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DESIGN AND OPTIMISATION OF ROTARY ROBOT ACTUATORS FOR HIGH-PRECISION CARTRIDGE CAP ASSEMBLY APPLICATIONS IN THE MANUFACTURING INDUSTRY

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Abstract.

The use of Rotary Actuators in Industrial Automation systems requires adequate mechanical protection to ensure product quality, system reliability, component durability, and safe operation. However, many existing machine designs and assembly processes do not fully account for structural strength, precision, ease of adjustment, and maintenance efficiency. This study aims to develop the assembly process for high-quality cartridge covers and their installation system for rotary robotic actuators, with attention to quality, safety, functionality, and practical implementation. The research methodology includes a literature review, cause analysis, testing, and evaluation. Testing was conducted based on the defect rate and the system's accuracy and precision. The evaluation results showed a significant performance improvement after replacing the pneumatic actuator systems with electric actuators and making mechanical design improvements. Repeatability increased by about 87.6%, the DPPM-defect rate decreased by about 92%, and the safety factor reached 2.4, indicating a strong mechanical safety margin. In addition, the operation cycle time remains stable, supporting production needs without compromising reliability. The decrease in DPPM is a manufacturing quality metric that measures the number of defective units per million units produced and is commonly used to assess the quality and reliability of the production line. These findings confirm that the cartridge cover assembly and installation design developed provide better mechanical protection, facilitate installation, and reduce product defects. Thus, the rotary electric actuator is superior at reducing DPPM and improving precision.

Keywords: Rotary actuator, Automation industry, Solid Edge, CAD-Based design, smart manufacturing.

INTRODUCTION

In industrial automation systems, the accuracy and consistency of actuator movements are crucial to ensuring the quality of the assembly process. During cartridge installation, the precision of position and the actuator's pressing force directly affect the installation success rate and the potential for product defects. Inaccurate positioning, angular deviation, or variations in pressing force can cause misalignment, component damage, or imperfect assembly.

Problems that often occur during cartridge assembly with pneumatic actuators include air pressure fluctuations, dynamic system response, and mechanical tolerances that result in variations in the actuator's final position. This instability contributes to an increased defect rate, including improperly installed cartridge covers, cracks in the housing, and leaks caused by excessive pressure and improper installation positions.

Although pneumatic systems are widely used due to their relatively low cost and quick response, their precision control is still limited compared to servo-based electric actuator systems. Some studies show that improving actuator control accuracy can reduce process variation and increase repeatability, but implementation in industrial-scale cartridge assembly systems still faces integration and cost challenges. An automated system using rotary actuator robots is designed to cap cartridges without defects due to impact or vibration, conveniently.

Automation enables the optimisation of energy use by reducing waste, increasing precision, and minimising downtime in the production process. (Pramudita et al., 2024). The integration of robotic rotary actuators also opens the door to closed-loop control. A closed system is one in which the output value or number influences the result, and the reference serves as the system's input, providing feedback to the predetermined reference. (Putranto et al., n.d.)

An actuator is a mechanical device that moves or controls a system, typically used to follow the output of a sensor or controller. Actuators can be divided into three categories: pneumatic, hydraulic, and electric. (Oktariawan, 2013). In this study, defects occurred during the cartridge cap installation process using a pneumatic actuator system. Pneumatic cylinders indeed have many useful functions, but their basic function remains unchanged: converting air pressure or potential energy into motion (kinetic energy). (Muhammad Natsir et al., 2025)

Meanwhile, the cartridge assembly process will be optimised using the IAI electric rotary actuator system. An electric actuator is an actuator that converts electrical signals into mechanical motion. (Simanjorang et al., 2021). The mechanical design of the actuator must be analysed for torque, speed, and position accuracy. A robo-rotary actuator is an actuator based on a servo motor or DC motor with a closed-loop control system. The main advantage of a DC motor is that its speed is easy to control and does not affect the quality of the power supply. This DC motor can be controlled by adjusting the armature voltage and the field current. Increasing the armature voltage will increase the speed. (Simanjorang et al., 2021)

The issue of defects becomes increasingly critical in high-volume and large-batch production systems. Delays in detecting defects can cause a single production batch to produce a large number of products that do not meet specifications before corrective actions are taken. It not only impacts cost wastage but also reduces process stability and customer trust.(Pauline et al., 2026). Robotic precision assembly systems with non-destructive imaging and gripping can save costs, deliver higher-quality results in less time, and greatly enhance the reliability of precision assembly and microstructure automation.(Syamsuar & Reflianto, 2019)

The research began with the identification of an existing problem: the high DPPM in the cartridge cover installation process in the printer manufacturing industry. Before the research started, results from 3 days of monitoring showed that the DPPM was around 1303. The next step is to identify the root cause of the problem using the Ishikawa method (fishbone diagram) and Why-Why analysis, and to continue through implementation and evaluation. Testing was carried out using system optimisation with an IAI electric actuator to assess the actuator's accuracy and repeatability, as well as its impact on cartridge cover installation.

