Design and Fabrication of an Exoskeleton Suit for Flight

B. Tech Project – Stage-I Report

Submitted for fulfilment of credits to complete honors.

Autumn Semester, 2017-18.

Submitted by,

Karan Jain (140100023)

under the Guidance of,

Prof. Arindrajit Chowdhury

Department of Mechanical Engineering

Indian Institute of Technology, Bombay

Powai, Mumbai – 400 076

November 2017

Acceptance Certificate

Department of Mechanical Engineering
Indian Institute of Technology, Bombay

The B.Tech Project report titled "Design and Fabrication of an Exoskeleton Suit for Flight" submitted by Karan Jain (140100023) may be accepted for being evaluated.

____

Date: 27th November 2017

Abstract

This report presents my idea on how to build the ExoFly – an externally powered exoskeleton suit which can enable humans to fly at a personalized and domestic level. ExoFly will be a light-weight, battery-powered suit which the user can 'wear' within minutes. The controls will belong to the user, and a computer interface will also be present to override passenger control if the need arises.

This system will allow a single passenger to fly safely for approximately 5 minutes, and at the same time, give the user the thrill of flight.

Word of Thanks

To Prof. Arindrajit Chowdhury for accepting my idea to not only design and simulate this suit but also grant funds for buying components to test the idea at full-scale.

To Mr. Shantanu Thada (150100072), a junior mechanical engineering undergraduate, for his valuable contributions to this project.

To Prof. K. P. Karunakaran for sharing his ideas and current research on contra-rotating propellers.

To Mr. Ansel Misfeldt, who made the FlytCycle™ right in his garage, and gave me priceless inputs and a great start to the project by sharing his ideas and thoughts.

And lastly, to my family for continuous support and giving ideas for this project at every stage.

Table of Contents

1. Introduction

With the advancements in motor technology, research on high energy-density batteries, advent of exotic high specific-strength materials such as carbon fibers, and the decades of mastery of propeller technology, the dream of experiencing the thrill of flight at a personalized level is possible now.

My vision was inspired by the famous Marvel Comics' character 'Iron Man'. The idea is to have thrust generating devices coupled to the limbs of the passenger to generate enough force to lift the user in the air at a fair speed.

The choice of thrusters was extensive, with an entire spectrum ranging from motor-driven propellers to gas turbines. I decided to go ahead with the electric option because of 2 reasons:

i. Battery technology is advancing at a good pace, and soon the energy densities will be high enough to allow extremely light-weight electric power sources.
ii. No electric powered exoskeleton suit exists to this date which can enable human flight.

These technological advancements and the increasing demand for faster transportation are excellent motivators to work on compact flying technology at a personalized level.

ExoFly will essentially serve this purpose and can be applied in the real-world in a lot of areas such as transportation, firefighting, exploration, quick response to distress calls and defense. Last but not the least, it will be fun to develop this technology and to enjoy flying around in it.

2. Literature Review

Over a period of one month, I reviewed several existing technologies in the domain of personalized flight. I shall be mentioning the ones with specifications close to what I wanted to build.

2.1. FlytCycle™

Founder: Ansel Misfeldt. This is a big multi-rotor device on a light-weight chassis in which a single person can sit and fly around for 10-15 minutes. The prototype was finished in December 2016.

Below is an image of FlytCycle being tested by its designer.

2.1.1. Specifications:

Number of propellers	: 12 (6 pairs in contra-rotating configuration)
Motors	: 12x Rotomax 150cc motors – - 14 cell (51.8 V) supply - 190 A current rating - 9.8 kW power
Propellers	: 27x13" custom made propellers
ESC	: Turnigy Fatboy v2 300A ESCs
Batteries	: Multistar 20.0Ah 6S 10C battery (18-24 of them in total)

2.2.Sky-Hopper

Founder: Peter Dobber. This device is similar to the previous device conceptually. A noticeable difference is that the passenger sits 'inside' the chassis of the multi-rotor instead of the top.

2.2.1. Specifications:

Number of propellers : 16
Propellers : 18-20" diameter; pitch unknown

2.3.Daedalus

Founder: Richard Browning, Gravity. Company was founded in March 2017. Prototype of a full-scale gas turbine driven exoskeleton suit was made. A picture of it is shown to the right which will give a clear idea.

