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The Application of Foldable Structure in the Multi-functional Cart

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Abstract. In daily life, flatbed and framed carts, the two most common hand carts, have their own strengths but clear functional flaws: flatbed carts are ideal for large items yet cannot fix small goods steadily, while frame carts hold small items properly but cannot handle oversized loads. Current optimization mainly focuses on better functionality and folding performance, but none achieves switch between the two configurations, leaving a practical gap. This study designs a multifunctional foldable cart that combines the merits of both types, inspired by the folding mechanism of paper shopping bags and taking thin plates and hinges as core components. We established a 3D model with SolidWorks, analyzed key angles (∠θ, ∠a, ∠c, etc.) and their kinematic relationships, and calculated the degree of freedom as 4 via the Kutzbach-Grübler Equation. Two cardboard prototypes were made; the first had folding interference, which was solved by adjusting hinges and adding movable linkages to improve structural stability. This new cart enables smooth conversion between flatbed and frame modes and saves storage space, suiting shopping, moving and other scenarios well. However, it has drawbacks: multiple DOFs bring operational complexity, hinges may fatigue after long-term use, and structural stiffness is insufficient under overload. Future improvements will focus on reducing DOFs, reinforcing hinges and adopting modular design to boost usability, durability and maintainability.

Keywords: foldable, trolley, thin plate, hinge, DOF

1. Introduction

In contemporary life, trolleys have become an indispensable part. When shopping, we push a cart to carry things. When moving large items, we choose a flatbed cart to transport them. However, whether it is a cart or a flatbed cart, they excel only in one aspect and lack the functions of the other type of trolley. For instance, although a cart can carry items, it is inadequate when transporting objects larger than its volume. A flatbed cart can carry larger objects, but cannot ensure the stability of most small items during transportation. Currently, almost all optimization schemes for these two types of trolleys on the market focus on enhancing functionality and increasing the folding ratio, but lack the ability to convert between the two types of trolleys. Therefore, our research objective is to

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solve the conversion problem between flatbed carts and carts. For this purpose, we have referred to various models and ultimately decided to improve the folding model of packaging bags to realize our concept.

2. Literature review

Foldable and reconfigurable structures have long been widely explored across fields from aerospace to consumer product design. The core challenge is achieving large deployable motion, while still keeping structural integrity and easy operation. This section reviews relevant literature on foldable mechanisms, scissor-type structures and trolley design.

Scissor mechanisms are widely used in deployable structures since they feature single-degree-of-freedom (DOF) motion and symmetric expansion. You, J. and Pellegrino, S [1]. analyzed the kinematics of planar scissor structures, pointing out they're well-suited for space frames and temporary shelters. Similarly, Kwan, A. S. K. and Pellegrino, S [2]. discussed scissor systems' packaging efficiency and deployment reliability—findings that apply directly to handcart folding mechanisms.

For multifunctional hand carts, many studies have looked into transformable structures that switch between different configurations. A good example is Lee, J. and Kim, J [3]., who proposed a convertible shopping cart that turns into a stair-climbing trolley via a linkage-based mechanism. Their work emphasizes user-friendly transformation and load stability as key factors, both central to our design as well.

Besides, Chen, Y. and Wang, H. [4] addressed prototype fabrication errors and how they affect mechanism mobility. They note that dimensional tolerances in manual prototypes can falsely increase DOF, leading to misleading foldability—a problem we also found in our initial cardboard model.

Finally, fatigue and durability matter greatly for foldable consumer products. Ashby, M. F [5]. lays out material selection guidelines for repeated loading scenarios, which is crucial for designing hinges and joints in foldable trolleys.

3. Conceptual design and analysis

3.1. Description of design

Our design inspiration originates from the paper shopping bag, whose folding mechanism offers both a high expansion-to-compression ratio and a straightforward folding sequence. At present, most commercially available trolleys are either foldable camping carts based on scissors-like systems or non-folding utility carts. The objective of our design is to use a folding structure to enable the cart to easily convert between a cart shape and a platform-trolley shape, thereby ensuring it can transport different kinds of items under different usage scenarios.

3.2. Solidworks model

For the model construction of our design, we used SolidWorks. Thin plates and hinges were used to build the model. The main body parts were built by thin plates, then hinges connected the plates together and acted as creases. The following steps will show how the main body part of our design works, how it deploys and how it can be folded.

