A Novel Hand Pallet Truck and Multi-objective Optimization Design of It's Lifting Mechanism

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Abstract. Hand pallet truck is widely used to carry baggage and cargoes in daily life and work. However, rotary-lift based luggage hand pallet truck is inconvenient to handle and difficult to carry heavy goods. Hydraulic cylinder based hand pallet truck is also used commonly, but its lifting speed is not fast enough. In addition, most of them can't save energy. To this end, a novel rotary-lift based hand pallet truck is proposed. Auxiliary and cushioning forces are provided by gas springs. Its lifting height is adjustable. Critically, its lifting mechanism can be locked automatically after ascending or descending into the target positions. Thus, it’s easy for just one person to operate. Aiming at saving time, force and energy, a multi-objective optimization design model for the lifting mechanism is built, based on which most key parameters and dynamics indexes can be calculated. Numerical analysis and experiment results show that the proposed model is effective and the design scheme of the novel hand pallet truck is feasible.

1. Introduction
Hand pallet truck, also named as hand forklift, can move goods to required locations quickly. By virtue of saving labor and working efficiently, it is widely used in logistics, gardening and other fields. It’s also important for the ground service support in aviation or aerospace enterprises. Two types of hand pallet trucks are used most commonly. One is based on rotary-lift, such as baggage truck. It generally adopts two wheels, and the lifting height is not fixed. Although it has simple structure and response sensitively, it’s inconvenient to control and difficult to carry heavier items, because human force should be applied in both horizontal and vertical directions when transporting goods. Another kind of hand pallet truck uses single-stage plunger hydraulic cylinder to lift cargoes. The hydraulic cylinder needs to be driven by shaking or pedaling, which leads to a relatively slow lifting speed. Besides, it is difficult to be used outdoor because of the small tires.

Literature [1] designed a new lifting and guiding mechanism for forklifts, which not only expands the vision field of the driver but also reduces the whole weight of the vehicle. Literature [2] designed an electric lifting mechanism to facilitate the transfer of wheelchair riders. In the literature [3], a new design method was proposed to obtain the optimum design parameters of the scissor-fork lifting mechanism. Literature [4] presented an optimal design method for lifting mechanism of construction tower crane. Although they are enlightening, they can not be used in hand pallet trucks directly. In addition, the traditional design methods usually ignore the importance to store and utilize nature energy[5], such as the work done by gravity when cargoes falling. It does not save manpower work. In general, too little related improvement work has been done. Thus, it is necessary to design a new hand pallet truck with good maneuverability, high efficiency, energy-saving and green environmental protection [6], especially for the transport of specific items.
2. Proposition of a Novel Hand Pallet Truck

The proposed novel hand pallet truck is composed of three modules as shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Proposed novel hand pallet truck. 1-truck body; 2-lifting mechanism; 3-joint locking mechanism.

As a transportation platform, truck body mainly includes chassis, lifting height adjusting device, guardrails and wheels. Mounting bases for both lifting mechanism and joint locking mechanism are set under the chassis. The lifting height adjusting device consists of sleeve base, lifting rod and fixing bolt. The sleeve seat is hollow, and there is a threaded hole in the middle of its upper part used to locate the lifting rod. The U-shaped part of the lifting rod can limit the lifting mechanism’s position. There are several holes in the middle part of the lifting rod’s lower part along the vertical direction. Through adjusting the lifting rod to the desired position, making its appropriate hole aligned with the hole on the sleeve base, then tightening with the fixed bolt, the lifting height can be controlled.

Lifting mechanism is the key function module. Figure 2 shows its composition. Rotating frame is the skeleton of lifting mechanism, which is connected with truck body by rotating axle pin. Its bottom end is connected with two forks by bolts, and they are perpendicular to each other. When not in use, two forks can be folded up to save space. Several rows of holes are arranged below the side of the rotating frame to adjust the initial height of the forks. Down in the middle of the rotating frame, the descending positioning link as well as the fixed plate of the gas springs and the speed stabilizer are welded in turn. By virtue of large elasticity, small size and low price, gas springs are used to provide auxiliary and cushioning force [7]. It consists of cylinder, piston rod and rotary base. Two gas springs are articulated with the truck body and the rotating frame through the rotary bases at both ends. The piston rod should be installed below. As the rotating frame rotates, the piston rotates upward and the cylinder moves axially. The compressed gas springs provide auxiliary force to make the rising process easier. When descending, it acts as a buffer because its acting moment is opposite to that of gravity. Hydraulic speed stabilizer can stabilize the speed of the descending. It produces little stretching force, and the speed can be adjusted. Of course, it could be omitted in common cases.

