THE MINISTRY OF SCIENCE AND HIGHER EDUCATION
OF THE RUSSIAN FEDERATION

ITMO University
(ITMO)

Faculty of Control Systems and Robotics

Report
about production, design practice

on the topic:
DESIGN OF A LOADING AND UNLOADING SYSTEM FOR A WAREHOUSE ROBOT

Student:
Group No. R3237 *Guevara Riaño, Geraldine*

Tutor:
Docent *Bzhikhatlov, Islam*

Saint Petersburg 2025

CONTENTS

INTRODUCTION

The goal of this project is to develop a loading and unloading system for a warehouse robot, designed for precise and reliable vertical (z-axis) and horizontal (x-axis) movement. The design was inspired by Geek+'s *Tote-to-Person* robotic transporter [1], a benchmark in automated warehouse systems, and the *Prusa MINI+* 3D printer [2], renowned for its compact and high-precision motion mechanisms.

Due to the limited duration of the internship period, the scope of work was restricted to developing the core mechanisms for z-axis and x-axis movement. A lead screw linear actuator was selected for the z-axis due to its stability, reliability, and high precision, making it ideal for vertical movement under load. However, its drawbacks include relatively low speed and higher cost. For the x-axis, a belt-and-pulley system was chosen for its lightweight construction, high speed, and cost-effectiveness, though it may suffer from reduced precision and potential belt slippage under heavy loads.

The design was developed and modeled in *SolidWorks* [3], where a detailed assembly model was created to verify the system's intended functionality.

1 DESIGN OF CORE MECHANISMS

1.1 Ball Screw Linear Actuator (Z-axis Mechanism)

The Z-axis mechanism employs a ball screw linear actuator to provide precise vertical movement for the warehouse robot's loading/unloading system. The system is designed to support a total mass of 30 kg (20 kg payload + 10 kg platform) with target speed of 0.3 m/s and acceleration of 0.5 m/s^2. Key components include:

- **Aluminum profile**: Structural frame measuring 2000 mm in length with 30 mm × 135 mm cross-section, providing a rigid base for the mechanism.
- **Lead screw and guide rods**: 25 mm diameter ball screw with 10 mm pitch and 1960 mm length, paired with guide rods for stable linear motion.
- **Upper and lower support elements**: Custom-designed components to secure the ball screw and guide rods, ensuring proper alignment and structural integrity.
- **Additional components**: Screws, bolts, washers, linear bearings, ball screw support bearing, and motor coupling for smooth power transmission.
- **Assembly**: Components integrated into a single assembly designed and validated in SolidWorks. The aluminum profile serves as the base, while support elements fix the ball screw and guide rods. Linear bearings ensure smooth motion, and the coupling provides efficient torque transfer from the motor.

The following figures show the ball screw linear actuator assembly:

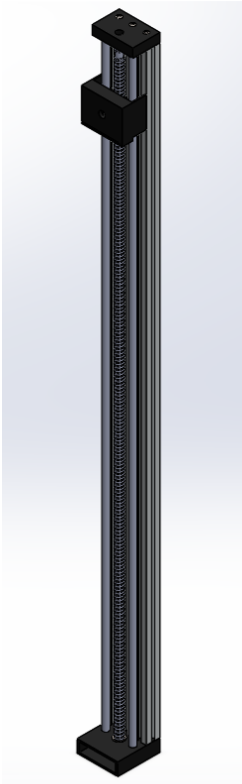
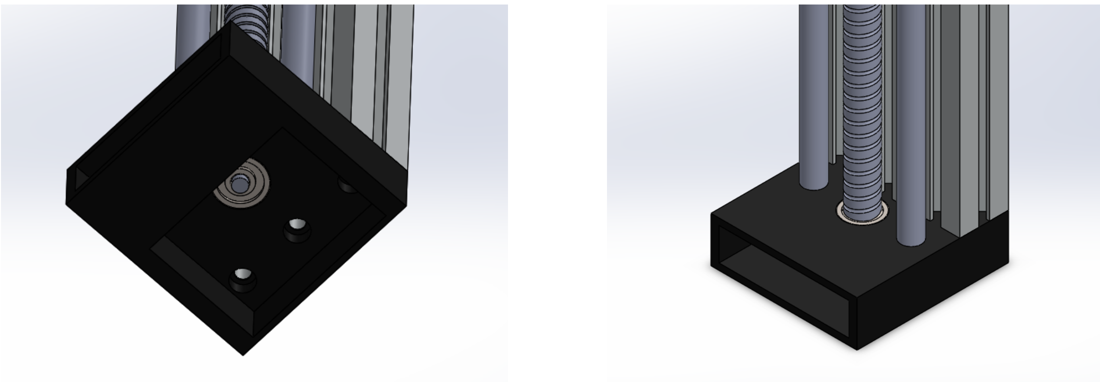


