Mind The Gap

ENSC 384

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1 Introduction

In this report, we discuss the design, analysis, and testing of the truss structure chosen for our project. The construction of the structure, objectives, design approach, and constraints, are all described. Quantitative analysis is presented for three truss structures using MATLAB finite element (FE) analysis leading to evaluation of the truss design alternatives. An analytical analysis of the optimal structure was completed using the Method of Joints and this was compared with the results from MATLAB FE analysis as well as the mechanical testing performed in class.

2 Design Approach

We began the design process by considering the factors involved in building a truss that would maximize efficiency for applied loads, in both the vertical and horizontal planes. This involved searching for a truss design that would simultaneously minimize both overall deflection and total weight. Using 2D finite element analysis tools available to us, we investigated different truss designs and determined key elements that could produce high efficiency. The 2D analysis was limited in that it made many assumptions and could not be relied upon to give accurate results when applied to three 3D structures. In order to overcome this problem, we specifically chose to design our truss by connecting a 2D vertical truss together with a 2D horizontal truss. In doing so, we were able to greatly simplify the design, and thus permit us to do a thorough mathematical analysis of applied forces in both directions.

In our first task, ten different vertical structures were analyzed using finite element analysis and an optimal design was chosen (as presented in Lab Report 1) that could carry a maximum of 5N as well as the total weight of the structure. From our analysis, we knew that failure due to deflection was not the most serious problem, though buckling in long members still remained a concern. The vertical design we chose optimized for maximum efficiency while also incorporating resistance to buckling in the vertical plane. One weakness in our analysis that emerged was that we assumed cantilever end conditions instead of the correct conditions for attaching the truss to the motor. This means that we likely underestimated the potential vertical deflection of our structure.

Our second task, and the focus of the rest of this report, was to design a truss to resist deflection in the horizontal plane. Three designs were analyzed in MATLAB and the deflection of the optimal design was verified by analytical hand calculations. The results were compared, and the optimal design was chosen, from which a 3D model (vertical + horizontal) was generated using SolidWorks. We felt that since the horizontal truss didn't carry the weight of the structure, an optimal design would focus more on minimizing the weight rather than minimizing deflection. By minimizing weight, we would use less overall brass, which ensured a sufficient surplus in the event of construction errors. In addition, keeping the weight down was an important design decision for reducing the total strain upon the motor during operation. We also believed that it would give us an advantage during the final competition of faster acceleration/deceleration of the truss due to a lower moment of inertia.

Part of our horizontal design considerations were to create a structure with enough width such that we could add two support members to stabilize the upper members of the vertical truss. These two members are labeled *M2* in figure 6. The motor mounts were designed to be attached symmetrically to the truss - two washers at the back and one washer closer to the front. This was done to evenly balance the weight of the truss. Also, to ensure that failure would not occur at the motor mounts, we attached them to the top of brass members which were in in turn attached on top of the horizontal members of the truss. This means that the when the truss is attached to the motor, the weight of the structure is not being borne by the solder that attaches the washers to the brass members.

The magnet mount was purposely designed to account for potential height differences at the end of the truss. These differences could either come by unforeseen deflection or by alterations in the basic set-up for the competition. In order to accommodate this, we designed our magnet to be mounted slightly higher than required with the option of adding extra washers to bring the magnet lower. This provided a useful degree of flexibility in our design.

Our analysis and qualitative experiments determined that joints were far more likely to fail than the members themselves. This caused us to take special efforts during construction to ensure joints were well soldered. Firstly, we created jigs to hold the brass members in place while solder was applied to joints. Secondly, a grinder was used on members to create close fits at the joints. Lastly, we took special care while soldering to use good technique such that joints would receive maximum support.

Task throughout the project were broken down as follows:

- Dan Hendry - Created SolidWorks 3D model and contributed to editing of report.
- Brian Hook - Evaluation of design alternatives. Contributed to editing of the report.
- John Jamel - Performed analytical analysis using Method of Joints. Also contributed to lab and report

introductions.

