UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING

MIE301: Final Report

Warehouse Transport Vehicle with Single-Motor Lifting Mechanism

Group 22

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1.0 Introduction

The automated service and maintenance team of 301 Publishing House has developed a four-legged walking robot mechanism based on a series of belt drives and clutches. The robot mimics the motion of quadrupeds in nature and is capable of maneuvering complex terrains and carrying light loads, allowing it to be used for searching and maintenance activities in small spaces with height differences across the shop floor. Upon learning about the team's expertise in walking robots, the shipping and distribution department of 301 Publishing House requested a modified mechanism to transport and lift packaged boxes of books for stacking on shipping pallets. To meet these demands, the team has identified a set of functions, objectives, and constraints:

1.1 Function

- Transport boxes across flat warehouse floors and lift the boxes to two predetermined heights

1.2 Objectives

- Mechanism should maintain stability and control when subjected to high levels of acceleration
- Mechanism should be power-efficient by minimizing torque required from input motor
- Lifting pace should be relatively quick and controlled

1.3 Constraints

- Power lifting mechanism with single motor
- Support cubic box filled with books that are 35cm on a side stably
- Support the weight of the box (52 kg), and lift to two different preset heights at least 35 cm apart.
  - Values for weight and height requirements derived in the redesign analysis section

Considering the above requirements, the team will focus on motor efficiency and the design of a height-elevating mechanism while considering power economics, mechanism stability, and motion path. Given that the floor of the publishing warehouse is flat, the team will make adaptations to best fit the service environment, including the usage of Mecanum Wheels to support the planned weight and carry with ease.

2.0 Current Design

2.1 Mechanism components and operation

The current design is a three-Degrees-of-Freedom leg mechanism of a dynamically walking quadruped robot. It is composed of two links, a thigh link and a shank link, connected in series and driven by three independent motors. The details of the components are visualized in Figure 1. The actuators describe hip abduction/adduction (HAA), hip flexion/extension (HFE), and knee flexion/extension (KFE). This design employs a clutch mechanism to engage a parallel spring as shown in Figure 2, with the position of the HFE and KFE joints represented by $\theta_1$and θ_2 [1].

The hip motor directly drives the HFE joint. A two-stage transmission system (green in Figure 1) increases the maximum torque and transfers the torque to the knee joint. The belt runs over a smaller pulley fixed on an intermediate shaft on the thigh link, and a bigger pulley directly fixed to the shank link at the knee joint, connecting the transmission system to the shank link. Figure 3 shows the details of the clutch mechanism and the spring. One side of the spring is fixed to the thigh link, and the other side is tied to a non-stretchable cable. The other terminal of the cable is winded on a spool. Thus, the linear force generated by the spring is shifted into torque on the spool. The spool then transfers the torque to the shank link through another set of spur gears.

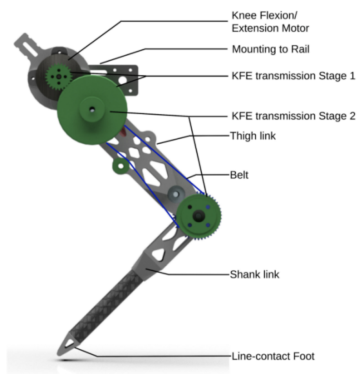

Figure 1. Schematic Drawing of the Robot Leg [1].

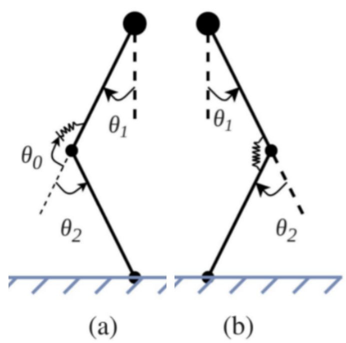

Figure 2. Skeleton Drawing of Leg Mechanism [1].

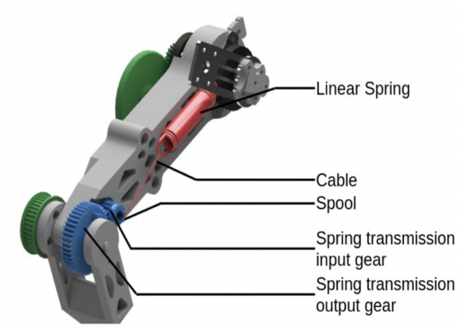

Figure 3. Detailed view of the spring and clutch mechanism [1].