LITERATURE REVIEW

A pneumatic cylinder is an actuator or mechanical device that uses pressurised air (compressed air) to generate power in the linear reciprocating motion of a piston (in-and-out movement). A pneumatic cylinder is a tool or device we often encounter in industrial machines across the automotive, packaging, and electronics industries, as well as in various other industries and institutions. Pneumatic cylinders are generally used to clamp objects, drive cutting machines, press pressing machines, absorb vibrations, operate sorting doors, and so on. Pneumatic cylinders indeed have many useful functions, but their basic function remains the same: converting air pressure or potential energy into motion (kinetic energy) (Muhammad Natsir et al., 2025). The drawback is that it must be equipped with springs, additional accessories, and system equipment when the machine is operating. The positioner also causes higher costs because a deceleration process is required (Yusman et al., 2025). The Rotary Cylinder Pneumatic is shown in Figure 1.

Figure 1. Rotary Cylinder Pneumatic

Some factors that affect the capability of pneumatic cylinders that the author found in the field include the influence of air pressure, where the higher the pressure, the greater the output force, cylinder bore diameter size, if the cylinder bore is larger then the force will be greater, the factor of airflow speed affected by the size of the fitting, tube diameter, and type of cylinder stopper to achieve a precise position as well as the difficulty in adjustment.

An electric actuator is an actuator that converts electrical signals into mechanical motion (Simanjorang et al., 2021). The mechanical design of the actuator must analyse torque, speed, and load. A robo-rotary actuator is an actuator based on a servo motor or DC motor with a closed-loop control system. The main advantage of a DC motor is that its speed is easily controlled and does not affect the quality of the power supply. This DC motor can be controlled by adjusting the armature voltage and field current. Increasing the armature voltage increases speed (Simanjorang et al., 2021).

The technical feasibility of the proposed system involves machine learning and robot control for practical industrial assembly problems. The proposed system consists of teaching, learning, and control (Lin, 2020).

Industrial robotics is a technology well-suited to flexible, reconfigurable manufacturing systems, and robots are often used to perform various industrial tasks, such as material handling, welding, assembly, spray painting, machine maintenance, and milling (Iglesias et al., 2018). The extensive use of aluminium across various aspects of modern industry prompts engineers to study its mechanical properties more closely. It is intended to prevent material failure, as the mechanical properties of a material play an important role in selecting materials for modern industrial components to avoid premature failure (Leni, 2023). The electric actuator from IAI is made of aluminium and weighs only about 2kg. Specification data is shown in the table. 1.

Table 1. Actuator Specifications

Item	**Description**
Drive System	Hypoid gear
Positioning Repeatability	±0.01 degrees
Homing Accuracy	±0.01 degrees
Lost Motion	±0.1 degrees
Allowable Thrust Load	200 N
Allowable Load Moment	17.7 N·m
Weight	2.2 kg
Ambient Operating Temp./Humidity	0 ~ 40°C, 85% RH or less (non-condensing)

From the robot specification table, the Position Repeatability and Homing Accuracy are very high, namely 0.01 degrees, which will be very helpful for adjusting the cartridge cover assembly position, which becomes a challenge when we use a pneumatic cylinder, as it is difficult to find the adjustment position.

SolidWorks and Solid Edge are widely used Computer-Aided Design (CAD) software for designing 3D models of mechanical components. One of SolidWorks' standout features is SolidWorks Simulation, an add-on module that enables users to perform finite element analysis (FEA). This feature allows users to simulate various loads, including static forces, vibrations, heat, and pressure. SolidWorks Simulation provides visualisation of stress, deformation, and safety factors, facilitating design validation before production, as shown in Figure 2. Another advantage is the direct integration between the 3D model and simulation module, allowing every design change to be quickly and efficiently retested.

Figure 2. Solid Edge Software

METHOD

Based on the problems outlined in the introduction section, the research process is organised as shown in Figure 3 to obtain an appropriate solution that achieves the main goal.