- Reza Khatami - Created MATLAB finite element models. Contributed to design approach section of report.

3 Structure Analysis

Given the extensive analysis in Lab Report 1, which analyzed trusses in the vertical plane, this report focuses on analyzing trusses in the horizontal plane. Three design alternatives were considered as seen in figures 1, 3 and 4. Using the MATLAB finite element analysis code, maximum predicted deflections were calculated. All results, including efficiency calculations are given in table 1.

4 Design Alternatives

Truss design one (figure 1) is based loosely on the first truss design found in lab one. This design was chosen as the horizontal truss component in the final structure. The criteria by which this decision was made is as as follows:

Overall simplicity - Jigs were used to simplify truss assembly. Design one has the fewest members, minimized the possibility of errors during construction. Designs two and three both have twice as many members and more nodes than the first choice making them more difficult to construct and increasing the possibility of mistakes during cutting, grinding and soldering.

Sufficiency - From previous calculations made in lab one, it was concluded that design one would be sufficient to support the horizontal force produced by motor acceleration. More complicated designs were deemed unnecessary.

Efficiency - Design one was seen to have optimal efficiency when compared to the alternatives. Truss two and truss three are 31% and 63% less efficient than the first design, which made them significantly less desirable given the design goal of optimizing efficiency.

Overall Length - The first design had an overall length that was relatively small, allowing greater freedom to build the truss without concern for running out of material. Designs two and three had an overall length that was approximately 0.7 m longer than the first design, which would have left less room for error during construction.

