

# Load analysis and product line recommendations for EE3 parallel arm SCARA robot.

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## Abstract

Nowadays, with increasing automation in factories and industrial environments, many companies such as Kuka and ABB among many others, have started to offer off-the-shelf, highly customizable, serviced industrial robotics solutions [2][3]. As such demand for SCARA robots is predicted to also increase as faster and more accurate solutions for assembly and other industrial applications [4].

The EE3 Parallel SCARA robot was initially designed as a pick-and-place solution for packaging pétanque balls but has the potential to be used for a variety of other industrial applications. This report aims to explore the possibilities for expanding its range of applications and increasing potential load capacities for the EE3 Parallel SCARA by identifying its mechanical limitations and ultimately creating a product line catering to a larger market.

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*Keywords*: SCARA robot;

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## 1. Introduction

Robots and machines are typically designed to handle a range of loads or load classes, rather than just a single load case or application, allowing them to be versatile and adaptable to a wide range of tasks and ultimately cater to a larger market.

To evaluate the possible development of the EE3 Parallel Arm SCARA robot, as a full-fledged product line for many different pick and place applications an in-depth analysis of the limitations of the design of the robot is conducted to reach cost-efficient solutions for various load capacities while maximizing the SCARA's capabilities.

By using tools such as finite element analysis and mechanical simulations using Siemens NX 2007 both static and

dynamic limitations were analyzed and expanded upon for the robot to obtain a comprehensive picture of its operation and potential improvements that could be implemented.

## 2. Methods & Materials

The current design of the EE3 parallel SCARA is comprised of two sets of aluminum arms, a left arm, and a right arm. These amount to a total arm weight of 50 Kg and are controlled by a 2-axis servo drive powering two medium inertia Allen Bradley servo motors at a speed and acceleration of 120 %/s and 480 %/s<sup>2</sup> respectively.

While designed for a 1 kg spherical load, the operating range of the robot is expected to be much more diverse. For this reason, two types of analysis are conducted to study both the

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static and dynamic/kinematic behaviors of the SCARA robot and evaluate the mechanical limitations of the installation.

### 2.1. Static Analysis

In this first analysis, the goal is to determine a preliminary estimate for the load capacity of the robot, by analyzing the mechanical limitations of its arms. This analysis was conducted using the Siemens NX Finite Element Analysis environment where a simplified version of one of the two SCARA arms was loaded with a distributed force on the 5<sup>th</sup> joint while the connection to the supporting base tube was fixed.

By increasing the loading on the 5<sup>th</sup> joint, values for deflection at the joint and maximal Von Mises stresses were found, allowing us to first understand at which static load the arms would fail by comparing them to literature values of yield stresses of Aluminum 5086, but also give a picture of their precision to their target position, namely %accuracy defined as:

$$\%accuracy = \frac{100}{r_h} \cdot l_{pist} \cdot \sin\left(\text{atan}\left(\frac{\delta}{l_{arms}}\right)\right) \quad (1)$$

Where  $r_{hole}$ ,  $l_{pist}$  and  $l_{arms}$  are constants with values 25mm, 459.37mm, and 1696.13mm respectively, while  $\delta$  is the deflection obtained from the FEA.

To obtain these results, several assumptions were made such as the use of a simplified model of the SCARA's arms during the simulations. It was also assumed that the load was split 50-50 between the two arms and that there would be no play in the bearings within the joints, adding to the deflection. For integrity, these assumptions were made throughout this report.

### 2.2. Dynamic and Kinematic analysis

Using the NX Mechatronics Concept Designer, a simulation was run to test the SCARA robot's performance over a 4-second cycle with varying loads ranging from 0 to 150 kilograms, resulting in time series data for positions, accelerations, speeds, and torques, for each load. These were processed and analyzed using MS Excel to obtain relevant values and allowed the following characteristics of the SCARA robot to be evaluated:

- The impact of load mass on the peak required power for each of the robot's arms.
- The effect of arm mass on the peak required power, as a function of load mass.
- The influence of angular speed of the arms on the peak required power, as a function of load mass.