2.3.1. Specifications

Number of engines: 6
- 2 on the back
- 2 on each hand

Thrust per engine: 22 kg

2.4. Prof. K. P. Karunakaran's mini-helicopter

Single pair of contra-rotating propellers powered by IC engines. This is closer to an actual helicopter because of the size of its propellers.

2.4.1. Specifications

Propellers	: 2x, Dia. = 4 m; Chord – 100 mm; NACA 0012 airfoil
Rotation Speed	: 800 rpm
Engine	: 2x 7-cylinder radial engine

3. Calculations

Listed below are some back of the envelope calculations. Detailed calculations will follow in dedicated sections for each component.

Estimated weight of exo-skeleton	: 80 kg
Average weight of Passenger	: 70 kg
Total expected weight	: 150 kg
Thrust required (70% times the weight)	: 255 kg
Distribution (Legs : Hands :: 2 : 1)	
Leg thrust	: 170 kg
Hand thrust	: 85 kg
Total no. of propellers	: 12
Thrust due to each propeller	: 21.25 kg (47 lbs.)
Minimum thrust to just lift the system	: 150/12 = 12.5 kg (28 lbs.)
Power required (assuming 10 m/s upward velocity)	: 25 kW (from propellers)
Power output per propeller	: 2.1 kW
Power input (shaft) required per propeller	: 3.5 kW (assuming 60% efficiency)
Total required power	: 12*3.5 kW = 42 kW

3.1. Dimensional Analysis

Let us assume that the following variables are enough to describe all other parameters: air density (ρ), RPM of propellers (N) and diameter of the propellers (D). These variables are enough to dimensionally relate all other parameters, for example – Thrust (F), Power (P) and Torque (T).

On performing the dimensional analysis, we get the following results:

$$F \propto \rho N^2 D^4$$

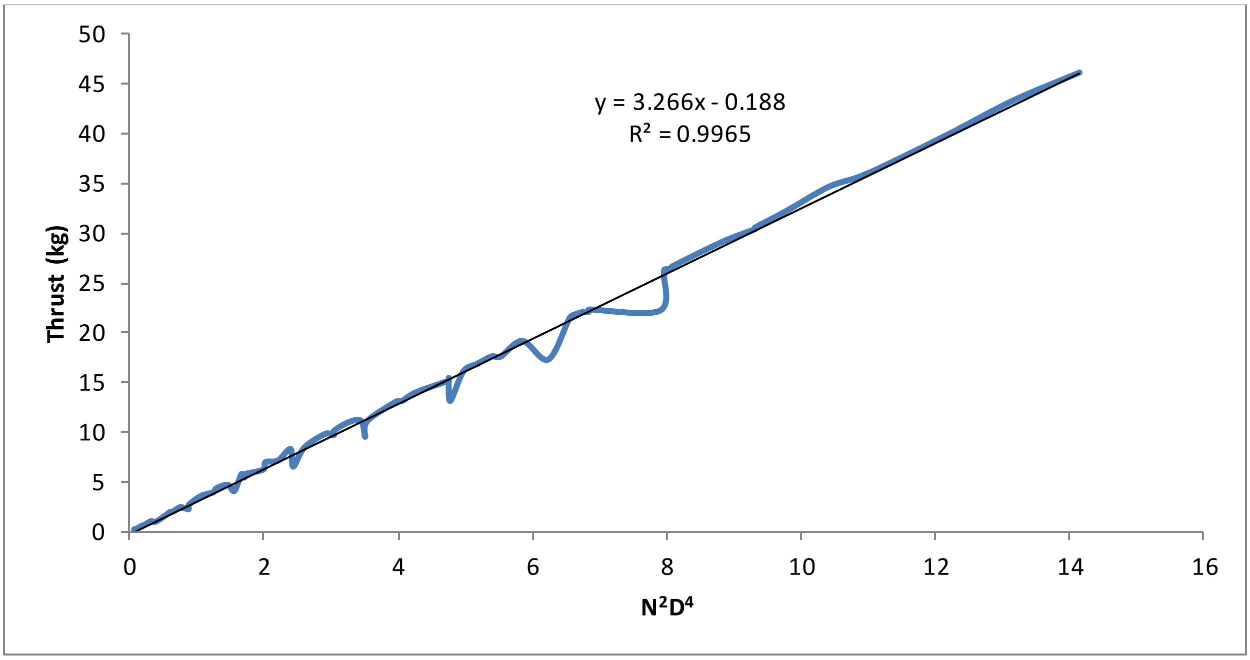
$$T \propto \rho N^2 D^5$$

$$P \propto \rho N^3 D^5$$

The above 3 equations will be useful to calculate the proportionality constants C_F, C_T and C_P, also known as the thrust coefficient, torque coefficient, and power coefficient respectively. Density of air can actually be assumed to be constant (incompressible) as a start, and can later be included to get more accurate results.