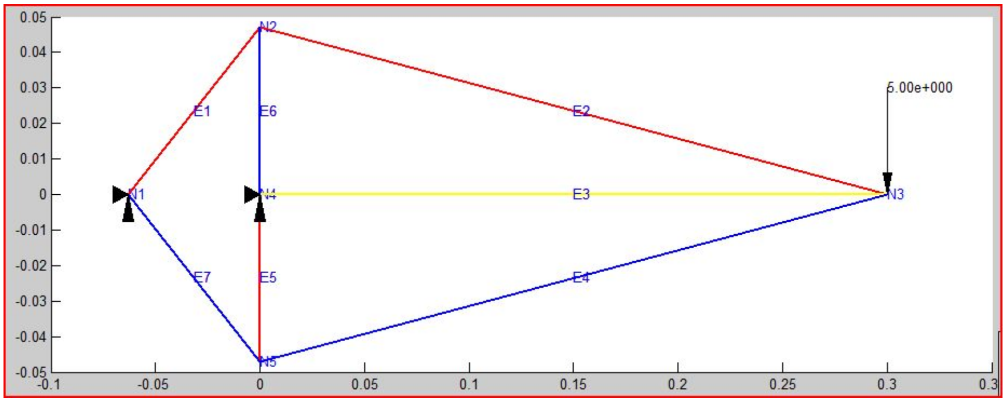

Figure 1: Horizontal Truss Design 1

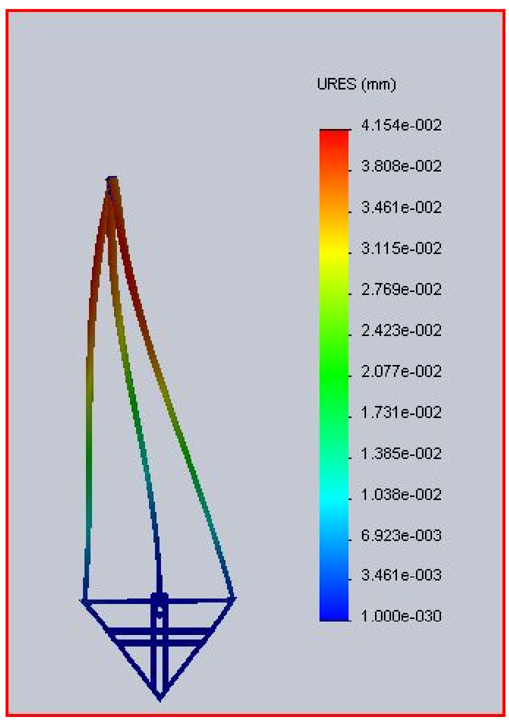

Figure 2: Horizontal Truss Design 1 - SolidWorks

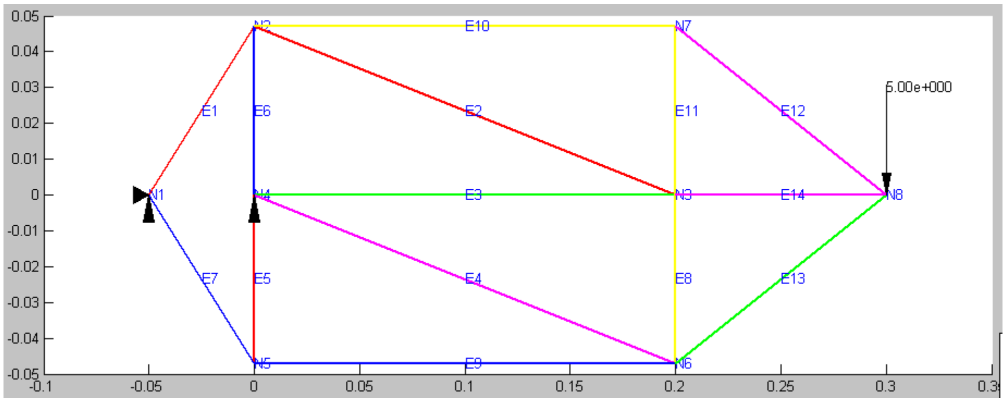

Figure 3: Horizontal Truss Design 2

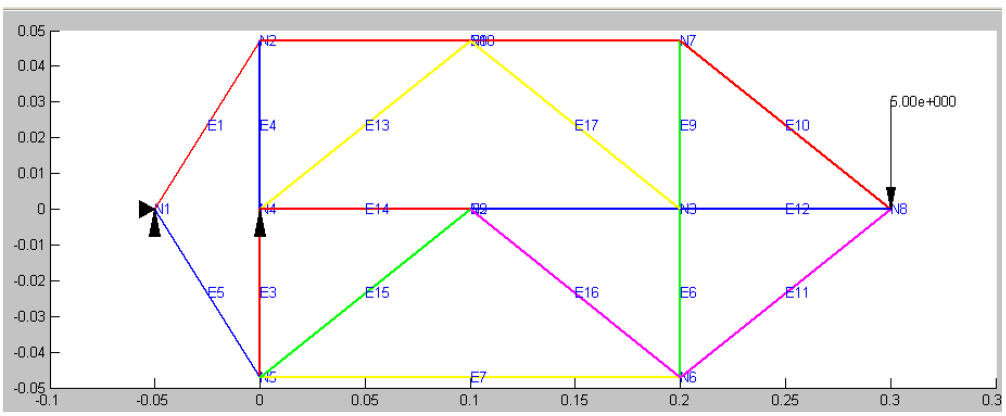

Figure 4: Horizontal Truss Design 3

Table 1: Comparison of Designs - FE Analysis Results

	Design 1	Design 2	Design 3
Material Length	1.063 m	1.675 m	1.709 m
Number of Members	7	14	16
Mass	71.5 g	112.5 g	114.9 g
Max Deflection	6.322e-005	5.814e-005	1.071e-004
Efficiency	1,106,138	764,438	406,313

5 Analytical Analysis

As previously discussed, design and analysis was performed separately for vertical and horizontal designs.