Step 1: Fold the side panels downward until they are parallel to the base plate. Step 1 will be shown in Figure 1.

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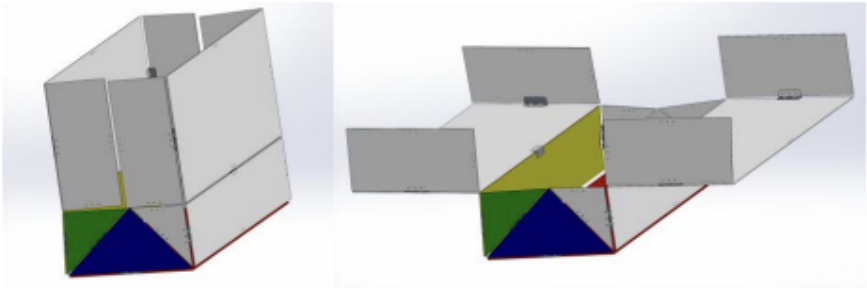

Figure 1. Folding process 1

Step 2: Fold the central triangular panel inward to collapse the entire structure into a flat plane. This step is demonstrated in Figure 2.

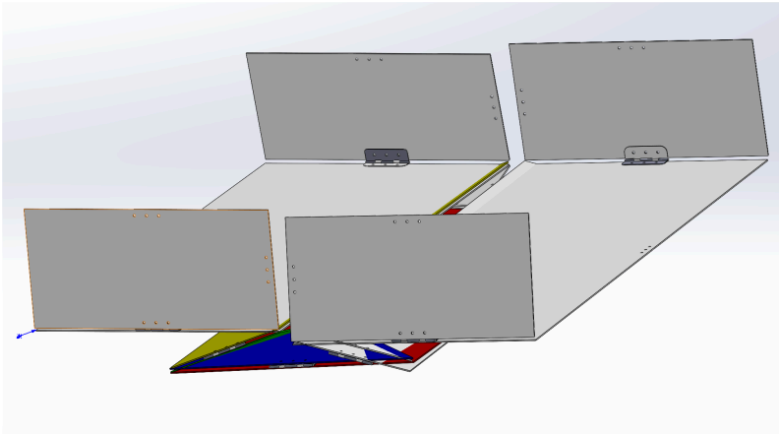

Figure 2. Folding process 2

Step 3:As shown in Figure 3, fold the four small rectangular plates inward.