The primary objective of evaluating these characteristics was to determine the power that the installation would need to deliver to accommodate different loads, allowing comprehensive selection and understanding of the required motor and servo powers.

Additionally, by manipulating the inertia of the arms using Equations 2, 3, and 4, it would be possible to observe the effects of modifications to the cross-section or material selection of the arms on the required powers, while keeping the length of the arms constant. This was achieved, by keeping the inertia caused by the load  $J_{load}$  constant while scaling the original inertia of the arms  $J_{arms,0,l}$  by an arbitrary factor  $k_{\%}$  and ultimately re-calculate the power  $P_{\mu}$ , required to move the scaled installation at a 0-load speed of  $\omega_{0,l}$  and angular acceleration of  $\alpha_{0,l}$  mentioned earlier.

$$P_{\mu} = \omega_{0,l} \cdot \alpha_{0,l} \cdot J_{total} = \omega_{0,l} \cdot \alpha_{0,l} \cdot (J_{load} + J_{arms,\mu}) \quad (2)$$

$$J_{arms,\mu} = J_{arms,0,l} \cdot (k_{\%} + 1) \quad (3)$$

$$P_{\mu} = \omega_{0,l} \cdot \alpha_{0,l} \cdot (J_{load} + J_{arms,0,l} \cdot (k_{\%} + 1)) \quad (4)$$

As these two previous characteristics assumed operation at a peak speed of 120 %/s and constant acceleration of 480 %/s<sup>2</sup>, an analysis was also conducted to understand the effect that different speeds would have on the installation allowing the robot to operate at different cycle times. This was simply done by scaling the speed similarly to the inertia and re-calculating the required peak powers.

## 3. Results & Discussion

### 3.1. Static Analysis

From the static analysis, the deflections and stresses obtained through FEA were compiled in Table 1.

Table 1. Results from Finite Element Analysis for static loads.

Load Weight in Kg	$\delta$ Deflection in mm	%accuracy in %	Max Von Mises Stress in MPa
4.08	0.53	0.57	2.70
10.20	1.32	1.43	6.90
20.39	2.64	2.86	13.81
30.59	3.96	4.29	20.71
40.79	5.28	5.72	27.62
61.18	7.92	8.58	41.42
142.76	18.47	20.01	96.65
224.34	29.03	31.44	151.88
407.89	52.78	57.15	276.15

Considering that 0.2% yield strengths for Aluminum 5086, depending on the temper as shown by ASM's Handbook, range between 115-255 MPa (-O or -H34) [1], load weights above 170 Kg, the interpolated load mass corresponding to  $\sigma_b = 115\text{MPa}$ , would probably be unadvised. Furthermore, by accounting for an arbitrary safety factor of 40%, we can conclude that the robot should be used for loads within the range of 0-100 Kg. While this would result in a position error of 14%, which may not be an issue for smaller and spherical objects, larger and more diverse loads may require further improvements to the arm's structure to minimize this error.

### 3.2. Dynamic Analysis

Having found a preliminary value for the SCARA robot’s load capacity, we can now evaluate the feasibility of operating at diverse loads and operating conditions. As can be seen in the time-series data obtained from the simulated cycle in Fig. 1, the arms during their test cycle required large peaks of torque during short durations, which can be also seen from Fig. 2 as the peaks in torque are several times larger compared to the average torques.

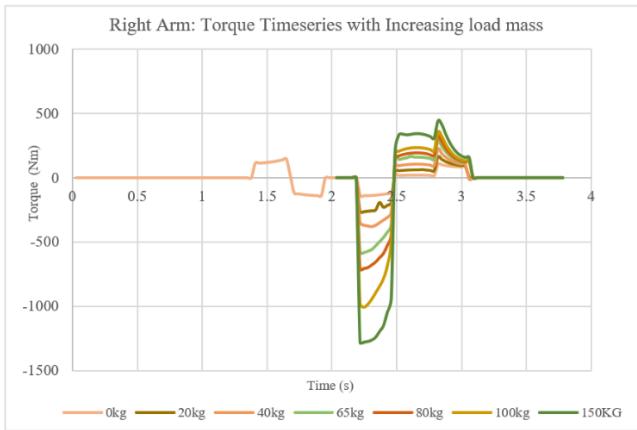


Fig. 1. Simulated results for Right Arm Torque as 4s time series.