5.1 Vertical Truss Analysis

A detailed analysis of various truss designs suitable for resisting deflection in the vertical plane was presented in Lab Report 1. The optimal design was found and may be seen in figure 5. Using the Method of Joints, forces and deflections in each member were calculated and are presented in table 2. Analysis of the vertical truss considered only cantilever end constraints, not those actually used to mount the structure. Such analysis is valid to determine which structures are optimal by their measure of efficiency but significantly underestimates actual deflection.

Unfortunately pure truss analysis may not be used to analyze the structure which was built and tested (seen in figure 6, without member *M1*). The vertical truss design (again, missing member *M1*) has 8 members, 6 joints and 3 reaction forces; an unstable structure given conditions for static determinacy in equation 1.

$$2j = M + C \tag{1}$$

5.2 Horizontal Truss Analysis

Design one from section 3 (figure 1) was analyzed using the Method of Joints to validate the finite element analysis results. The force and deflection for each member is shown in table 3; refer to figure 6 for a diagram of the structure and labeled elements. The overall deflection of 0.0409 mm under a load of 5 N compares well with the results obtained using finite element analysis. The structure analyzed is somewhat different from that constructed and seen in figure 6. Many short members in the vicinity of the motor mount were neglected. Additionally, the position of reaction forces were changed such that they occur at joints, not the actual position of the washers. These simplifications were necessary to make the structure determinate and were required for many of the assumptions of the analysis, such as pin joints. Refer to the appendix for calculation details.

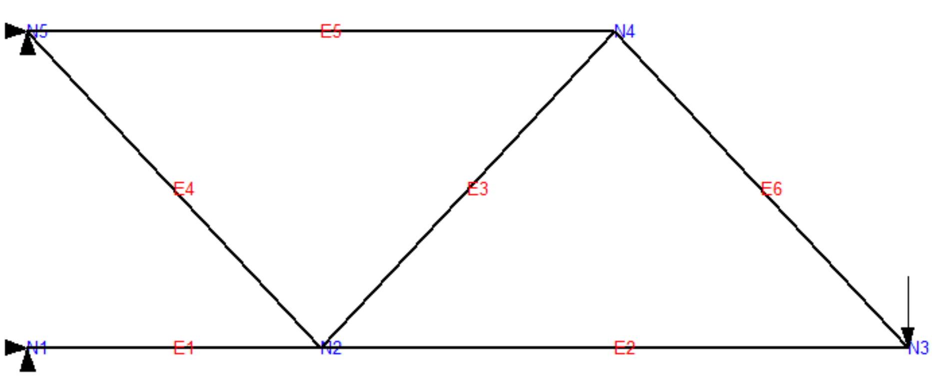

Figure 5: Optimal Vertical Truss

Table 2: Optimal Vertical Truss - Method of Joints Analysis

Element	Force (N)	Element Deflection (m)
1	-3	3.947e-7
2	-1	2.63e-7
3	-1.4142	2.60e-7
4	1.41421	2.63e-7
5	5	5.26e-7
6	1.41421	2.60e-7