2.2 Functional specifications

The motivation behind the existing design is to replicate leg motion found in the animal kingdom with improvements to the range of motion at the joints. Functional specifications are identified accordingly:

- Use cases include surveillance, transport of lightweight items, and companionship
- Should be able to perform various stances, walk, and maneuver over complicated terrains such as stairs and rocky or uneven grounds
- High degree of precision and flexibility in control
- Minimize power consumption, achieved through spring suspensions which enable it to stand passively without relying on additional torque supplied by the motors

2.3 Incompatibility for required functions

The existing designed is overengineered for current client needs. Our team believes that a mechanical system with mechanical legs as a way of mobility is not appropriate for the new operating environment for the following reasons:

- Required load of 52 kg is too significant for the legs to support
- Advantage of mechanical legs to help the machine move over uneven terrain
  - Ground in the warehouse is flat, and wheels will allow the product to have higher moving speed and stability
- Each robotic leg requires at least two motors to achieve 2-DOF motion (control the direction and distance between the grounding point and the leg connection point)
  - Total of 8 motors required, far exceeds the client's preference of a single motor
- Lifting distance of mechanical legs is limited
  - Considering that the client needs to lift items to two different heights, with ideal lifting distance being greater than 40 cm (side length of the box plus shelf thickness)

2.4 Initial redesign concept

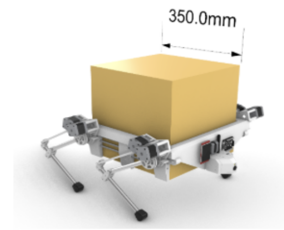

Figure 4. Initial redesign

The initial redesign was inspired by the existing walking robot mechanism and is similarly fitted to maneuver complex, three-dimensional surfaces (Figure 4). However, after further analyzing the client's needs, it was identified that designs based on walking robot legs are not the most efficient for warehouse transportation settings.

3.0 Proposed Design Changes with Functional Specifications

3.1 Proposed design changes

The current product has the following design changes (Figure 5):

- Leg-lifting mechanism replaced with a scissor-lift mechanism which only requires one motor and has a longer vertical lifting range
- Single stepper motor lying on the bottom of the mechanism granting linear actuation
  - Motor rotates bolt and screw actuation mechanism, which pushes and pulls the end of the link to move horizontally
- Method of horizontal motion changed to Mecanum Wheel system to allow the unit to move efficiently in a factory environment with flat floors
- 2 Extension springs in parallel attached at the bottom of link 3 in the space shown in Figure 5
  - Reduces force requirement from the motor (details explained in analysis section)

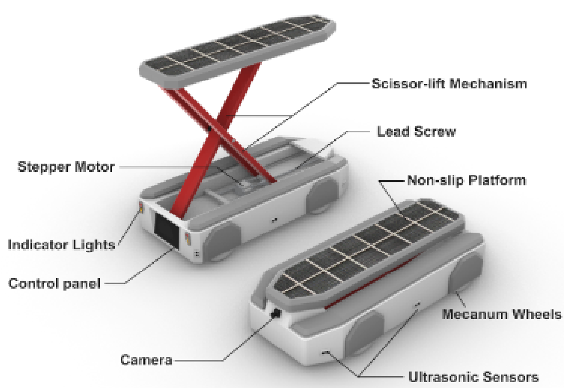

Figure 5. Rendering of mechanism with proposed design changes in maximum and minimum lifting positions.

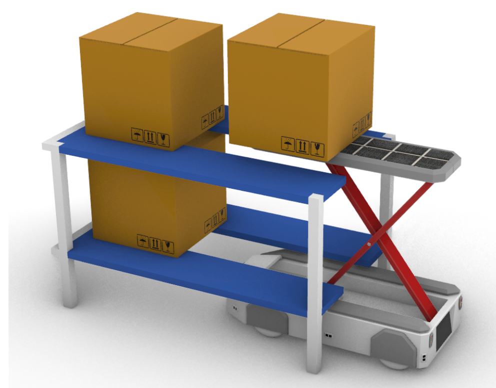

Figure 6. Loading and discharging from the customized shelf.

Additional details not shown in the rendering in Figure 5:

- Mechanism only performs one of horizontal translation or lifting motions at once
- 12-cm tall barrier around perimeter of cart (does not rise with the platform) to prevent the box from sliding off when cart is in motion, horizontal motion only when platform at minimum height
- Knob which rotates 90° to raise a stopper located 6.4 mm from the front end of the cart
  - Limits height raised to height 1 (12.3 cm, just above barrier) to unload first layer of boxes

The new design has a total length of 777mm and a width of 370mm, and it can lift a cubic box with 35cm edges. Using simply this mechanism and a modified shelf, the design can draw a box away from the shelf or discharge to a shelf (Figure 6).

