Midterm #1

Senior Design (EML4551) -Fall 2013

Team #15 Conformable Battery Pack

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Abstract:

Three design concepts are being considered to make a shape conformable battery pack. Different plane types are explored because the battery must fit in the wing of an RC plane. Double-sided graphite coated copper foil sheets were selected for anodes. Aluminum foil coated with $LiFePO_4$ sheets will be used for cathodes. The lithium hexafluorophosphate ($LiPF_6$) electrolyte will be used from the Aero-Propulsion, Mechatronics and Energy (AME) battery lab. The materials have been ordered. The first prototypes can be made after materials arrive. Two RC planes were ordered. One plane will serve to test and teach how to fly. The other will be the plane the batteries are modeled for. So far, the team has successfully built a test cell battery. The next step will to build a successful pouch battery, implement design concepts, and practice RC plane flying.

Project Overview:

The main objective of this project is to design a battery that can be integrated into the wing of a UAV system. The battery can form around the wing, make up the wing, or fit inside the wing. The focus is that the battery be conformable (not cylindrical or flat rectangular). The goal will be to fly the plane for at least five minutes. A successful flight will be defined by takeoff, flight, and landing without crashing or loss of power. The ideal battery design will be easily deformed and lightweight. The success of this project could signify a milestone in battery technology and could give rise to new products. The sponsor requirements are summarized in the objectives and constraints:

***Objectives*:**

- Build a battery that can be integrated into the wing of a UAV system
- Utilize existing technology to stay under budget
- Develop uniquely shaped battery or formable battery
- Design must be safe for operator and should not explode or catch fire
- The battery must satisfy the power need of the RC plane
- Battery is to be detachable for charging

***Constraints*:**

- Project budget $2000
- Limited research or experience available
- Mass of each battery should not exceed 200 grams
- RC plane should be able to fly outside under reasonable conditions
- Battery must not explode or catch fire
- Enough power must be supplied for at least a 5 minute flight without switching batteries or recharging
- To be completed by Spring 2014

Design & Analysis:

Functional Analysis

Since the main scope of the project is related to making conformable batteries, all the project specifications are of battery design and performance. A few requirements put forth by the sponsors are summarized in RC plane design specification and performance specifications:

RC Plane Specifications:

- **Design Specification**
  - Needs to have detachable wings
  - The plane needs to have spare wings
  - The battery needs to be installed inside the wing or be the wing
  - The voltage input of the control system of the plane needs to match the voltage output of the battery
- **Performance Specification**
  - The plane has to take off, stay in the air for 5 minutes and land safely
  - The weight of the battery needs to be balanced in order for the plane to be stable
  - If the battery is the wing, it needs to be well insulated
  - The airfoil has to be stable throughout the flight

Battery Specifications:

- **Design Specification**

  Battery material was selected. A lithium ion type battery with a cathode made from lithium iron phosphate ($LiFePO_4$) coated on aluminum foil, and an anode made from graphite coated on a copper foil substrate. The electrolyte would be liquid $LiPF_6$. The anode and cathode will be layered depending on the concept, and layered together with a thin (<50µm) polyethylene terephthalate (PET) separator in series.
- **Performance Specification**
  - The battery must be able to be integrated into the wing of a UAV system
  - The Battery must be uniquely shaped or shape conformable (i.e. not cylindrical or box shaped)
  - The design must be safe for an operator and should not explode or catch fire
  - The battery must satisfy the power need of the RC plane, such that the plane is able to take off, sustain flight for a minimum of five minutes, and land
  - The battery is able to be detached for charging

Battery Design Concepts

The most common design used to make lithium ion batteries is what is known as the pouch cell. Anode and cathode sheets are layered in the desired configuration (this can be series or parallel) in order to create a cell. The cell is then wrapped in a flexible, foil-like material that acts as the pouch. Electrolyte material is injected and the pouch is air-tight sealed in order to keep moisture out. Two tabs serve as the interface between the anode and cathode terminals. Figure 1 shows a working lithium ion pouch cell made at the battery lab in the Aero-Propulsion, Mechatronics and Energy (AME) building at FSU.