Figure 1 — Z-axis Assembly

(a) (b)

Figure 2 — Close-up view of the upper assembly. (a) Front view and (b) rear view



(a) (b)

Figure 3 — Close-up view of the lower assembly. (a) Bottom view and (b) top view

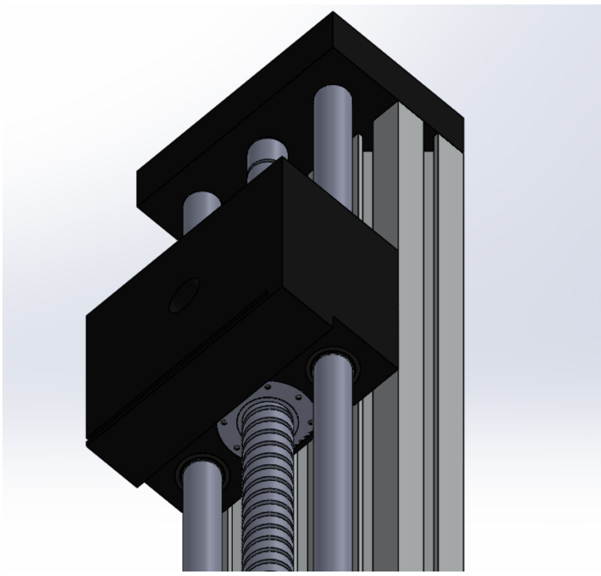


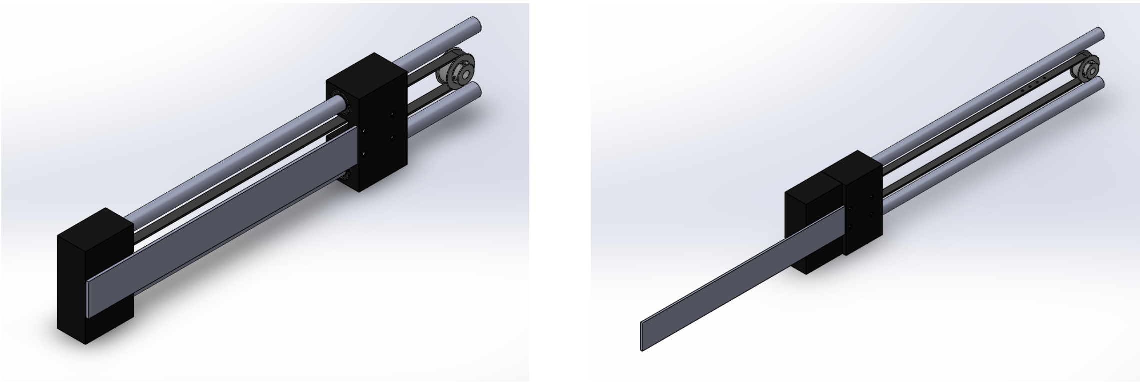
Figure 4 — Close-up view of the slider's lower assembly

1.2 Belt-and-Pulley Transmission (X-axis Mechanism)

The X-axis mechanism uses a belt-and-pulley system for rapid, cost-effective horizontal movement during cargo handling. While lightweight and optimized for speed, it offers slightly lower precision compared to the Z-axis mechanism. Key components include:

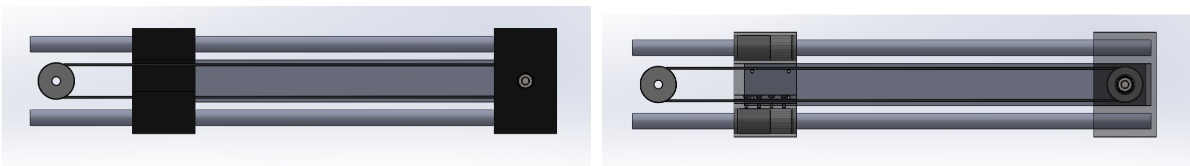
- **Flat idler pulley**: Sourced from McMaster-Carr[4] (1.4” OD, 0.5” ID, 1.125” width) for smooth belt guidance.
- **Modified timing pulley**: From McMaster-Carr[5] (35mm OD, 8mm shaft diameter, 29.1mm pitch diameter), customized for system requirements.
- **Belt**: Flat belt selected for its flexibility and cost efficiency.
- **Slider, end effector, and aluminum rail**: The belt-connected slider moves along an aluminum rail that provides a stable path for horizontal motion. The end effector maintains proper belt tension.
- **Additional components**: Screws, bolts, nuts, and linear bearings for smooth operation and assembly integrity.
- **Assembly**: The belt drive system mounts on a SolidWorks-designed frame with precisely positioned pulleys. The slider moves along the aluminum rail, guided by linear bearings for accurate cargo handling.

The following figures show the belt-and-pulley assembly:



(a) (b)

Figure 5 — Belt-and-pulley assembly. (a) Aluminum rail in home position (b) Extended position



(a) (b)

Figure 6 — Side view of belt-pulley assembly. (b) Shows transparent view of slider and end effector

2 COMPLETE ASSEMBLY AND OBSERVATIONS

2.1 Complete Assembly

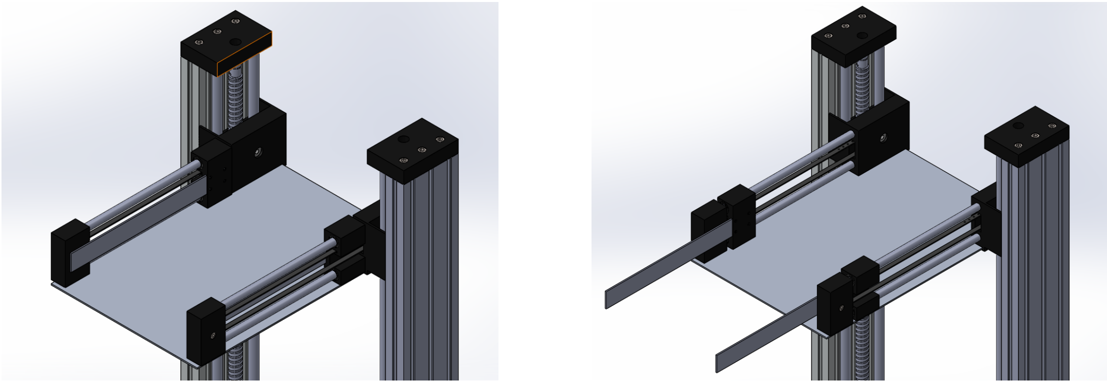
The preliminary complete assembly integrates both the Z-axis (ball screw linear actuator) and X-axis (belt-and-pulley system) mechanisms into a unified loading/unloading system for the warehouse robot. Key additions to the assembly include:

- **Payload platform**: A flat platform designed to hold cargo during transport, measuring 360 mm × 540 mm with a usable area of 300 mm × 530 mm. The 3 mm thick platform's material remains undetermined, with lightweight yet durable options like aluminum or composite materials under consideration to balance strength and weight.
- **Lower aluminum profile**: An additional structural base providing stability and support for the entire system. The profile matches the Z-axis frame dimensions (30 mm × 135 mm cross-section, 2000 mm length) to maintain structural integrity.