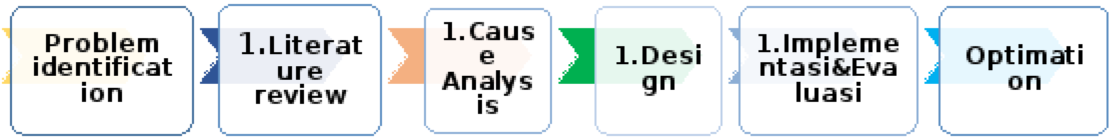

Figure 3. Research process stages

The research began by identifying the existing problem: the high DPPM in the cartridge cover installation process in the printer manufacturing industry. Before the study began, results from 5 days of monitoring showed that the number of defects found each day ranged from 15 to 25 out of a total product output of 11,000, as shown in Figure 4**.** The next step was to identify the root cause of the problem using the Ishikawa method (fishbone diagram) and Why-Why analysis, and to continue through implementation and evaluation. Testing was conducted by optimising the system using an IAI electric actuator to assess the actuator's accuracy and repeatability, as well as its impact on cartridge cover installation.

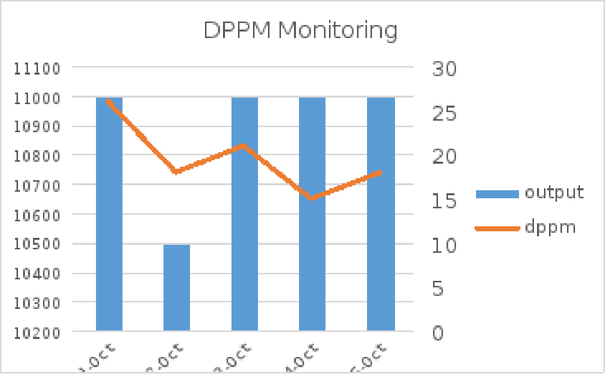

Figure 4. Defect Trend Chart

Then the researchers collected and reviewed scientific references, engineering books, journals, and previous research related to rotary robot actuators, the working principles of pneumatics and mechatronics, and the use of Solid Edge software in the design process and drawing creation for fabrication.

Based on the literature review, the researcher began designing a rotary actuator in Solid Edge. The design includes the main components of the cartridge cover assembly, such as the robot base mount, cartridge work holder assembly, rotary mechanism, and floating detection sensor. The machine design and manufacturing process are carried out using readily available, low-cost materials or components without compromising their quality (Bukhari et al., 2022). Material informatics is a new approach in materials science that integrates information technology and materials science to optimise the discovery of new materials (Leni et al., 2024). The rapid adoption of stainless steel in the modern industrial era has prompted steel industry players to develop material properties that meet current industrial needs continuously. It is closely related to improvements in steel quality and other aspects.

After the 3D model is completed, proceed to the fabrication section and continue with the assembly, setup, and adjustment of the new robot actuator mechanism, including teaching the robot's positions. The researchers formulate conclusions from the entire research process and provide suggestions for further development of the rotary actuator robot, both in terms of physical design and advanced simulation integration.

RESULTS AND DISCUSSION

In this section, the research results will be presented and explained in detail. The results include the initial design, fabrication, and system analysis. At this early stage, before determining activities for improvement and optimisation, the author conducted an assessment of several possible actions to achieve the desired results. For example, Table 2 is used as a reference for improvement activities.

Table 2. Improvement assessment

No	**Activity**	**Category**			**Point**	**Result**
		Cost	**Time**	**Time**		
1	Change type Pneumatic cylinder	5	3	3	11	
2	Change to Index Servo	3	3	3	9	
3	Change to Electric Actuator	3	5	5	13	Selected

Legend: 1= Bad 3=Good 5=Excellence

The selection of an electric actuator is also prioritised because it makes precision adjustment easier and provides more ergonomic dimensions. Then, the designed parts include the base or actuator mount and the working mount for cartridge assembly or installation. The actuator we use is a rotary actuator from IAI, part number RCS2-RTC10L-A-60-24-360-T2. Table 3 shows the actuator specifications.

Table 3. Actuator IAI Specification

Allowable Thrust Load	220N
Allowable Load moment	17.7N.m
Weight	2.2Kg
Positioning accuracy	0.01 degrees
Homing accuracy	0.01 degrees
Size	L 166mm x W 94mmx H 71mm

This research focuses on the design and assembly of precise cartridge caps, resulting in high-quality, defect-free final products. The design of the Rotary Actuator/Robot has several advantages for adjusting the degree of rotation position to avoid tilting of the cartridge caps.

The output from the cover assembly using the robot has been identified, and the Floating sensor for early defect detection in the cover assembly has been detected. It will provide an alarm or error signal if the installation is outside the specified specifications. As shown in Figure 6, the conceptual design for this robot actuator includes a rotary actuator mount, a sensor support, a floating sensor and robot mount, and a work table bearing.

