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1. MSDII SYSTEM INTEGRATION AND ASSEMBLY – TIMELINE OF EVENTS (Mechanical)

1.1. Following the conclusion of MSD I, the materials for the components as intended in the documented re-design were purchased in order to begin the assembly process. Several further design changes were made, along with first-iteration designs for components that had previously not been specified due to time constraints. A list of the components can be found below under Section 2.

1.2. Due to inexperience with machining and further time constraints during the first 5 weeks of MSD II, there were multiple delays with component fabrication, which ultimately led to component designs that were less-than-optimal for their intended function. This is most notably the case of the spring shaft adapter (see Sec. 2.8). Due to the design of the springs (stock part), the shaft could not physically be fit through the inner section of the springs. Initial plans were to split the axle shaft and clamp the spring shaft adapter to the split shaft at each side, allowing one spring to be placed on each side of the system, were two such spring shaft adapters to be used. However it was deemed by Dr. Gomes (Customer) and Prof. Hanzlik (Guide) that this was an inappropriate choice, as it would undoubtedly lead to angular misalignment in the split shafts. For simplicity, the spring shaft adapter piece was modified to hold two springs, such that both springs would fit on one side of the shaft, and be mounted outboard of the structure (not the intended design). The open end of the adapter would be used to fit a potentiometer.

1.3. (Upon assembly of the truss structure and wheel, a first functionality test was performed. The test was unsuccessful as the structure began to crack at the epoxied carbon fiber truss joints at only 180 degrees of spring deflection, which was below the expected required initial condition of 196 degrees. The structure was also weighed to determine its actual weight. The weight was found to be almost 1kg higher than in the original design (mainly due to reinforcing components). A feasibility check with the simulation followed, and yielded that the device could still function, albeit with a much increased deflection of 235 degrees. Consequently the required torque was also increased, as was the speed of operation.

1.4. Carbon twine was ordered to reinforce the truss joints and improved joints were re-epoxied and reinforced with the carbon twine. For details on the process, see [Final Paper - Manufacturing]. Mock models of the truss joints are also made from scrap carbon tubing, comparing the truss joints with just epoxy, and the joints with epoxy and carbon twine. The carbon twine reinforced joints were able to resist much higher loads, and were much more rigid than the regular joints. See [Carbon Fiber Joint Test.xlsx] for specifics.

1.5. Reinforced truss is tested and it is revealed to be much stiffer than before, now being able to handle much higher loads without any issues, and much lower deflection. No cracking is observed.

1.6. A successful first step is taken on an inclined plane. Concern is raised about the apparent lack of torque from the springs, despite the apparent high speeds (at this point the calculated max spoke velocity @ CG was already above 2.0 m/s). Racking between the two halves of the truss is observed. Improved stiffening between the connecting rods is suggested.

1.7. A third spring is added to compensate, but device still has trouble taking a step.

1.8. (Friday, February 8th - Week 9) It is now observed, more clearly than before, that the oscillation of the springs causes the wheel to move forward/backward at very high speed, and the truss is unable to catch up. The wheel is already completing its oscillation while the truss is still taking its first step. The consensus is that there may be a major issue with the four spoke design, and that it may not be physically feasible, as getting the torque and speeds lower would obviously require a much lighter spoke structure, and the structure is already quite light at only 1.545 kg.

1.9. A feasibility check of the four spoke design is conducted via the Matlab/Simulink model. Despite variation of the mass and inertia parameters, it becomes clear that it is not physically feasible for the device to have a lower speed than ~2 m/s.