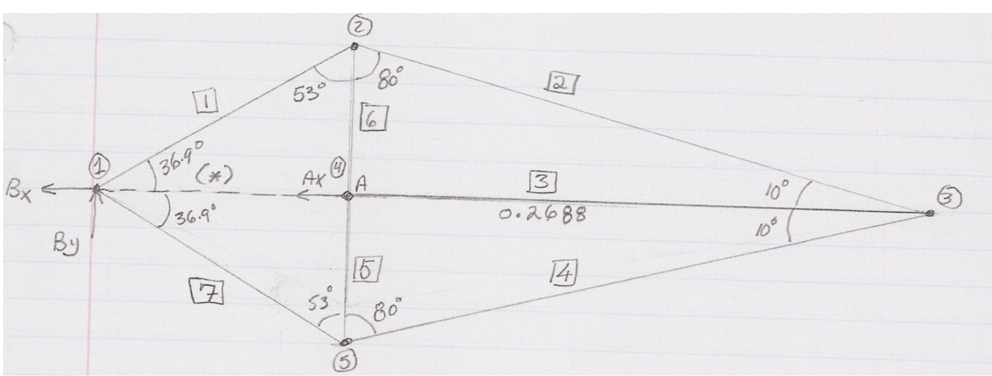

Figure 6: Horizontal Truss Member Diagram

6 Final Design and Drawing

A diagram of the truss may be seen in figure 6. Please note that member *M1* was not part of the initial design and was not present during testing. This oversight is discussed further in section 8. Member *M3* was deemed unnecessary due to the strength of the joints, qualitatively analyzed during construction. It was neglected in an effort to save wight and improve efficiency.

7 Results

The final design was built and tested. It was found to meet all criteria. A comparison to predicted results for both horizontal and vertical loading is presented in the two sections below.

7.1 Vertical Deflection and Performance

During testing, the vertical deflection under a load of 5 N was observed to be 3.10 mm. Results obtained through a finite element analysis performed in SolidWorks were comparable with a predicted deflection of 3.95 mm. The difference between the tested result and that generated by SolidWorks is not unexpected and likely caused by imperfect modeling of end conditions, material properties and joint properties. Analytical and finite element analysis performed in MATLAB predicted deflections of orders of magnitude less than those observed. This discrepancy is likely due to the faulty assumptions about end-conditions of the truss.

7.2 Horizontal Deflection and Performance

During testing, the horizontal deflection under a load of 5 N was observed to be 0.21 mm. The SolidWorks finite element analysis predicted a much lower deflection of 0.042 mm. The SolidWorks result is similar to that predicted by the MATLAB finite element analysis which suggested a deflection of 0.0409 mm. Additionally, the analytical result from section 5.2 gives a virtually identical result of 0.0409 mm. There are many factors the analysis techniques do not account for which could cause the discrepancy between predicted and actual results. For example, the motor mount could have shifted or the screws attaching the truss bent; each of which is not considered by the analysis. It is also possible the assumptions made when analyzing the structure are invalid.

