Design and Fabrication of a Material Lift Machine

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Abstract *— This article describes the design, and implementation of a prototype of a self-propelled material lifter with high payload capacity, used to lift materials to the roofs of two-story buildings. It uses a gravity clamping mechanism inspired by pole-climbing robots used to maintain highway light poles, wind turbines, and palm trees. This will solve the problem that homeowners and small business owners face when having to lift materials onto the rooftops. Current alternatives such as cranes, bucket trucks or scaffolding, lead to storage problems and excessive costs. This prototype is light enough for one person lift and compact enough to carry it on an average size car cargo area. These two characteristics are possible by utilizing economical lumber as the body structure. The machine will clamp the 2 x 6 lumber with an A shape point of contact and roll up its edges to the required height.*

Key Terms *— Climbing, friction, lifter, portable.*

Problem Statement

In a residential energy study made by Worchester Polytechnic Institute showed that 84% of the surveyed Puerto Rican population's houses poses at least one AC unit in their homes and a 59% of the surveyed population poses two or more units [1]. The Compressor unit usually installed in roofs or high places weights between 28 to 97 lbs. depending on its capacity [2]. Because an Air Conditioning installer business requires minimum investment, most assistants part ways with their employers to start their own installing business. A high percentage of these installers start with minimum resources and see themselves in the situation of having to carry the AC components up a ladder or pull it up with a rope to the roof. This practice represents a safety issue for the installer and the homeowner's property. In Puerto Rico approximately 42,000 photovoltaic systems have been installed on residential roofs, 10,000 of them just in 2022 [3]. Just like AC units, photovoltaics systems, roof sealing products, water heaters and roof repairs require lifting material and equipment to the roof with the same safety risk. Carrying a 5-gallon bucket of sealer or paint is not an easy task, especially if the house does not have access to the roof. The current alternatives are to place a ladder and carry the materials up the stairs, pull materials up using rope, or use scaffolds or heavy equipment to lift the material to the repair location. The problems with these solutions are that they represent a high safety risk or are expensive and difficult to store within the house. Hence, the idea is to investigate a portable lift machine that can be stored easily inside a closet or a storage box in the yard. The general idea is to design a portable machine capable of lifting 200 lbs. of material to 20-foot-tall roofs.

Research Description

Regarding portable lifting machines, two main types of equipment jump out: a material lifter or stacker and a winch/hoist-style crane. The material lifter or stacker, on Figure 1 can be used in warehouses, factories, shipping facilities, supermarkets, and other industrial environments [4]. The lift consists of a hand-operated winch (also available motorized), which extends its steel body up to eighteen feet vertically. The benefits of this system are that it is a one-person operation, works from the floor up, and is portable [4]. Its downfall is the height is limited to the reach of the body. The portable crane, Figure 2, is available with a powerful motor also available as a hand crank [5]. This equipment consists of a steel frame that holds a steel cable of various lengths and pulls material up. The benefits are its portability, and high payload hoisting capabilities [5]. The two concerns with the system are that it requires to be placed at the destination of the material and is limited by the amount of cable the reel can hold. Another equipment often utilized is the winch, Figure 3, by itself built into some sort of site-built structure [6]. The benefits are its portability, easy handling, versatility, and structure material regularly available within the construction site. The concerns are like cranes and the addition of safety concerns due to the site-built structure.

Figure 1
Sumner 2015 Material Lift[4]

Figure 2
Surya Millar 150Kg Material Lift Machine[5]

Figure 3
RUNVA EWB20000 Premium Winch 24V with Steel Cable[6]

Research Objectives

The objective of this paper is to document the design, analysis, and prototype of the Material Lift Machine (MLM). The MLM must fit on a regular car or SUV trunk without special attachments or carriers. To be easily loaded to a trunk It must weigh under 60 lbs. The MLM must have the capacity to transport loads up to 200 lbs. to two story building roofs. To be easy to maneuver it must be a one-person operation. For safety it must be self-leveling while operating.

Research Contributions

This research adds to limited information on the application of commercial and industrial climbing robot technology to solve residential and small business problems. It has the purpose of improving safety on DIY projects or small service contractors by providing a portable and easy to storage lifting mechanism. By making it a 1-person operation it minimizes human effort while improving efficiency. While it requires an initial investment, the MLM will help to maintain low cost of labor for contractors.

