Design and Performance Analysis of an RPPR Robotic Arm for Palletizing in Industrial Applications

Nevin Kopp
Department of Electrical and Computer Engineering
University of California, Riverside
Riverside, USA
nkopp002@ucr.edu

***Abstract* – This research paper presents the design and analysis of a Revolute-Prismatic-Prismatic-Revolute (RPPR) robotic arm tailored for palletizing applications within industrial settings. The increasing demand for automation in material handling has spurred the need for specialized robotic solutions, particularly in palletizing tasks. The proposed RPPR robotic arm can address the specific challenges associated with the palletizing process, aiming to enhance operational efficiency and adaptability. The design phase involves a systematic approach, considering key factors such as kinematics and statics. The kinematic and static analyses are then applied to a sample problem to evaluate the arm's motion capabilities during palletizing operations.**

Keywords – RPPR robotic arm, Palletizing application, Industrial automation, Robotic arm design, Kinematic analysis, Statics analysis, Material handling, Versatility

I. INTRODUCTION

In the rapidly evolving landscape of industrial automation, the demand for sophisticated robotic solutions has become increasingly pronounced, especially in the realm of material handling [3]. Palletizing, a fundamental task in logistics and manufacturing, requires precision, adaptability, and efficiency to meet the growing demands of modern production facilities [2]. This research endeavors to address this need by presenting a study on the design and analysis of a RPPR robotic arm tailored specifically for optimal palletizing application]. Recognizing the unique challenges posed by palletizing operations, this research focuses on the design of an RPPR robotic arm, strategically configured to navigate the complexities of arranging and stacking varied loads onto pallets. The inherent flexibility of the RPPR configuration allows for precise control of the end-effector, ensuring seamless integration into diverse palletizing scenarios.

To substantiate the proposed design's viability, a thorough kinematic analysis is conducted, evaluating the arm's motion capabilities and determining its ability to reach specified positions within the workspace. Static analysis is employed to assess the robotic arm's response to a test load of 1 kg. Ultimately, the findings presented are anticipated to propel advancements in automated material handling, furthering the integration of robotics into the fabric of modern manufacturing and logistics.

II. ROBOT DESIGN

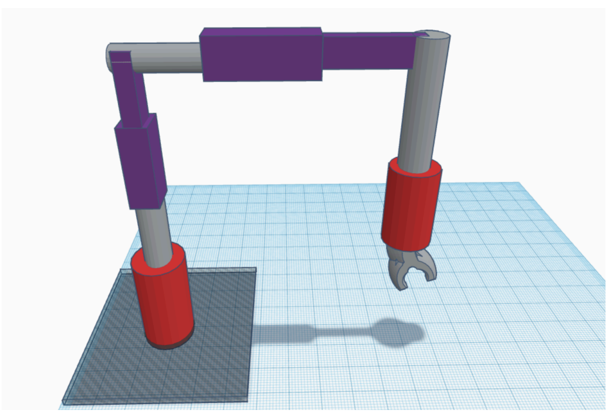

Figure 1. RPPR Robotic Arm

Figure 1 represents the overall design of the industrial robotic arm. The revolute joints are shown in red, and the prismatic joints are shown in purple. The exact dimensions of the robot will vary depending on the exact application. The dimensions used in this case study are given in Figure 5. The overall design of this RPPR platform is inspired primarily by the need for adaptability within the palletizing application. The revolute joint at the base allows the robot to move between the products and the pallet.

As pallet stacks get taller, the robotic arm will need to adapt to the new height. The vertical prismatic joint ensures adaptability for various pallet stack heights. The horizontal prismatic joint sitting between the vertical prismatic joint and the revolute joint at the end effector allows the robot to cover various pallet widths. Finally, the revolute joint at the end effector allows the orientation of the product to be adjusted as needed. If the robot were stacking brick shaped objects for example, the revolute joint allows perpendicular orientations for each layer of product to increase stability.