Figure 1: Lithium Pouch Battery

This pouch cell design carries with it several advantages over more traditional rigid-case designs (such as the ones used for cylindrical batteries). The pouch material is lightweight. This allows more weight to be shifted into the cathode and anode layers in order to meet the power requirements for the plane. The reduction of weight should make it easier to fit the battery within the structure of the airfoil without upsetting its aerodynamics. Additionally, this flexible pouch is cheaper and easier to manufacture at larger scales.

Because of the benefits outlined above, the cell pouch design has been chosen for the conformable battery. The next step is also the biggest challenge of this project: how to meet the conformability requirement? This is a goal that is closely related to the anode and cathode stack in the cell pouch. Three designs have been developed for the layering of these battery elements:

1-Multiple Cell Pouch Layering

This approach consists of creating several lithium ion cell pouches of different sizes and layering them on top of each other in order to form the airfoil shape of the wing. The conformability requirement is satisfied in the sense that to an outside looker, the final battery will be airfoil-shaped after it has been placed in its housing. However, on the inside, the individual elements that make up the battery are still very standard. This is by far the simplest and probably the easiest design to implement. Figure 2 provides a graphical illustration of this design.

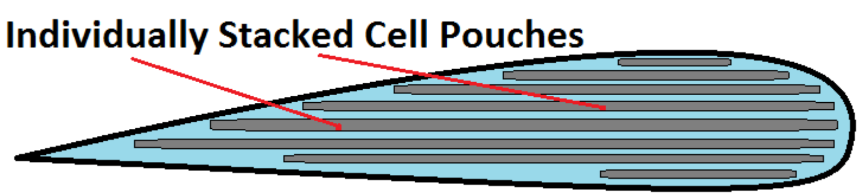

Figure 2: Concept #1 Cell pouch Layering

Some of the benefits associated with this design are:

- Cheaper design. can implement it by using tools already available to us at the AME battery lab
- No need to reinvent the wheel. Rectangular-shaped lithium ion cell pouches are very common. We would be taking an existing and common design and layering it in such a way that it conforms to the structure of the RC plane
- More room for error. The simple design would allow more time for building and testing batteries

The following limitations and issues arise with this design:

- Limited to series connection. Because of varying cell pouch sizes, the final design would be limited to a series connection. A parallel connection would be constrained to the voltage rating of the smallest cell pouch.
- There is concern that this simple design would not fully satisfy the customer requirements for creativity.

2-Single, Airfoil Shaped Pouch

This design approach revolves around the creation of a single lithium ion cell pouch. The anodes and cathodes would be stacked in such a way that they end up resembling an airfoil. In this way, true conformability is achieved as the actual components that make up the battery are shaped to fit the structure of the wing rather than just the housing. This scheme is illustrated in Figure 3.

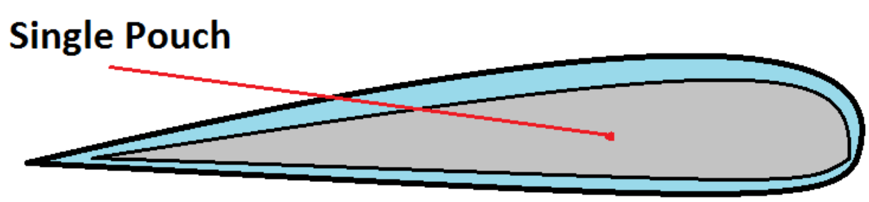

Figure 3: Concept #2 Airfoil Shaped Pouch

Design benefits:

- True conformability. The customer's conformability specification would be fully satisfied.

Design limitations and possible issues:

- Additional tools required. Perhaps the biggest challenge with this design lies in how to properly seal the stack of anodes and cathodes. There is not an answer to this problem yet.
- Unknown variables. There is limited literature available on non-standard battery shapes. Knowledge of how the anode and cathode stack would operate in this odd layering is not readily available. Lots of testing and benchmarking would be required to fully figure this out.

3-Thin Pouch C-Stack

The third and final design involves the creation of very thin cell pouches. Because the thickness of the stack inside the pouch is very small, a certain level of bendability is present in the cell pouch. Figure 4 shows a way to take advantage of the flexibility and a C-shape. The conformability requirement is once again satisfied, this time along the width of the wing.

