic gripper's pincer. For this experiment, 0.1 kg carton boxes are chosen for the results. The FlexiForce sensor's experimental results for a 0.1 kg carton box are shown in **Table 3**.

Table 3. Flexiforce sensor experimental results for 0.1 kg of carton box.

Date	Time	Carton box weight (kg)	FlexiForce sensor values (N)		
			<i>Pneumatic System ON</i>	<i>Cylinder extend</i>	<i>Cylinder retract</i>
13/6/2022	4.42 PM	0.100	0	0	1.096

The grip force equation, as shown below, is derived from Equation (5) where it is used to calculate the force applied to the pneumatic gripper system's carton box. The grip force of 0.1 kg carton box is 4.3 Newton.

The digital SMC pressure switch with pressure values displayed in red is shown on **Figure 11**, whereas the digital SMC pressure switch displayed in green is shown in **Figure 12**. The SMC pressure switch series ISE30A is a high-precision digital pressure switch with a two-color (red and green) digital display, allowing the user to choose the appropriate setting based on the application. The SMC pressure switch displays values in digital form.



Figure 12. Digital SMC pressure switch display pressure value in green.

The minimum pressure on the SMC pressure switch is set to 5 bar, while the maximum pressure is set to 7 bar. The digital SMC pressure switch displays green for the pressure value when the pneumatic gripper system is running. The pneumatic cylinder extends and retracts when the push button is pushed on. Currently, the pressure value is displayed in red color. When the pneumatic gripper system is running, the digital SMC pressure switch values are shown in **Table 4**.

Table 4. Digital SMC pressure switch values.

Date	Time	Digital SMC pressure switch values (bar)		
		<i>Pneumatic system ON</i>	<i>Cylinder extend</i>	<i>Cylinder retract</i>
13/6/2022	4:35 PM	0.01	5.32	5.08

5. Integrated and Evaluation System Performance

5.1. Machine Reliability

The analysis of the palletizing machine's downtime is called machine reliability. The total number of problems in 2021 and 2022 is depicted in **Figure 13**. In October, November and December of 2021, there were a total of 81 problems, whereas in January, February, and March of 2022, there were only 70 problems.

In the years 2021 and 2022, this system will face a variety of issues. Palletizing machines in 2022 are more reliable than palletizing machines in 2021 after improvements.

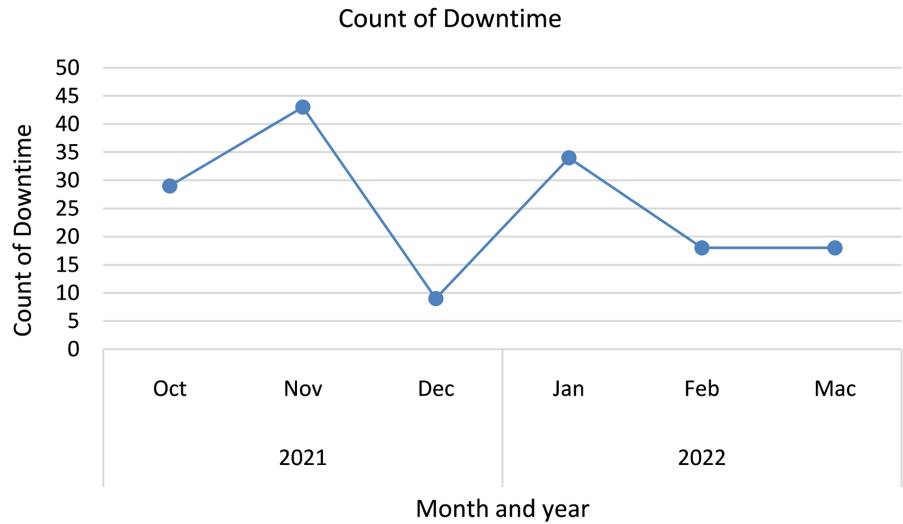


Figure 13. Total count of downtime for 2021 and 2022.

5.2. Machine Availability

Machine availability is the study of a palletizing machine’s availability. **Figure 14** shows the total amount of production stopping time (minutes) in year 2021 and year 2022. October, November and December of 2021, there are a total of 3145 problems, whereas in January, February, and March of 2022, there are only 1805 problems.