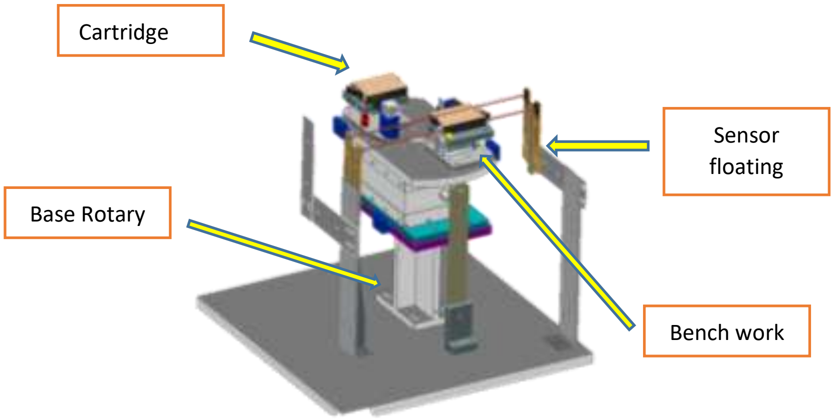

Figure 6. Design concept

During fabrication, several tools are used to support success, including conventional milling machines, CNC machines, and welding machines, to produce the mechanism and the worktable base for installing the cartridge cover.

The preparation and assembly stages are very important for this research because they directly affect the overall performance of the cartridge assembly with the robotic system. The assembly process ensures that all mechanical, electrical, and control system components are installed correctly and function as designed. Assembly, as shown in Figure 7, begins by attaching the robot's main basic structure to the machine. The robot base serves as the main support, maintaining stability during cartridge assembly. Assembly is carried out using fastener bolts with a specific torque to minimise vibration and shifting during robot operation.

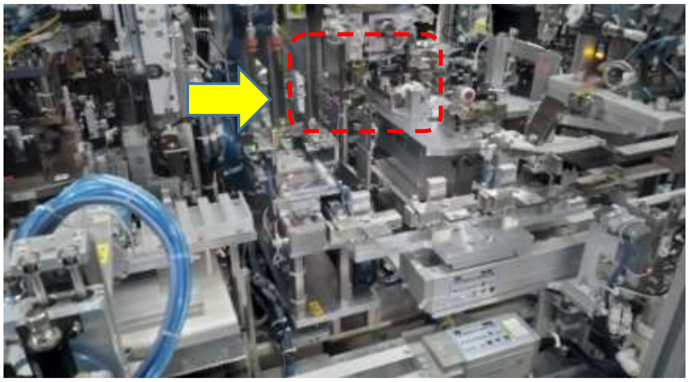

Figure 7. Position Assembly

Next, the Rotary Actuator and mounting mechanism are installed on the robot axis according to the design configuration. The actuator is aligned with the table axis and cartridge to avoid misalignment, which could cause increased deviation and decreased movement accuracy. After mechanical installation is complete, a manual inspection is carried out to ensure that all components move smoothly and without obstruction, manually and without electricity. The actuator is manually turned to ensure smooth, seamless movement before being subjected to a workload.

Figure 8. Measurement repeatability accuracy

The next step, as shown in Figure 8, is installing the electrical system and controller. Sensors, detectors, and actuators are connected to the main control unit according to the designed electrical diagram. The cables are installed neatly and securely to prevent mechanical damage or electrical interference during system operation. In addition, the connections are checked to ensure there are no installation errors or short circuits.

After all components are installed, the control system configuration process is carried out, including setting motor parameters, calibrating the initial position, and testing the robot's basic functions. This testing ensures that the robot can execute movement commands according to the specified cartridge assembly sequence. Overall, the assembly and installation process of the cartridge-cover robot system is carried out systematically to ensure reliability, safety, and system performance before entering the stage of further testing and analysis.

Testing And Evaluation

Testing was carried out systematically by operating the robotic system under actual operating conditions. The electric actuator was operated to perform the cartridge assembly process according to the pre-programmed work sequence. Each test cycle consisted of picking the cover component from the tray, transferring it, and assembling the cartridge cover until the desired final condition was achieved. Figure 9 shows a diagram of the cartridge cover installation sequence process.