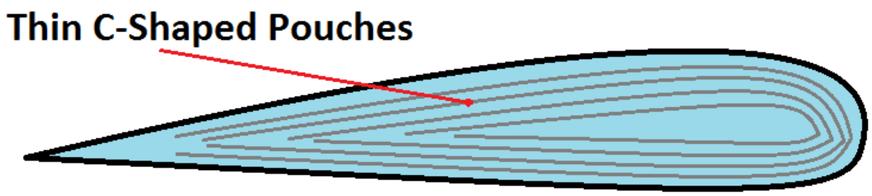

Figure 4: Concept #3 C-shaped pouches

Design benefits:

- Easy to make and cheap. Lithium ion cell pouches with very thin stacks of anodes and cathodes would be relatively easy and cheap to make. The tools needed for this are already available at the AME battery lab.
- Not limited to a specific configuration, there is no limitation to a series or parallel design.

Design limitations:

- The results of this configuration are unknown. It is very possible that bending the cell pouch in the proposed way will result in a short. Significant testing as well as trial and error will be required in order to find the bending limitations of this cell pouch.
- Potentially time consuming. Because this type of design will call for a lot of testing, it has the potential of being the most time consuming of all three.

Battery Housing

The method of connecting the battery has not been selected. The general idea is to remove a section of the wing and replace it with a custom-built housing that will store the shape conformable battery. This housing will be made out of the same material as the original wing and will be designed in such a way that it will be fully removable.

For the sake of simplicity, an RC plane that has a single, over the top wing should be selected. The placement of the battery housing, the aerodynamics of the plane, and center of mass have to be considered. Two possible options arise: 1) put two identical battery packs and incorporate them at equal distances from the middle of the plane, or 2) design a single battery pack that will fit at the center of the wing. Both schemes are illustrated in Figure 5.

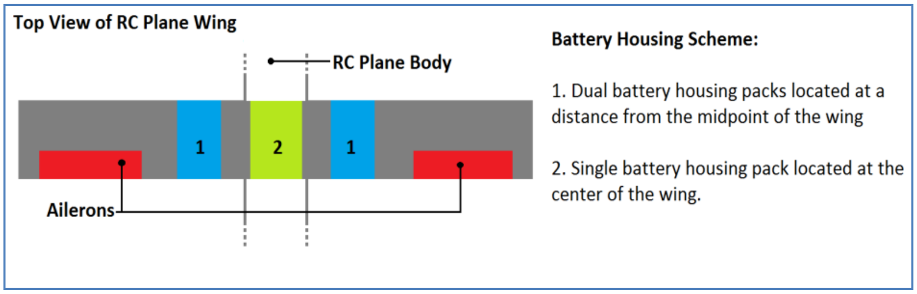

Figure 5: Battery Housing Scheme

Scheme #1 is the least desirable of the two because it involves attaching extra weight into the wings of the plane. It also places the batteries very close to the ailerons required for proper control of the plane during flight. The preferred option is scheme #2, as it puts the battery near the plane's center of mass, reducing the possibility of interfering with the aileron system and reducing the wiring distance to the plane's control system.

RC Plane Design concepts and Analysis

Keeping the project goal in mind, two designs for an RC plane were chosen. A finalized design will be chosen after further experimental analysis on the two types of RC planes is performed. While choosing an RC plane design, following points were considered:

- The wings need to be easily attachable and detachable
- The wings need to be able to fit conformable batteries inside of them
- The wings need to be able accommodate for the added weight of the batteries
- The airfoil needs to generate enough lift to fly the body weight and the battery weight

Since the main goal of the project is Conformable Battery Pack, a lot of emphasis is given to design and making of the battery pack. A new RC plane will not be designed; an off-the-shelf plane will be purchased. Two types are under consideration:

1- Wing over the Body

This design has a wing attached on top of the body. The RC plane will be driven by an electrical propeller attached to its head. This design will also have two supporting rods, going from the body of the plane to the wing of the plane, giving additional support to the wings.

