Design and Fabrication of an Exoskeleton Suit for Flight

B. Tech Project – Stage-II Design Report

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Submitted by,

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Software Licenses

We have used licensed versions (student licenses) of the following software:

1. SolidWorks 2016 SP02, student license; developed by Dassault Systèmes
   Used for Computer Aided Design and structural analysis of spaceframe chassis, and image rendering of our CAD models.
2. MSC ADAMS Student Edition; developed by MSC Software
   Used for Multibody Dynamics Simulation, analysis of suspension (spring-damper) system for the base of our device.

Acknowledgements

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.

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To team ExoFly, an interdisciplinary team of 17 members (including myself) for all the effort they put in to speed up the design process and completing the design well in time.

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 continuously providing support to queries over the last 10 months.

And lastly, to my family for continuous support and giving ideas for this project at every stage, without which, this project would not have been possible.

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.

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 personalized 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.

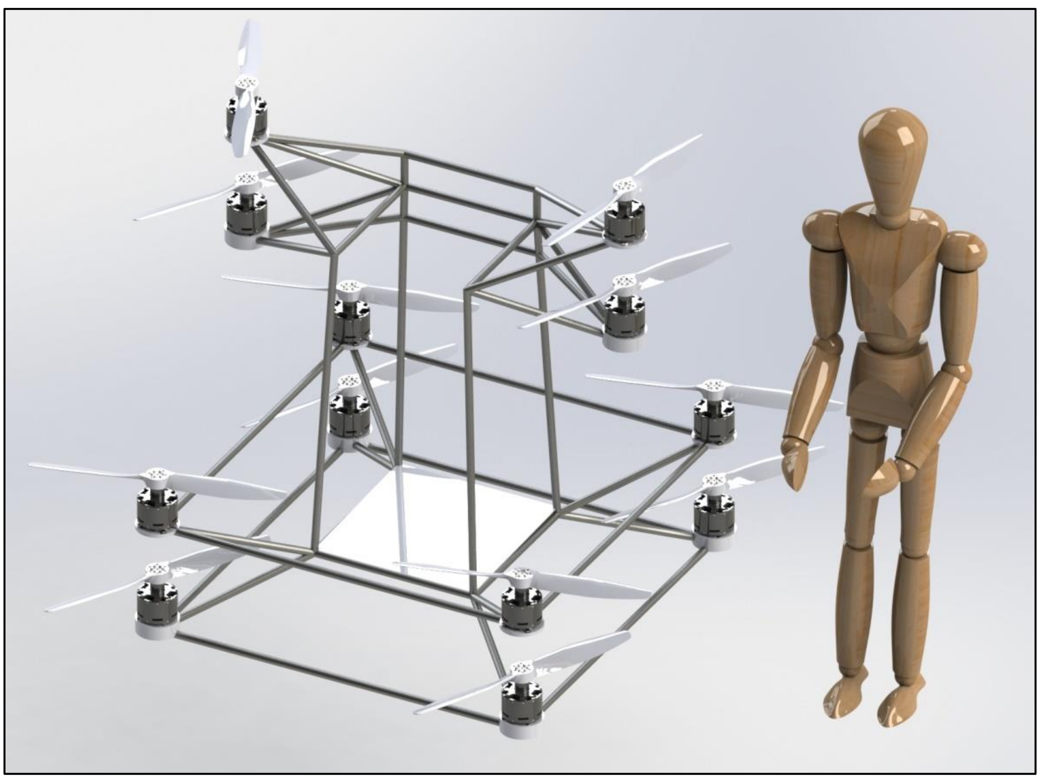

Fig 1 - An initial render of our Device 'ExoFly' (without batteries) with a 5' 9" person beside it for scale

2. Calculations

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

Expected weight of Passenger	: 90 kg
Estimated weight of exo-skeleton	: 40 kg (motors+propellers) + 20 kg (Chassis)
Estimated weight of batteries	: 90 kg
Total expected takeoff weight	: 240 kg
Max Thrust required (1.5 X weight)	: 360 kg (will reason factor of 1.5 subsequently)
Total no. of propellers	: 12 (will explain why subsequently)
Max Thrust required per propeller	: 30 kg (66 lb)
Minimum thrust per propeller	: 240/12 = 20 kg (44 lb)

2.1. Reasoning

The only thing we know initially is that our device must lift a 90 kg passenger and provide a flight time of 20 minutes.