2. LIST OF COMPONENT DESIGNS - Mechanical

Component Effectiveness Scale:
5=Very Good – 4=Good – 3=Satisfactory – 2=Needs Improvement – 1=Unsatisfactory

2.1. **Carbon Fiber Truss Structure:**

- 2.1.1. Initial: Poor performance due to weakness at joints. Epoxy cracked at lower stresses than required for device operation. Device seemed otherwise satisfactory in terms of stiffness, although there is a racking issue between the two sides of the truss. <u>Rating: 2</u>
- 2.1.2. Final: Reinforced joints greatly improved rigidity and overall toughness of truss, able to withstand even higher stresses than designed for. Maintained low degree of deformation even with 3 springs fully deflected. Racking issue persists but is improved by more evenly distributed mass. <u>Rating: 5</u>

2.2. **Truss Hub Pieces:** Light weight, good performance, precisely machined parts contributed to dimensional integrity of system (perpendicularity of spokes). <u>Rating: 5</u>

2.3. **Truss Cross-Pieces:** Light weight and high stiffness (CF tubes) contributes to low truss inertia. Racking issue could have been reduced by application of high-friction gel at ends within the cross-piece connectors. <u>Rating: 4</u>

2.4. **Truss Cross-Piece Connectors:** Highly effective, well-manufactured, provide stiffness and still allow structure to be easily disassembled. <u>Rating 5</u>

2.5. **Rubber Truss "Feet":** High friction, simply press-fit and zip-tied onto end of carbon tube spokes, yet able to withstand high loads without losing their position. Some did fall off at very high loads, although they were higher than designed for. <u>Rating: 4</u>

2.6. **Bike Wheel Assembly (Wheel + Shaft Adapter):** Mountain bike wheel ideal for application, wheel hub flange provided ideal mounting point for adapter piece to axle shaft. Choice of set-screws less than optimal, as it required the machining of a flat onto the shaft, but fully functional without slipping or damage to the shaft. Could opt for rigid attachment via roller pin in future. <u>Rating: 5</u>

2.7. **Battery-to-Wheel Mount:** Mounted on outside of wheel rim for inertia maximization with electrical tape. <u>Rating: 5</u>

2.8. **Spring Shaft Adapter:** Initially designed to be fit onto two split shafts and fit a single spring in between them on one side of the structure. The same would have been done on the other side, in order to have one spring on each side. However it was deemed by Dr. Gomes (Customer) and Prof. Hanzlik (Guide) that this was an inappropriate choice, as it would undoubtedly lead to angular misalignment in the split shafts. For simplicity, the spring shaft adapter piece was modified to hold two springs, such that both springs would fit on one side of the shaft, and be mounted outboard of the structure on one side. The open end of the adapter would be used to fit a potentiometer. This was not the intended design. The part actually performed even worse than expected, due to slight

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play (dimension mismatch) between the springs and the part. Yet the part was extremely hard to fit onto the shaft. Modifications to the part likely altered the tolerances on the tight-interference dimensions. Play between springs and shaft adapter essentially caused the springs to not be perfectly rigidly attached to the wheel, leading to the release of stored energy at each oscillation. Rating: 2

2.9. **Spring Hub Mount:** Choice of aluminum for weight savings not ideal due to fatigue characteristics. Visibly large amount of flex when loaded by springs. In addition, slot to fit springs slightly over-dimensioned (machining and time constraints) leading to “clicking” at each oscillation, effectively bleeding energy from the system. Sliding of outer spring end in and out of the slot due to spring deflection → friction energy loss in spring. Different solution desirable in future. Rating: 2

2.10. **Hub Reinforcing Plates:** Aluminum reinforcing plates for the hub piece that has the springs mounted on it. Light-weight, simple solution creating an effective composite structure as the nylon hub piece is sandwiched between two aluminum plates. Very effective, although some deflection of the aluminum is visible under stress. Rating: 4

2.11. **Motor Mount:** Brass stand-offs connect motor to hub piece. Light weight and effective. Sufficient rigidity for low torque requirement from DC motor. Rating: 5

3. MSDII SYSTEM INTEGRATION AND ASSEMBLY – TIMELINE OF EVENTS (Electrical)

3.1. During the last week of MSDI and the first week of MSDII all of the initial electrical parts were ordered. A few parts that were delivered to the RIT office were difficult to get a hold of; they were accidently misplaced and after a week of search they were retrieved. During this period, schematics were formulated using the expected pin-outs of the ordered parts.