Figure 6: Wing over the body design

Advantages:

- More support for the heavy wings
- Having a single wing makes attachment and detachment process easier
- Long-thin battery concept will be much easier to implement in a single wing.

Disadvantages:

- Additional rods add additional weight, which will require more power to take-off
- These rods will increase the drag related to air flow

2- Wings to the side of the Body

This design looks somewhat like the modern day commercial plane design, only with the propeller attached to the planes head and not to the wings. Unlike concept 1, the wings have no additional support.

Figure 7: Wings on the side of the body

Advantages:

- Less induced drag compared to concept 1
- Will weigh less than concept one, since there are no additional components
- Will be able to stack batteries in multiple ways

Disadvantages

- Attachable/detachable wing will be very unstable
- Due to the weight of the wings, if the wings do not have a good support system, they have a high probability of detaching themselves from the body during take-off or landing.

In order to get a detailed analysis of the aerodynamic aspects of the RC-plane, a wing-turbine experiment of a flow over an airfoil needs to be done. However this experiment can be avoided if a few assumptions are made, and analysis is completed theoretically.

Analysis:

In order to do the theoretical analysis, the following assumptions are made:

- Thin airfoil: Using this assumption will help a theory called 'Kutta Condition for thin airfoil' which given the coefficient of lift in terms of angle of attack

$$c_l = 2\pi \propto \qquad (1)$$

- The flow over the airfoil will always be laminar
- Equal weight distribution along an airfoil

Using these assumptions, a finite element model of a flow over an airfoil is made. Since it is assumed that it is a thin airfoil, the analysis will be done in 2-D. In order to set up a finite element model, the density per unit area of the airfoil is needed, the final dimensions of the airfoil and boundary conditions at the leading edge and the trailing edge of the airfoil. The final finite element model obtained can be verified using various sources. However in order to validate the model, a few experiments need to be completed.

In order to validate the finite element model, an experiment is completed using wind turbine and flow over an airfoil. Using pressure probe and different angles, the coefficient of lift can be calculated and compared to theoretical values.

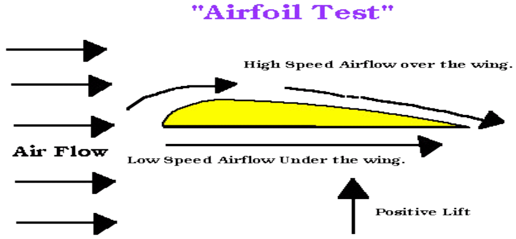

Figure 8: Flow over an airfoil

House of Quality

The Voice of the Customer

Because of the broad nature of this project, it has taken a considerable amount of time to zero in on a final set of requirements or customer demands. After several meetings with advisors, following list could be created for the conformable battery pack. The battery pack has to be:

- Conformable
- Reliable
- Detachable
- Recharge able
- Shape restricted
- Safe

Conformability

One of the most important requirements for this project is the conformability of the battery itself. The battery pack has to structurally fit the device it is going to power. For this particular project, the conformability requirement will be satisfied by designing the battery pack such that it fits (and replaces) a portion of the wings of the RC plane. The final battery pack will be airfoil shaped.

Reliability

A battery has to be able to provide consistent power to the vehicle or device it is attached to in order to sustain its operation. For a conformable battery pack, the sponsors have determined that 5 minutes of uninterrupted operational time are required in order for the battery to pass the reliability requirement. For the RC plane test vehicle, the plane needs to be able to take off, fly for 5 minutes, and land safely. This requirement imposes a hard constraint for the project and is therefore a very important customer requirement.

Detachability

The battery pack is required to fit into the structure of the RC plane, but it also has to be detachable and reattach able. There are various reasons for this requirement, such as the need to remove the battery from the plane in order to recharge it. This requirement also follows naturally from the need to test multiple batteries moving forward with the project.

Recharge able

Recharge ability is a very important consideration when it comes to batteries. Because of the type of battery and the conformability requirement, it is unfeasible to come up with a disposable battery that is also conformable to the structure of the RC plane. Therefore, it is very important to both the customer and the design team to be able to reuse the battery.