4.0 Redesign Analysis

4.1 Load mass estimation

Assuming that the volume of the box $V_{book} = (35cm)^3 = 42875cm^3$, and the density of paper ρ_{book} is $1.2101g/cm^3$ [2], and the box itself has negligible mass, the mass of the box of books can be estimated:

$$M_{book} = V_{book} \times \rho_{book} = 42875cm^3 \times 1.2101g/cm^3 = 51878.8g \simeq 52kg$$

The topmost platform which supports the box is estimated to be 1 kg. The two links which make up the scissor lift mechanism are assumed to have negligible mass, and the cart only supports the lift mechanism so its mass is not necessary to consider for the analyses that follow.

4.2 Strength required for Mecanum Wheel motor

The maximum weight required to be supported by the cart unit is 53kg (see above), which is distributed to each wheel, is 17kg load. The given data for the load capacity of the Mecanum Wheels from the supplier is 200 lb (or 90.7 kg) per set of four wheels [3], which is much higher than the estimated load.

4.3 Static Force Analysis

The team performed a static force analysis for the mechanism to find the required motor force to safely support the lifting of the mechanism in each position throughout its range of motion. *Let right be the positive direction of forces, and counterclockwise be the positive direction of momentum.*

Forces analysis on link 4 (see Figure 7):

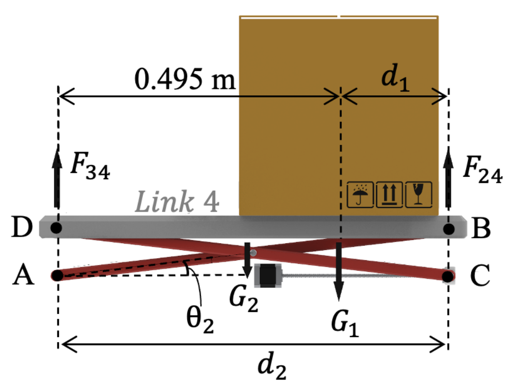

Figure 7: Force analysis on link 4.

Sum of moments at point B

$$\Sigma M_B = G_1 d_1 + G_2 \cdot \frac{690}{2} - F_{34} \cdot d_2 = 0$$

where

$$d_1 = r_2 cos\theta_2 - 0.495, d_2 = r_2 cos\theta_2$$

$$F_{34} = \frac{G_1 d_1 + 345G_2}{d_2}$$

Sum of forces in the vertical y direction

$$\Sigma F_y = F_{24} + F_{34} - G_1 - G_2 = 0$$

$$F_{24} = G_1 + G_2 - F_{34}$$

where G_1 is gravity force of the box,

G_2 is gravity force of the platform,

F_{24} is the force acting on link 4 by link 2,

F_{34} is the force acting on link 4 by link 3,

θ_2 is the angle between link 2 and the horizontal axis,

d_1 is the distance between the lines of action of G_1 and F_{24},

d_2 is the distance between the lines of action of F_{34} and F_{24}.

Forces analysis on the overall mechanism (see Figure 8):

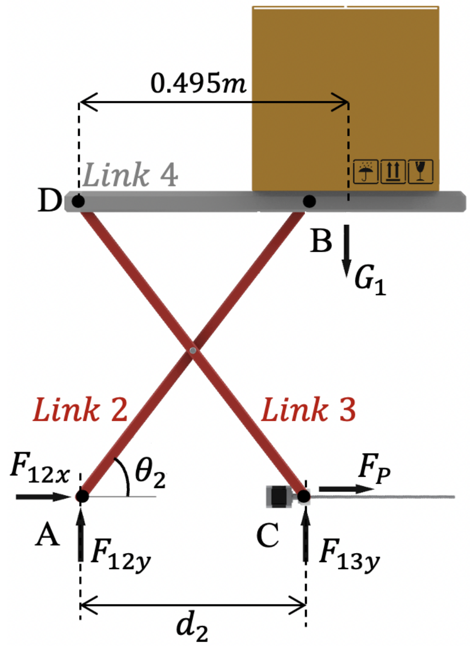

Figure 8: Force analysis on the entire lifting mechanism.

Sum of moments at pint A

$$\Sigma M_A = F_{13y}\, d_2 - (0.495)G_1 = 0$$

$$F_{13y} = \frac{0.495 G_1}{d_2}$$

Sum of forces in the y direction

$$\Sigma F_y = F_{13y} - F_{12y} - G_1 = 0$$

$$F_{12y} = G_1 - F_{12y},\ F_P = F_{12x}$$

where F_{12x} is horizontal ground reaction force on link 2,
F_{12y} is vertical ground reaction force on link 2,
F_{13y} is vertical ground reaction force on link 3,
F_P is required motor force,
θ_2 is the angle between link 2 and the horizontal axis,
d_2 is the distance between points A and C.