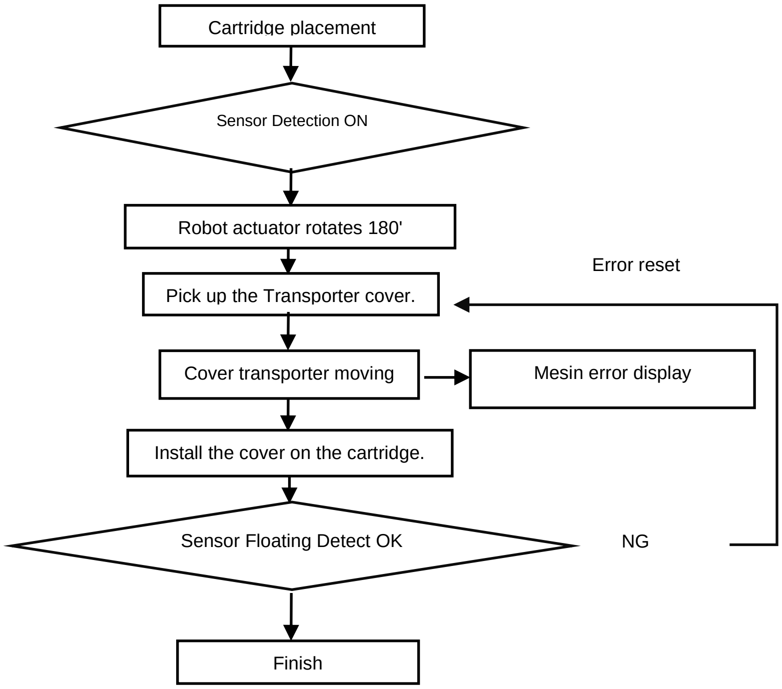

Figure 8. Cartridge cover installation process diagram

The trial and technical evaluation stage is conducted to verify the cartridge assembly robot system's performance against the performance parameters established during the design phase. The evaluation focuses on motion accuracy, repeatability, operational stability, and system reliability during repeated cartridge assembly. Furthermore, to achieve the desired results, several performance parameters are evaluated at this stage, including:

1. Homing accuracy

Homing accuracy is the difference between the standby position and the actual position reached by the robot's end actuator. Accuracy is measured using mechanical tools such as a pin adjusted with the mating between the robot and the Datum point.

2. Position repeatability stability using a dial gauge, as shown in Figure 10.

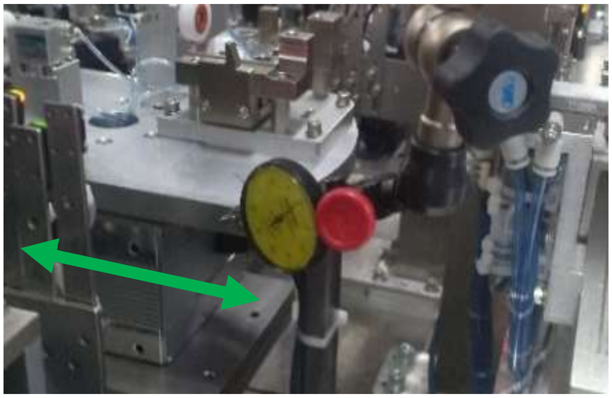

Figure 10. Index alignment uses a dial gauge

Position repeatability is evaluated by the actuator's ability to reach the same position across multiple test cycles consistently. This parameter is calculated from the variation in the end-effector's final position during assembly. In this study, we require accuracy and stability using a dial gauge at each 180-degree rotation of the robot, because the cartridge cover assembly process alternates between 2 workstations. Figure 11. shows the repeatability data for the 2 systems being evaluated.

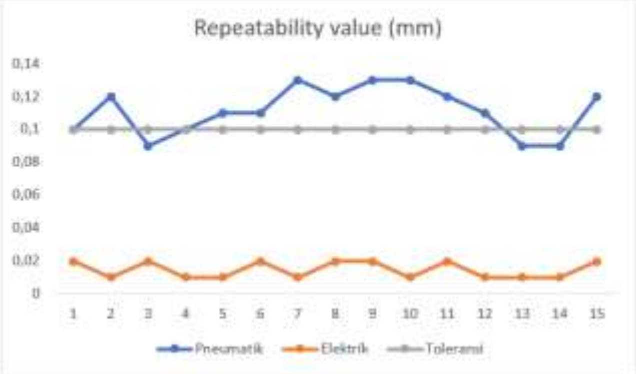

Figure 11. Graph data repeatability

Based on the repeatability graph, the pneumatic system exhibits a relatively large, fluctuating position deviation of 0.09-0.13 mm. Some test points exceed the 0.10 mm tolerance limit, indicating end-position instability across repeated cycles. This variation reflects the characteristics of the pneumatic system, which are influenced by air compressibility and pressure fluctuations, resulting in less consistent movement and potentially increasing the risk of assembly defects. On the other hand, the electric actuator system shows a much more stable performance with repeatability values ranging from 0.01 to 0.02 mm, all well below the set tolerance limits. The very small and consistent deviations in each test indicate that servo-based position control can significantly enhance precision. These results confirm that a redesign using rotary electric actuators provides substantial improvements in repeatability and directly supports a reduction in assembly-process defects.