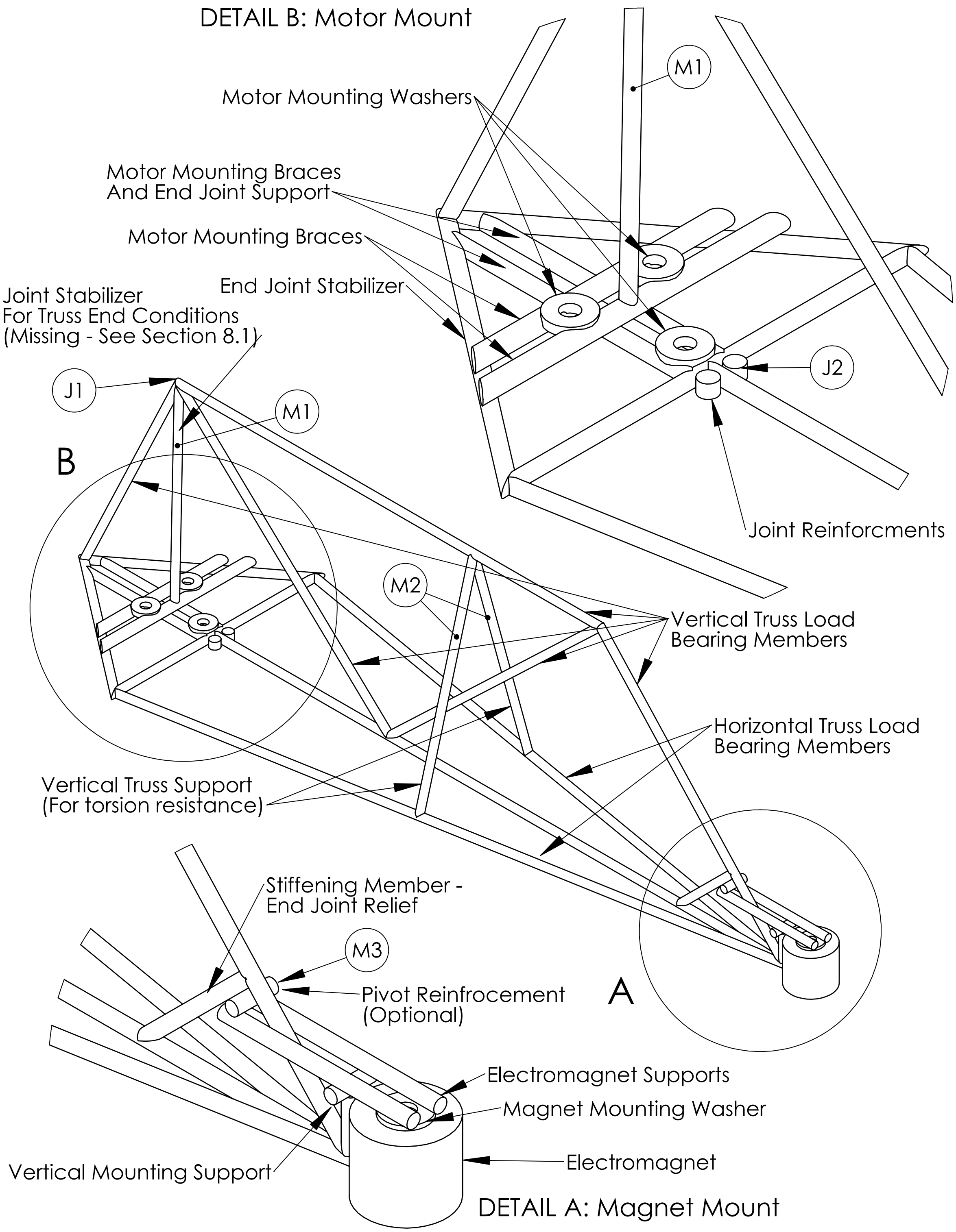

Figure 7: Labeled Truss Design

8 Design Revisions

A critical oversight made during initial design and construction of the truss significantly reduced performance. An important member (member *M1* in figure 6) was neglected. When evaluating truss designs to resist vertical deflection and maximize efficiency, cantilever end conditions were assumed. As such, the displacement at joint *J1* (figure 6) was assumed to be negligible. By failing to include member *M1*, there was no structure able to sufficiently resist deflection of joint *J1*, invalidating many assumptions and the results related to overall deflection.

A finite element analysis may be used to estimate the performance gained by adding the additional member. Using *SolidWokrs* as the simulator, two tests were performed, one with the additional member and one without. The SolidWorks FEM predicted a deflection of 3.95 mm for the design without member *M1*; comparable to the deflection observed during testing of 3.1 mm. By adding member *M1*, the predicted deflection decreased to 1.66 mm; more than doubling the efficiency of the structure. Given this result, adding the member is likely the single most important action which could be taken to improve the overall efficiency performance of the structure.

9 Conclusion

Using analytical and finite element analysis, two separate truss structures were designed for the vertical and horizontal planes, each having slightly different requirements and constraints. Each was found to be optimal (at least within the context of designs considered) for resisting bending in the plane of interest. A final truss structure was designed, analyzed and constructed which incorporated both truss components. Based on mechanical testing, finite element models were found to predict vertical deflection reasonably well but performed less well when predicting horizontal deflection.

Table 3: Element Forces and Deflections (See figure 6)

Element	Force	Deflection
1	17.8sin(37)	1.11e-6
2	14.4 cos(80)	1.206e-5
3	0	0
4	-14.4 cos(80)	-1.206e-5
5	13.2	8.16e-7
6	-13.2	-8.16e-7
7	-17.8sin(37)	-1.11e-6