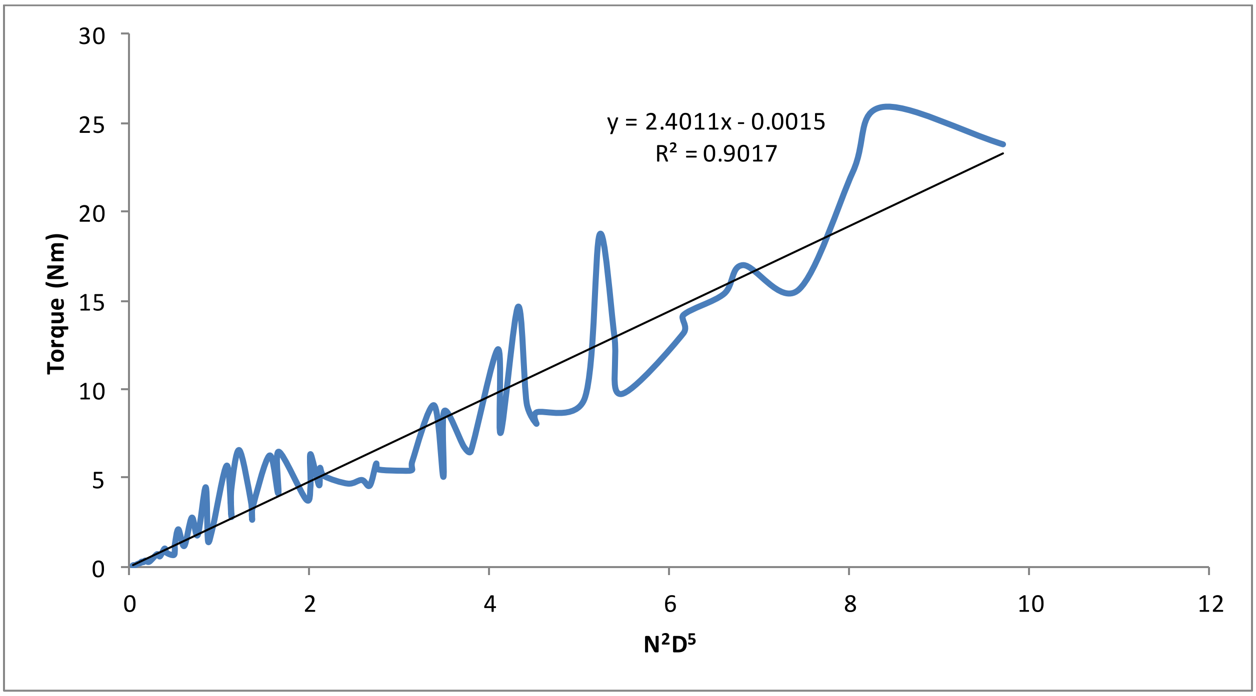
On searching for propeller thrust data online, I got an excel sheet by APC props, which gives the power-RPM-thrust characteristics of various propellers ranging from 20" to 27" in diameter, for various pitch values. Dimensional analysis was applied to find a correlation between thrust, torque, power with the speed and diameter of the propellers. Plots are shown below for each variable. Speed was taken as N=(RPM/1000) and diameter was taken in meters.