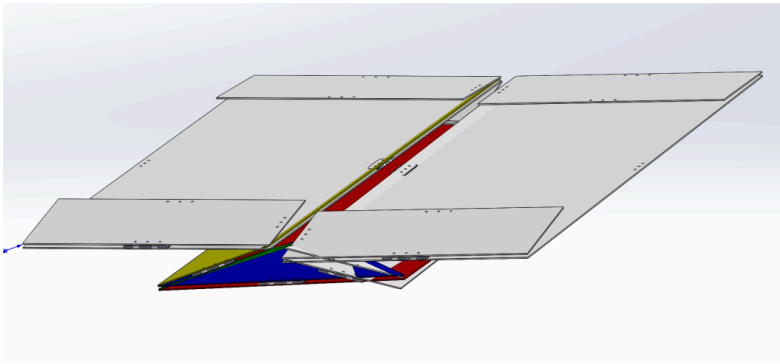

Figure 3. Folding process 3

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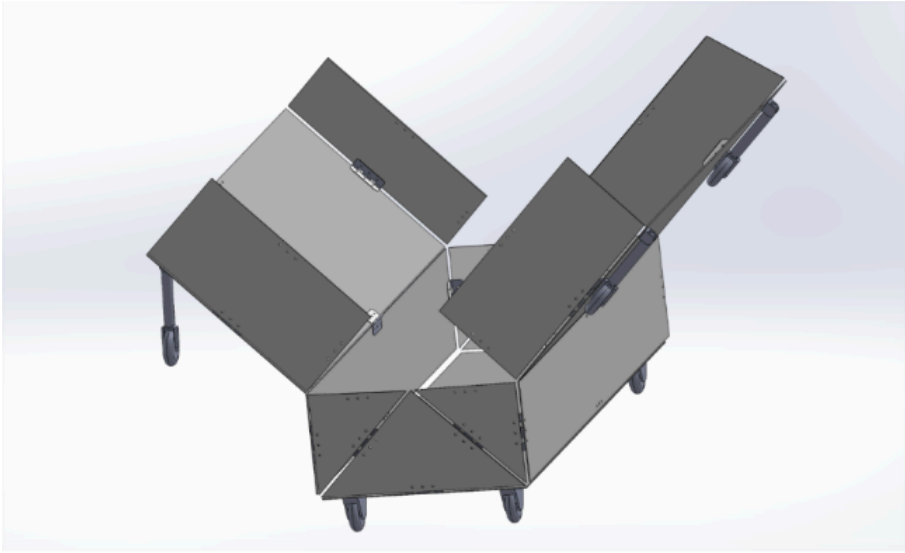

Figure 4. Model with wheels

Figure 4 shows the ideal form of our design, which has deployable wheels on it. Four wheels on the left-hand side and right-hand side can be folded when they are not needed, like the wheels on the right-hand side show; and deployed when they are needed. However, this model has a flaw. The structural changes we made after creating this model were not shown by it. Changes like adding movable linkages that will be mentioned later.

3.3. Data analysis

3.3.1. Angel analysis

For ease of subsequent discussion, the definitions of all referenced angles are provided below.

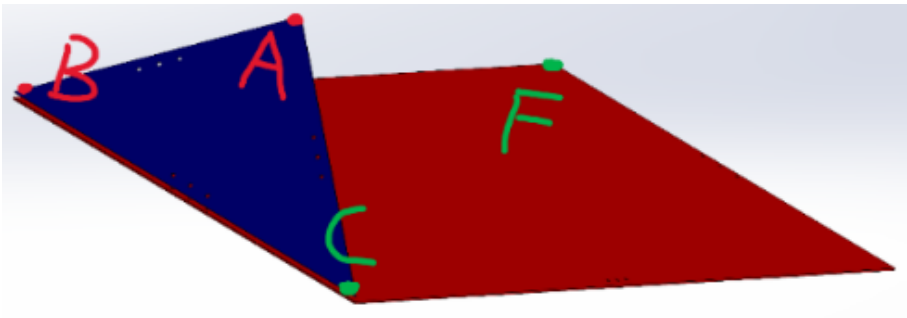

Figure 5. Display of ∠θ

∠θ (∠ABF):The angle between the red base plate and the blue triangular plate—treated as the independent variable. Shown in Figure 5.

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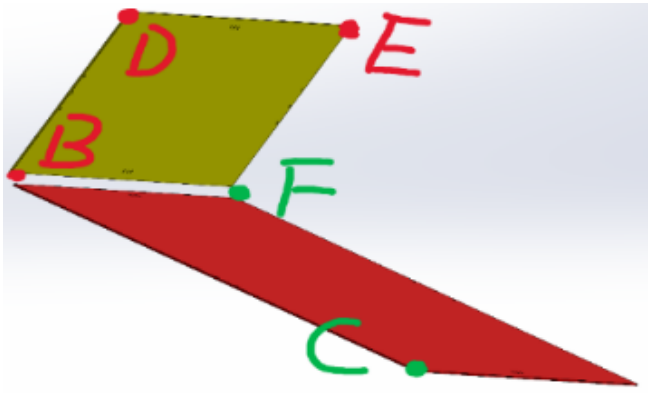

Figure 6. Display of ∠c

∠c (∠DBC): The angle between the yellow plate and the red base plate. Shown in Figure 6.

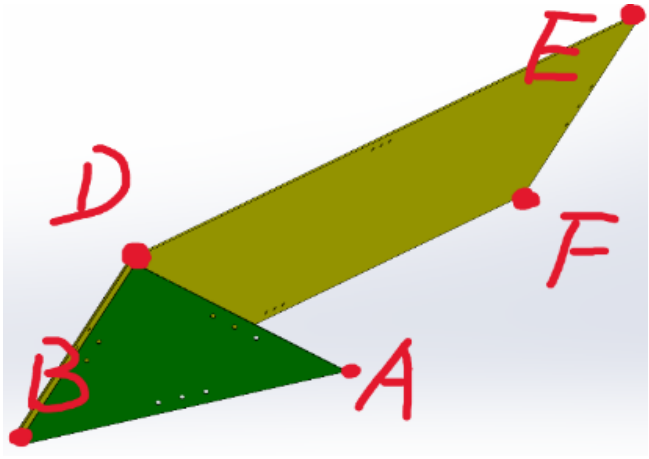

Figure 7. Display of ∠g

∠g (∠ADE): The angle between the yellow plate and the green plate. Shown in Figure 7.