Forces analysis on link 2 (see Figure 9):

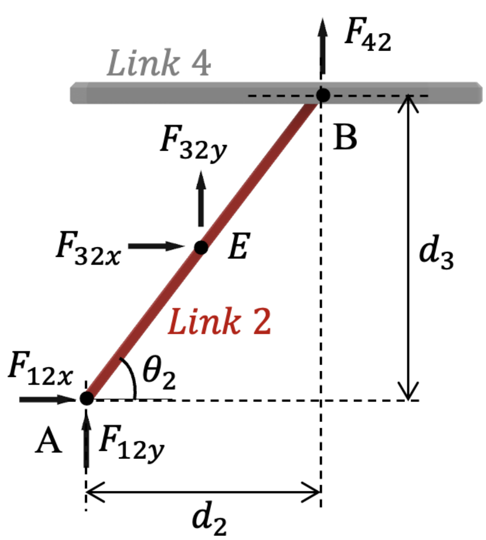

Figure 9: Force analysis on link 2, box hidden for clarity.

Sum of moments at point E

$$\Sigma M_E = F_{12x} \cdot \frac{d_3}{2} - F_{12y} \cdot \frac{d_2}{2} + F_{42} \cdot \frac{d_2}{2} = 0,$$

and $d_3 = r_2 sin\theta_2$,

$$F_{12x} = \frac{F_{12y} - F_{42}}{tan\theta_2}$$

Sum of forces

$$\Sigma F_x = F_{32x} + F_{12x} = 0,$$

$$F_{32x} = - F_{12x}$$

$$\Sigma F_y = F_{12y} + F_{32y} + F_{42} = 0,$$

$$F_{32y} = - F_{42} - F_{12y}$$

where F_{12x} is horizontal ground reaction force on link 2,
F_{12y} is vertical ground reaction force on link 2,
F_{32x} is horizontal reaction force on point E,
F_{32y} is vertical reaction force on point E,
F_{42} is the force acting on link 2 by link 4,
d_2 is the distance between points A and C,
d_3 is the distance between point B and the horizontal axis.

Forces analysis on link 3 (see Figure 10):

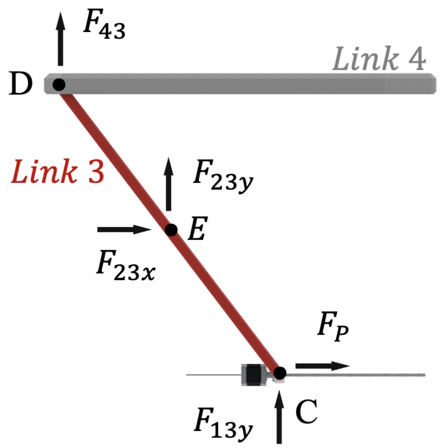

Figure 10: Force analysis on link 3.

$$\Sigma M_E = F_{43} \cdot \frac{d_2}{2} - F_p \cdot \frac{d_3}{2} + F_{13y} \cdot \frac{d_3}{2} = 0$$

$$F_p = \frac{F_{43}}{tan\theta_2} - F_{13y}$$

F_p is the total horizontal reaction force acting on point C, it equals the sum of the force from the spring and the force on the threads of the screw and bolt actuator connected to the motor. By plotting these three forces on the same graph, as shown in Figure 12, the required motor force can be visualized and determined.

4.4 MATLAB Dynamic Motion Simulation

The resulting equation for the total horizontal reaction force from the static force analysis done above is applied to a MATLAB model which cycles through the mechanism's range of motion (Figure 11) and calculates and plots the total horizontal reaction force with respect to the displacement of point C (Figure 12). As point C moves from right to left, the mechanism goes from minimum height $0.08\ m$ to maximum height $0.5519\ m$.

