DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING
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IMPROVING THE ACCESSIBILITY OF PATIO UMBRELLA MECHANISMS

MIE301: Final Design Report

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Group 14

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1. Introduction

The purpose of this design project is to analyze and improve the accessibility of residential patio umbrellas for users with reduced physical abilities. The results of this project hope to highlight a gap in the current market for patio umbrellas that properly address usability and ergonomics, as they require the operator to apply forces and motions which may be inaccessible by members of this community. By employing various kinematic analysis methods, this project also aims to propose a design solution that supports the key stakeholders by resolving experienced problems when operating patio umbrellas.

Figure 1.1: Patio umbrellas can be found in many homes across North America [1].

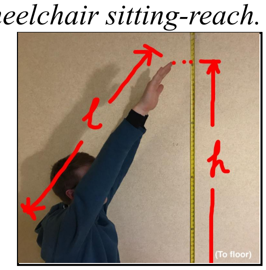
1.1 Background

Patio umbrellas are a commonly used backyard accessory whose large canopy provides shelter for furniture and multiple users from the elements [2]. Key features of patio umbrella mechanisms include:

A. Large Structure/Mechanism Scale: Patio umbrellas require higher input forces in order to adjust components between different configurations;
B. Height Adjustability: As patio umbrellas have multiple uses, they sometimes need to be raised or lowered to accommodate users' activities, whether sitting or standing;
C. Tilt Adjustability: Due to their heavy weight, it can be hard to move patio umbrellas as the sun moves throughout the day. This is addressed by adjusting the angle of the canopy [3].

Patio umbrellas exist in a variety of different forms, popularly as tilting, free-standing (shown in *Figure 1.1*), and cantilever beam. For the scope of this project, the latter variant warrants the greatest amount of attention due to its rather robust structure and considerable mass, which translate into higher force and mobility requirements when operating.

Figure 1.2: Wheelchair sitting-reach.



1.2 Design Opportunity

Many people live with conditions that limit the relative ease with which physical tasks can be performed. Examples include neuromuscular impairments (weakness, fatigue, or atrophy) and skeletal impairments in movement when reaching or grasping due to mechanical limitations and/or pain [4]. Also noteworthy, wheelchairs greatly curb mobility (especially with vertical reach - note that the measured height h in *Figure 1.2* is the approximate operation height of many patio umbrellas [7]). Many seemingly trivial activities are out of reach for many, and this is the case with current designs of patio umbrellas that require a combination of strength, reach, and height to operate. For demographics that may be more vulnerable to injury, such as senior citizens, this becomes a safety hazard. As such, an opportunity for an engineering solution is realized. The key objective to be satisfied is an increase of patio umbrella accessibility. For the scope of this project, accessibility is defined as the equivalent of usability, or the perceived notion of the ability to use. An accessible design achieves all its designated height and angle configurations while enabling the user to do so regardless of potential limitations.

2. Design Specifications

2.1 Requirements

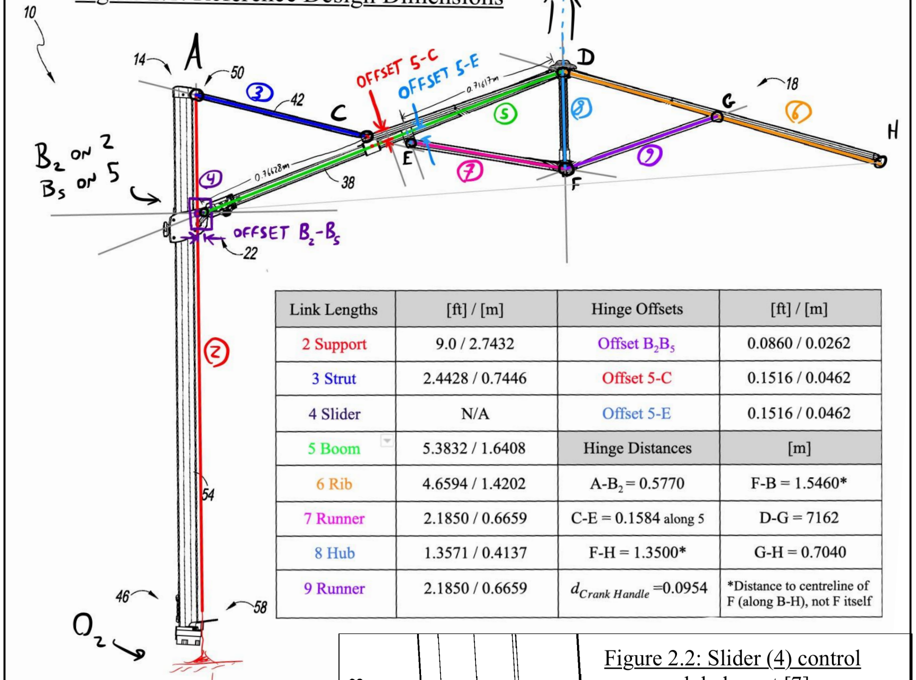
The key objectives met by an accessible design solution address functional components placed in compromising access locations, and those that require certain amounts of force which may be inaccessible by those with physical limitations outlined earlier, while still preserving all required functions/configurations, such as fast operation. To achieve this, the solution will satisfy:

- Key Objective 1: Reduce operating height of crank to meet accessibility guidelines [6];
- Key Objective 2: Deployment/Distow time of umbrella should be below 10 s [5];
- Key Objective 3 : Minimize required input force for operation;
- Aux. Objective 4: Deploy umbrella to different range of height and tilt configurations;
- Aux. Objective 5: Minimize number of hand cranks required to deploy/distow canopy;
- Constraint 1: Necessary Input Force must not exceed 38 N [5];
- Constraint 2: Dimensions of canopy (9.5ft x 9.5ft) & height (9.0ft) remain unaltered [5];

2.2 Reference Design

The current design supports an umbrella canopy from a beam supported at one end, i.e. a cantilever, (See **5** on *Figure 2.1* [7]), connected to the ground through the mounting pole (**2**). It is comprised of 2 main mechanisms:

Figure 2.1: Reference Design Dimensions



Link Lengths	[ft] / [m]	Hinge Offsets	[ft] / [m]
2 Support	9.0 / 2.7432	Offset B_2B_5	0.0860 / 0.0262
3 Strut	2.4428 / 0.7446	Offset 5-C	0.1516 / 0.0462
4 Slider	N/A	Offset 5-E	0.1516 / 0.0462
5 Boom	5.3832 / 1.6408	Hinge Distances	[m]
6 Rib	4.6594 / 1.4202	A-B_2 = 0.5770	F-B = 1.5460*
7 Runner	2.1850 / 0.6659	C-E = 0.1584 along 5	D-G = 7162
8 Hub	1.3571 / 0.4137	F-H = 1.3500*	G-H = 0.7040
9 Runner	2.1850 / 0.6659	$d_{Crank\ Handle}$ =0.0954	*Distance to centreline of F (along B-H), not F itself

2.2.1 Canopy Deployment Mechanism

The canopy opens when its ribs (**6**) (only 1 is visible in cross section, but there are 7 in total + 1 boom (**5**) = 8 arms), are lifted by pulling a cable attached to runners (**9**/**7**) under each rib/boom (**6**/**5**). The cable is run through the hub (**8**), then through an internal pulley system within (**5**), to a control module located on the canopy positioning slider (**4**). The cable is retracted by manually turning an actuator crank (labelled 236 in *Figure 2.2*) on slider (**4**). Reversed cranking will close the canopy.

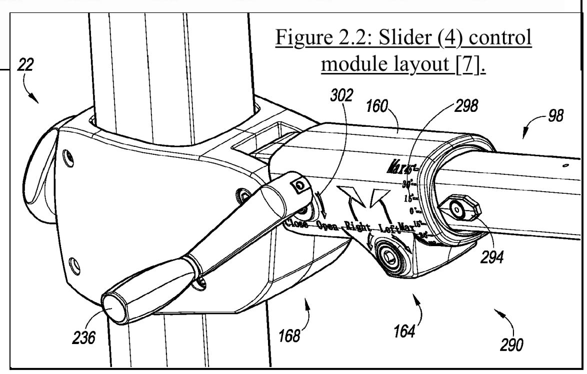


Figure 2.2: Slider (4) control module layout [7].