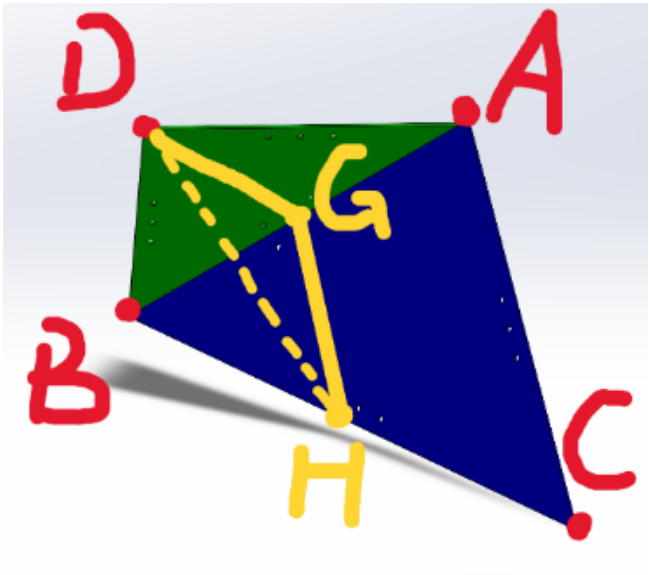

Figure 8. Display of ∠e

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∠e (∠DGH):The angle between the green plate and the blue plate. Shown in Figure 8.

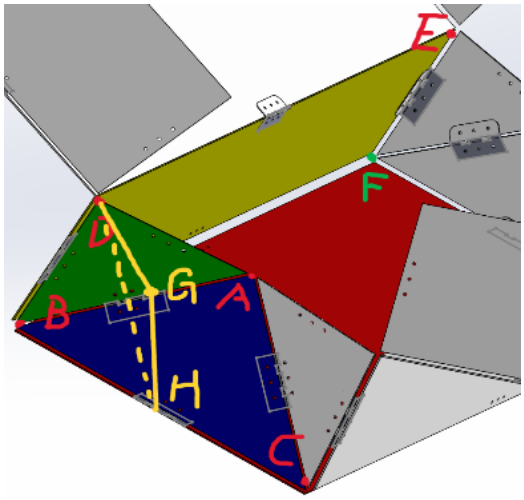

Figure 9. Display of overview model with angles

The figure above, Figure 9, shows the overview of all angles in our model. It is shown that the model is symmetric, so angles on the left hand side are equal to angles on the right hand side, which means ∠c (the angle between the yellow plate and the red plate) is equal to ∠d (the angle between the right white side plate and the red plate, the opposite of ∠c), ∠e (the angle between the blue triangular plate and the green triangular plate) is equal to ∠f (the angle between the blue triangular plate and the gray triangular plate). ∠a and ∠b are supplementary angles of ∠c and ∠d, so that ∠a is equal to ∠b.

Based on the preceding analysis, all these angles can be measured in SolidWorks; the corresponding data are summarized in Table 1.

