**Box and Lid**

This section outlines the design specifications for a box containing shafts, bearings, and blades. The box provides secure, organized storage for these precision components, ensuring safety when using the blades to cut durian stems. Additionally, it covers the design of a lid for accommodating a motor and enclosing the box. For analysis, the box and lid will be treated as a single entity, and finite element analysis (FEA) will be used to examine their stress and deformation characteristics. Optimization measures will be proposed based on the analysis results.

**Box Dimension Specification Design**

The design of the end effector box emphasizes symmetry to enhance stability and functionality. Symmetry is crucial for maintaining the box's stability, preventing the center of gravity from shifting, and minimizing the risk of torsion. To achieve this, the box is designed with shafts, gears, and blades symmetrically placed. This balanced arrangement ensures even weight distribution and reduces potential distortion, keeping components securely in place.

Additionally, the inner length of the box is meticulously designed to ensure that the blades can be fully opened and removed without any obstruction. Here, we developed a relationship to determine the inner length of the box offering a safe and stable solution for box dimensions.

Now, we consider a scenario where the scissors become obstructed by the box opening during deployment (**Figure 1.a**), several geometry dimensions are supposed to be given, such as rotational angle for each single blade , diameter of the gear , width of the scissor , and box width .

In **Figure 1.b**, we find that the minimum half inner length can be determined by the information from purple square, brown and green triangles.

For further simplification and arrangement, the minimum inner length as a function of rotational angle for each blade , gear diameter , scissor width , and box width is shown as follows.

Considering the varying thickness of durian stems and the complexity of harvesting durians, the blade rotation angle is set to , with each individual blade rotating . To accommodate all components, the box is designed with an internal width of 100mm, ensuring sufficient space for storage. Based on dimensions shown in **Table 1**, the minimum inner length is calculated as follows.

The end-effector container must ensure adequate safety, then we incorporate a safety factor of 1.25. Accordingly, the inner length of the box is , and the fundamental dimensions about the latest version box are shown in **Table 2**, where and represent overall length, width, height of the box and wall thickness respectively. More details about inner structure of the box please check the **Appendix**.

|  |  |
| --- | --- |
| A drawing of a circle with lines and a circle with a circle  Description automatically generated with medium confidence | A drawing of a circle with lines and numbers  Description automatically generated |
| (a) Brief inner dimension of box | (b) The minimum inner length of box |

**Figure 1.** The relationships of inner dimensions about the box.

**Table 1.** Rotational angle, gear diameter, scissor width and box width.

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**Table 2.** Fundamental dimensions of the latest version box.

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|  |  |  | 10 |

**Brief Introduction to Lid Design**

According to **Table 2**, the latest version of the lid is designed with the same width and length as the box, which are and , respectively. Two holes which have the diameters of and respectively, are drilled for building the room for coupling and bearing. The thickness of the lid is .

The lid will be connected to box by four screws, and there are two beams attached to below of the lid for locating. More details about the lid dimensions please check the **Appendix**.

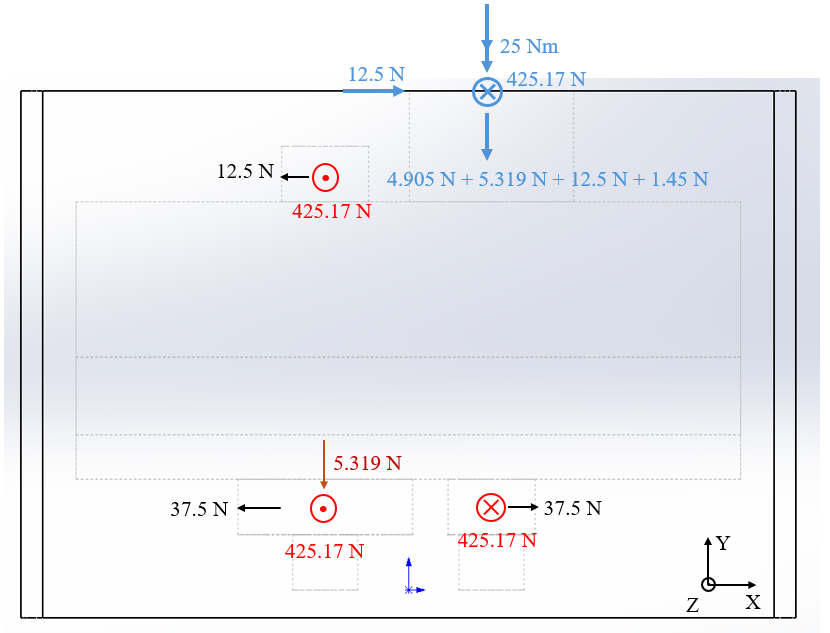
|  |  |
| --- | --- |
| A white square with a hole in it  Description automatically generated | A grey rectangular object with a circular object in the middle  Description automatically generated |

**Figure 2.** Brief views about the latest version lid.

**Finite Element Analysis – Free Body Diagram**

Based on discussions with Prof. Theron, for simplicity in force and deformation analysis, we consider the box and lid as a single unity. The free body diagram of the box and lid combination is shown as follows. In the box and lid combination, there are many forces involved. For simplicity, we have categorized them into three main types: forces and torques acting on the lid (marked in blue); forces transmitted to the box due to gear meshing (marked in red); and forces transmitted to the box by the shaft through the bearings (marked in black). Some fundamental force components will be provided in **Table 3** for reference.