2.2.2 Canopy Positioning Mechanism

The canopy's position is determined by boom (**5**)'s height and angle relative to the mounting pole (**2**). The height of the canopy is controlled by a 2nd actuation mechanism on slider (**4**) (labelled 164 in *Figure 2.2*), which must be disengaged to manually slide (**4**).

The canopy tilt is controlled in a similar way to distowing: the 2 cantilever arms (**3** and **5**) attached to (**2**) collectively form a triangular linkage. By reducing the distance between (**3**) and (**5**), (i.e. manually moving slider (**4**) upwards in *Figure 2.1*), the angle between them is decreased, aligning the canopy horizontally with the ground. The opposite is done to increase the tilt.

3. Design Analysis

The team redesigned alternative mechanisms as improvements of the reference design, informed by the requirements model (*See Table 4.1* for final rating matrix). The reference design requires 2 different inputs to operate (slider and hand crank) and employs numerous moving parts to achieve complex trace paths/motions. However, constraining full operation of the umbrella with a single input would amalgamate multiple motions given the right trace path, drastically reducing both operation effort and time. Thus, simplifying the cantilever linkage and canopy was the first major design choice, which trimmed the number of major components **from over 20 to under 10** (*Figure 3.1*, [Animation Links]; [CAD Link]). The reference design's triangular linkage was inverted such that the cantilever boom (**5**) now pivots from where the strut (**3**) used to be (*Figure 2.1*) . Instead of a slider, this design employs sliding rack (**9**) and fixed pinion (**7**) such that height control may be actuated from a fixed lower location (Note: pinion crank mechanism (**7**) in *Figure 3.1* is not to scale for illustrative purposes - see *Figure 3.5* for accurate configuration). The canopy itself consists of 2 hinged rectangular frames (**6**) mounted on the strut (**3**) and boom (**5**), as seen in *Figure 3.2*. Manual lifting of the slider is now supplemented with a stationary crank at the base (**7**), which translates rotation through a belt drive to the pinion and rack. Turning the crank lifts the rack the strut, while the reverse lowers them. It may be fixed at any location using similar braking clamp systems as the reference design, which was dismissed from the scope of analysis.

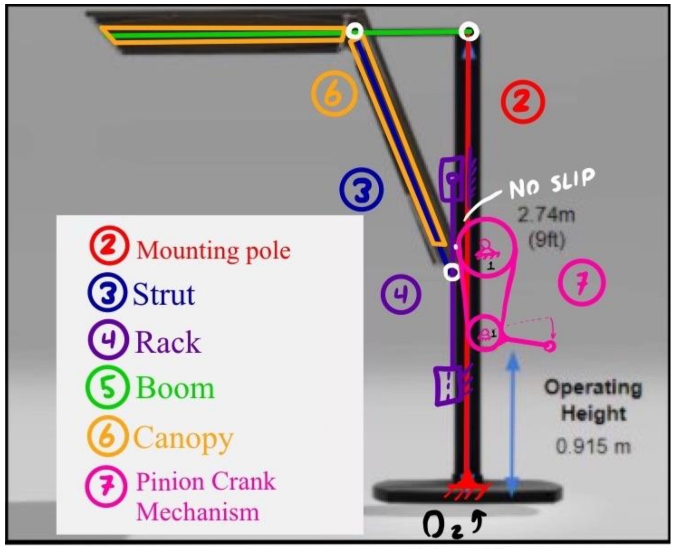


Figure 3.1: Proposed Design Mechanism Sketch

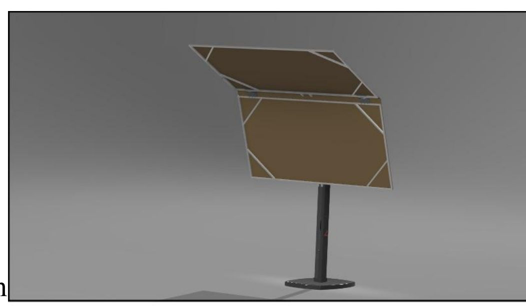


Figure 3.2: Proposed Design Renderings in (a) open and (b) closed configuration.