Using the datasheet of small propellers (20” to 30” diameter) obtained from APC Propellers website, we could see that the typical maximum thrusts range between 22 kg to 35 kg for a 8-10 kW maximum power supply. Thus we assumed a 30 kg thrust can be delivered by each propeller and to get a thrust of 360 kg, we will require 12 propellers.

As each propeller will consume maximum 8-10 kW and about 5-6 kW on an average, we choose a motor with a max power rating of 10 kW and use 12 of those (one for each propeller). Each motor will also require an Electronic Speed Controller (ESC) of appropriate voltage and current rating.

The battery weight of 90 kg was arrived at using energy calculations assuming a steady power is being consumed throughout 20 minutes and is just used to lift the entire system, along with a safety factor.

Lastly, the factor of 1.5 for the max thrust to weight ratio comes from the fact that the system should lift at 60-70% of the maximum thrust to have some leeway in maneuvering and accelerating upwards. This factor is actually 2 for smaller systems, but in our case, it would make the system too heavy to be considered as a personalized flying device.

The component selection was not a linear open-loop process, but an iterative one where selection of one would lead to changes in other until we finally converged to a perfect configuration which met our desired requirements.

3. Component Selection

Compactness was the primary consideration behind this entire project. Selection was based on considerations of requirements of the GoFly problem statement, and several other factors which have been covered in the respective sections.

3.1. Propeller

Initially, we had selected 20” propeller to make the device really compact (could fit within a 1.2 meter bounding sphere). The objective then was to achieve a flight time of about 5-10 minutes. But, with the new objective of 20 minutes flight time, using 20” props was out of question as would have to keep adding propellers, motors and batteries which would lead to a vicious loop of ever increasing weight.

Increasing the propeller size was the only option and thus, we gradually increased propeller size and calculated the battery weight and entire system weight at each step until finally we converged to a **27” propeller** which could provide the flight time and also fairly meet the compactness requirement.

Tabulated below is the data for 27x13 composite propellers at various RPM values.

RPM	Thrust (kg)	Power (kW)	Thrust (lb)	Power (HP)
0	0.000	0.000	0.000	0.000
1,000	0.680	0.037	1.500	0.050
2,000	2.722	0.224	6.000	0.300
3,000	6.214	1.044	13.700	1.400
4,000	11.068	1.939	24.400	2.600
5,000	**17.599**	**3.430**	**38.800**	**4.600**
6,000	**25.855**	**6.115**	**57.000**	**8.200**
7,000	**35.562**	**11.409**	**78.400**	**15.300**
8,000	46.130	19.910	101.700	26.700

Table 1 - RPM-Thrust-Power response of 27x13 propeller

The values for 5,000-7,000 RPM are shown in bold as that will be our range of operation during flight. Using interpolation, we can tabulate the RPM and power required to produce the minimum and maximum thrust as shown in Table 2.

Thrust (kg)	RPM	Power (kW)
20	5290	4.211
30	6430	8.376

Table 2 - RPM, Power requirements for minimum and maximum thrust

3.2. Motor

RPM, thrust and power requirements were given by the propeller chosen. A motor had to be chosen accordingly which could deliver that power output and RPM. Generally it is very difficult to get a motor that can suit both requirements simultaneously. But, in the case of 27" props, we found a motor which seemed to be made specifically for these props.

An extensive survey was done on motors available in the market suited for flight applications. Tabulated below is a list of those motors which were suited for our design.

Model	Kv rating (RPM/V)	Voltage	Max RPM	Max rated Current (A)	Max Power (W)	Battery (no. of cells)	Weight (g)
Turnigy RotoMax 50cc Brushless	172	37	6,364	120	5,300	10	1380
Turnigy RotoMax 80cc Brushless	195	51.8	10,101	150	6,600	14	2475
Turnigy RotoMax 100cc Brushless	167	44.4	7,415	170	7,992	12	3083
Turnigy RotoMax 150cc Brushless	**150**	**51.8**	**7,770**	**190**	**9,800**	**14**	**3464**

Table 3 - Motor Shortlist

The 'Turnigy RotoMax 150cc' BLDC motor was almost ideal for our application. It provided a maximum RPM and power as required by the propellers (considering an 80-85% efficiency of the motor itself). Testing data and sketches of the motor were also available and well documented. Hence we finalized this motor for our device.