Table 1. Summarized angular data measured in SolidWorks

∠θ (degree)	∠a (degree)	∠b (degree)	∠c (degree)	∠d (degree)	∠e (degree)	∠f (degree)	∠g (degree)	supplementary of ∠θ (degree)	supplementary of ∠g (degree)
90	90	90	90	90	180	180	90	90	90
84.84	90.23	90.23	89.77	89.77	172.7	172.7	84.84	95.16	95.16
79.87	90.9	90.9	89.1	89.1	165.61	165.61	79.87	100.13	100.13
74.86	92.02	92.02	87.98	87.98	158.34	158.34	74.86	105.14	105.14
69.97	93.57	93.57	86.43	86.43	151.09	151.09	69.97	110.03	110.03
65.04	95.61	95.61	84.39	84.39	143.57	143.57	65.04	114.96	114.96
60	98.21	98.21	81.79	81.79	135.59	135.59	60.01	120	119.99
54.94	101.4	101.4	78.6	78.6	127.21	127.21	54.95	125.06	125.05
50.08	105.03	105.03	74.97	74.97	118.78	118.78	50.09	129.92	129.91
44.92	109.55	109.55	70.45	70.45	109.32	109.32	44.93	135.08	135.07
39.91	114.63	114.63	65.37	65.37	99.58	99.58	39.91	140.09	140.09
35.09	120.22	120.22	59.78	59.78	89.63	89.63	35.09	144.91	144.91
29.95	126.94	126.94	53.06	53.06	78.34	78.34	29.95	150.05	150.05
25.03	134.14	134.14	45.86	45.86	66.87	66.87	25.03	154.97	154.97

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Table 1. (continued)

19.99	142.26	142.26	37.74	37.74	54.44	54.44	19.99	160.01	160.01
15	150.97	150.97	29.02	29.02	41.51	41.51	15	165	165
9.96	160.35	160.35	19.63	19.63	27.9	27.9	9.96	170.04	170.04
5.09	169.73	169.73	10.13	10.13	14.35	14.35	5.09	174.91	174.91
0	180	180	0	0	0	0	0	180	180

According to the data in Table 1, the following relationships shown in Figure 10 to 12 can be found.

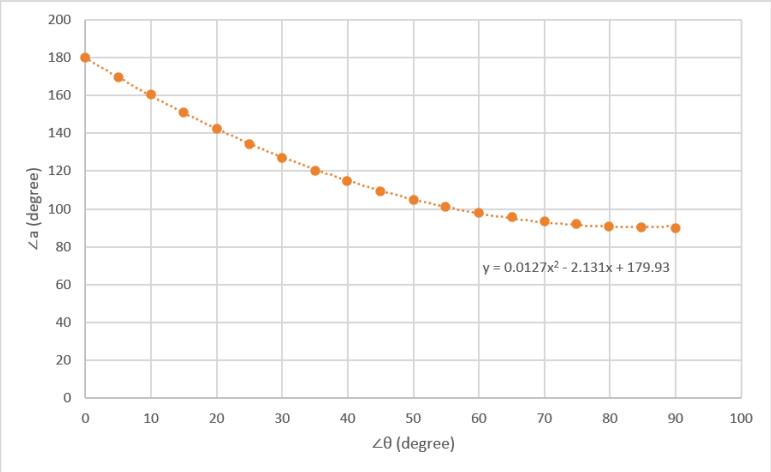

Figure 10. The relationship between ∠θ and ∠a (∠a=∠b)

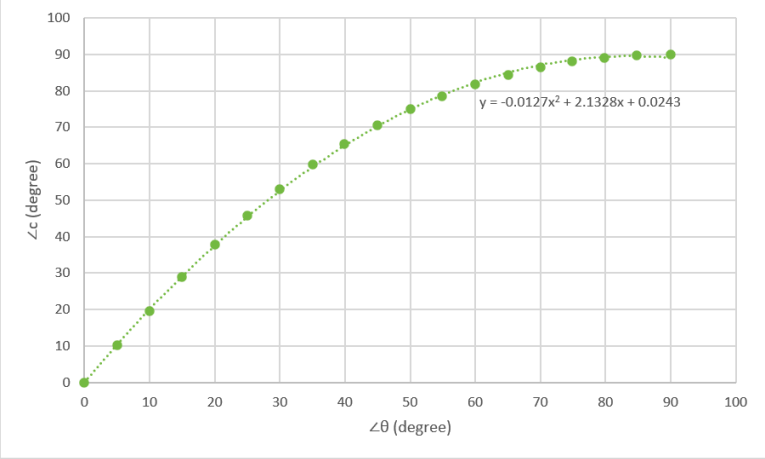

Figure 11. The relationship between ∠θ and ∠c (∠c=∠d)