The following figures show the complete assembly:

(a) (b)

Figure 7 — Complete assembly. (a) Front view (b) Rear view



(a) (b)

Figure 8 — Complete assembly. Close-up of the bed platform with aluminum frames (a) Retracted position (b) Extended position

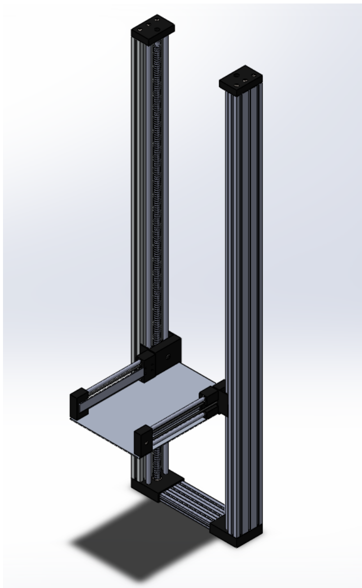


Figure 9 — Complete assembly at alternate Z-axis position

2.2 Observations

Key observations during design and assembly:

- **Structural stability**: The lower aluminum profile significantly enhances system stability, particularly during dynamic vertical loading. However, additional analysis is required to verify the profile's resistance to vibrations or lateral forces during high-speed X-axis operation.
- **Precision and alignment**: While SolidWorks modeling indicates precise alignment of screw and belt systems, physical assembly may intro-

duce minor deviations. Prototype calibration and testing are necessary to verify performance.

– **Weight considerations**: The preliminary assembly's weight (including platform and lower profile) may affect torque and motor power requirements. If final materials or additional components increase total mass beyond 30 kg, the current 200W AC servo motor selection may require reevaluation - potentially necessitating a 400W motor as noted in the conclusion.

3 MOTOR SELECTION FOR BALL SCREW LINEAR ACTUATOR

The system requires precise and efficient Z-axis movement using a 25 mm diameter ball screw with 10 mm pitch and 1960 mm length. The maximum payload is 20 kg, with total moving mass (excluding platform) requiring 0.3 m/s velocity and 0.5 m/s^2 acceleration. The following calculations determine torque, speed, and power requirements for motor selection, assuming 30 kg total mass (20 kg payload + 10 kg platform).

3.1 System Parameters

Calculation parameters:

- Ball screw diameter: 25 mm
- Pitch (p): 0.01 m
- Length: 1.96 m
- Maximum payload: 20 kg
- Platform mass: 10 kg
- Total mass (m_{total}): 30 kg
- Target velocity (v): 0.3 m/s
- Acceleration (a): 0.5 m/s^2
- Gravitational acceleration (g): 9.81 m/s^2
- Ball screw efficiency (η): 0.9

3.2 Force Requirements

For vertical upward movement, total force considers both gravity and acceleration:

$$F = m_{\text{total}} \times (g + a) \tag{1}$$

Substituting values:

$$F = 30 \times (9.81 + 0.5) = 30 \times 10.31 = 309.3\,\text{N} \tag{2}$$

3.3 Torque Calculation

Required torque during acceleration:

$$T_{\text{screw}} = \frac{F \times p}{2\pi\eta} \tag{3}$$

Substituting:

$$T_{\text{screw}} = \frac{309.3 \times 0.01}{2\pi \times 0.9} \approx \frac{3.093}{5.6549} \approx 0.547\,\text{Nm} \tag{4}$$

Steady-state operation torque (constant velocity, gravity only):

$$F_{\text{steady}} = m_{\text{total}} \times g = 30 \times 9.81 = 294.3\,\text{N} \tag{5}$$

$$T_{\text{continuous}} = \frac{294.3 \times 0.01}{2\pi \times 0.9} \approx 0.520\,\text{Nm} \tag{6}$$

3.4 Rotational Speed

Required rotational speed for target linear velocity:

$$n = \frac{v}{p} \times 60 \tag{7}$$

Substituting:

$$n = \frac{0.3}{0.01} \times 60 = 1800\,\text{RPM} \tag{8}$$

3.5 Acceleration Torque

Angular acceleration:

$$\alpha = \frac{2\pi a}{p} = \frac{2\pi \times 0.5}{0.01} = 314.16\,\text{rad/s}^2 \tag{9}$$