3.1.1. Thrust



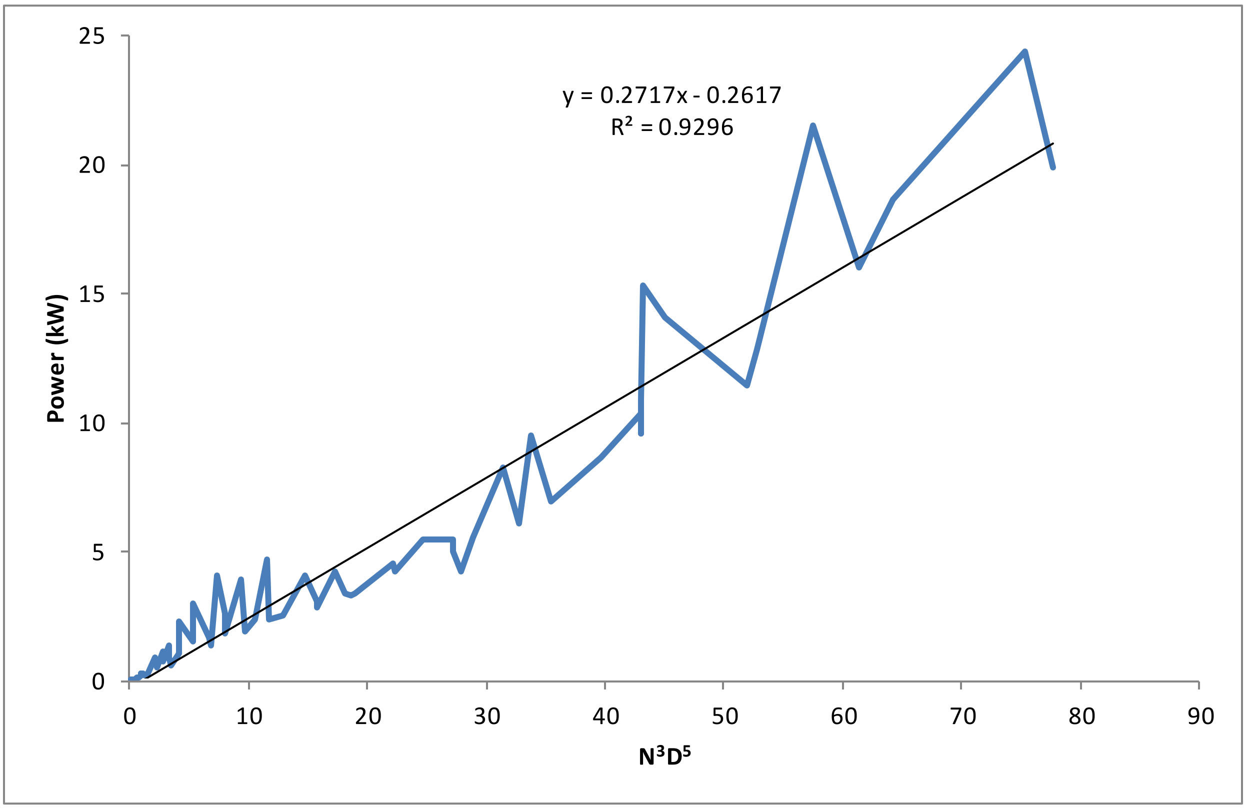
As can be seen, thrust has a very high correlation with its expected relation with N and D. Hence we can say that C_F=3.266

3.1.2. Torque



Torque is not very nicely correlated, with a correlation coefficient of about 0.95. Still, for our purposes, we can claim that C_T=2.401

3.1.3. Power



Power has a 'fair' correlation, but with a lot of oscillations. For initial calculations, we can use the graph and say that C_P=0.2717

3.1.4. Conclusion for Dimensional Analysis

Dimensional analysis is a good start and initial guesses can be obtained using the coefficients found above. But for later calculations which have to be more accurate, it is best to refrain from using dimensional analysis. In fact, even interpolation should be avoided.