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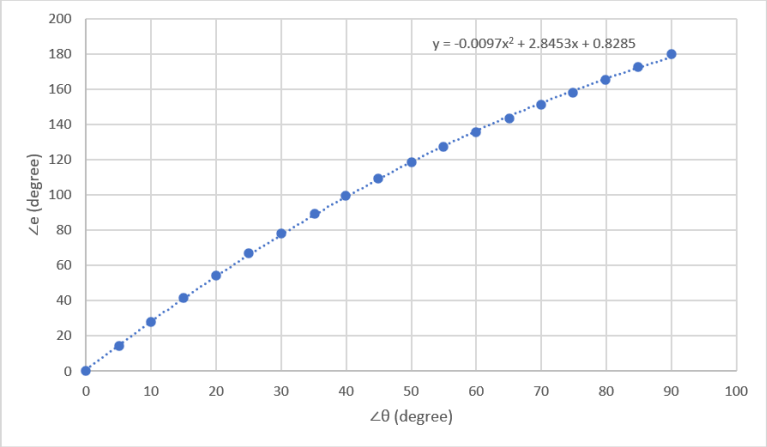

Figure 12. The relationship between ∠θ and ∠e (∠e=∠f)

3.3.2. DOF

The degrees of freedom of our design can be calculated by the Kutzbach-Grübler Equation:

$$DOF = m\ (N - 1 - J) + \Sigma f_i \tag{1}$$

Where m is the number of dimensions of the system, 3 for planar mechanisms, 6 for spatial mechanisms. In this case, m is equal to 6. N is the total number of rigid bodies, including the ground, which is 15 in this case. J is the total number of joints, which is 16. f_i is the number of degrees of freedom provided by the i-th joint, in this case it is always equal to 1. Based on the calculation, the DOF of the main body part of our design is 4.

4. Construction of prototype

In the initial prototype phase, a physical model was fabricated from cardboard sheets joined with adhesive tape, serving as a thin plate and hinges, respectively. A geometrically identical 3D model was subsequently constructed in SolidWorks. However, the SolidWorks model could not be folded without interference, indicating that the physical prototype contained substantial errors, which allow the physical structure to be folded.



Figure 13. Folding steps of initial prototype

Figure 13 shows the folding steps of the initial prototype. Figure 13 (a) is the overview of the unfolded prototype, Figure 13 (b) is the half-folded prototype, and Figure 13 (c) is the full folded

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prototype. Because of the verification in SolidWorks, the non-foldable issue had been found, so we made some changes on our prototype; some hinges (tapes) were deleted.

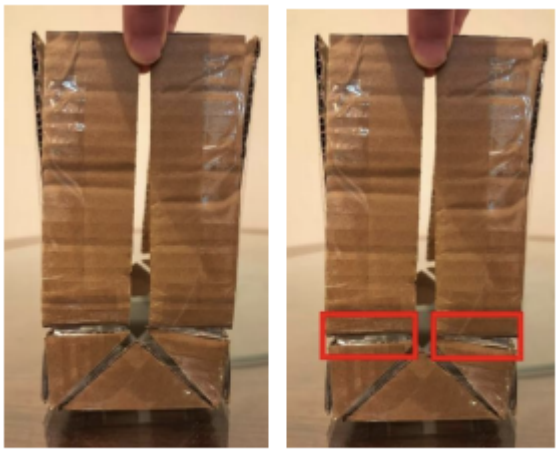

Figure 14. Details of deleted hinges (tapes)

Figure 14 (a) is the front view of the initial prototype. Figure 14 (b) shows which hinges (tapes) were deleted, and it shows the exact places of these tapes.

After this modification, there was a new problem. Removing these four hinges, two on each side, front and back, caused more DOFs. Therefore, we decided to add two movable linkages to the model, one on the front and one on the back. Each linkage links up the two small rectangular plates on each face. The details of how linkages link are shown below.



Figure 15. Top view and front view of final prototype

In Figure 15, similar to the initial prototype, the final prototype uses cardboard as thin plates and tapes as hinges, but it has wires serve as the shaft for the two individual linkages. Adding these links can make sure two small rectangular plates on one side lay down together, which can reduce 2 DOFs caused by removing the four hinges. Figure 16 below shows the folding steps of the final prototype.