Literature Review

Elevators are traced back to the 236 B.C. where the roman Architect Vitruvius reported that Archimedes built his first elevator [7]. Elevators were not invented for human transport but for raw material animals, and cargo. Elevators lacked security features and regulations and were powered by men or animals. The material Lift Machine is a trip back in time to the origins of the elevator but with a modern twist. The MLM provides a way to lift materials to high places by way of disposable two-by-four lumber. The two by four lumbers are used to provide the structure of the Material lifter machine. A threated two " x 4" pine lumber can support up to 300 lbs. on its edge and up to 1000 lbs. vertically [8]. This material is available as standard dimension lumber in most hardware stores at exceptionally low prices. Also is a common material found on construction sites.

By displacing the center of mass of the system away from the contact points as shown on Figure 4, a tangential force is created. This concept has been utilized for pole climbing boots, tree pruning robots, and flagpole mechanism. A more compact and specific application is presented on this paper. Gravity plays a key role in the functioning of this system.

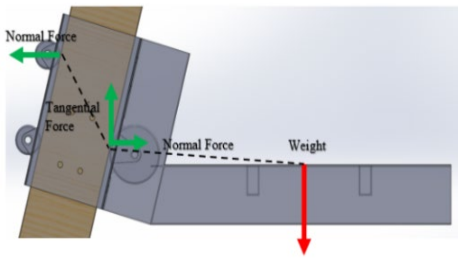


Figure 4
Forces Acting on Lifter

METHODOLOGY

The MLM is inspired by the old ways of climbing trees shown on Figure 5 where the man is exerting a force equal to his weight normal to the palm tree. The friction between his leather covered feet and palm tree surface provides a few seconds to reposition upper rope at higher position and pull himself up. Friction is the result of the normal force created by weight and the rope against the surface and the coefficient of friction of his feet and the rope.

Figure 5
Climbing on Palmyra Tree[9]

Two 2x4s leaned at 75^0 from the floor are fed to the MLM. The machine will clamp the wood member by leveraging the distance of the center of mass from the driving wheel contact point and generate a moment forcing the driven wheel against the wood member on the other side. On Figure 6 the forces acting on the lifter are depicted and analyzed to determine the required conditions to achieve static equilibrium.

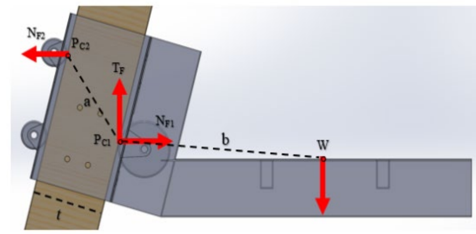


Figure 6
Forces Acting on Lifter

The MLM is recommended to lean at 75^0 from the floor. To obtain a non-slip condition at the footing of the MLM The following calculations are required, the coefficient of static friction between the MLM footing and the floor is μ=0.7

Force of friction equals weight times coefficient of friction. The coefficient of friction is found experimentally and tabulated.

$$F_f = W * \mu \tag{1}$$

Where Ff is friction force, W is weight and μ is the coefficient of friction between the two materials in this case wood and rubber. Utilizing the sum of forces in the y and x direction along with the sum of moments the forces acting on the carriage basket are determined.

$$\sum F_X = F_f - N_1 = 0 \tag{2}$$

$$\sum F_Y = N_2 - W_S - W_W = 0 \tag{3}$$

$$N_2 = W_S + W_W \tag{4}$$

$$CW + \sum M_A = 0 \tag{5}$$

$$W_S * cos(\theta) * l + W_W * cos(\theta) * \frac{l}{2} - N_2 * cos(\theta) + F_f * sin * l \tag{6}$$

Divide by cos(θ) to get:

$$tan(\theta) = \frac{-W_S - \frac{W_W}{2} + N_2}{F_f} \quad (7)$$

The posts exert normal forces of equal magnitude but opposite directions due to moment generated by the weight hence (8).