Shape restricted

The battery shape restriction is a constraint imposed by the sponsors on the final design of the battery. As has been mentioned before, standard batteries come in rectangular, cylindrical and square shapes. The conformable battery has to stay away from these common designs, hence the goal is to create an airfoil-shaped battery.

Lightweight

One of the main challenges with this project lies in trying to come up with a design that can satisfy the power requirements of the RC plane without upsetting its aerodynamics. Although the actual design of the battery is open ended, weight will play a major role because the plane needs to be able to take off. Even though the sponsors have not explicitly asked for a lightweight battery, this will be a very important point to consider when designing.

Safety

This is an important unspoken customer requirement. For how common batteries are in our daily lives, they can also be quite dangerous if their production process is faulty or if they are exposed to extreme conditions. For this project, the battery needs to be as safe as it can.

Budget

Budget constraints have to be met. This projects has a spending cap of $2000.00.

Importance Ranking of Customer Needs

Before proceeding forward, priority ratings of customer needs have to be assigned. For the sake of simplicity, a 1 to 5 scale is used to place appropriate weights on each of the customer requirements. These ratings are summarized in Table 1 below.

Table 1 – Customer Needs Rated and Weighed

Customer Need	Rating	Weight (%)
Conformability	5	18.52
Reliability	4	14.81
Detachability	2	7.40
Recharge ability	3	11.11
Shape Restrictions	4	14.81
Lightweight	2	7.40
Safety	3	11.11
Budget	4	14.81

Clearly, the conformability of the battery pack is the most important requirement for this project, followed closely by the reliability of the battery and the shape restrictions. Safety and recharge ability are also very important considerations, but these are requirements that can be more easily satisfied than those judged to be more important. At the very bottom of the priority list are the lightweight requirement of the battery pack and its detachability.

Satisfying Customer Needs

In order to satisfy both the spoken and unspoken customer requirements for this project, following set of quality characteristics exist:

Power

The power output of the conformable battery pack is what will ultimately determine if the RC plane can fly, assuming the aerodynamic considerations of the plane have been taken into account. This is a very important quality characteristic because it may need to provide slightly more power than required by the plane.

Weight

The overall weight of the battery pack and its housing will have to be minimized in order to meet the lightweight constraints. It is important to keep in mind that the weight constraint arises from the need to upset the plane's aerodynamics as little as possible.

Cathode/Anode Stack Volume

This is one of the most important quality characteristics for this project. An increase in the volume of the cell pouch stacks increases the amount of anode and cathode layers and thus gives more power to work with, increasing the reliability. The volume of the stack also impacts the conformability and weight of the battery and pushes the limits of the shape restriction constraints.

Lithium Ion

Lithium ion batteries are used in a wide variety of customer electronics today for good reason. They offer very good reliability, high energy density and they are rechargeable. Unfortunately, lithium ion batteries also place a strain on the safety requirements because they can be volatile under certain circumstances.

Type of Connection (Series vs. Parallel vs. Combination)

Connecting the battery components in series or parallel is a decision that will impact the overall capacity of the battery. In general, parallel connections increase battery capacity but keep the voltage constant, whereas series connections increase the voltage while keeping the capacity constant. The type of connection is a decision that is ultimately constrained by the final physical design of the battery. The connection is important so that power requirements are supplied for liftoff and proper operation of the plane.

Custom Battery Housing

One of the main design challenges in this project is attaching the battery to the plane. The solution involves the creation of a custom battery housing made from the same material of the plane. This custom housing has to be designed in such a way that permits detachability for recharging purposes and fits within the structure of the plane.

Sealing Process

Out of all the quality characteristics, the sealing process is the one most strongly related to the overall safety of the battery pack. An airtight seal is necessary regardless of how the anodes and cathodes are stacked. A bad seal could cause the battery to short or electrolyte fluid to leak out, or worse, combustion of the lithium ions.

Type of Anode/Cathode Material

The selection of materials for the cathode and anode components of the battery will have an important impact on the overall budget, reliability and shape conformability of the battery. Different types of materials have different weights and energy densities associated with them, therefore placing additional limitations on the design.