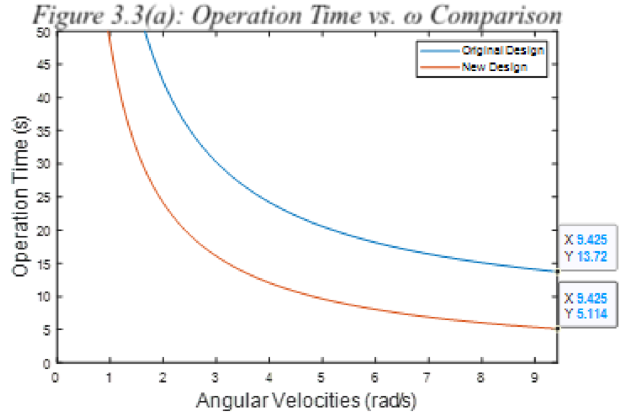
3.1 Fixed and Lowered Operating Crank Height

The decision was made to fix and lower the input crank position to 0.915m to satisfy ***Key Objective 1*** and increase the accessibility of reaching control features. As mentioned, a sliding rack and fixed pinion with belt transmission was chosen to translate input crank rotation into linear motion driving the canopy slider, where pinion diameter is maximized and the lowest gear module is chosen to maximize motion conversion per turn. Through this, the number of rotations required to deploy the rack from its two limit positions was found, and an analysis was conducted to compare respective time objectives for both designs. A consequence of this design choice is torque increase: since the pinion for the rack is required to be near the center of the mounting pole to accommodate the range of movement, the input and output must reside on independent shafts. To connect these two non-collinear shafts a pulley-belt transmission was chosen to amplify torque by a factor of 2 from the input pulley to the output. A force balance analysis was conducted to factor additional mechanical advantage, and contrasted against the required input force objectives for each design (See *3.3*).

3.2 Minimizing Operation Time & Crank Rotations

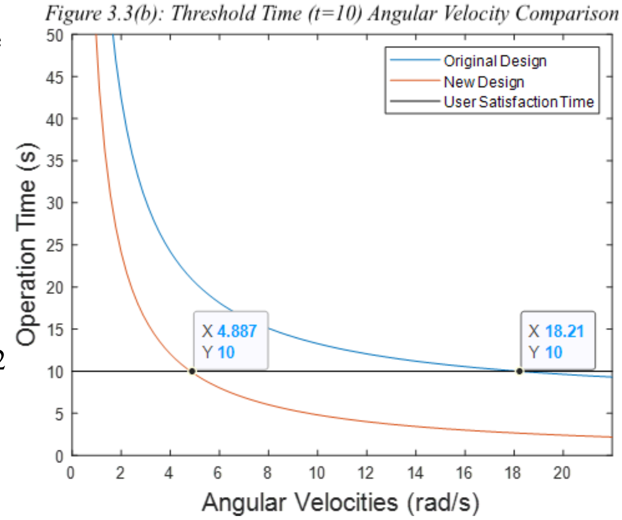
3.2.1 Opening Time VS Angular Velocities With Hand Crank Relation

Figure 3.3(a): Operation Time vs. ω Comparison



Original Design: The position of the hand crank is located on the slider. Users have to raise the slider to the maximum height and then hand-crank to open the canopy. This involves 2 steps. From several user data [9] it has been seen that it takes roughly 6 seconds to push the slider up to the desirable max height. After that, the time taken for the opening of the canopy through hand crank is achieved by the relationship: $t = 72.76/\omega$. This relationship was found by analyzing the length of cord needed to be retracted from closed to open position, which was 3.03 ft, ie. 0.924 m. With a hand crank spool of 1-inch diameter, the relationship was found as $v = \omega * r$,where r = 0.5 inch = 0.0127 m. Since $time\ taken = \frac{length\ of\ cord}{velocity\ of\ pulling\ cord}$, the relationship obtained was $t = \frac{0.924}{0.0127\omega} = \frac{72.76}{\omega}$. Hence, the total time taken in terms of ω is equal to $6 + \frac{72.76}{\omega}$s.