3.3. Electronic Speed Controller (ESC)

Selection of the Electronic Speed Controller (ESC) is based on the current and voltage rating of the motor. The current rating of the ESC should be more than the current rating of the motor. Voltage rating should of the ESC should be same as that of the motor.

Based on these considerations, 3 ESCs were shortlisted as shown below.

Model	Constant Current (A)	Burst Current	Maximum Cells	Weight (gm)
Turnigy Fatboy V2 300A ESC 4~15S	**300**	**380**	**15 (55.5 V)**	**406**
Turnigy dlux 250A HV 14s 60v ESC	250	275	14 (51.8 V)	680
Turnigy AquaStar 200A Watercooled Sensorless High Voltage 6-12S (ESC)	200	250	14 (51.8 V)	300

Table 4 - ESC shortlist

Considering weight and current rating (steady and burst), we finally decided to go for the slightly more expensive Turnigy Fatboy ESCs.

3.4. Battery

We had decided to go for Lithium Polymer (LiPo) batteries because of the high energy density and high level of discharge. Lithium ion (Li-ion) batteries were another promising option with an even higher energy density. But, their discharge is lower compared to their LiPo counter-parts and they are also more hazardous – there have been several incidences of Li-ion batteries heating up and catching fire, but not many for LiPo.

Some nomenclature before proceeding – nS battery means that there are ‘n’ cells in series in that particular battery, with each cell being 3.7 volts. The pool of batteries available and the open-endedness in choosing a battery made the selection really difficult.

To achieve a 14S, or 15S considering the voltage drop across the ESC, we have got a variety of options – 5x 3S, 2x 7S per motor, or 5x 6S for 2 motors in series. Listing all possibilities would be redundant, but have been considered during selection.

The top batteries that were shortlisted are shown 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**	**1450**	**0.3552**	**0.24497**
6	**22.2**	**15**	**16000**	**240**	**1885**	**0.3552**	**0.18844**
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
7	25.9	25	5800	145	930	0.1502	0.16153

Table 5 - Battery Shorlist

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

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

3.5. 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) ESC Programming Card – for user-friendly programming of the ESC.
ii) PSoC 2 – As a controller for the entire device.
iii) Turnigy high quality 8AWG silicone wire – for connections that can carry 150-200 A current with low heating.
iv) Golden connectors (5.5 mm and 6 mm; male and female) – for snap-fit connections at ends of batteries, ESCs and motors.

4. Configuration

After component selection, we come to the placement of these selected components in such a configuration so as to meet certain criteria such as compactness, safety, redundancy, maneuverability, etc.

4.1. The Contra-Rotating Propeller (CRP) configuration

Considering the above criteria, we decided to arrange the 12 propellers as follows:

We will be using them in a CRP configuration. So we shall have 6 sets of CRPs, which we shall call one 'unit' from now on. Each unit has 2 propellers, one rotating clockwise, the other counter-clockwise so that the 2^{nd} propeller accelerates the already moving air supplied by the 1^{st} propeller. More details about the CRP configuration follow:

a. Compactness: 2 propellers one on top of other takes up lesser space (top view area) as compared to 2 propellers side-by-side.
b. Torque cancellation: There would be no net torque exerted on main body of the exoskeleton suit because the torque due to the pair cancels out.
c. Higher efficiency: CRPs have been found to be 6-16% more efficient than propellers in regular configuration.

There are some disadvantages of CRPs as listed below:

a. They are noisier than the conventional single propeller configuration.
b. 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 from one unit would only be 1.7-1.8 times that of a propeller in isolation.

The advantages outweigh the limitations and thus we went ahead with CRPs. Also note that conventional CRPs use single motor/engine to power rotate both the propellers, whereas we shall be using 2 motors to power 2 propellers separately. They will only be arranged in a CRP configuration.