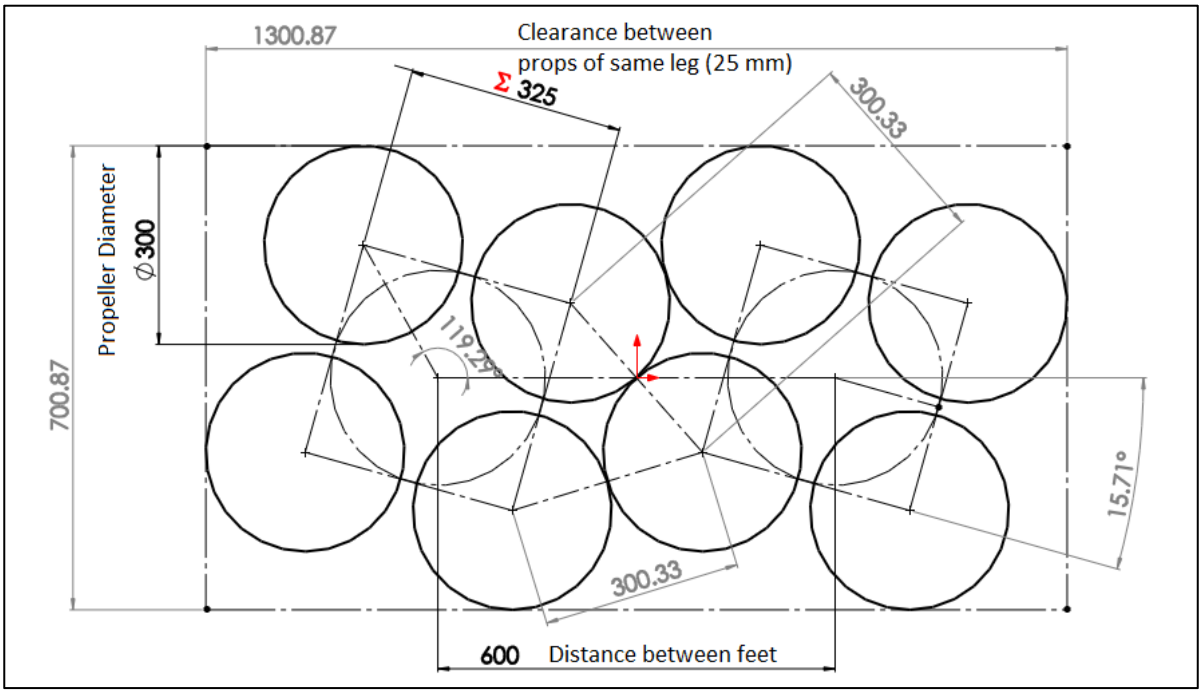
Best way to find values is by actual testing, if the components and facilities are available.

4. Component Selection and Design Discussion

Details of selection of each and every component are covered in this section. Compactness was the primary consideration behind this entire project. Hence the components will smallest possible size and lowest possible weight were shortlisted. Final selection was based on considerations of several other factors which have been covered in the respective sections.

4.1. Propellers

Initially, we wanted to go for small propellers in the diameter range of 10” to 12”. A configuration to place the propellers was sketched and is shown below:



The above image shows the configuration as seen from top: the two feet are separated by a distance of about 600 mm. This ensures that there is a safe distance between the any pair of propellers. This had a bounding rectangle of about 1.3m × 0.7m, which is pretty big. Moreover, the rpm-thrust characteristics of the 12” propellers weren’t available.

Dimensional analysis suggests that these propellers would need to rotate at about 21000 rpm for the minimum thrust generation of 12.5 kg. Even the power consumed at this thrust would be about 6.7 kW. The rpm was simply out of the range of any kind of motors, and using a gearbox for such cases is never a good option. Thus this configuration was rejected.

We had data available for 20” to 27” propellers. All this data was analyzed. After long discussions, brainstorming and taking compactness into consideration, we decided to go for 20” propellers, placed in a contra-rotating configuration, with a pitch in range of 10” to 13”. More on contra-rotating propellers (CRP) is covered in the next section (5.1).

Tabulated below is the data for the 20x13 composite propellers at various RPM values.

RPM	Power (HP)	Power (kW)	Thrust (lbs.)	Thrust (kg)	Torque (Nm)
0	0.00	0.00	0.00	0.00	0.000
1,000	0.01	0.01	0.48	0.22	0.071
2,000	0.08	0.06	1.91	0.86	0.288
3,000	0.30	0.22	4.31	1.95	0.707
4,000	1.19	0.88	7.91	3.59	2.110
5,000	3.14	2.34	12.68	5.75	4.478
6,000	5.54	4.13	18.28	8.29	6.569
7,000	6.37	4.75	24.23	10.99	6.480
8,000	**5.73**	**4.27**	**30.82**	**13.98**	**5.097**
9,000	**7.34**	**5.47**	**38.81**	**17.60**	**5.804**
10,000	**12.77**	**9.52**	**48.22**	**21.87**	**9.096**
11,000	**18.92**	**14.11**	**58.28**	**26.43**	**12.248**

The minimum thrust requirement was about 28 lbs. per propeller. Hence, the last 4 RPM values are important as these will predominantly be the speeds that we will be operating at during the flight.

Since our required range of thrusts was 12.5 kg to 21.25 kg (best case), the RPM from dimensional analysis for the 2 cases comes out to be (assuming diameter is 20"):

Thrust, F (kg)	Expected N (RPM/1000)	Expected power (kW)
12.5	7.580878	4.0046695
21.25	9.884255	8.8764652

This helps in selecting a suitable motor by giving the expected RPM and power requirements.