Based on Fig. 2, it can also be inferred that the right arm, which requires higher torques, will be the limiting factor in the motor selection. Therefore, for the subsequent analysis, it can be assumed that the conclusions reached for the right arm will be equally applicable to the left arm.

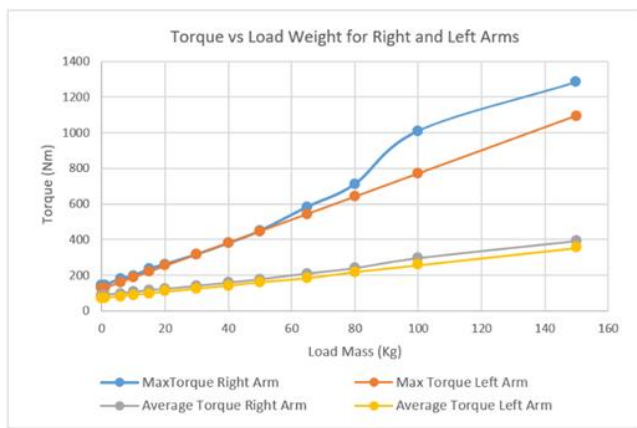


Fig. 2. Peak (Max) and Average Powers, for right and left SCARA arms, with respect to increasing load weight.

Moreover, to cater to different applications and load capacities one of the possible modifications that was envisioned was a redesign of the arms specifically for small payloads, to for example reduce the required torque in turn allowing the use of smaller cheaper motors. As previously explained, by scaling the inertia of the arms it was possible to obtain the results in Fig. 3, as a percentage increase in required power compared to the initial SCARA robot design. This clearly shows, as expected, that the required power increases with increasing arm mass and that this effect is even more

pronounced at low payload weights when compared to the original design.

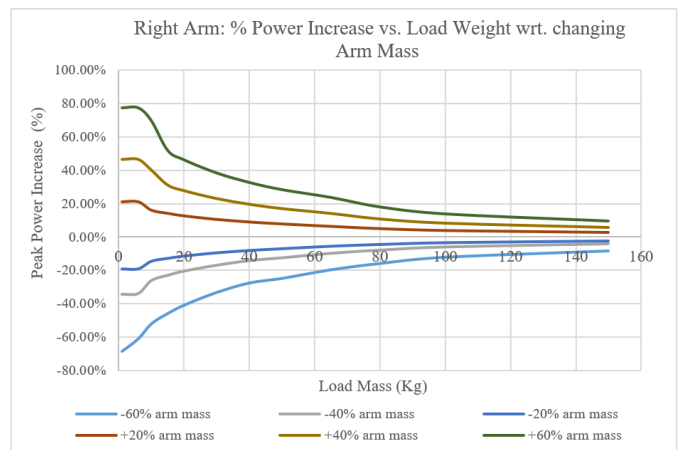


Fig. 3. % increase in peak required power as a function of load mass, with changing arm mass in %.

The first conclusion that can be drawn from these results is that increasing arm mass, as a method to decrease deflection and increase the accuracy of the robot, would only be interesting at higher loads as otherwise, it would almost double the required power to move the arms. On the other hand, reducing the mass of the arms would be beneficial for lower load weights reducing significantly the required power, although potentially leading to higher deflections.

To evaluate the changes in required power at different speeds, In Fig. 4 the increase in peak required power is shown with varying speed as a percentage of the original design speed being 120°/s. While the use of servo motors would allow operation, given the current design, at speeds lower than the designed one, this analysis intended to evaluate how much the maximal speed of the arms could be increased for the installation to still require realistic values for peak power.