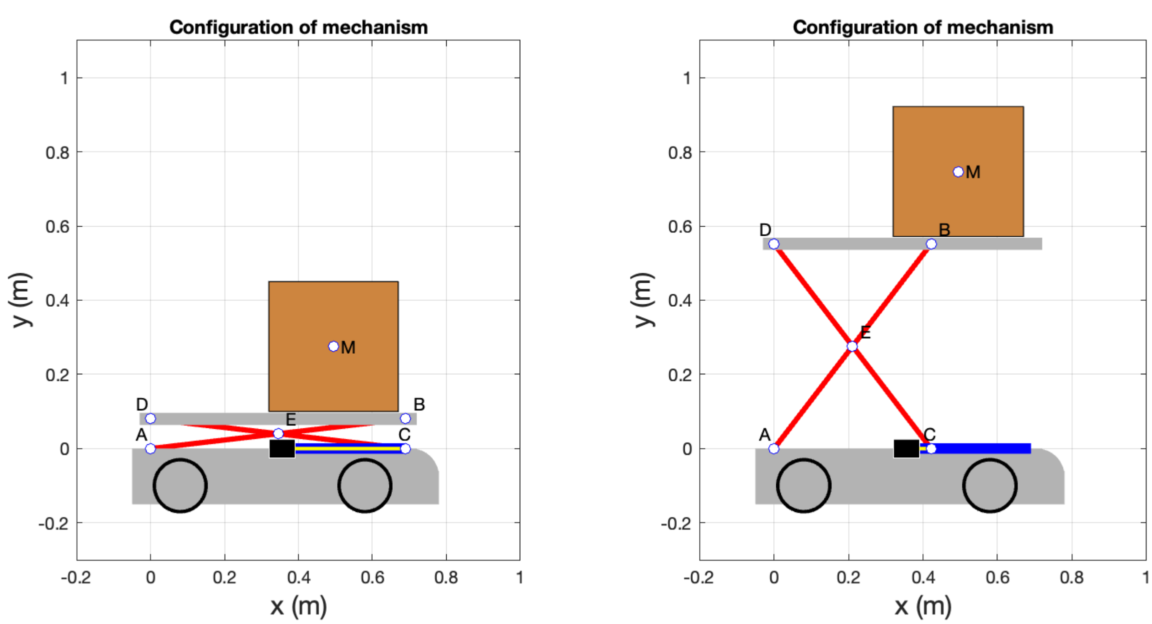

Figure 11. Lifting mechanism initial (left) and final (right) states.

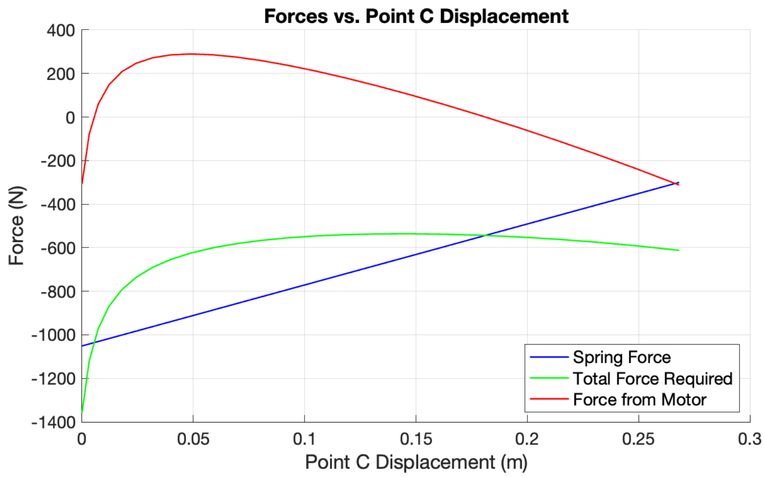

Figure 12. Force vs. Point C Displacement plot.

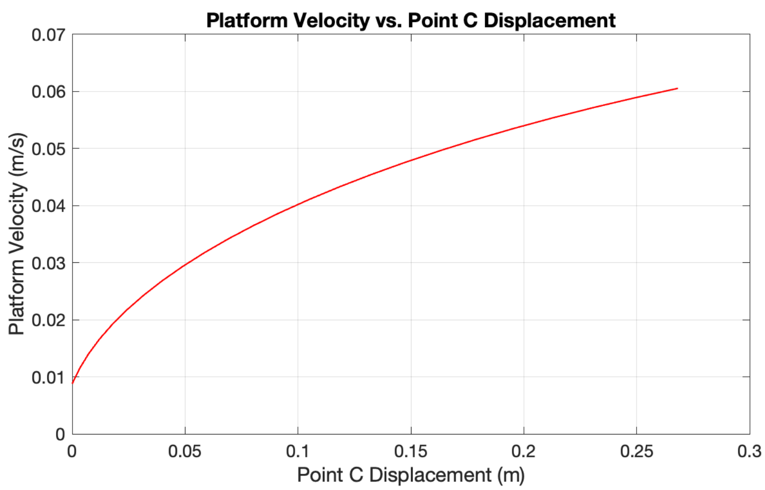

Figure 13. Platform Velocity vs. Point C Displacement plot.