4.2. Motor

Thrust and power requirements were given by the propeller chosen. But we cannot have the cake and eat it too. Motors are available only for certain rated powers and generally, getting a motor that suits both the power and RPM requirements is close to impossible.

An extensive survey was done on motors available in the market suited for flight applications. 10 motors were shortlisted which were close to our requirements and the best motor was then selected.

Model	Kv rating (RPM/V)	Voltage	Maximum RPM	Max rated Current (A)	Max Power (W)	Battery (no. of cells)	Weight (g)
Turnigy RotoMax 1.20 Brushless	280	29.6	8288	65	1924	8	902
Turnigy RotoMax 1.40 Brushless	228	37	8436	75	2775	10	1184
Turnigy RotoMax 1.60 Brushless	231	37	8547	80	2960	10	1150
Turnigy RotoMax 50cc Brushless	172	37	6364	120	5300	10	1380
Turnigy RotoMax 80cc Brushless	**195**	**51.8**	**10101**	**150**	**6600**	**14**	**2475**
Turnigy RotoMax 100cc Brushless	167	44.4	7414.8	170	7992	12	3083
Turnigy RotoMax 150cc Brushless	150	51.8	7770	190	9800	14	3464
9225-90KV Turnigy Multistar Brushless	90	44.4	3996	36	1200	12	673
9235-100KV Turnigy Multistar Brushless	100	44.4	4440	57	2800	12	991
9225-160KV Turnigy Multistar Brushless	160	29.6	4736	48	1200	8	679

Firstly, the RPM criteria should be satisfied. Only a few motors could go to more than 7000 RPM, which was necessary for the minimum thrust generation. Out of the motors which satisfied the RPM criterion, only 3 could provide the required power close to the maximum thrust (The Turnigy Rotomax outrunner series – 80cc, 100cc and 150cc). Considering that we required high RPM and light-weight motors, finally we chose the Turnigy Rotomax 80cc brushless motor for our application.

Note that its power is limited, but will not pose a big issue. Minimum power required for just lifting off is 4 kW, which this motor provides. Using dimensional analysis, expected RPMs and thrusts have been calculated for powers ranging from 4 kW to 6.6 kW.

Electric motors typically have an efficiency of at least 80%. So assuming the worst case, we have at 80% efficiency, the maximum power being delivered as 5.3 kW.

For this worst case, we have an expected thrust per propeller of 15 kg.

This gives a total thrust due to 12 propellers to be 180 kg, which is still fairly more than the weight of the entire system (150 kg). The thrust is still 1.2 times the weight of the system. Hence we can go ahead with this motor.

Power (kW)	Expected N (RPM/1000)	Expected Thrust, F (kg)
4.0	7.578	12.490
4.1	7.641	12.698
4.2	7.702	12.903
4.3	7.763	13.107
4.4	7.823	13.310
4.5	7.881	13.511
4.6	7.939	13.710
4.7	7.996	13.908
4.8	8.053	14.105
4.9	8.108	14.300
5.0	8.163	14.494
5.1	8.217	14.686
5.2	8.270	14.878
5.3	8.323	15.068
5.4	8.375	15.257
5.5	8.427	15.445
5.6	8.477	15.631
5.7	8.528	15.817
5.8	8.577	16.001
5.9	8.626	16.185
6.0	8.675	16.367
6.1	8.722	16.548
6.2	8.770	16.729
6.3	8.817	16.908
6.4	8.863	17.086
6.5	8.909	17.264
6.6	8.955	17.441

4.3. Controller

Selection of the Electronic Speed Controller (ESC) is based on the current and voltage rating of the motor. Essentially, the current rating of the ESC, should be more than the current rating of the motor. Voltage rating should of the motor should be satisfied by the ESC.

Based on the ratings of the selected motor, 3 ESC's were shortlisted.

Model	Constant Current (A)	Burst Current (10 seconds)	Maximum Cells	Weight (gm)
YEP ESC 180A HV (4~14S) Brushless Speed Controller (OPTO)	**180**	**200**	**14 (51.8 V)**	**324**
Turnigy dlux 250A HV 14s 60v ESC	250	275	14 (51.8 V)	680
RotorStar 180A HV (4~14S) Brushless Speed Controller (OPTO)	180	200	14 (51.8 V)	300

Weight was the first consideration as there would be 12 of these ESCs. Rejecting the 2^{nd} one in the above table gives a direct weight saving of more than 4 kg. Every gram matters in the case of flight, and a gram reduced implies more flight time, along with greater acceleration.