$$N_{F1} = N_{F2} \quad (8)$$

A tangential force (T_F) will be generated at point of contact 1 (P_{C1}) equal to the weight (W) of the carriage. Weight is the product of mass (m) times the acceleration of gravity (g). Hence 2.

$$T_F = W = mg \quad (9)$$

The angle (θ) formed with segment P_{C1}-P_{C2} and a line normal to the wood member is obtained.

$$\theta = arc\cos\left(\frac{t}{b}\right) \quad (10)$$

The moments respective P_{C1} generates an equation to find F_{N2}.

$$mga\cos(\theta) = b\sin(\theta)\,N_{F2} \;\rightarrow\; N_{F2} = \frac{mga}{b\tan(\theta)} \quad (11)$$

The non-slipping condition at P_{C1} is obtained utilizing the Coulomb friction law where it states that a coefficient of friction (μ) times a normal force gives the friction force (f). The friction force must be equal or greater than the tangential force to make the wheels roll without slipping on the edge of the two-by-four.

$$\mu\, N_{F1} \geq T_F \quad (12)$$

The magnitude of the normal force 1 (N_{F1}) is unknown but it should be greater than the tangential force per the coefficient of friction.

$$N_{F1} \geq \frac{T_F}{\mu} \rightarrow \frac{mg}{\mu} \quad (13)$$

To obtain the magnitude of normal force 1 (N_{F1}) (8) and (11) are combined and rewritten to obtain (14).

$$N_{F1} = \frac{a\,m\,g}{b\tan(\theta)} \quad (14)$$

Equation (15) will provide the minimum angle allowed to obtain a no slip condition.

$$a \geq \frac{b\tan(\theta)}{\mu} \quad (15)$$

After obtaining a non-slip condition attention is paid to the electronics. An Arduino UNO [10] controls the input and outputs while a pair of two 350W permanent magnet DC motors provide the lifting power. The motors require a 24V to operate therefore a 24V motor driver and external power source are required since the microcontroller only provides 5V output. The L298N [11] is chosen for this application since it can run both motors with an external power supply.

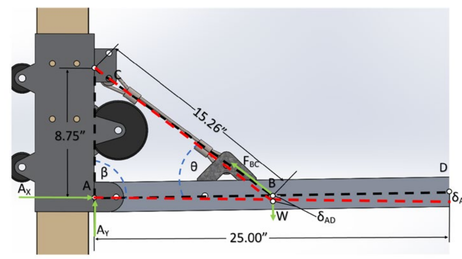


Figure 7
Carriage Deflection[7]

From Figure 7 force BC is obtained by applying moment equilibrium about point A.

$$CCW + \sum M_A = 0 \quad (16)$$

$$F_{BC} * \sin(\theta) * \overline{AB} - \overline{AB} * W = 0 \quad (17)$$

$$F_{BC} = \frac{\overline{AB} * W}{\sin(\theta) * \overline{AB}} \quad (18)$$

With the force (F_{BC}) we calculate the deflection of segment BC with (19)

Where P y tension force on segment BC, L is length of segment BC, A is for cross section Area and E is the modulus of elasticity.

$$\delta_{BC} = \frac{PL}{AE} = \frac{F_{BC} * \overline{BC}}{A * E} \quad (19)$$

With the deflection of segment BC, the Pythagorean Theorem is used to determine the new angle β.

$$a^2 + b^2 = c^2 \quad (20)$$

$$(\overline{BC} + \delta_{BC})^2 = (\overline{AC})^2 + (\overline{AB})^2 - \overline{AC} * 2\overline{AB} * COS(\beta) \quad (21)$$

$$1 = cos^{-1}\left(\frac{(\overline{BC} + \delta_{BC})^2 - (\overline{AC})^2 - (\overline{AB})^2}{-\overline{AC} * 2\overline{AB}}\right) \quad (22)$$

$$\delta_{AD} = (\beta - 90) * \overline{AD} \quad (23)$$

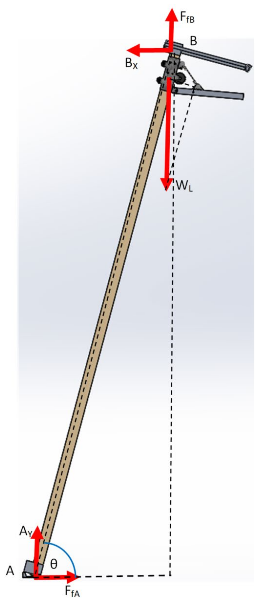


Figure 8
Static analysis on MLM[8]