Quantitatively, there was an increase in precision of 87%, after the implementation of the electric actuator, the increase in precision can be calculated using equation 1:

$$\%\text{Repeat} = \frac{Me\ \text{before} - Me\ \text{after}}{Me\ \text{before}} \times 100\%$$

Were,

Me before = Middle value before

Me after = Middle value after

Then we can calculate,

$$\%\text{Repeat} = \frac{0{,}113 - 0{,}014}{0{,}113} \times 100\%$$

$$\%\text{Repeat} = \frac{0{,}099}{0{,}113} \times 100\%$$

$$\%\text{Repeat} = 87{,}60\%$$

Repeatability improved by around 87.6%

3. Cycle Time

Cycle time is the time required by the machine to complete the overall process and produce a complete cartridge assembly, measured in seconds. This parameter is used to assess the potential for improving system productivity. Based on experimental data with a sample of 30 pieces, an average cycle time that meets the standard was obtained, as shown in the image below.

For this industry, the cycle time standard has been agreed upon at 5.5 seconds. The monitoring results are shown in Figure 12.

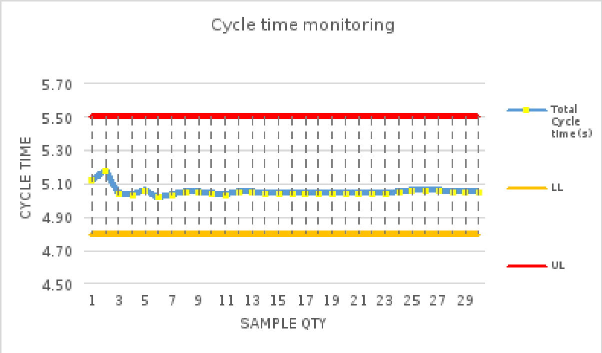

Figure 12**.** Graph cycle time

To determine the cycle time of a machine, generally, equation 2 is used:

$$\textit{Cycle time} = \frac{\text{Total production time (seconds)}}{\text{Output amount } \textit{(pcs)}}$$

4. Torque dan safety factor

The next step is to perform calculations and analysis on torque and the safety factor. In the rotary actuator cartridge cover mounting system, it is installed with a horizontal axis configuration. It supports 2 work tables (work sets) and a base, with a total mass of 6kg. Since this mass is mounted offset at a radius of 125mm from the centre of rotation, the load generates a bending moment on the actuator shaft. The force due to the system's weight is calculated using the normal force from gravity. (Ilham, n.d.) with equation 3:

$$F = m \times g$$

Were,
F = Force
m = mass total
g = gravitation (9.81m/s2)
F = 6 x 9.81
= 58.86 N

Because the load is at a radius distance of 125mm (0.125m) from the axis of rotation, the moment acting on the shaft is calculated using Equation 4:

$$M = F \times r$$

Were
F = Force (N)
r = Radius from axis (m)
and then we calculate,
M = 58.86 x 0.125
= 7.36 Nm

The calculation results show that the actual moment received by the actuator is 7.36 Nm. Based on the technical specifications of the IAI rotary actuator, the allowable moment permitted is 17.7 Nm.

The evaluation of safety factors is carried out using the general definition in machine design using Equation 5:

$$SF = \frac{\text{M allowable}}{\text{M actual}}$$

And the calculation,

$$SF = \frac{17.7 \text{ Nm}}{7.36 \text{ Nm}}$$

SF = 2.4

A safety factor of 2.4 indicates that the actuator is operating under safe conditions and is well below the allowable maximum torque limit. With this safety factor, shaft deformation and potential misalignment due to static loads can be minimised. The analysis results reinforce that selecting the electric actuator not only meets the system's motion requirements but also provides better mechanical stability than the previous system, thereby improving position consistency and reducing In defects.

Based on the test results from the 3-day trial, the DPPM obtained meets the mass-production specification criteria. Table 4 serves as a benchmark and standard for DPPM across various industries worldwide.