Among the first and third one, the sole reason for selecting the first one was availability in market.

4.4. Battery

Selecting a battery pack was the toughest task because of the pool of batteries available and the open-endedness in choosing a battery. Some nomenclature before proceeding – nS battery means that there are 'n' cells in series in that particular battery. These are Lithium Polymer (LiPo) cells and on an average, each cell is 3.7 volts. In the market, typically cells are available as 1S (common), 2S, 3S (most common), 4S (uncommon), 5S, 6S (common), 7S (uncommon) and 10S (rare).

We have to get a 14-15S cell configuration for our purpose (15 is considering there is some voltage drop across the ESC). It is clear that there are too many combinations to achieve the same. Some examples are listed below:

i) 5x 3S batteries per motor
ii) 2x 7S batteries per motor
iii) 5x 6S batteries for 2 motors in series

Listing all possibilities would be redundant, but have been considered during selection.

The most important consideration was the **energy density** (kWh/kg) of the battery pack. This will essentially determine the weight of the exoskeleton suit because the energy required will come from the required flight time and will be constant.

More than 50 battery packs were considered and analyzed in terms of energy density, price and the current rating. The top 10 battery packs according to energy density are listed in the table below:

Number of Cells	Voltage (V)	Discharge (C)	Capacity (mAh)	Maximum Current (A)	Weight (gm)	Energy (kWh)	Energy Density (kWh/kg)
6	22.2	25	16000	400	1900	0.3552	0.18695
3	11.1	5	2500	12.5	155	0.0278	0.17903
3	11.1	30	8400	252	528	0.0932	0.17659
6	22.2	10	16000	160	2044	0.3552	0.17378
6	22.2	10	16000	160	2044	0.3552	0.17378
7	25.9	25	5800	145	930	0.1502	0.16153
3	11.1	40	5200	208	360	0.0577	0.16033
5	18.5	25	5000	125	581	0.0925	0.15921
6	22.2	25	8000	200	1125	0.1776	0.15787
3	11.1	40	3000	120	215	0.0333	0.15488

Note: The discharge rating (C rating) gives the maximum current calculated as

$$I_{max} = C_{rated} * Capacity(in\ Ah)$$

The names of the batteries have not been mentioned for the sake of brevity.

4.4.1. A small issue

Most of our parts were bought from Hobbyking website. But for the batteries, there is a rule that in India, we cannot import more than 100 Wh worth of batteries in a single order. From the list, it can be seen that most of the batteries are above this limit, and the ones below it need to be bought multiple times to even run a single motor. Hence many of these options had to be ruled out. Some of the above batteries are available in India, but their cost is generally 2.5-3 times the price at Hobbyking or any other foreign e-commerce website.

4.5. Miscellaneous components

Apart from the main components, there are several other components that need to be bought such as connectors, wires, bolts, programming cards which have been listed below:

i) YEP ESC Programming Card – for user-friendly programming of the ESC.
ii) Turnigy high quality 8AWG silicone wire – for connections that can carry 150 A with low heating.
iii) Golden connectors (5.5 mm and 6 mm) (male and female) – for snap-fit connections at ends of batteries, ESCs and motors.

5. Conclusions and Final Design

The process of selection of all the components was not a linear open-loop kind, but was a heavily iterative process. For example, selection of one propeller led to choice of one motor which gave only a limited power, so we had to choose a different propeller. Sometimes a motor chosen did not have any ESCs for it. The process continued and fortunately converged to a set which is not the ideal one, but good enough to build the entire working system with a sufficient margin for errors and sufficient redundancy.

To get closer to ideal values, some parts such as propellers will have to be custom made, and propeller design is a whole other ball game.

5.1. The contra-rotating configuration

There are several reasons for selecting the configuration as contra-rotating propellers (CRP):

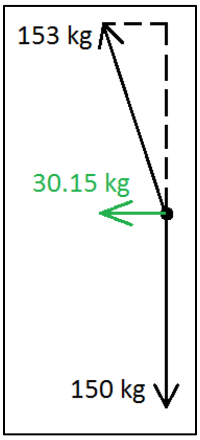
i) Torque cancellation: There would be no torque exerted on the exoskeleton limb attachment by a pair of CRP because the torque due to the pair cancels out.
ii) Higher efficiency: CRPs have been found to be 6-16% more efficient than normal propellers.
iii) Space constraints: They occupy lesser area in the horizontal plane, and there is no restriction in particular in the vertical direction. This will reduce the dimensions of the suit.