Figure 3.3(b): Threshold Time (t=10) Angular Velocity Comparison



New Design: Users will operate a hand crank, whose linked pinion drives the slider rack up. The slider is directly attached to links that open fully from a closed position and the stroke length of the slider from its minimum to maximum position determines the time needed to fully deploy the canopy. A stroke length of 3.52 ft (~40% of the total height of umbrella) and a crank input ω gives the relationship $t = \frac{1.073}{0.02225\omega} = \frac{48.22}{\omega}$ where the stroke length = 3.52 ft = 1.073m. This relationship was found by analyzing that users will rotate the handle with ω, but since there is a gearing ratio of 1:2 in the belt drive system, the pinion will receive only $\frac{1}{2}\omega$. Since the pinion has a diameter of 3.5 inch, or a radius of 0.0445 m, we can formulate that the upward velocity of the rack:$v = (\frac{1}{2}\omega * r) = 0.02225\omega$. Note that for time to be minimized, the gear ratio also had to be minimized to a 1:2 ratio. If a higher ratio of 1:4 was used, the time taken would increase and break even with the original design. It has been estimated that the average user would hand crank 1.5 revolutions every second, so ω=1.5*(2π rad/s)= 3π = 9.425 rad/s [10] From *Figure 3.3(a)*, it shows how at 9.425 rad/s, the time taken for original design is=13.72 s and time taken for new design=5.114 s – a drastic reduction of time by 8.606 s. **This is a 63% reduction in time.** Additionally, the number of hand cranks can easily be calculated (also demonstrated in CAD animation):

- For original design: (13.72 - 6) seconds *1.5 revolutions per second=11.6~ 12 rotations;
- For new design: (5.114) seconds *1.5 revolutions per second=7.7~ 8 rotations.

Thus, with the new design, a **33% reduction in the number of rotations is achieved.** An important concluding aspect of our design is also that if we were to see how much angular velocity is needed to deploy within 10 seconds, which is the 'user satisfaction time', then we see for our design to be able to reach opening of canopy in 10s, it would take 4.887 rad/s ~ 0.78 revolutions in a second, but in original design to open canopy in same 10s, it would take the total of 18.21 rad/s ~2.8 revolutions in a second. This is shown in *Figure 3.3(b)*. Realistically since our users are elderly people and we can assume they would rotate it slower than the average user, then in new design, with only minimum 0.78 revolutions/second the user will be satisfied since it would take maximum 10 seconds operation time. This means any higher revolutions per second will yield less than 10s operation time.

3.2.2 Velocities of Canopy Tip

Using a different approach, we analyze the velocity of the canopy tip throughout the opening process on both the original and new designs (*Figure 3.4*). Notice that the original design has two distinct regions separated at t = 6 s. By comparing the new design with only the second region of the original design, which represents the opening process of the canopy that is driven by a hand-crank, we can make two observations. First, the canopy tip moves at a higher velocity in the new design. Second, the original design completes the opening process within a shorter time frame of 4 seconds (vs. 4.5 seconds) despite having a lower velocity. Both these observations corroborate our previous analysis. The new design takes longer than region 2 of the old design, but is able to combine motions 1 and 2 into a single operation by moving quicker, leading to an overall shortened time.

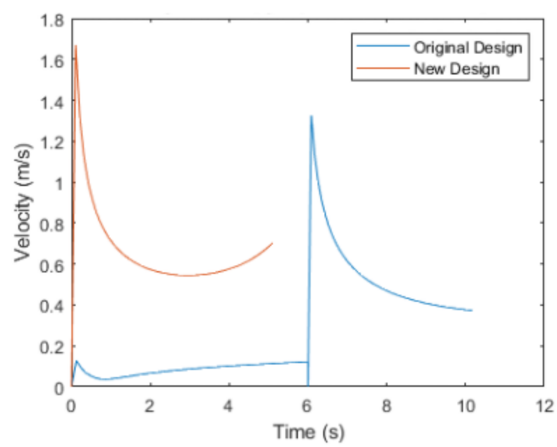


Figure 3.4: Velocity of Canopy Tip from Closed to Open.