Joint locking mechanism is used to fix the lifting mechanism. Figure 3 shows its composition. All the three lock switches of it are similar in structure. They are basically made up of positioning pin, outer frame and spring. The two ends of the connection plate are connected with the positioning pin of the down lock switch. Initially, springs are all extended, the forks are horizontal and fixed by the down lock switch. (a) When the pedal is pressed downward, the positioning pin of the lock switch limits the pedal link to the lowest position, the connection plate is raised, the positioning pin of the down lock switch is moved upward, thus the rotating frame is released. (b) When pulling the handle, the rotating frame starts to rotate and then contacts the positioning pin of the up lock switch, which makes the positioning pin to be extruded and move away. It is then jammed after fully passing through the positioning pin, as the positioning pin restores driven by the spring at the same time. Meanwhile, the pedal link is released because its lock switch is driven by the pulley assembly connected with the up lock switch. (c) Through pulling the handle at right end of the up lock switch, the rotating frame can be released and descend to the vertical position, and then will be jammed by the positioning pin of the down lock switch, which keeps the fork horizontal.
3. Multi-objective Optimization Design Model for the Lifting Mechanism

To manufacture the novel pallet truck, it’s very important to determine the size, installation position and mechanical parameters of each component, especially for designing the lifting mechanism.

3.1 Determining the size of rotary frame

As shown in Figure 4, $L_1, L_2, L_3, L_4, L_6$ are respectively denoted as the length from the bottom of the rotating frame to the rotary base of the cylinder, the length from the rotary base of the cylinder to the shaft of the rotating frame, the length from the shaft to the top of the handle, the length of the handle’s profile, the horizontal length between the cargo and the rotating frame. $\Phi, H_0, H_{m1}, H_{m2}$ and $\Delta H$ are respectively denoted as the angle from the vertical position to the target position for the rotating frame, the height between the upper surface of the forks and the ground when the forks are horizontal, the maximum height of the handle in the design of the truck, the ideal height from the handle to the ground, the allowable deviation of $H_{m2}$. Assuming that the cargo is a homogeneous cuboid, the length, width and height are denoted as $a, b$ and $c$ respectively. Limited by wheels size and other constraints, $L_1, L_2, L_6, H_0, H_{m1}, H_{m2}$ and $\Delta H$ are deterministic. Longer $L_3$ and smaller $\Phi$ can lead to smaller human force and less work. Hence, other parameters can be got at the boundary of the constraint conditions.

3.2 Determining the specification of gas spring

Let $L_0$ denote the length of the gas spring when the fork is horizontal, $L_5$ denote the length of the gas spring extending out after the cargo is lifted to target position, $L_9$ denote the distance between the left rotary base of the gas spring and the shaft of the rotating frame, $\varphi_0$ denote the angle between $L_5$ and the vertical direction. According to the cosine theorem, the following relationship is established:

$$L_5 = (2L_0 - 2L_9 \sin \Phi)^{\frac{1}{2}} \left[ 2L_9^2 (1 - \cos \varphi_0) - L_0^2 \right]$$

(1)

The size of gas spring mainly includes total length $L$ and stroke $S$, and usually need to be selected from the product list. Here, they are defined as a set of gas spring sizes $A$ containing different numerical pairs ($L, S$). In addition, to ensure safety, the gas spring should have enough safety margin during compression or stretching, which is defined as $\Delta S$. The optimal value of $L_0, L$ and $S$ can be obtained by solving the following optimization problems by using classical linear search algorithm.

$$\begin{align*}
& \min_{L_0, L, S} \quad L_0, L, S \\
\text{s.t.} \quad C_1 : L - S + \Delta S \leq L_0, \quad C_2 : S - 2\Delta S \geq L_0, \quad C_3 : (L, S) \in A
\end{align*}$$