Some disadvantages are also associated with CRPs:

i) They are noisier than the conventional single propeller configuration.
ii) They do not exactly double the thrust. In fact, in the worst case, there might be a drop in thrust of 10-15%, i.e. the thrust would only be 1.7-1.8 times that of a propeller in isolation.

The advantages outweighed the limitations and hence we decided to go ahead with the CRP configuration. This will be achieved by having 2 motors attached back-to-back on the 'chassis' of the exoskeleton suit.

5.2. A worst case analysis



In the Motor section, we saw that even in the worst case, our system can generate a 180 kg thrust. But we did not take the consideration that the propellers are in contra-rotating configuration.

From the disadvantage of CRPs, we see that one pair of CRP generally provides 1.7-1.8 times the thrust of a single propeller. Taking the worst case, we have a 15% reduction in thrust. (Note that we have ignored the increase in efficiency due to the CRP configuration for this analysis.)

This means that the total thrust force now generated is 153 kg. This is barely more than the weight of the entire system. But does it actually matter? Say we do get a thrust of only 153 kg, then how fast can we move in the horizontal direction?

A simple FBD will provide the answer. Say we are flying at an angle with respect to the vertical such that the vertical component of the thrust balances the weight.

By applying Pythagoras theorem, we get a horizontal component of about 30 kg. That is still a good amount of thrust to drive the system. To get an idea of what this thrust can do, let us see how much acceleration it can provide. Using Newton's second law, F=ma, with F=30 kg (300 N) and m=150 kg, we get an acceleration of 0.2g or about 1.9 m/s^2 which is still faster than most of the commercial IC engine cars (exclude sports cars).

Let us also see the speed at which we can go with this. For this, a CFD simulation is required to calculate the drag coefficient. But for now, we can do a simple back of the envelope calculation. Terminal velocity of an average fully spread-out human body falling under gravity is about 50 m/s. We can assume that the drag coefficient is the same for this case and our case, only that instead of 'g', we have a 0.2*g acceleration.

We know that, $F_D = {}^1\!/_2 * C_D * \rho * A * v^2$

Or equilibrium, $F_{applied} = F_D$

In free-fall case, $mg = {}^1\!/_2 * C_D * \rho * A * v^2$

Assume that m/A is a constant. Also assume that air density and drag coefficient remain the same. So in effect, we have $v_{terminal} \propto \sqrt{g}$

Therefore, when going from free-fall case to our case we have, 'g' becoming 0.2*g.

So the velocity will become $v_{terminal,suit} = v_{terminal,freefall} * \sqrt{0.2}$

Hence, the terminal speed of the suit comes out to be 22.3 m/s, or approximately **80 km/h** which is still pretty huge. So even in the worst case, our suit can almost go at highway speeds.

6. References

i) https://flytaerospace.com/ - FlytCycle project details
ii) https://www.apcprop.com/ - composite propeller manufacturer
iii) https://www.apcprop.com/technical-information/performance-data/ - RPM-thrust-power characteristics of propellers
iv) https://newatlas.com/sky-hopper-manned-multicopter/47974/ - SkyHopper project details
v) https://en.wikipedia.org/wiki/Bensen_B-8 - Bensen B-8 helicopter details
vi) https://www.gravity.co/ - Daedalus project details
vii) https://aviation.stackexchange.com/questions/14820/what-is-the-purpose-of-having-contra-rotating-props-on-an-aircraft - details on CRPs
viii) https://www.rcgroups.com/forums/showthread.php?1667267-Counter-rotating-propellers-Vs-Conventional – more details on CRPs
ix) https://www.rcgroups.com/forums/index.php - useful forum for questions related to propellers, batteries, motors, etc. related to flight
x) http://www.rcuniverse.com/forum/ - another useful forum
xi) http://batteryuniversity.com/learn/archive/the_high_power_lithium_ion
xii) https://en.wikipedia.org/wiki/Free_fall
xiii) http://www.dcgeorge.com/ - project falcon, different project, similar task, excellent documentation, great sketches