3.3 Minimizing Required Input Force

To reduce input force, the new design replaces the hand slider in the original design with three synchronized systems, with the simplifying assumption that all the umbrella weight of 95.2 N is concentrated at the slider hinge as shown in *Figure 3.5*. This replacement allows users to vertically position the umbrella with **14.1 N** of input force. In comparison, the original design requires an input force of **95.2 N**. Note that the umbrella weight was calculated by assigning Al-6061 as the linkage

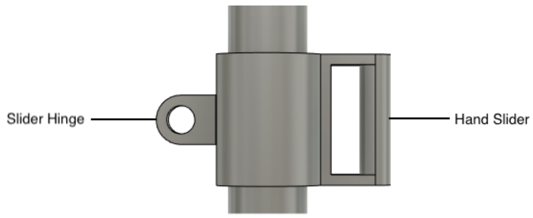
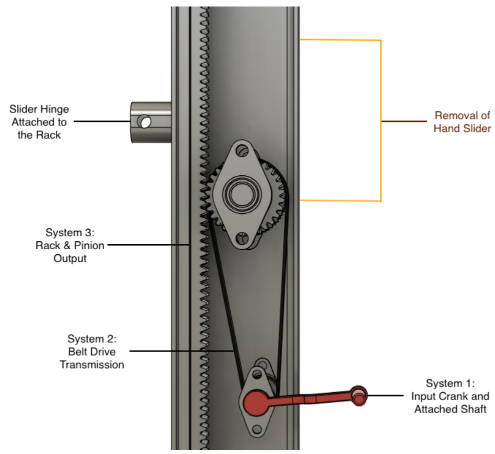


Figure 3.5: Upward Movement Mechanisms: a) Manual Slider in Original Design, b) Three Synchronized Systems in New Design



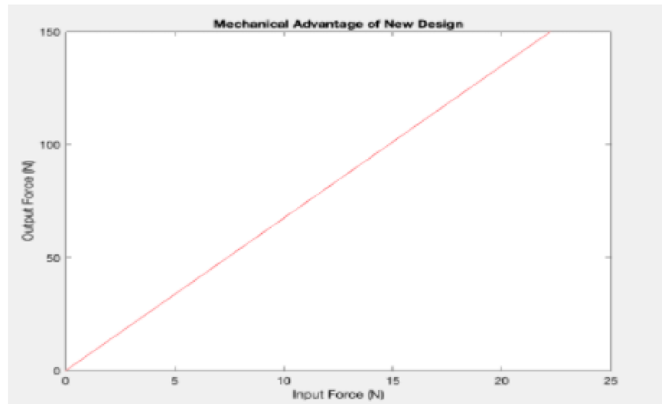
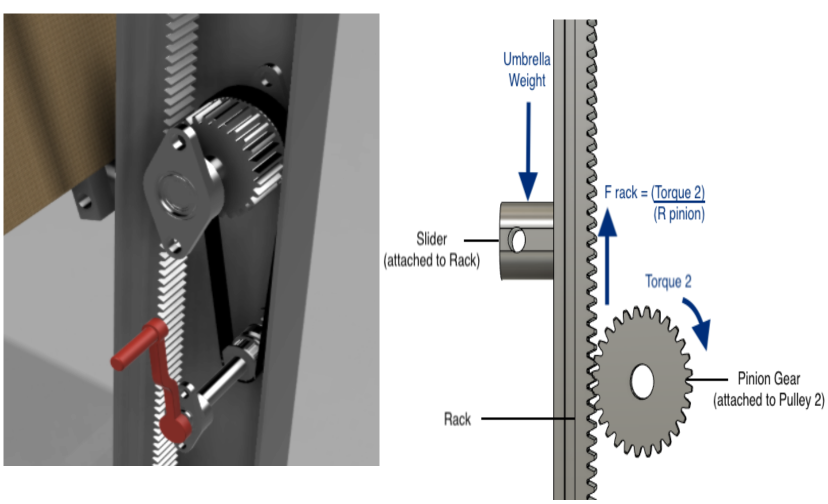