Table 4. DPPM Industrial standard

Industry	Typical DPPM Target	Quality Level
Automotive	< 50 DPPM	World-class supplier level
Electronics	**< 100 DPPM**	**High precision assembly**
Consumer Goods	< 200 DPPM	Standard mass production
Medical Devices	< 10 DPPM	Critical-quality manufacturing

To obtain the DPPM comparison results, data collection was conducted over 3 days of production, both before and after the implementation of the electric actuator and the mechanical system redesign. Before optimisation (pneumatic system), the total output was 33,000 pcs, with 43 pcs recorded as defects; the DPPM value can be calculated using equation 6:

DPPM = DEFECT / (DEFECT+OUTPUT) x

Were,
DPPM = Defect Part per Million
Defect = total defect product
Output = Output Finish Good running
So, the condition before optimisation (pneumatic system)
DPPM Before = 43 / (43+33000) x 1.000.000
DPPM Before = 1303 DPPM
So, the defect rate before optimisation was 1303 DPPM,

After optimisation (electrical system), the total output over 3 days of production was 30,000 pcs, with 3 defects recorded, then
DPPM *After* = 3/ (3+30000) x 1.000.000

DPPM *After = 100 DPPM*

Thus, the defect rate after optimisation is 100 DPPM. The percentage of defect reduction can be calculated using equation 7:

Defect *Reduce* = (DPPM *Before*- DPPM After) / DPPM *Before* x 100%

Thus obtained,

Defect *Reduce* = (1303-100) / 1303 x 100%

= 1202 /1303 x 100%

= 92%

The results showed that after implementing the electric actuator and mechanical design improvements, the defect rate decreased by 92% compared to the previous pneumatic actuator system, as shown in Table 5.

Table 5. Monitoring Test Run Result

Item	Before			After		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Output (pcs)	11000	11000	11000	8000	11000	11000
Defect (pcs)	15	18	11	3	0	0
DPPM	1361.8	1633.7	999	374.85	0	0
Cycle time (sec)	5.1	5.1	5.1	5.1	5.1	5.1

Figure 13. Shows a graph comparing the overall situation before optimisation and after optimisation with an electric actuator with 3-day monitoring results. Positive results were obtained, with the target plan achieved and the defect rate decreasing.

Figure 13. Graph comparison before-and-after

The 'Comparison of Defects' chart shows a significant improvement in process quality after making improvements to the cartridge cover installation system. In the initial condition, with a stable production output of around ±11,000 pcs per day, the DPPM (Defect Parts Per Million) value was still at a high and fluctuating level, approximately 1,500 DPPM on the first day, increasing to nearly 2,000 DPPM on the second day, and dropping to around 1,000 DPPM on the third day. Indicates that before the improvement, the process was still unstable, and variations in actuator positions contributed to the high defect rate while production volume remained consistent.

On the contrary, after implementation, the output quantity remained consistent (±8,000–11,000 pcs), but DPPM decreased by a very significant amount. The DPPM value dropped drastically from around 500 DPPM on the first day to zero on the second and third days. This decrease indicates that improvements in actuator precision, stability, and accuracy directly reduced cartridge assembly defects. In other words, the system improvement not only maintained production capacity but also enhanced process capability and precise product quality.

Overall, the graph indicates that actuator precision optimisation is strongly correlated with reductions in product defect rates. Implementing a more stable and precise system has been proven to improve quality without sacrificing productivity, thus supporting an overall enhancement in manufacturing performance. Based on the experimental results, the control parameters and mechanical configuration of the system were evaluated. Adjustments were made to the actuator's movement speed and acceleration, as well as the incremental points and reference position points, to improve the stability and consistency of the robot's motion. After the optimisation process, the system was tested again to ensure that the performance improvements met the expected criteria. Table 6. Shows a comparison of both systems.

Table 6. Comparation Pneumatic and electric system

Parameter	**Before (pneumatic)**	**After (electric)**	**Improvement**
DPPM	1303	376	↓92%
Defect rate (%)	0,85%	0,07%	↓92%
Repeatability (mm)	0,115	0,014	↑87,6%
Position accuracy (mm)	0,12	0,015	↑87%
Out of tolerance 0,10 mm	Yes	No	Eliminate deviation
Cycle time (det)	5,2	5,1	Stable
Torque stability	Fluctuate	Stable & controlled	Control increased
Safety factor	1,6	2,4	↑ Safety margin

The performance comparison table before and after optimisation shows a significant improvement in system performance across all key parameters. The DPPM value decreased by 92%, indicating a drastic reduction in defects after the implementation of the rotary electric actuator. Repeatability also increased by 87.6%, with all test values within the established tolerance limits. In addition, cycle time became more stable, with smaller deviations, while the safety factor increased to 2.4, indicating a better design safety margin than the previous system.