(2)
Next, to determine the elasticity of the gas spring, the optimization method is used. In reality, just 1-2s is needed to lift the cargo. We think that the rising time expressed as $T$ increases linearly with the cargo weight, and the aim to save lifting time can be satisfied as soon as it does not exceed a maximum weight. The second goal of labor-saving can also be gotten if only the maximum human force required does not exceed a certain bearing range. The ultimate goal is to minimize human effort. In general, the above three physical quantities are negatively correlated with the elasticity of the gas spring, so the greater elastic force, the better performance of the lifting mechanism. However, the elasticity cannot be arbitrarily large, and certain constraints should be met. We denote $f_h$, $F_s$ and $G$ respectively as human force, gas spring elasticity and gravity. $f_{h_{\max}}$, $F_{s_{\max}}, F_{hp_{\max}}, W_f, T_{\max}$, $\Phi_0$ are respectively denoted as the maximum human pull force during the rising procedure, the maximum human force human can afford to lift the handle upward without payloads, the maximum pull force human can bear, the work done by human force during the rising procedure, the maximum lifting time, the angle between gas spring and the rotating frame after the cargo is lifted in place. We denote $r$, $\theta$, $\gamma_0$, $\phi$, $\delta$, $\Delta l$ respectively as the distance between the cargo center of mass and the rotating axis of the truck, the rotation angle of the rotating frame, the angle between $r$ and the vertical direction when $\theta$ is equal to 0, the angle between the gas spring and the rotating frame, the rotary angle of the gas spring, the expansion length of the gas spring. Thus, the multi-objective optimization model is built as follows:

$$
P_f : \min_{T, F_s, f_{h_{\max}}, W_f} f_{h_{\max}}, W_f
$$

s.t. $C_1 : F_s L_2 \cos(\Phi - \Phi_0) \leq G \left( (2^{-1}b + L_0)^2 + (L_s + L_2 - 2^{-1}c)^2 \right)^{1/2} \sin(\gamma_0 + \Phi),$

$$
C_2 : F_s L_2 \leq f_{h_{\max}},
C_3 : f_h \leq F_{hp_{\max}},
C_4 : T \leq T_{\max},
C_5 : \theta \leq \Phi,
C_6 : F_s, \theta > 0
$$

This optimization problem can also be solved by using search algorithm. To simplify the calculation, we assume that the cargo rotates at uniform acceleration during the first $0.5\Phi$ with acceleration $\alpha_0$ and then at uniform speed at last $0.5\Phi$ with angular velocity $\omega_t$. The following equation is gotten:

$$
\alpha_0 = \left(4T^2 \right)^{-1} 9\Phi, \quad \alpha_t = 3\Phi (2T)^{-1}
$$

The mean angle of the direction of human force deviating from the vertical direction of the rotating frame is set as $\delta$. $f_h$ can be calculated as below:

$$
f_h = \begin{cases}
(Gr - F_s L_2 \sin \phi + I\alpha_0) (L_s \cos \delta)^{-1}, & \theta \leq 2^{-1} \Phi \\
(Gr - F_s L_2 \sin \phi) (L_s \cos \delta)^{-1}, & \theta > 2^{-1} \Phi
\end{cases}
$$

$$
r = \left( (2^{-1}b + L_0)^2 + (L_s + L_2 - 2^{-1}c)^2 \right)^{1/2} \sin(\gamma_0 + \theta)
$$

$$
\gamma_0 = \arccot \left( (L_s + L_2 - 2^{-1}c) (2^{-1}b + L_0)^{-1} \right)
$$

$$
\delta_l + 2^{-1} \pi = \phi + \delta
$$

$$
\phi = \arccos \left( \left( L_0^2 + (L_0 + \Delta l)^2 - L_s^2 \right) \left( 2L_2 (L_0 + \Delta l) \right)^{-1} \right)
$$

$$
\Delta l = \left( L_2^2 + L_0^2 - 2L_2 L_0 \cos \left( \arctan \left( \frac{1}{L_0 L_2^{-1}} + \phi \right) \right) \right)^{1/2} - L_0
$$

Let $W_{fr}$ denote as the work done by gas springs. $\Delta h$ and $I$ are respectively denoted as the lifting height and the moment of inertia of the cargo. Because it is difficult to be calculated with an analytic expression, $W_{fr}$ can be obtained by adapting numerical calculation method. According to the kinetic energy theorem, the work done by manpower is expressed as follows:
\[ W_f = G\Delta h - W_g + 2^{-1}I\omega^2 \]  
\[ \Delta h = \left( \left( b^2 + L_0 \right)^2 + \left( L_1 + L_2 - 2^{-1}c \right)^2 \right)^{1/2} \cos \gamma_0 - \cos(\gamma_0 + \Phi) \]  
\[ I = \frac{G}{3g} \left( (b^2 + 3bL_0 + 3L_0^2)c + (c - L_1 - L_2)^3 + (L_1 + L_2)^3 \right) \]  
\[ W_f = \sum_{i=1}^{N} F_i L_2 \cos \left( \theta - \theta_i \right) \Phi N^{-1} \]