4.2. Arrangement of CRP units on the device

We will be keeping 4 units (out of the 6) on the bottom board of our device. The user will get to stand on the bottom board. These 4 units will be placed at vertices of a square and the controls will be governed by quadcopter dynamics, for which literature is plenty.

The algorithms for quadcopter control have been optimized over the years and have now become really robust in terms of both stability and maneuverability.

The other 2 units will be placed at the waist level of the passenger. This will shift the center of thrust up, thus stabilizing the system. The user will also get to place his arms on a support in such a configuration.

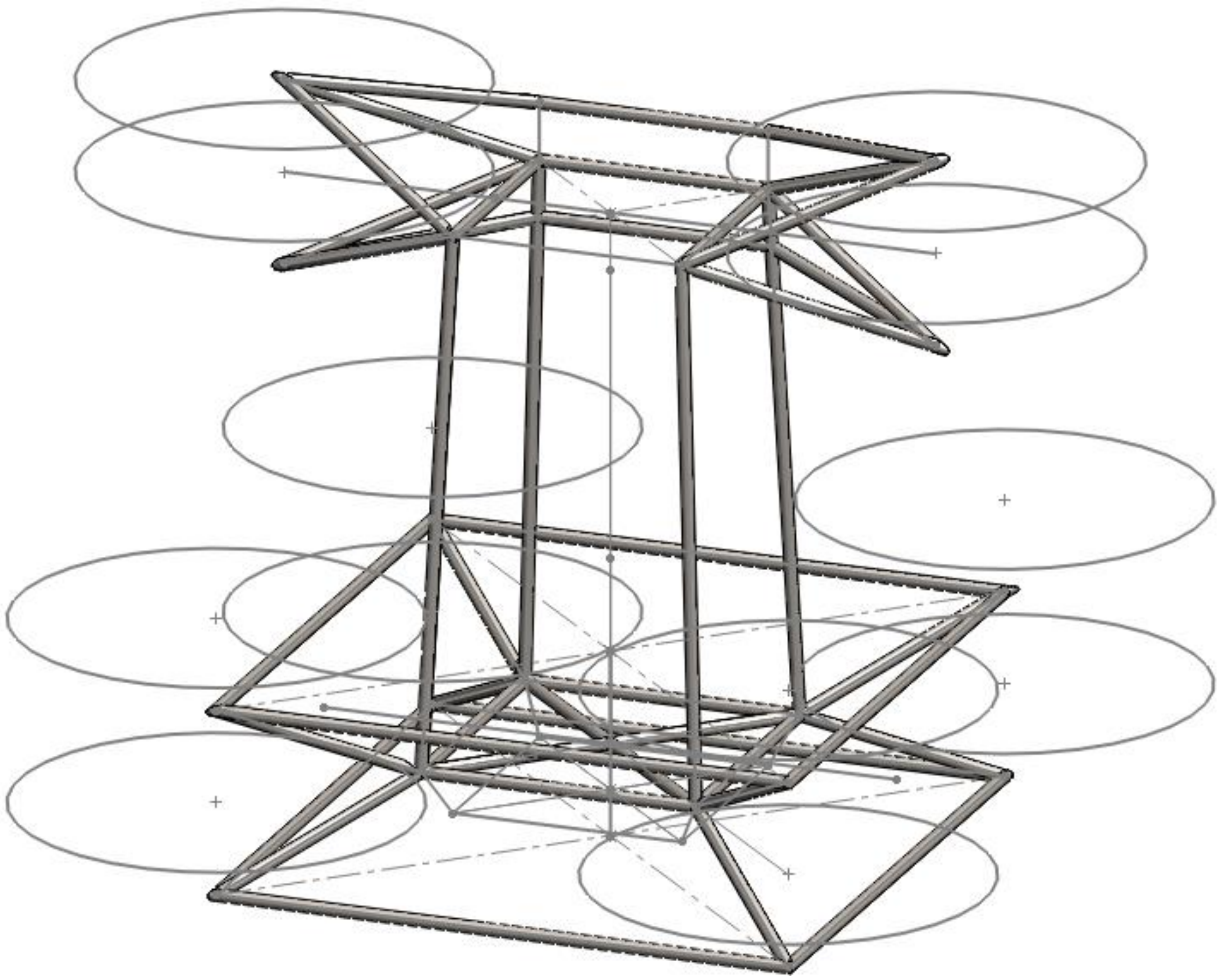

Fig 2 - Representation of configuration (each circle represents a propeller)

Figure above gives an idea of how the components will be placed. There will be 8 motor-propeller sets on the bottom board (4 on each plate). 4 units will be placed on the top board. The user will be present in the middle.