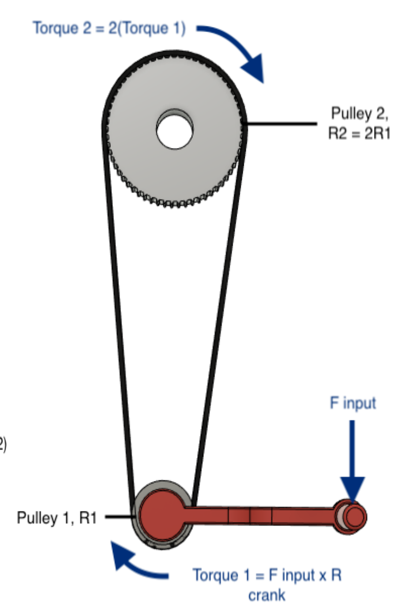
Figure 3.6: Mechanical Advantage of New Design = (Output Force)/(Input Force)

material, as per industry standard [3]. The primary cause of this difference in input forces is the mechanical advantage present in the new design. The three systems together are capable of amplifying all input forces by a factor of 6.75, as tested through the system of free body equations on MATLAB. The results are summarized in *Figure 3.6*.

To analyze the free body equations, the motion transmission in the system must first be covered. As observed in *Figure 3.5(b)*, a hand crank serves as the input in the new design, transmitting applied torque onto the attached shaft. The shaft's torque is amplified through belt drive pulleys, which have a 1:2 diametric ratio. The pinion attached to the larger pulley then transmits the amplified torque from the pulley to the rack, exerting an upward force on it. Due to the smaller pinion radius relative to input crank length, the force amplification of the transmitted torque is significantly higher than even the belt drive's diametric ratio.

Figure 3.7: Force Analysis of Proposed Design Input Mechanism.





The free body diagrams arising from the aforementioned transmission process have been highlighted in *Figure 3.7*. Considering an umbrella weight of 95.2 N, an input of 14.1 N is required for the rack (and attached slider hinge) to move vertically upwards. In comparison, a free body analysis of the original design's hand slider comprises a single downward weight force and a single upward input force. This yields a mechanical advantage of 1, and a significantly larger required input of 95.2 N. As evident from this analysis, not only does the new design require significantly lesser input force, but it is also the only option that satisfies the constraint of requiring a lower input force than 38 N. Implementing this design would provide greater operational accessibility for physically weaker users, allowing the client to serve a larger customer base.

3.4 Height and Tilt Adjustment

For both original and new designs, once they have reached their default open states, their tilt angles θ can further be increased, resulting in height changes. The max tilt adjustment is bound by additional physical properties of the links and mechanisms such as width that are beyond the scope of this report. Instead, this is defined based on a condition of the smallest angle between the links, α = 14°. The reasoning is that the original design constrains its max tilt at this condition, which is found through calculations based on the minimum slider height of existing designs on the market (refer to the reference design in *Figure 2.1*).

Looking at *Figure 3.8*, we see that for a constant α = 14°, the new design can reach a maximum tilt angle of 69° vs the 59° of the original, a **10° increase**. When increasing the tilt angle, the span of the canopy *increases* its height in the new design, while it *decreases in* the original design. This occurs for the entirety of the tilt adjustment process regardless of angle, which allows more space for users underneath the umbrella; however, the higher height may also remove the user from coverage when operating the hand-crank at the pole. The drawback is that the minimum tilt angle cannot go as low as that in the original design, which we consider a valid tradeoff for the benefits of key objectives described in previous sections since tilt adjustment is a secondary objective.