Overall, the quantitative data in the table confirm that optimisation not only improves motion precision but also enhances process stability and overall system reliability. The transition from pneumatic systems to rotary electric actuators has been shown to directly reduce process variation, increase production consistency, and improve assembly quality without compromising operational efficiency.

This research discusses the results of experiments and evaluation of an assembled robot system for cartridge covers, with an emphasis on the influence of the system's mechanical characteristics, particularly backlash, stiffness, and actuator tolerance, on the accuracy and position repeatability performance of the robot's actuators.

Backlash is one of the main factors affecting position deviation in pneumatic actuator systems, depending on the transmission mechanism. In the developed system, backlash is mainly identified at the actuator transmission joints and the end-effector drive mechanism. This backlash causes differences in the final position when the direction of movement changes, thus contributing to the variation in position errors observed during testing. In this test, the high-precision rotation angle of the actuator is highly influential and very helpful for perfectly installing the cartridge cover, overcoming gaps that previously occurred when using this pneumatic air cylinder and facilitating adjustment with a tolerance of 0.01mm. It is reflected in a 87.6% decrease in repeatability deviation after the actuator replacement.

The robot's mechanical structure plays an important role in maintaining the stability of the end-effector position during the assembly process. In this system, the elastic deformation of mechanical components, such as the robot arm and actuator mounts, contributes to variations in the final position when the robot operates under load conditions. Testing shows that increased load during cartridge installation leads to greater mechanical deflection, thereby reducing positional accuracy. This phenomenon indicates that the system's structural stiffness remains a limiting factor for precision performance, especially in the final stages of the assembly process, which require a certain contact force. However, this deformation is elastic and does not cause structural failure during testing.

The accuracy of the electric actuators and other mechanical components also affects the overall system performance. With high position accuracy and repeatability, during testing, the electric actuator system defects decreased by 92% and produced precise product outputs. As shown in Figure 14, the Finished Good product output.

Figure 14. Finish Good Product

The interaction between backlash, stiffness, and actuator tolerance has a cumulative effect on the performance of the cartridge assembly robot system. Backlash causes errors due to changes in the direction of movement. At the same time, stiffness affects position stability under load, and the accuracy and repeatability of the actuator influence the consistency of position precision. The combination of these three factors explains the patterns of weaknesses and variations in repeatability in the previous system. Thus, the experimental results show that the electric actuator system can operate within acceptable tolerances for precise cartridge assembly applications.

CONCLUSION

This research successfully designed, implemented, and optimised an automatic cartridge cover assembly system based on a high-precision rotary electric actuator. Based on experimental test results and system performance evaluations, a significant quantitative improvement in process quality was achieved.

The results show that the DPPM value decreased by 92% from the initial condition before optimisation. This decrease indicates that improvements in position accuracy and actuator torque control directly contribute to reduced cartridge assembly defects. Furthermore, the repeatability parameter increased by 87.6%, indicating improved motion consistency and greater stability of the actuator's final position in each work cycle.

From a mechanical design perspective, the system has a safety factor of 2.4, indicating that the structure and mechanical components are within safe limits against operational loads and have an adequate safety margin for industrial applications. Evaluation of the cycle time also shows stable, consistent results after optimising control parameters, with no significant fluctuations between production cycles. It confirms that precision enhancement does not compromise the system's productivity.

Specifically, the main contribution of this study lies in the redesign and optimisation of the rotary electric actuator as a replacement for conventional pneumatic systems. Compared to pneumatic actuators, which are affected by air compressibility, pressure fluctuations, and nonlinear characteristics such as hysteresis, the rotary electric actuator developed in this study provides more precise position and torque control, more stable responses, and higher repeatability. Implementing the electric system enables more accurate parameter settings through servo-based control, thereby significantly reducing end-position variations. These results demonstrate that the transition from pneumatic to rotary electric systems is not merely a component change, but a strategic design approach that directly optimises precision and substantially reduces defects in automated assembly processes.

The integrated optimisation between mechanical design, robotic configuration, and control parameter tuning successfully resulted in an assembly system with high precision, high consistency, and significantly improved operational efficiency. This research's contribution confirms that measurable improvements in actuator accuracy can drastically reduce defects without compromising production stability. Nevertheless, this study still has limitations in terms of long-term testing. The evaluation conducted has not yet included an analysis of performance degradation due to mechanical wear, material changes, or variations in component characteristics in continuous mass production. Therefore, further research is needed to conduct long-term durability tests, perform process capability analysis (Cp/Cpk), and integrate sensor-based adaptive control systems to ensure precision stability under more complex operational conditions.

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