The sum forces in the x and y direction along with the sum of momentum in terms of A provide the minimum angle required to lean MLM against the wall as shown on Figure 8. In this case μ_S is the static coefficient of friction between rubber and wet concrete.

$$F_{fB} = \mu_S * B_X \quad (24)$$

$$F_{fA} = \mu_S * A_Y \quad (25)$$

$$+\sum F_x = 0 \quad (26)$$

$$F_{fA} - B_x = 0 \therefore A_Y = \frac{B_x}{\mu_S} \quad (27)$$

$$\uparrow + \sum F_Y = 0 \quad (28)$$

$$F_{fB} + A_Y - W_L = 0 \;\therefore\; W_L = \mu_S * B_X + A_Y \quad (29)$$

From (27) we obtain new value for A_Y and incorporate on (29) to obtain

$$W_L = \mu_S B_X + \frac{1}{\mu_S} B_X \;\therefore\; W_L = B_X\left(\mu_S + \frac{1}{\mu_S}\right)$$

$$or\ B_X = \frac{W_L}{\left(\mu_S + \frac{1}{\mu_S}\right)} \quad (30)$$

$$CCW + \sum M_A = 0 \quad (31)$$

$$-\cos(\theta) * W_L * l + \sin(\theta) * B_X * l + \cos(\theta) * F_{fB} * l = 0 \quad (32)$$

Substituting (24) in (32) and rewriting we obtain:

$$-\cos(\theta) * W_L * l + \sin(\theta) * B_X * l + \cos(\theta) * \mu_S * B_X * l = 0 \quad (33)$$

$$\sin(\theta) * B_X * l = \cos(\theta) * B_X\left(\mu_S + \frac{1}{\mu_S}\right) * .9735l - \cos(\theta) * \mu_S * B_X * l \quad (34)$$

Dividing by cos(θ)*B_X*l on both sides the equation becomes:

$$\sin(\theta) = \cos(\theta)\left(\mu_S + \frac{1}{\mu_S}\right) .9735 - \cos(\theta) * \mu_S \quad (35)$$

$$\tan(\theta) = \left(\mu_S + \frac{1}{\mu_S}\right).9735 - \mu_S \quad (36)$$

The minimum angle at which the MLM can be set from the floor is given by (37).

$$\theta = tan^{-1}(\tan(\theta)) \quad (37)$$

Result and Discussion

Currently, the existing home improvement retail stores do not carry products for consumers that allow them to lift material or heavy equipment to two story house roofs. People's alternative options are to rent expensive heavy equipment or purchase a crane like equipment which is not only heavy but too big to store. If the user does not have the capital for the mentioned alternative the other ways is to carry the material up a ladder or pull it up with a rope, becoming not only a safety hazard but an inefficient time-consuming task.

A prototype has been created with alternate parts due to the costs and time constraints. Parts were manufactured at a garage with simple power tools.

Gears were extracted from manual marine winch devices while the 4:1 gear ratio was maintained. All Rectangular tubing was purchased at local retailers. Obtained 4 2 in casters from spare parts available at home and electronics from a previous sun tracker project. Driver wheels and motor were purchased online. All components together weighed approximately fifty-nine pounds. The actual MLM with all the designed components is expected to have a weight of less than 60 pounds.

By utilizing a reduction gear train as shown in Figure 9, the speed will be reduced from 2700 RPM to 42 RPM with a gear ratio of 64:1. As shown in Table 1.