3.2. It was discovered early that the complementary wireless package ordered from TI was not going to work for our purposes. For the motor, the motor test plan was executed to determine the transient behavior of the Brushed DC Motors supplied by Dr. Gomes. The goal of this motor test plan was to either demonstrate that the supplied DC motor was adequate for our design and if need of a different motor, to better understand how to correlate the required transient response to the steady state response data available online. Our first test retuned positive for the supplied motor but after discussing the results with Dr. Gomes (Customer) we realized that the test velocity of the wheel in the test bed was low and that a higher speed would negatively impact our results.

3.3. To resolve the wireless selection trouble, Dr. Gomes suggested the use of a Xbee wireless microprocessor which was then chosen as a replacement to the original selection (see section 2.x). The Xbee proved to be a great choice because it has the ability to be used as a direct wireless data transfer system. This immediate transfer prevents the need of an intermediate storage device and therefore allows for ease of implementation. In order to move forward with our goals with the motor test, the speed of the wheel at which the motor was actuated (as described in the motor test plan) was increased to a desirable range. This new test demonstrated that the motor that was provided by Dr. Gomes would be adequate for our needs and that we can move forward with it.

3.4. After testing the preliminary power sensing circuitry, it was discovered that a Hall Effect current sensing device that was used consumed a lot of power for our application especially when compared to a differential amplifier with a very small resistor. Therefore new parts including breakout boards for the differential amplifier were ordered.

3.5. The communication protocols used to acquire and send data proved to be a much more complicated task than initially anticipated. I^2C protocol that were planned to be used to

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communicate between the sensors and the microprocessors proved to be very difficult serial protocol to configure. A lack of documentation and support available for interfacing introduced an unforeseen roadblock.

3.6. To advance in the communication interfacing portion of the project, after much consulting with other teams and a few faculty members, we migrated to SPI protocol for sensor interfacing and SCI (UART) for wireless interfacing because they seemed to be easier to implement.

3.7. On the structural aspect, all of electronics were planned to reside on the development board of the microprocessor in order to ease the implementation on the mechanical outer wheel structure. Soldering the power sensing circuitry onto the design board was tedious; keeping the power sensing circuitry as condensed as possible was important to leave room on the board for the other electronic devices. It was very difficult to solder the differential amplifier because they were very small and did not come pre-solder on break-out board. I would recommend not buying surface mount components unless they come pre-soldered on break-out boards.

3.8. It was discovered during the programming that SCI only sends ASCII characters. Following a brainstorming session around how to mask the decimal characters, it was decided to convert the ADC data to hexadecimal so our scale would go from 0x000 to 0xFFF instead of from 0 to 4095. Since one less digit would need to be sent at a time, this change saves time while sending of data and allows for a faster sampling rate for the data.

4. LIST OF COMPONENT DESIGNS - Electrical

Component Effectiveness Scale:
5=Very Good – 4=Good – 3=Satisfactory – 2=Needs Improvement – 1=Unsatisfactory

4.1 **Xbee Wireless**: When using SCI protocol, both analog and digital input data are successfully communicated wirelessly between the devices and a computer operating the required application. Rating: 5

4.2 **Motor:** Motor test showed that the motor provided by Dr. Gomes satisfies the needs required based on the mechanical simulations. However since, the project did not reach a progress point to which actuation would be required, the actual effectiveness of the motor is unknown. Rating: 3

4.3 **Power Sensing Components:** The power sensing components all work effectively to produce the proper data in the appropriate ranges. The one hiccup in assembling the power sensing circuitry was the surface mount current sensing components. They needed an externally purchased break out board in order to be implemented into the system. It is highly recommended that an assembly layout plan be formulated before ordering components. Rating: 4

4.4 **Batteries:** The batteries did exactly what they were intended to do, although we were never able to test how long they would last while under operation in the device. Rating: 5