III. KINEMATIC ANALYSIS

Forward Kinematics

The forward kinematic problem aims to find a set of values representing the x,y and z coordinates of the end effector, given some joint angles (θ). In this paper, the forward kinematics were solved using the product of exponentials formula.

$$T(\theta) = e^{[S_1]\theta_1} \cdots e^{[S_{n-1}]\theta_{n-1}} e^{[S_n]\theta_n} M$$

Eq. 1. Product of Exponentials

Where $[S_n] =$

$$\begin{bmatrix} [w_n] & v_n \\ 0 & 0 \end{bmatrix}$$

And $[w_n] =$

$$\begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix}$$

Where a_i denotes the index of vector w_n and θ_n denote the joint values. This method involves viewing each joint as a screw type motion. Matrix {s} is assigned as the stationary matrix at the base of the robot and matrix {b} will be assigned as the moving end effector frame. It is important to start with the robot in the “home” configuration, ideally where all joint angles are zero. This is also referred to as the robot’s zero configuration. The matrix M is the configuration of the end-effector frame as compared to the base frame [1]. The first step is to find matrix M.

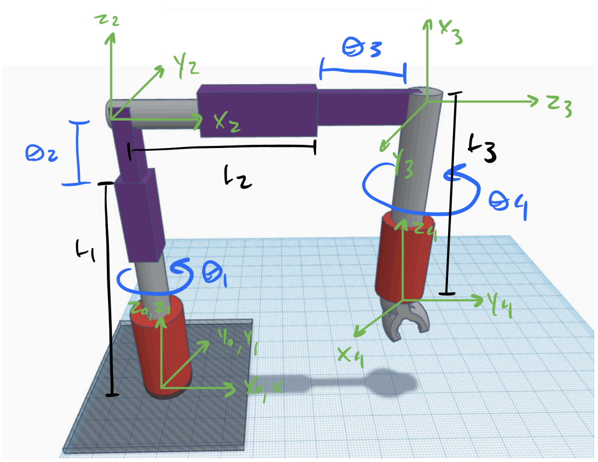

Fig. 2. RPPR Robotic Arm with Coordinate Frames and Variables

Using figure 2, matrix M can be assigned as

0	1	0	L_2
-1	0	0	0
0	0	1	$L_1 - L_3$
0	0	0	1

Fig. 3. Matrix M

The next step is to find the screw matrices associated with each of the joints. Using Fig. 2, the values can be assigned as the following:

i	w_i	q_i	$v_i = -w_i \times q_i$
1	0,0,1	0,0,0	0,0,0
2	0,0,0	-	0,0,1
3	0,0,0	-	1,0,0
4	0,0,1	L_2,0,L_1-L_3	0,L_2,0

Fig 4. Joint Screw Axes

Now that we have M and the screw axes, we can solve for the forward kinematics using Eq. 1. For this test case, the following specifications were used.

L_1	0.80 m
L_2	0.80 m
L_3	0.160 m
θ_1	$\pi/3$
θ_2	0.915
θ_3	0.450

Fig 5. Test Specifications for Calculations

with the resulting matrix:

```
T = 4x4

    0.9116    0.4110         0    0.4827
   -0.4110    0.9116         0    1.1555
         0         0    1.0000    1.5550
         0         0         0    1.0000

x = T(1,4)

x = 0.4827

y = T(2,4)

y = 1.1555

z = T(3,4)

z = 1.5550
```

Fig 6. Forward Kinematics Test Results

Looking at Fig 5, we can see our resultant x, y and z values. The value of θ_4 depends on the desired orientation of the product.

Inverse Kinematics

The inverse kinematics equations aim to solve the same problem but with the other set of variables. That is, given some x, y and z values, determine the joint angles necessary to reach that point [1]. In this paper, trigonometric analysis was used.

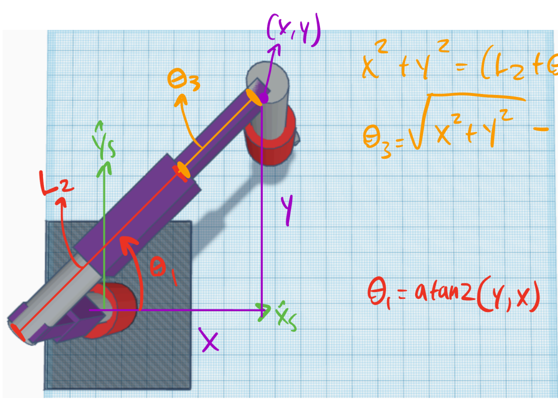

Fig 7. Aerial View of RPPR Robotic Arm

Using fig. 7, we can use a two-argument arctangent relation to solve for θ_1 (in red). The final equation was found to be $\theta_1 = atan2(y, x)$. Using fig. 7, we can also solve for θ_3. Using the law of cosines (in orange), the final equation was found to be $\theta_3 = \sqrt{x^2 + y^2} - L_2$. For θ_2, we can use fig 2. Since θ_2 is on the z axis only, we can use the value of z along with the link lengths. Doing so gives the value for θ_2 as $z + L_3 - L_1$.