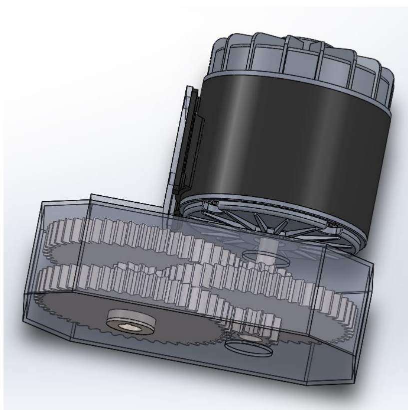


Figure 9
Reduction Gear Train

Table 1
Train Reduction Gear Selection

Train Reduction		
Input		
Speed	2700	RPM
Torque	10.94767593	Lb.in
Power	350	W
Number of teeth		Gear Ratio
Driver Gear	15	
Idler 1	60	4
Idler 2	15	
Idler 3	60	4
Idler 4	15	
Driven Gear	60	4
Resultant Ratio		64
Output		
Speed	42.1875	RPM
Torque	700.6512593	Lb.in

According to the calculation on the different components shown on Figure 10, the deflection of the loaded carrying basket cantilever beam is expected to be 0.0965 as shown on Table 2.

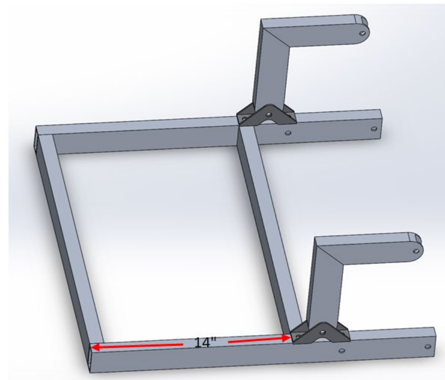


Figure 10
Aluminum Rectangular Cantilever Beam Deflection Analysis

Table 2
Hollow Aluminum Tube Cantilever Beam Deflection

Moment of Inertia Hollow Rectangular Aluminum Tube 6061 T6			
Outside Width	W	1	in
Outside Height	H	2	in
Inside Width	w	0.75	in
Inside Height	h	1.75	in
Moment of Inertia	I	0.3317057	in^4
Cantilever Beam Deflection			
Force or Load	F	350	lbf.
Distance from Fixed Point	x	14	in
Length of Beam	L	14	in
Modulus of Elasticity	E	10000000	psi
Deflection	δ	0.0965112	in

Meanwhile as shown on Figure 11, at the base AD and the cross-member BC of the carriage basket, the deflection is 0.0089in. and 0.0304in. respectively.

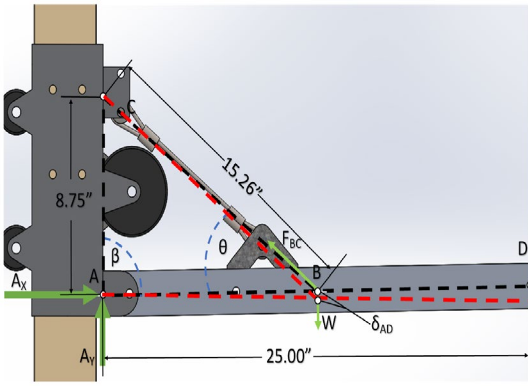


Figure 11
Carriage Rectangular Cantilever Beam Deflection Analysis

Table 3
Non-slipping Condition at Footing

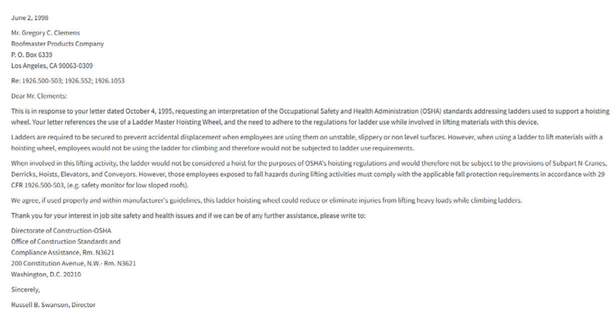
Non-slip Condition Calculation Footing to Ground			
Given:			
Static Coefficient of Friction Rubber on Wet Concrete	μs	0.7	ratio
Weight Loaded	WL	550	lbs.
length of Wood Members	l	240	in
% of Length for Carriage Position	x	97.35%	
Reactions			
Wall Reaction	Bx	258.3893	lbs.
Floor Reaction	Ay	369.1275	lbs.
Friction			
Force of friction at floor	Ffa	258.3893	lbs.
Force of friction at wall	Fjb	180.8725	lbs.
Tangent(θ)	tan(θ)	1.3722	Rads
Minimum Angle from the floor	θ	**54**	0