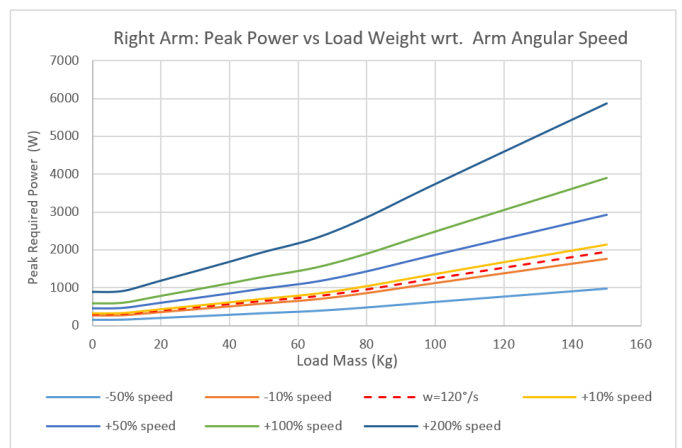


Fig. 4. Peak required power as a function of Load Mass with changing arm angular speeds as a % of the designed speed = 120°/s

Ultimately it can be concluded that while increasing rotational speeds would not be interesting for larger loads due to large increases in required power, for lower loads, as the increase is much smaller, it would be interesting to incorporate

higher-rated motors to allow for decreases in cycle time, allowing for low cycle time and lower load capacity solutions. According to these speeds, it was also possible to calculate estimates of cycle time, based on the simulated test cycle, with increases in speed resulting in:

- 0% increase, speed of 120 deg/s, test cycle time of 3.78s
- 50% increase, speed of 180 deg/s, test cycle time of 3.435s
- 100% increase, speed of 240 deg/s, test cycle time of 3.09s
- 200% increase, speed of 480 deg/s, test cycle time of 2.75s

#### 4. Conclusions & Future Work

The characteristics researched in this paper allow for a large variety of adaptations that could be implemented in the SCARA robot, concerning motor powers and changes in the design of the SCARA arms depending on the application and the required load capacity. While this is the case, from the above-mentioned results it can be easily concluded that the implementation of a lower-powered, low cycle time solution suited for lower load capacities along with a higher power, higher cycle time solution suitable for larger payloads would already cater to many diverse applications and make effective use of the designed SCARA robot.

Furthermore, modifications to the arm's cross section or material selection could prove beneficial for the incorporation of a low capacity, low cycle time solution by for example decreasing the mass of the arms by 20%. Ultimately, a possible series of products that could be developed based on these conclusions can be the following:

- High-capacity, High-cycle time, High-cost solution: For Loads from 0-100 Kg, maximum speeds of 120 deg/s (test cycle time of 3.78s), with 1.5kW motor.

- Medium-capacity, High-cycle time, Medium-cost solution: For Loads from 0-50 Kg, maximum speeds of 120 deg/s (test cycle time of 3.78s), with 1kW motor.
- Medium-Capacity, Low-cycle time, High-cost: Loads from 0-50 Kg, maximum speeds of 240 deg/s (test cycle time of 3.09s), with 1.5kW motor.
- Medium-Capacity, Low-cycle time, High-cost: Loads from 0-50 Kg, maximum speeds of 240 deg/s (test cycle time of 3.09s), with 1.5kW motor.
- Low-Capacity, Low-cycle time, Medium-cost: Loads from 0-20Kg, maximum speeds of 240 deg/s (test cycle time of 3.09s), with 1kW motor.
- Very-Low-Capacity, Very-Low-cycle time, Medium-cost: Loads from 0-10Kg, maximum speeds of 480 deg/s (test cycle time of 2.75s), with 1kW motor and arm mass reduced by 20%.

While these solutions would most likely provide coverage for a wide range of applications further improvements to reduce cycle time could be made with regards to the pneumatic actuator and the conveyor as well as adjustments concerning the mass of the arms as several variants could potentially be manufactured to further reduce the required powers depending on the application. The presented solutions also do not consider current market needs and when implemented in practice should be carefully evaluated to judge the necessity of such a wide range of adaptations.

Overall, it is clear that the EE3 Parallel SCARA can be an effective, customizable alternative for several automated industrial applications, and shows great in the current world of increasing serviceable robotics.

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