4. Numerical Simulations and Mechanics Experiments

Table 1 and Table 2 respectively show the initial parameters of the lifting mechanism for the case of 1600N cargo load, and the optional specifications of gas spring. Sizes of the rotating frame and the handle are calculated firstly. \( L_1 \) is 1300mm, \( L_2 \) is 420mm. We consider that the truck has two lifting heights expressed as \( H_{\Delta L} \) and \( H_{\Delta h} \). They refer to the distance from the lowest point of cargo feet to the ground. Based on our model, the size of gas spring is gotten according to \( H_{\Delta h} \). \( L \) is 450mm, \( S \) is 150mm. The elasticity of gas spring and relevant kinetic indexes are calculated according to \( H_{\Delta L} \). The total elasticity of gas springs needed is 1000N. Using the parameters above, the kinetic indexes with or without gas springs are calculated when the cargo weight changes from 900N to 1600N, as shown in figure 5. The cargo is a homogeneous cuboid with a length of 600mm and a width of 600mm. Both the centroid height of the cargo and \( T_{\text{max}} \) vary linearly with the cargo weight.

Table 1. Input parameters

| \( L_1 \) | \( L_2 \) | \( L_0 \) | \( H_0 \) | \( H_{\Delta L} \) | \( H_{\Delta h} \) | \( \Delta x \) | \( T_{\text{max}} \) | \( F_{\text{h max}} \) | \( F_{\text{p max}} \) | \( G \) | \( g \) | \( \delta \) | \( N \) |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 112 | 208 | 130 | 80 | 1700 | 1100 | 210 | 80 | 185 | 10 | 1.6 | 160 | 320 | 1600 | 10 | 0.26 | 100 |
| mm | mm | mm | mm | mm | mm | mm | mm | mm | mm | s | N | N | N | m/s^2 | rad |

Table 2. Optional specifications of gas springs

| \( L \) (mm) | \( S \) (mm) | Elasticity (N) |
|-----|-----|-----|
| 340 | 130 | 100-1400 |
| 400 | 150 | 100-4500 |
| 537 | 225 | |
| 580 | 245 | |
| 200 | 60 | 100-1400 |
| 250 | 85 | 100-4500 |
| 300 | 110 | |
| 350 | 130 | |
| 390 | 150 | |
| 400 | 180 | |
| 450 | 190 | |
| 470 | 190 | |
| 480 | 205 | |
| 500 | 230 | |
| 550 | 255 | |
| 600 | 280 | |
| 650 | 305 | |
| 700 | 300 | |
| 765 | | |

A prototype was made. Its mechanical properties were tested by SH-III-500N push-pull force tester. The human pull force measured can be output to the software in the host computer in real time through USB for display and storage, as shown in Figure 6 (a). With the cargo weight changing, the human force required for lifting was measured under the conditions with or without gas springs, as shown in Figure 5 (a, b). The human force required for horizontal walking was also measured on a site about 20m long. The statistical result is shown in Figure 6 (b). Figure 5 (a) shows the human force in the process of rotating ascending varying with time when \( G \) equals 1600N. Figure 5 (b) and (c) show the average human force and the work by manpower varying with cargo weight. They show that about 150N and 105J can be saved with the help of gas springs. Without gas springs, the work done by manpower is more than that of gravity, because there’s still kinetic energy when the cargo getting to the target height. The analytical results of the proposed model are in good agreement with the experimental results. The truck weight without payload is about 1600N. When the cargo weight increases, the required horizontal force increases from 83N to 115N, which can be tolerated.

5. Conclusion and Future Work

To address the problems, such as slow lifting speed and unstable operation, a novel rotary-lift based hand pallet truck assisted by gas springs is designed, a multi-objective optimization model for the design of lifting mechanism is proposed, based on which a functional prototype was made. The results of numerical calculation and mechanics experiment show that the proposed model is basically...
consistent with the actual situation. The design goal of saving lifting time, human force and work can be achieved. The novel truck is convenient, safe, reliable and green. However, it can not be used to carry goods requiring limited sloshing, and more useless work is done due to the inherent defects of rotary lifting mode. Next, we will design a horizontal lifting truck assisted by gas springs.

![Mechanical properties comparison with or without air spring](image1)

(a) Human Force ($G = 1600N$)  (b) Average Human Force  (c) Work

**Figure 5.** Mechanical properties comparison with or without air spring

![Pull force in horizontal movement](image2)

(a) Payload equals 1600N  (b) Payload varies from 900N to 1600N

**Figure 6.** Pull force in horizontal movement

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