The results shown on Table 3 demonstrates that the carrying structure is structurally sound. Also forces of the max loaded MLM acting on the wood members were calculated and resulted on 258.39lbs between the two, normal to the edge of the two-by-four. Two-by-four are rated and evaluated for 300lbs minimum each. The members vertically support one thousand and calculation shows reaction forces of loaded MLM of 369.13 total. The system is recommended to be set at 75^0 from the floor, calculation on Table 4 shows that the system minimum angle of inclination to sustain a nonslip condition on wet concrete is 54^0.

Table 4
Carriage required Angle and Distance for non-slip Condition

Non-slip Condition Calculation			
Given:			
Static Coefficient of Friction	μs	0.9	
Kinematic Coefficient of Friction	μk	0.7	
Wood Member Thickness	t	3.5	in
Segment Pc1-W	a	10.5	in
Segment Pc1-Pc2	b	4.63	in
Mass	m	16.7837	slug
Gravity	g	*32.17405*	ft/s^2
Calculations (Governing Equations):			
Weight	W	539.999603	
Tangential Force	Tf	539.999603	
Theta Angle	θ	40.89246877	
Normal Force 2	Nf2	1414.116854	
Normal Force 1	Nf1	1414.116854	
Non-Slip Indicator			
Minimum Angle Allowed Indicator Green =Succeeded, Red = Failed	Succeeded		

A letter shown on Figure 12 answered by director Russell B. Swanson of OSHA states that because hoist is placed on ladder-like structure and is not climbed it is not subjected to ladder use requirements and the lifting activity for which is being used it is not considered a hoist of OSHA' s hoisting regulation. Users must follow the fall protection requirements in accordance with 29 CFR 1926.500-503.


June 2, 1998

Mr. Gregory C. Clemens
Roofmaster Products Company
P. O. Box 6339
Los Angeles, CA 90063-0309

Re: 1926.500-503; 1926.552; 1926.1053

Dear Mr. Clements:

This is in response to your letter dated October 4, 1995, requesting an interpretation of the Occupational Safety and Health Administration (OSHA) standards addressing ladders used to support a hoisting wheel. Your letter references the use of a Ladder Master Hoisting Wheel, and the need to adhere to the regulations for ladder use while involved in lifting materials with this device.

Ladders are required to be secured to prevent accidental displacement when employees are using them on unstable, slippery or non level surfaces. However, when using a ladder to lift materials with a hoisting wheel, employees would not be using the ladder for climbing and therefore would not be subjected to ladder use requirements.

When involved in this lifting activity, the ladder would not be considered a hoist for the purposes of OSHA's hoisting regulations and would therefore not be subject to the provisions of Subpart N-Cranes, Derricks, Hoists, Elevators, and Conveyors. However, those employees exposed to fall hazards during lifting activities must comply with the applicable fall protection requirements in accordance with 29 CFR 1926.500-503, (e.g. safety monitor for low sloped roofs).

We agree, if used properly and within manufacturer's guidelines, this ladder hoisting wheel could reduce or eliminate injuries from lifting heavy loads while climbing ladders.

Thank you for your interest in job site safety and health issues and if we can be of any further assistance, please write to:

Directorate of Construction-OSHA
Office of Construction Standards and
Compliance Assistance, Rm. N3621
200 Constitution Avenue, N.W.- Rm. N3621
Washington, D.C. 20210

Sincerely,

Russell B. Swanson, Director
Directorate of Construction

Figure 12
OSHA Response Letter to Hoist or Ladder Safety Standards

Results of the prototype testing and pictures will be provided after building up.

CONCLUSION

This research presented a new application to climbing robot technologies to provide a solution for individuals looking to lift material and equipment to their two-story buildings. The governing mechanical principles have been calculated and described. The non-slip condition is dependent on the geometry of the contact points and the coefficient of friction but not on the center mass. Later configuration will include all components as designed to lower cost and weight and upgrade performance. More capabilities can be added like battery operation, different carriage basket configurations, and ride on capabilities.

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