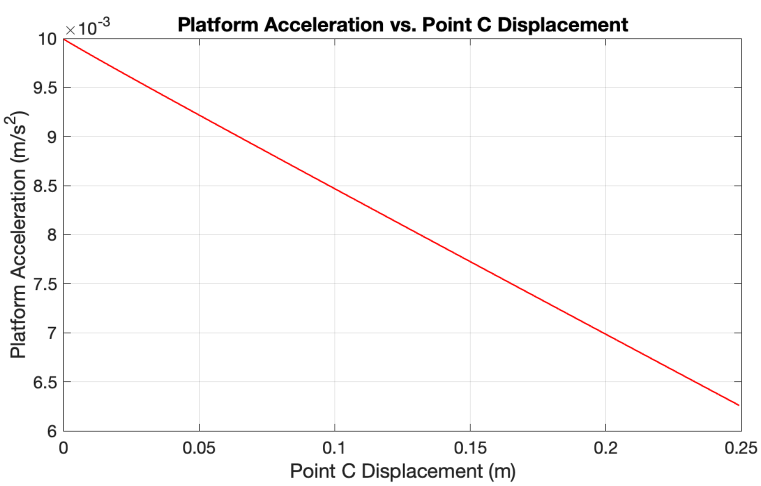

Figure 14. Platform Acceleration vs. Point C Displacement plot.

As seen in Figure 12, The total horizontal reaction force (green) is greatest at minimum height. However, if the motor/actuator system alone is to supply this force, it would be too great and even if it could be achieved with the use of speed-reduction gear trains, the lifting speed would be too slow for the use case. Therefore two $1400\ N/m$ springs with an initial minimum stretch of $21.4\ cm$ (producing spring force of $\left|F_{spring}\right| = [1400(\Delta x)\ +\ 300]\ N$) are used. The spring is stretched the most This reduces the amount of force required from the motor to a maximum magnitude of $300\ N$.

In terms of Figure 13 and Figure 14, the tendencies of the velocity change and the acceleration change of the platform can be visualized. Based on the Matlab simulation, as the platform is lifted, its velocity increases, reaching the maximum velocity of approximately $0.0605\ m/s$; its acceleration slightly decreases from a maximum acceleration of $0.01\ m/s^2$.

4.5 Motor and Spring Selection

Based on previous analysis and MATLAB simulation, the design needs to use a gearbox with a 1:3 ratio to increase the torque and reduce the speed of the motor in order to lift the cargo, which will take about 72 seconds. To improve this, a force-saving system using springs can be implemented. This will reduce the time required to lift the cargo. When the motor power is insufficient, a common method is to increase the mass of the mechanical structure by adding weights similar to springs, thereby increasing the power of the motor. The advantage of this is that the weights can be easily disassembled and installed, and the power of the mechanical structure can be adjusted by adjusting the number of weights. In addition, weights can also reduce noise.

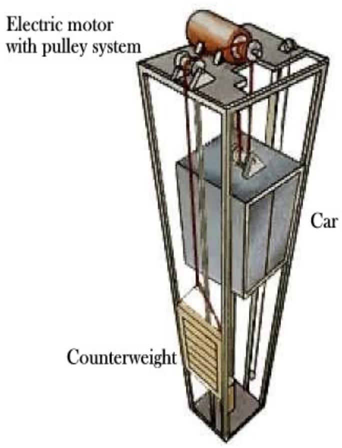

Figure 15: The use of counterweight on an elevator system [4].

This idea is widely used in the mechanical structure of elevators (see Figure 15). During the operation of the elevator, the weight of the elevator car can greatly increase the motor torque demand and energy consumption in the elevator system. So engineers balance out the weight of the elevator car by adding a counterweight at the other end. This idea can also be used in our design.

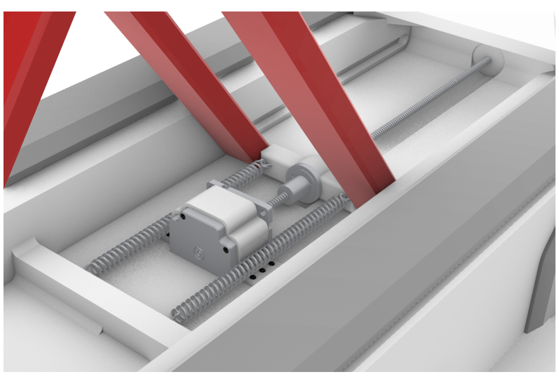

Figure 16: The force saving system on the design.