It should be reminded that **Figure 3** presents the final version of the force analysis diagram. In previous design versions, the forces varied with changes in the box structure dimensions. Although these variations are not detailed here, the general approach to force distribution remains consistent across versions. For instance, part of the meshing force of the right gear is transmitted to the lid surface via the coupling, while the axial force of the left shaft is transmitted to the locations of the upper and lower bearings, and so on.



**Figure 3.** Free body diagram about the box and lid combination.

**Table 3.** Weights of coupling, shaft-gear-scissor (SGS), motor with its gear head.

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| --- | --- | --- |
|  |  |  |
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**Finite Element Analysis – Deformation and Stress Results**

Through finite element analysis, we determined the maximum deformation, average deformation, maximum stress, and average stress of the box and lid combination, as shown in **Table 4**. We observed that the deformation in the vertical direction was the greatest. Using the height of the box and lid combination, we calculated the overall maximum deformation percentage to be , a very small value. This indicates that our design is successful, as the box and lid combination did not fail under the complex forces and torques applied.

|  |  |
| --- | --- |
|  |  |
| 1. The frontal overview | 1. Overview at an inclined angle |
|  |  |
| 1. Section plane about the lid | 1. Section plane inside the box |

**Figure 4.** Deformation demonstration for the latest version of the box-lid combination.

|  |  |
| --- | --- |
|  |  |
| 1. The frontal overview | 1. Overview at an inclined angle |
|  |  |
| 1. Section plane about the lid | 1. Section plane inside the box |

**Figure 5.** Stress demonstration for the latest version of the box-lid combination.

**Table 4.** Deformation and stress results for the latest version of box-lid combination.

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**Design Optimization**

Originally, our design for the box made of structural steel, which weighed highly , had a wider wall thickness and exhibited a slightly different inner structure than the latest one. When we did the FEA, it was found that the maximum deformation and maximum stress are and , respectively. Due to the excessive load that a heavy box and lid combination imposes on the robotic arm and the high production costs, we can optimize by reducing the wall thickness of the box and lid combination and using lighter materials instead of structural steel.

According to **Table 5**, we found that by reducing the wall thickness, our volume decreased from the original to , resulting in a reduction in mass for the same material structural steel. When we switched to lighter materials than structural steel, such as titanium alloy, aluminum alloy, and magnesium alloy, we discovered that aluminum alloy and magnesium alloy were two good candidates. They reduced the mass by and , respectively.

The corresponding deformation deviations only increase and for aluminum alloy and magnesium alloy respectively, comparing to the original design.

**Table 5.** Optimization results about the box and lid combination.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |
| Structural Steel |  |  |  |  |  |
| Titanium Alloy |  |  |  |  |
| Aluminum Alloy |  |  |  |  |
| Magnesium Alloy |  |  |  |  |

**Final Design Decision and its Manufacturing Process**

Aluminum alloy and magnesium alloy both present distinct advantages and disadvantages in practical manufacturing. Aluminum alloy is known for its excellent corrosion resistance, good mechanical properties, and ease of fabrication. It is widely available and generally more cost-effective compared to magnesium alloy. Magnesium alloy, on the other hand, is the lightest structural metal, providing significant weight savings, but it has limitations in terms of corrosion resistance and is more challenging to work with due to its flammability and the need for specialized handling during processing. Additionally, magnesium is typically more expensive than aluminum in terms of raw material costs.

Given these factors, aluminum alloy emerges as the preferred choice for our application. It offers a favorable balance of weight reduction, cost efficiency, and manufacturability. The superior corrosion resistance and ease of fabrication of aluminum alloy make it more practical for large-scale production, ensuring both performance and economic viability. Hence, despite the slightly higher weight compared to magnesium alloy, the overall benefits of aluminum alloy make it the optimal material for our box and lid combination.

In the manufacturing process, we use aluminum alloy to fabricate the box and lid by employing techniques such as extrusion and machining. These processes allow us to achieve precise dimensions and maintain structural integrity. After fabrication, the box and lid undergo surface treatments such as powder coating. Powder coating provides a durable, protective finish that enhances both the aesthetic and functional properties of the components. This approach ensures that the final product meets the required performance standards while remaining cost-effective and easy to produce.