4.5 **TI C2000 Microcontroller:** The C2000 is a very powerful microcontroller which can be used in a very broad range of systems. The downside is that there is a learning curve which is associated with the microcontroller. For our application, it would have been better to have a microprocessor a smaller learning curve and a larger support base. Rating: 2

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5. PROJECT SUCCESSES:

5.1. Successfully implemented torsional (clock) springs into rimless wheel concept (though their implementation was not optimal, as mentioned)
5.2. Successful construction of an extremely light, stiff, and durable truss structure as the spoke body of the device. Reinforced truss joints with the use of carbon twine were a major discovery of the project.
5.3. Successfully made the device take a step on an inclined plane (unpowered, 9º incline)
5.4. Rated clock springs and quantified their behavior across their deflection range.
   5.4.1. Springs have been proven to exceed their specification stiffness approximately two-fold.
5.5. Successfully constructed power sensing circuitry that returns values for total power consumed, and power consumed by the digital electronics. It also returns the operating voltage of the batteries, as they decrease over time. The data was successfully relayed through the Xbee wireless to a computer.
5.6. Successfully implemented SCI (UART) serial communication between the TI C2000 microcontroller and the Xbee wireless chip.
5.7. Successfully read and transmitted potentiometer data wirelessly. This was going to tell the angular displacement of the internal wheel in relation to the external truss.

6. PROJECT SHORTCOMINGS:

6.1. Device does not work on level surface, and unable to maintain steady motion, even on an inclined plane, unable to complete 25 steps (unmet customer needs)
6.2. Racking issue between the two sides of the truss. Remains unsolved due to the expected physical unfeasibility of the four spoke design, and time prioritization.
6.3. Spring shaft adapter and hub mount design have room for improvement.
6.4. I^2C serial communication was not able to be implemented.
6.5. SCI serial communication was implemented which collected data from the gyro meter. This data, however, could not be interpreted properly. It is unclear whether the inconsistencies in the data occurred within the gyro meter or during the serial communication process.

7. LESSONS LEARNED:

7.1. The four spoke design is not physically feasible due to the high speed and torque requirements. The truss will generally be unable to keep up in speed.
   7.1.1. This will occur even independently of spring constant. Compensating with a higher spring constant will not resolve the issue, but rather exacerbate it.
7.2. A significant amount of time was lost due to inexperience with machining. Care must be taken when planning such that issues may be avoided later. Machining time must be carefully taken into account, especially for high priority / high complexity parts.
   7.2.1. Always plan for an extra 30-60min of set-up time for any 3-axis mill or lathe.
7.3. Time management and setting realistic, achievable weekly goals is crucial to project success.
7.4. It is important to have resources for programming problems. Becoming familiar with microprocessors is a longer process than previously thought. Example code is very important to the learning curve of the new microprocessor.

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7.5. Even if a PCB board is not going to be used, it is important to check the footprints of components before purchasing. A provisional assembly layout plan should be drawn up before purchases are made.

8. HAND-OFF & FUTURE STEPS/RECOMMENDATIONS

8.1. It is recommended that a four spoke design not be used in the future due to extremely low mass requirements for spoke body and relatively high inertia requirement for wheel. System will typically require high operational speeds and high torque, and is highly sensitive to spoke body mass.

- 8.1.1. High operational speeds and energy result in operation that is unsafe for users and observers. \\\SAFETY HAZARD///

8.2. If clock springs are to be used in the future, a more appropriate means of attaching the springs to the wheel and spoke body will be favorable. Tight tolerance parts are a must, such that there is no play between the springs and the part, such that they are RIGIDLY attached, and do not dissipate un-quantified amounts of energy in an undesired manner. (*No "ticking" or "clicking"*)

8.3. It is recommended that a different microprocessor be used. Our group decided to try and use a microprocessor designed for industry, but we have decided the project would work exactly the same with a hobbyist board. The hobbyist board would be easier to manipulate into performing as desired.