θ_1	$atan2(y, x)$
θ_2	$z + L_3 - L_1$
θ_3	$\sqrt{x^2 + y^2} - L_2$
θ_4	$\Phi - \theta_1$ (where Φ is product orientation)

Fig 8. Summary of Inverse Kinematics Equations

```
x = 3;
y = 2;
z = 4;

theta_1 = atan2(y, x)

theta_1 = 0.5880

theta_2 = z + L_3 - L_1

theta_2 = 3.3600

theta_3 = sqrt(x^2 + y^2) - L_2

theta_3 = 2.8056
```

Fig 9. Inverse Kinematics Test Results

Velocity Kinematics

Velocity kinematics is similar to forward kinematics with the main difference being our interest in the twist of the end-effector rather than just the position of it [1]. Given a set of joint positions and their velocities, we can use the Jacobian matrix to find their relationship to the twist of the end effector. In this paper, we will find the space formulation for the Jabobian matrix. The process is very similar to finding the space screw axes as completed during forward kinematic section, however, we will use arbitrary values for θ instead of $\theta = 0$[1]. Looking back at fig 4, only the last column would change, joint 4 still points in the positive z direction so (0,0,1) will remain unchanged, however, we need to include values for θ. The point q we will choose this time will be $L_2 + \theta_3,\ 0,\ L_1 + \theta_2 - L_3$ and solving for -w x q will give us $0,\ -L_2 - \theta_3,\ 0$. We can now use fig 4 and these updated values to find the space Jacobian as:

0	0	0	0
0	0	0	0
1	0	0	1
0	0	$cos(\theta_1)$	0
0	0	$sin(\theta_1)$	$-L_2 - \theta_3$
0	1	0	0

Fig. 10. Space Jacobian

This is regarded as the geometric Jabobian since screw axes were used.

IV. STATICS ANALYSIS

For the statics analysis, we will assume the robotic arm is perfectly balanced. We then apply some force at the end effector. Once the force is applied, we need to calculate the torques each joint would generate to regain equilibrium. For this problem, we use the Jacobian matrix found in the previous section with the following formula:

$$\tau = J^T(\theta) f_{tip} \longrightarrow \boldsymbol{\tau} = \boldsymbol{J}^T(\boldsymbol{\theta})\boldsymbol{\mathcal{F}}$$

Equation 2. Statics Equation

From the formula, we simply multiply the transpose of the Jacobian matrix along with the force applied at the tip and we get the torques needed to generate equilibrium [1]. For this paper, a 1 kg brick will be used to model a sample product in the palletizing application. The force acting on the end effector would be:

$1\,kg\ *\ 9.8\frac{m}{s^2}\ =\ 9.8\,N.$

Multiplying the space Jacobian in Fig 10 along with the forces acting on the end effector as Eq 2 shows, we get the following result.

```
T = J'*[0, 0, 0, 0, 0, 9.8]'

T = 4×1
         0
    9.8000
         0
         0
```

This result is telling us that θ_2 (refer to figure 2) will need to exert 9.8 N of force to counter the force at the end effector provided by the brick. This makes intuitive sense as that joint is responsible for holding up the majority of the robot and acts in the opposite direction to gravity.

V. CONCLUSION

In conclusion, the research paper presents a comprehensive study on the kinematic and static analysis of a robotic arm with four degrees of freedom within the palletizing application in an industrial setting. The findings underscore the potential of such robotic arms in enhancing efficiency and precision in palletizing tasks. The kinematic analysis provides valuable insights into the motion characteristics of the robotic arm, while the static analysis offers an understanding of the forces and torques involved. These analyses collectively contribute to the optimization of the robotic arm's performance, paving the way for more advanced and efficient industrial automation solutions. Future research could focus on dynamic analysis and control strategies to further improve the performance and versatility of these robotic systems. This work, therefore, serves as a significant step towards realizing the full potential of robotics in industrial applications.

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