We shall be keeping batteries below the bottom plate in a battery box to lower the center of gravity – once again to gain additional stability.

The above design is just a representation to show the location of each motor-propeller set. It is unnecessarily overdesigned using 1 cm thick single piece plates. For the actual chassis, we have designed a 'space frame' structure which will be covered subsequently.

4.3. Moveable joints for the upper propellers

We are planning to give a rotational degree of freedom to the upper 2 units so that they can be intuitively moved by the user to move forward/backward (by rotating the units backward/forward respectively). The user will also be able to rotate about an axis passing through him along his height by rotating one unit forward and one unit backward.

An important point here is that the intent of motion through movements in the upper propellers will be assisted by the bottom quadcopter configuration. For example if the user points the upper propellers backwards to move forward, then this information will be detected by a sensor and passed on to the bottom board (BB) so that the 2 units on the rear of the BB can increase their RPM and the 2 units on the front can decrease to add to the forward acceleration. Other cases can be dealt with similarly.

This configuration is much more intuitive than simply having a remote control in our hands. It will also add to the feel and thrill of flying.

The sketches below will make the idea clear:

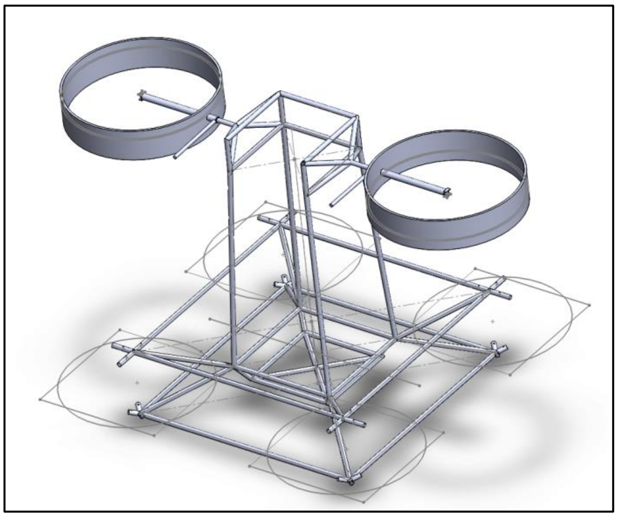

Fig 3 - Going vertically upward

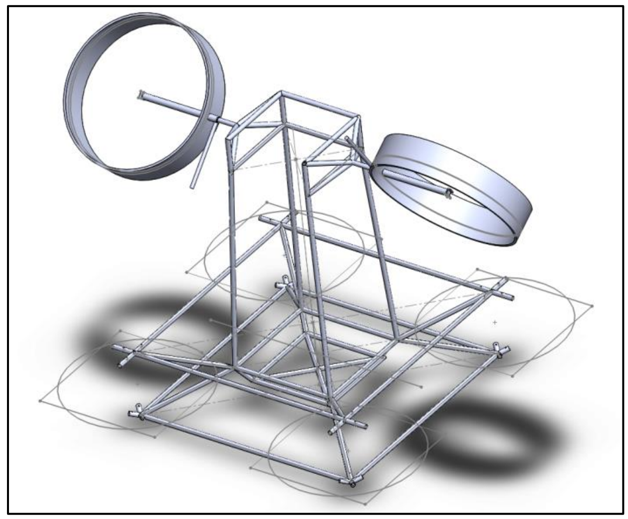

Fig 4 - Rotating anti-clockwise

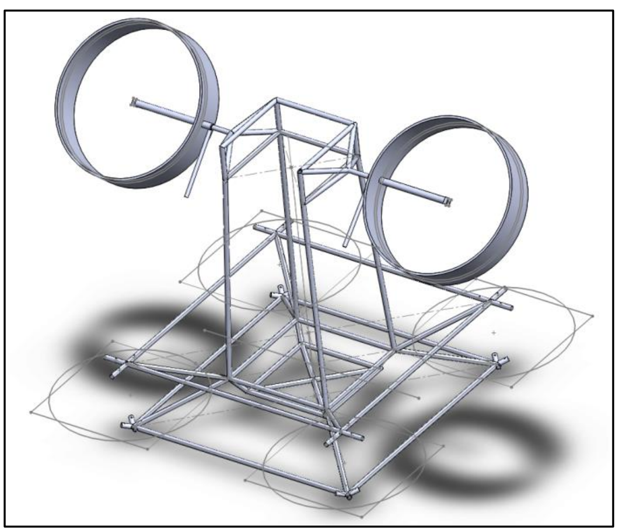

Fig 5 – Accelerating or moving forward