Summary of Design Concepts

Once materials are obtained, testing can begin. It will be convenient to try the first two concepts and choose the option that performs best. The C-shaped pouch battery might be difficult to build and will attempted after some initial batteries are made. The battery housing would be best in one pack over the body of the plane. A wing over body RC plane will be chosen. A house of quality matrix was used develop design concepts and can be

The house of quality matches customer needs with the team capabilities. This diagram also helped define ideas based on relations. The full house of quality diagram can be found in the Appendix on page 16. The sponsor needs were defined by conformability, reliability, detachability, recharge able, shape restricted, lightweight, and safety. These qualities were assigned ratings and weights to determine importance.

The customer needs will be compared to quality characteristics. These features were determined to be power, weight, lithium-ion, connection type, battery housing, and sealing process. The relations that form highlight the important aspects of the project. They are used when designing to know where to focus efforts of the team. From this diagram, it is determined that cathode/anode stacking and the sealing process are top priority in the design process.

Programming needs and Control:

Programming is not really needed for this project. The selected plane includes an E-flite Pro switch-mode brushless Electronic Speed Control (ESC). This is a protection circuit for the battery. Batteries cannot be overcharged or discharged otherwise the battery is destroyed. The ESC is used to prevent battery damage and cut off the motor to prevent plane damage. Figure 9 shows the speed control typically included with RC planes. This unit is programmable for motor braking, voltage cutoff, throttle input, and timing [8]. This is a convenient option to have in designing the battery.

Figure 9 E-flite® Pro Brushless ESC [8]

Many RC planes also include a radio control system. The RC planes under consideration include the Spektrum DX5e transmitter and a 5-channel receiver [8]. A 3-10 mile line of sight range is expected from a 2.4 GHz radio system. This would satisfy the radio needs for this project.

Procurement:

Battery materials have been ordered through MTI Corp and two RC planes have been ordered through HobbyZone. The Apprentice S 15e and Albatros micro are the RC planes ordered. Both are ready to fly out of the box. Only anodes and cathodes were ordered at this time. The other supplies will be provided by the lab for now.

Conclusions and Future work:

There are many ways to make a conformable battery. The three concepts outlined are the most feasible for this project. The pouch stack (concept #1) is the most attainable but the most obvious. The team will likely pursue more creative options after a successful battery has been made. Wing over body styled RC planes were selected and ordered. Once materials are received, the team will move forward with battery production, plane modeling, plane flight training, and testing.

Gantt chart:

Figure 10 is a team Gantt chart. The chart is updated frequently to reflect some past projects but mostly move the team forward. Deliverables are included but past tasks are not included. This chart was modified from the chart provided in class [1].