The slider needs a thrust between 600N and 1300N, and its horizontal position will change. When it is at the far right, the required force is the largest. Therefore, the characteristic that the elastic force of the spring is proportional to the expansion and contraction can be used in the design. We used MATLAB to select a set of springs with an initial tension (at the left point) of 300N and an elastic coefficient of 2800N/m. It saves effort by providing the slider with a force in the same direction as the power.

The specifications of the final motor and spring combination selected are listed in Table 1.

Table 1. Specifications for motor and spring combination selected to power the lifting mechanism.

Motor Selection	*Spring Selection*
Stepper Motor with Linear Actuation Dynamic load capacity: 75 lbs (333.6 N) Maximum speed 3 inch/second (7.63 cm/s) Polarity: Bipolar No. of wire leads: 4 Thread size: 3/8"-10	Sping category: Extension spring Number of spring: 2 Average spring pitch diameter: 10 mm Wire diameter: 1.6 mm Total number of coils of tension spring: 40 Initial pull: 150 N Length after stretching: 443 mm

4.6 Platform Friction Analysis

During the acceleration and deceleration process, the cargo will also experience a force according to Newton's Second Law. If the platform cannot provide enough friction force, the cargo will probably slide out of the platform. Therefore, it is important to calculate the frictional force it can provide using the equation:

$$friction \ = \ Normal\, force \ \times \ static\, friction\, coefficient$$

There coefficient between two surfaces should take the one with the lowest value, which is the surface of the cardboard with a value of 0.5 [5].

$$friction \ = 52kg \ \times 9.81N/kg \times 0.5 = 255.06N \ = ma$$

In this situation the allowed linear acceleration will be $4.905\ m/s^2$. For a design in the factory environment (no pump, flat surface), an $2\ m/s^2$ acceleration will be reasonable. So, the clients should not worry about the drop of cargo.

5.0 Summary of Redesign Performance

5.1 Redesign Performence

The mechanism can lift the $52kg$ box from minimum height $0.08\ m$ to maximum height $0.5519\ m$ in merely 6 seconds. Its maximum lifting velocity is approximately $0.0605\ m/s$, and its maximum lifting acceleration is approximately $0.01\ m/s^2$. These specifications indicate that the mechanism is capable of lifting the box at a relatively quick and steady pace, which meets the objective of the design purpose.

The new design is capable of resisting a maximum of $4.905\ m/s^2$ linear acceleration on a rough platform surface. Considering that it will generally operate at below $2\ m/s^2$, this ability allows the redesigned mechanism to operate effectively in challenging environments and ensures that it is able to maintain stability and control with a large safety factor. This is a valuable improvement over the previous design and will likely enhance the overall performance and reliability of the mechanism.

5.2 Comparison with the Initial Design

A walking robot mechanism served as inspiration for the mechanism's initial design, however it was subsequently discovered that this design was unsuitable for warehouse transportation applications. In order to raise a cubic box with $35\ cm$ edges, the design was adjusted to have a total length of $77.7\ cm$ and a width of $37.0\ cm$. The redesigned product draws a box away from or discharges it onto a shelf using a mechanism and a modified shelf.

The simplification from the old design with four degrees of freedom to the new design with just one degree of freedom also greatly increases stability and efficiency of the mechanism. The old mechanism involves 4 legs each with two links plus several gear and belt brive transmission systems per leg whereas the redesigned mechanism uses simply four links to achieve the lifting motion and wheels to achieve stable translation. The reduction of moving parts results in a more reliable design suitable for repetitive use in the shipping and distributions department. Compared to the first design, which was based on a walking robot mechanism, this one is more effective and reliable for warehouse transportation scenarios.

6.0 Conclusion and Final Recommendations

To satisfy the client's needs of transporting and lifting boxes of books in a warehouse setting, the team developed a new design involving a scissor lift mechanism power by a single motor mounted on top of a cart with Macanum wheels. Based on a series of static force analysis along with MATLAB dynamic simulations, the team verified that the new design is capable of lifting a box of books weighing up to $52\ kg$ from a minimum height of $0.08\ m$ to a maximum height of $0.5519\ m$, with a maximum lifting velocity of $0.0605\ m/s$ and a maximum lifting acceleration of $0.01\ m/s^2$ with the ability to overcome a $4.905\ m/s^2$ linear acceleration. The design is powered by a single motor mounted on the cart, and it uses Macanum wheels to provide stability and maneuverability. Overall, the new design is well-suited for the client's needs and is expected to perform well in a warehouse setting.