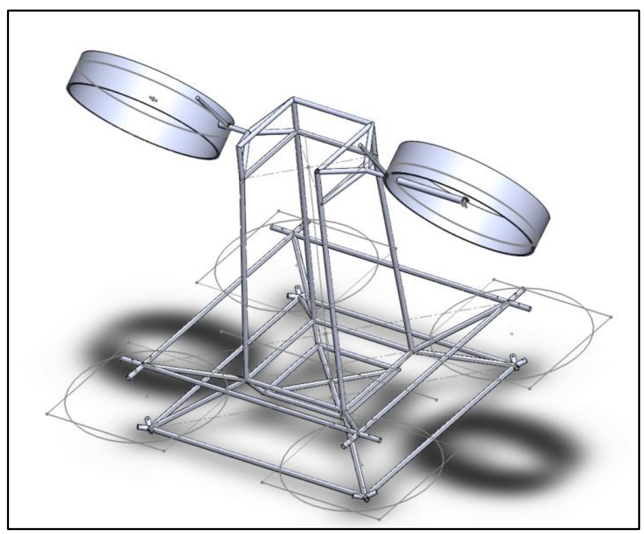

Fig 6 - Decelerating or moving backward

5. Chassis (Space frame)

Designing a space frame chassis involves the following steps:

1. Listing all the load cases. In our case, the following load cases would involve the extreme load cases:
   a. Full throttle which will give 30 kg per propeller.
   b. Full forward (or backward) motion – upper propellers turned backwards to the maximum angle and BB propellers with appropriate RPMs.
   c. Full rotational motion – one of the upper propellers turned forwards, other backwards and BB assisting the rotational motion. This will require centripetal force provided by the rods in the chassis.
2. Making an intuitive design using the above load cases. Procedure is as follows:
   a. Triangulation: At each node (point where multiple rods meet), ensure there are at least 4 rods, and no 3 of them are in one plane. This is the minimum number required to avoid bending.
   b. Ensure that every rod is only in tension or compression and try to avoid bending in any of the rods. This has to be done be following step (a) and also checking for all load cases (1. a, b, c).
   c. Attempt to get close to a tetrahedral angle between any pair of rods at the nodes. This provides symmetry and leads to nice distribution of load for the load paths.

With the above steps in mind, we designed a space frame chassis and made it as compact as possible, while ensuring that it does not fail in any of the load cases.

A diametric view of the frame is shown in Fig 7. We have used structural steel which can be heat treated to increase the yield strength to as high as 800 MPa.

The rod cross-section is an annulus with an outer diameter of 21.3 mm and thickness 2.3 mm.