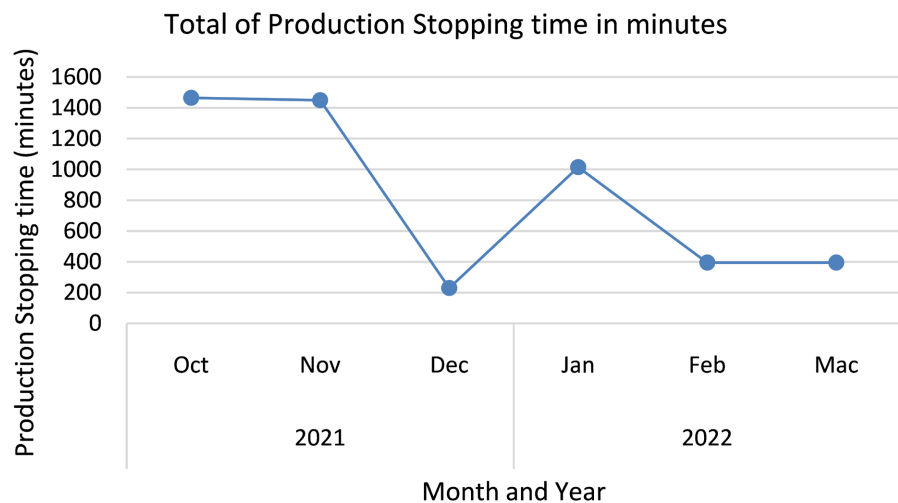


Figure 14. Total count of production stopping time in minutes for 2021 and 2022.

The analysis of the palletizing machine’s performance between 2021 and 2022 shows clear improvements in both reliability and availability. The number of problems decreased from 81 (late 2021) to 70 (early 2022), while production stopping time reduced significantly from 3145 minutes to 1805 minutes. These improvements indicate that the machine underwent effective enhancements, leading to fewer breakdowns and less downtime.

5.3. Overall Equipment Effectiveness (OEE)

The overall equipment effectiveness, OEE, as shown below, is derived from Equation (1)-(4). The data for the first shift is shown in **Table 5**. Based on the data recorded for first shift, the OEE percentage is represented in **Table 6**.

Table 5. Data recorded for first shift.

Items	Data
Shift length	480 minutes
Breaks	60 minutes
Downtime	45 minutes
Ideal cycle time	1 seconds
Total count	332 carton boxes
Reject count	6 carton boxes

Table 6. The OEE performance.

Availability, <i>A</i>	Performance, <i>P</i>	Quality, <i>Q</i>	OEE
89.29%	88.53%	98.19%	77.16%

Most of the production has no major issues based on the quality values that have been obtained. Regardless, the consistency rating should be increased to near 100%. As a result, it is suggested that the pincer with a pneumatic gripper system improves its current production yield.

The OEE percentage has been determined to be 77.16%. The results showed that using a pincer with a pressure-feedback mechanism on a pneumatic gripper allowed for proper gripper response.

From an energy efficiency perspective, reduced machine downtime translates into less wasted energy. In 2021, frequent stoppages meant that energy was consumed inefficiently due to repeated start-ups, idling, and unproductive machine operation. By 2022, the increased reliability and availability allowed the palletizing machine to operate more consistently, maximizing productive energy use while minimizing energy losses during idle or repair times. This directly supports more sustainable manufacturing practices by lowering unnecessary power consumption, improving overall energy efficiency, and potentially reducing operational costs.

6. Conclusion

This project successfully designed and fabricated a pincer and implemented pressure-feedback mechanism for a pneumatic gripper system that functions as a palletizer device. The design allows for the carton box to be gripped from one position to another without dropping and bending on the pincer of the pneumatic gripper. The testing was conducted and output that has been analyzed. The pal-

letizing machine showed improved performance with fewer breakdowns and reduced downtime. These enhancements increased reliability and availability, leading to more consistent operations. Consequently, energy efficiency improved as less energy was wasted during stoppages and idle periods, supporting cost savings and sustainable manufacturing.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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