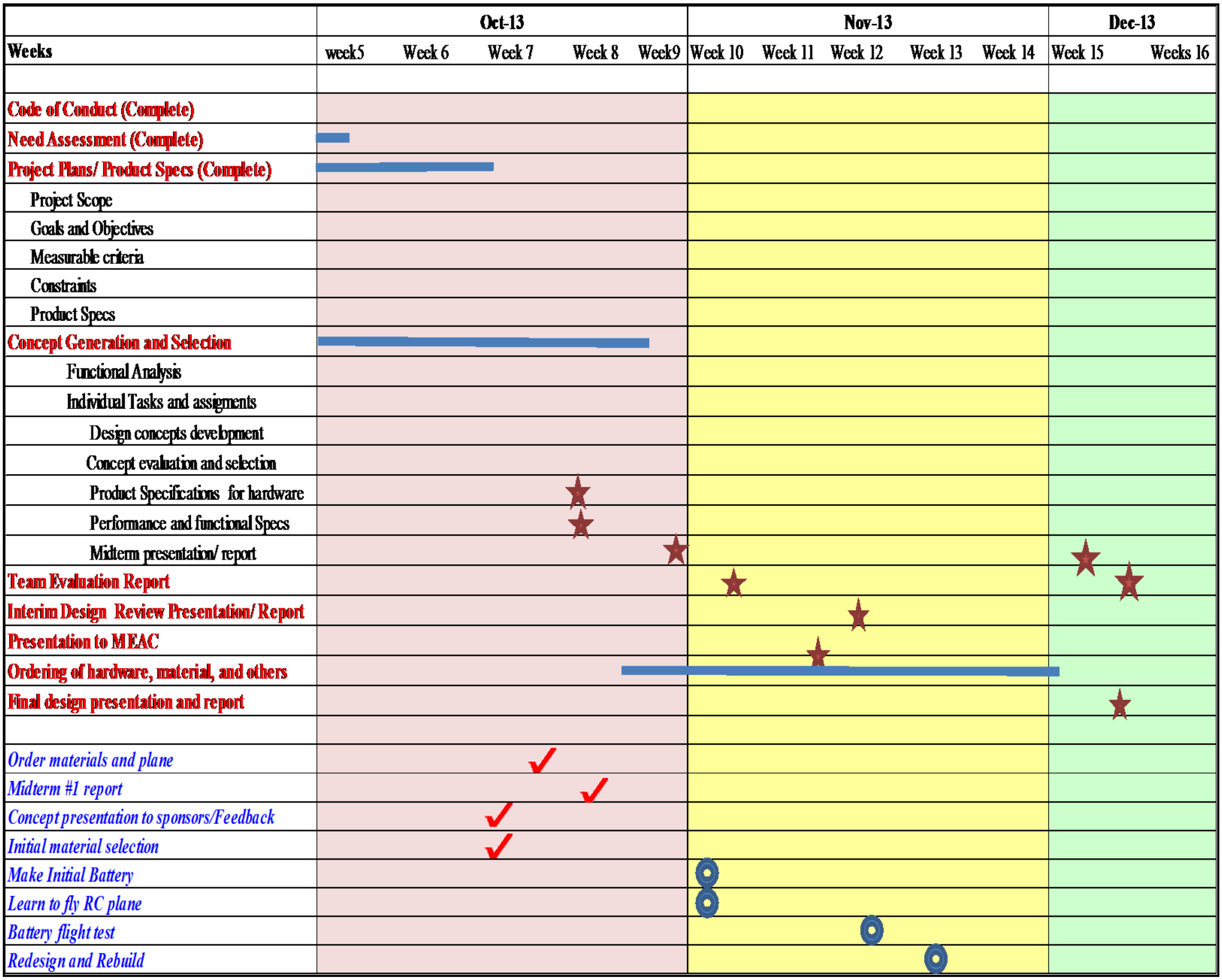

Figure 10: Team Gantt Chart [1]

References:

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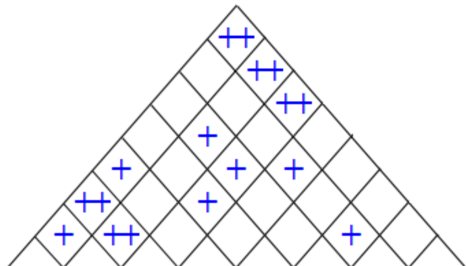
Appendix:

Legend		
⊙	Strong Relationship	9
○	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	



				Column #	1	2	3	4	5	6	7	8
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▼	x	x	x	x	x	
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	**Quality Characteristics** (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats")	Power	Weight	Cathode/Anode Stack Volume	Lithium Ion	Type of Connection (Series vs. Parallel vs. Combination)	Custom Battery Housing	Sealing Process	Type of Anode/Cathode Material
1	9	18.5	0.2	Conformable		▲	⊙		○		○	
2	9	14.8	0.1	Reliable	⊙	○	○	⊙			⊙	○
3	9	7.4	0.1	Attachable/Dettachable						⊙		
4	9	11.1	0.1	Good Rechargeability	▲			⊙				
5	9	14.8	0.1	Shape Restrictions		▲	○		○			⊙
6	9	7.4	0.1	Lightweight		⊙	⊙			○		○
7	9	11.1	0.1	Safety	▲		▲	⊙			⊙	
8	9	14.8	0.1	Budget			○			○	○	⊙
9												
10												

	1	2	3	4	5	6	7	8
Target or Limit Value								
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)								
Max Relationship Value in Column	9	9	9	9	3	9	9	9
Weight / Importance	155.6	144.4	377.8	333.4	100.0	133.3	333.4	333.3
Relative Weight	8.1	7.6	19.8	17.4	5.2	7.0	17.4	17.4

Figure A: House of Quality