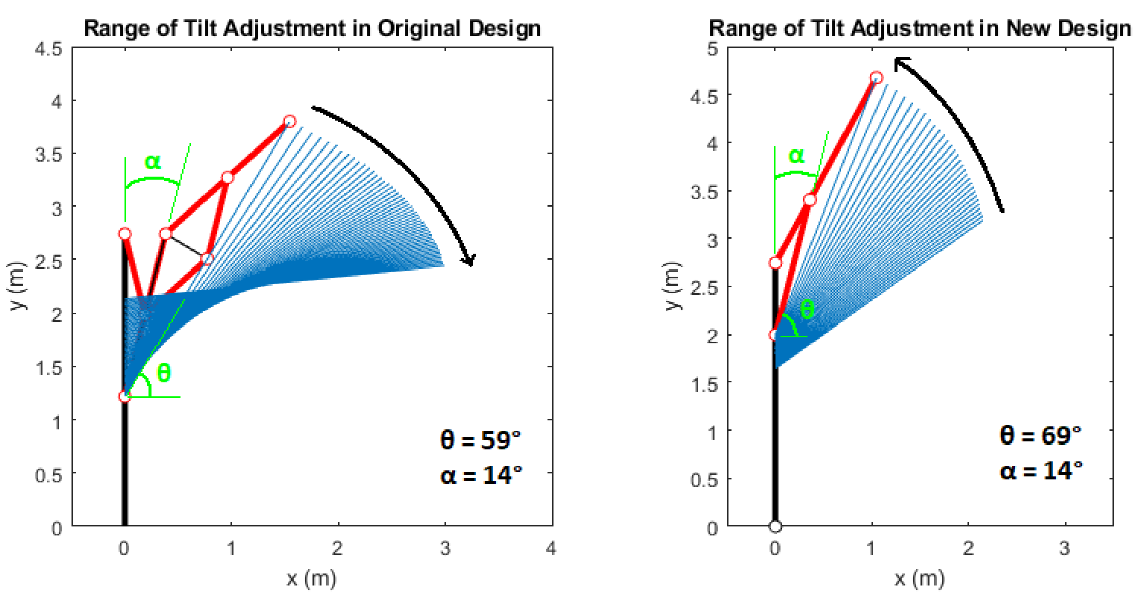


Figure 3.8: (a) Tilt Adjustment for Original Design, and (b) Proposed Design.

4. Conclusion

Table 4.1: Ratings Matrix - Analysis Results

Requirement	Criteria/Metrics	Reference Design	Proposed Design
KO1: Increase accessibility to control features	Sitting shoulder height: 0.915 [6]	3-7ft = 0.914-2.13m	0.915m
		Champion: Proposed Design (Δ= 0%-57.0%)	
KO2(A): Minimize Operation time in terms of cranks to open canopy	Constraint: $t \leq 10s$ [5]. Shorter time, or function of time, is better	t = 13.72 s	t = 5.11 s
		Champion: Proposed Design (Δ= 62.7%)	
KO2(B): Minimize Operation time in terms of deployment time	Faster deployment time is better.	t = 4.0 s Corrected: t = 10.0 s	t = 4.5 s
		Champion: Reference Design (Δ= 12.5%) *Corrected:* Proposed Design (Δ= 55.0%)	
KO3: Minimize Input Force to Operate Umbrella	Constraint: $F \leq 83N$ [5]. Shorter force is better	F = 95.2 N	F = 14.1 N
		Champion: Proposed Design (Δ= 85.1%)	
AO4: Maximize # of Height & Tilt Configurations	Larger continuous range or finite amount is better	$\theta = 5^{\circ}$-59°; $\Delta\theta = 54^{\circ}$	$\theta = 36^{\circ}$-69°; $\Delta\theta = 33^{\circ}$
		Champion: Reference Design (Δ= 38.9%)	

The reference design fared well in analysis, but as predicted when redesigning, the greatly simplified proposed alternative saw a 63% faster deployment time with the operation time being lesser than 10s, hence maximizing user satisfaction. The introduced rack and pinion system added the mechanical advantage necessary to gear down input force to 14.1 N, which is nearly 3 times smaller than the constraint of 38N stated in the requirements. The crank module was repositioned to a much more accessible location with static configuration and the required hand cracks was minimized by 33%.

There were a few areas where the original design fared better, even with optimization of the proposed design. This was ultimately a design decision in order to optimize the requirements that were defined to be more important. Increasing the angle range (*Requirement AO4* in *Table 4.1*) would have meant trading off with higher input forces, which would be unideal according to the values of primary users. Next, the reference design fared better *KO2(B)* on paper, but as discussed in *3.2*, the 2-phase operation of the reference design results in a longer overall time, and in practice the proposed design would actually actuate faster. It should be noted that the constraints of a 10 second maximum deployment time and 38N max input force were both unsatisfied by the reference design, confirming the motivation for redesigning a cantilever variant of patio umbrella.

In conclusion, all important objectives of time, accessibility, and force constraints were satisfied and surpassed by the design alternative. The results of this study distinguish the proposed design as a great champion alternative against the status quo. With metrics key to the targeted market properly analyzed, this project is recommended to proceed to the detailed design stage, where the solid mechanics, material selection, and environmental and safety analysis of the champion design may be examined.

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