Screw mass estimation (steel, $\rho = 7850\,\text{kg/m}^3$):

$$m_{\text{screw}} = \rho \times \pi r^2 L = 7850 \times \pi \times (0.0125)^2 \times 1.96 \approx 7.54\,\text{kg} \tag{10}$$

Screw inertia:

$$J_{\text{screw}} = \frac{1}{2} m_{\text{screw}} r^2 = \frac{1}{2} \times 7.54 \times (0.0125)^2 \approx 0.000589\,\text{kg m}^2 \tag{11}$$

Assuming 200W servo motor with $J_{\text{motor}} = 0.000029\,\text{kg m}^2$:

$$J_{\text{total}} = J_{\text{screw}} + J_{\text{motor}} \approx 0.000589 + 0.000029 = 0.000618\,\text{kg m}^2 \tag{12}$$

Acceleration torque:

$$T_{\text{inertia}} = J_{\text{total}} \times \alpha \approx 0.000618 \times 314.16 \approx 0.194\,\text{Nm} \tag{13}$$

Total peak torque:

$$T_{\text{total}} = T_{\text{screw}} + T_{\text{inertia}} \approx 0.547 + 0.194 = 0.741\,\text{Nm} \tag{14}$$

3.6 Power Requirements

Steady-state power:

$$\omega = \frac{2\pi n}{60} = \frac{2\pi \times 1800}{60} = 188.5\,\text{rad/s} \tag{15}$$

$$P = T_{\text{continuous}} \times \omega = 0.520 \times 188.5 \approx 98\,\text{W} \tag{16}$$

3.7 Motor Selection

A 200W AC servo motor optimally meets the warehouse robot's loading system requirements, providing:

- 0.64 Nm rated torque @ 3000 RPM
- 1.92 Nm peak torque
- Exceeds continuous (0.520 Nm) and peak (0.741 Nm) torque requirements
- 98W power consumption well within 200W capacity

Example: E6 Series 200W AC Servo Motor Kit (3000 RPM, 0.64 Nm, 17-bit encoder, IP65 rating)[6].

3.8 Summary Table

Table 1 — Torque and Power Requirements for Different Masses

Total Mass (kg)	Force (N)	Continuous Torque (Nm)	Peak Torque (Nm)	Power (W)
25	257.8	0.456	0.650	86
30	309.3	0.520	0.741	98
40	412.4	0.694	0.888	131

3.9 Conclusion

For 30 kg total mass, a 200W AC servo motor is recommended. If platform mass exceeds 10 kg, consider upgrading to a 400W motor.

BIBLIOGRAPHY

1. *Geek+*. Geekplus Tote-to-Person RoboShuttle. — URL: https://www.geekplus.com/product/roboshuttle ; Last accessed 25 June 2025.
2. *Prusa J.* Original Prusa MINI+ kit assembly. — URL: https://help.prusa3d.com/manual/original-prusa-mini-kit-assembly_1215/mini-2 ; Last accessed 25 June 2025.
3. *CADFolks*. SolidWorks 2020 - Step-By-Step Guide: Part, Assembly, Drawings, Sheet Metal, Surfacing. — Independently published, 2020.
4. *McMasterCarr*. McMasterCarr Flat-Belt Idler Pulley. — URL: https://www.mcmaster.com/1355K1/ ; Last accessed 25 June 2025.
5. *McMasterCarr*. McMasterCarr Corrosion-Resistant Timing Belt Pulley. — URL: https://www.mcmaster.com/1277N717/ ; Last accessed 25 June 2025.
6. *StepperOnline*. E6 Series 200W AC Servo Motor Kit 3000rpm 0.64Nm 17-Bit Encoder IP65. — URL: https://www.omc-stepperonline.com/e6-series-200w-ac-servo-motor-kit-3000rpm-0-64nm-17-bit-encoder-ip65-e6-rs200h2a2-m17s ; Last accessed 25 June 2025.