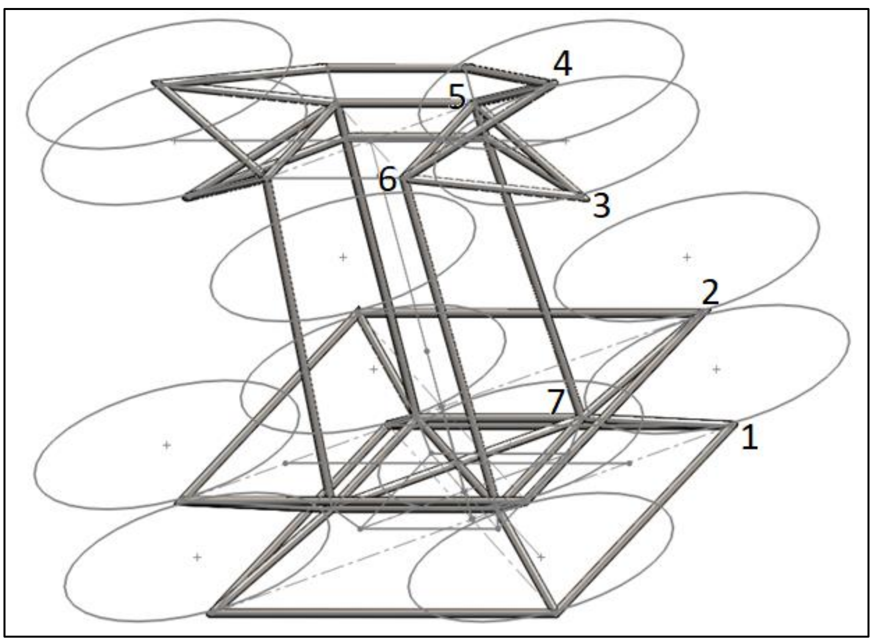

Fig 7 - Dimetric view of the exoskeleton frame

5.1. Nodes and Load Path

[Refer to Fig 7 - Dimetric view of the exoskeleton frame for node numbering] Node 1 is the bottommost node. There are 4 such nodes, each having one set of motor-propeller. Upward load (relative to the frame) from node-1 is distributed between 3 rods. The rods inclined upwards (between nodes 1 and 7) carry a compressive load transferred to load 7. The other rods which form a square simply balance the other components of the compressive load of the inclined rod.

Node 2 is the top node of the bottom board. The load path for the load at 2 is similar to 1, except for the fact that the inclined rod is now under tension.

For the top board, we have nodes 3 and 4 for the lower and upper propellers respectively. Upward load at node 3 is again distributed among 3 rods. Similar reasoning for node 4. Load from nodes 3 and 4 redistributes into nodes 5 and 6 with some amount of bending in the rods in the entire upper assembly. This happens due to the one missing rod in the front which we have kept for the user to enter. Finally the entire load is transferred to node-7.

Node 7 has a net upward force which is cancelled by the weight of the passenger plus the battery taken by the square with the diagonal rods (assuming steady velocity).

5.2. Analysis of various load cases

We analysed the design for the worst possible load case where all the propellers give maximum thrust and the user weight + battery weight is 200 kg. Shown below are some images of the analysis results.