7.0 References

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[5] U. U. (menton), "Appendix 2. Friction factors - transport - CTU code - UNECE wiki," *Unece.org*. [Online]. Available: https://wiki.unece.org/display/TransportSustainableCTUCode/Appendix+2.%09Friction+factors. [Accessed: 05-Dec-2022].

Design Proposal Report Rubric 2022

Instructions to students: Read the written feedback on this page and the marked performance on the learning objectives on the next pages. Think critically about the feedback you have received (page 5), in consultation with your assigned TA and Prof. Diller. As you work on your final report, prepare a written response under each learning objective on pages 3-4. You will turn in this rubric (with your review of the feedback and actions taken) when you submit your final report.

Assigned TA: Erik Fredin

Group number: 22

Strength of Proposal:

- You show that you have thought your redesign through, and present some good calculations for performance metrics

- Your visuals are well made and make it easy to understand the redesign

Suggested Improvements:

- It seems that the box may fall off easily, especially if there is a bump on the ground. What can be done to mitigate this? This consideration could add to the technical depth of your redesign

After weighing their options, the team decided to use a rough platform surface to counteract the effects of acceleration. The team chose not to use the lock mechanism because bump scenarios are uncommon in a factory publishing house.

1. Using a locking mechanism to securely attach the box to the mechanism and prevent it from falling off. This could involve the use of a latch, a clamp, or some other type of mechanism that can hold the box in place during transport.
2. Adding additional support or stabilization to the mechanism. This could involve the use of additional arms, braces, or other structures that can help keep the box securely attached to the mechanism and prevent it from falling off.
3. Using sensors and control systems to detect and respond to changes in the surface. This could involve the use of sensors to monitor the ground and detect bumps or other irregularities, and then using control systems to adjust the mechanism's movements in response to these changes.

The team performed an analysis on friction in 4.6. The results shows that the new design can overcome a 4.905m/s2 linear acceleration on a rough platform surface. This ability allows the redesigned mechanism to operate effectively in challenging environments and ensures that it can maintain stability and control even when subjected to high levels of acceleration.

Grade: 8.25 /10

Learning Objective	Unacceptable	Below Expectations	Meets Expectations	Above Expectations
Technical accuracy	Major flaws in mechanism description and analysis	Problem statement and description contains some errors or lacks clarity	The mechanism and problem are accurately described and appropriate for the target audience	Mechanism problem and definition are clearly defined for any audience
Identify specific sections/areas in document and what feedback means				
Describe action(s) to be taken				
Technical novelty/depth	Complexity of project is inadequate; analysis is unclear	Complexity of project is weak; clarity of analysis is lacking	Problem complexity and level of analysis required is adequate using the methods learned in the course	Problem analysis and conclusions which can be drawn from it are apparent
Identify specific sections/areas in document and what feedback means	Try to analyze your design in greater rigor and show that you have addressed any potential limitations.			
Describe action(s) to be taken	The team analyze the mechanism in different scopes load mass, power required, static force analysis, dynamic motion analysis and platform friction analysis. The team found out the lifting velocity was slow and implemented a counterweight spring to increase the motor efficiency.			

Motivation	Unclear why a redesign is required	Need for redesign is superficial or not fully addressed	Need for redesign is apparent	Need for redesign is apparent and strongly motivated by concrete evidence
Identify specific sections/areas in document and what feedback means	The ground needs to motivate the switch to a wheeled design that better suits the client's needs instead of initial design.			
Describe action(s) to be taken	Cut motivation for wheeled mechanism and provided			
Ability to make and communicate an engineering recommendation	No clear argument for redesign with little/no evidence of the problem or analysis techniques	Claim for redesign is made with only minimal evidence of the problem and/or analysis techniques	Claim for redesign is clearly stated and supported with evidence; analysis techniques used appropriate level of detail for the target audience	Claim for redesign is strongly made with evidence of the problem; selection of analysis techniques and the team's ability to carry them out
Identify specific sections/areas in document and what feedback means				
Describe action(s) to be taken	Used in-class analytical methods (static force analysis and dynamic simulation in MATLAB)			

Structure and Visuals	Lack of explicit structure of content; unclear or missing visuals	Proposal is only loosely organized; visuals are difficult to read, unclear, and/or lack sufficient context	Proposal organization and format allows for information to be accessed and understood quickly and easily through illustrations, tables, etc.	Audience can seamlessly navigate and access content; clear visuals are fully integrated with text
Identify specific sections/areas in document and what feedback means	I recommend that you make a technical drawing of your redesigned mechanism for the final report.			
Describe action(s) to be taken	The team utillized technical drawings in analysis sections and labled all links and names for all components.			