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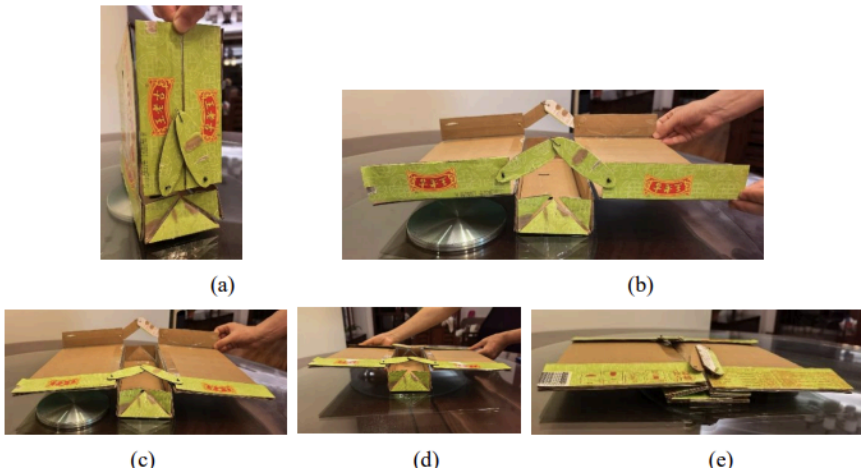

Figure 16. Folding steps of final prototype

5. Conclusions

5.1. Advantages

The foldable multi-functional cart offers three advantages over conventional designs. First, optimized scissor-like linkage yields a superior packaging-to-deployment ratio, reducing the storage space and being easier to load into vehicles for transportation. Second, the foldable structure allows the basket-type cart body to convert into a planar loading surface, which means the cart can work as a platform trolley and accommodate payloads whose lateral dimensions exceed those of the frame itself. and accommodate loads that extend beyond the platform's footprint (i.e., objects with a base area larger than the area of platform of the trolley can be loaded onto it.). Third, only one cart is needed to meet the requirements of different scenarios.

5.2. Disadvantages

Despite its kinematic efficiency, the proposed mechanism exhibits three inherent limitations. First, the system mobility is high, so the cart cannot be folded through a single continuous user motion; instead, it requires multiple coordinated steps, which increases operational complexity and raises the risk of misalignment. Second, the numerous hinges undergo repeated rotation under combined bending and bearing loads during deployment. These loads can cause the fatigue of hinges and potentially shorten the service life. Third, the proliferation of joints increases the system's overall DOF; under overload conditions, this leads to stiffness degradation, undermines stability, and creates latent safety hazards.

5.3. Future improvements

To address these limitations, our design can be improved in three possible areas. First, using a constrained–kinematic topology that reduces the total mobility to 1, which can combine the entire deployment/folding sequence to a single step, let users can deploy the cart by using only one action. If this improvement is feasible, it will reduce the possibility of misalignment and reduce operational complexity. Second, the hinge system is strengthened by using additional bearing-supported joints to distribute loads more evenly. By lowering the load and contact stress at each hinge, the design reduces wear and delays fatigue damage without a substantial increase in mass. Third, upgrading the

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cart to a modular architecture assembled from interchangeable modules. Two kinds of functional module—load-bearing modules and motion modules—are defined, and these two kinds of modules can be swapped as needed. This enables users to quickly replace broken or fatigued components in the field, improves maintainability, and allows the cart to adapt to different usage scenarios as future requirements evolve.

Acknowledgement

Shuai Zeng, Han Yan, and Ziqiang Jiang contributed equally to this work and should be considered co-first authors.

References

[1] J. You and S. Pellegrino, "Foldable bar structures, " International Journal of Solids and Structures, vol. 34, no. 15, pp. 1825–1847, 1997.
[2] A. S. K. Kwan and S. Pellegrino, "Matrix formulation of macro-elements for deployable structures, " Computers & Structures, vol. 40, no. 3, pp. 587–594, 1994.
[3] J. Lee and J. Kim, "Design of a transformable shopping cart for stair-climbing, " in Proceedings of the International Conference on Advanced Mechatronics, pp. 245–250, 2015
[4] Y. Chen and H. Wang, "Influence of manufacturing tolerances on mobility of deployable mechanisms, " Chinese Journal of Mechanical Engineering, vol. 30, no. 4, pp. 823–830, 2017.
[5] M. F. Ashby, Materials Selection in Mechanical Design, 5th ed. Butterworth-Heinemann, 2016.