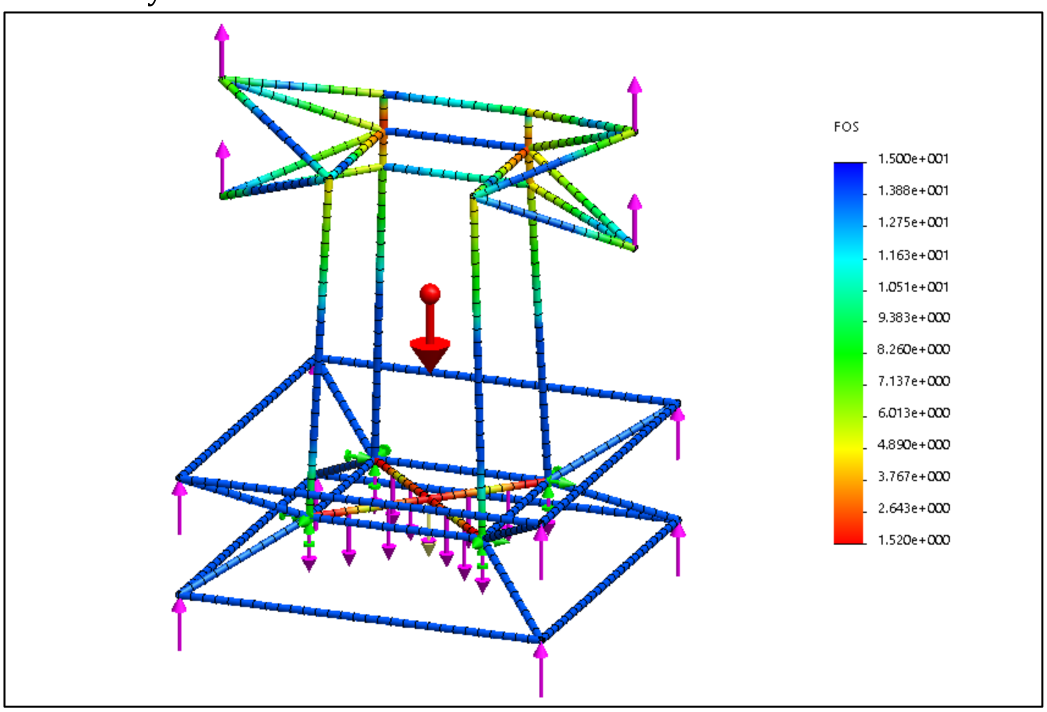

Fig 8 - Factor of Safety at each point in the Chassis

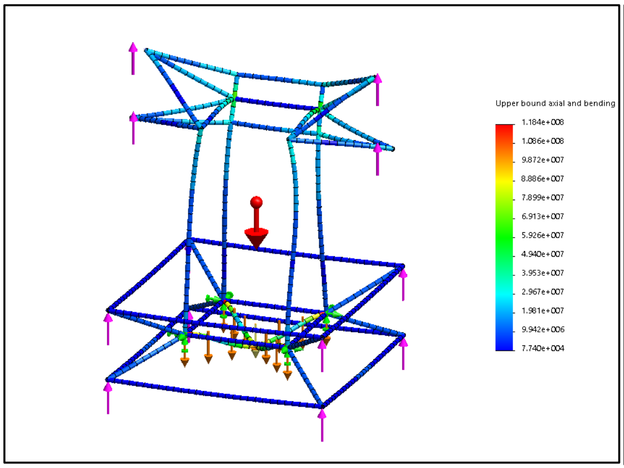

Fig 9 - Stress distribution in the Chassis

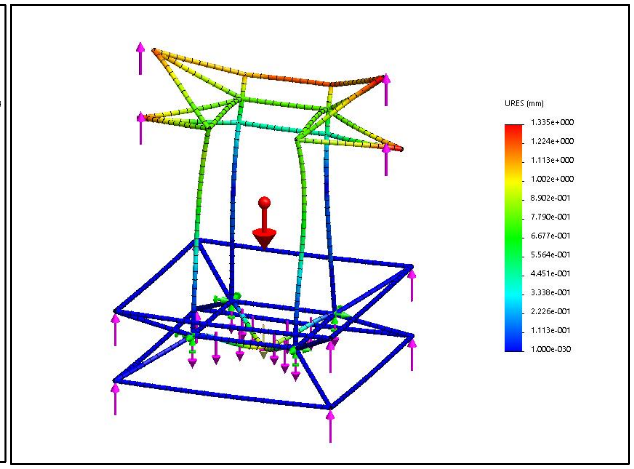

Fig 10 - Deformation of the Chassis

5.3. Post-Analysis comments

We can clearly see that all the rods do not undergo similar amount of loading and deformation. We can exploit this fact and use rods of different cross-sections to reduce the weight of the device, and also increase the factor of safety.

For example:

1. It can be seen that the 'square with the diagonals' which carries the passenger undergoes maximum loading and its nodes have a minimum factor of safety. We can use rods of larger outer diameter for the same which will reduce stress on these members of the chassis.
2. Similarly, the long rods which form a square on the bottom chassis have a safety factor of more than 10. Here, we can use thinner and smaller rods and reduce the weight by good amounts, as these are the longest rods in our chassis (length 1.1 m each, and 8 of them in total).

Another point to note is that we have used steel as the rod material in our initial design because of availability of good steel welders in the Indian market and the level of research on heat treatment of steel. The chassis weighs about 27 kg in this initial design, but after optimization, we have predicted a weight of less than 20 kg including the battery box. This will meet with our design requirement and get the dry weight (without batteries) of our device to less than 60 kg.

We will also try a new design with aluminium rods, and simultaneously search for excellent aluminium welders in the market to confirm the possibility of having an aluminium chassis. This will further reduce the weight and increase our flight time, acceleration, manoeuvrability, among many other factors.

6. Dynamics

The inertia of the chassis with the person on it makes it essential for the system to have some dynamic load bearing capacity. Landing the device is one of the essential tasks and it requires a dynamic system below the chassis to absorb the vibrations within the system. All the dynamic simulations and analysis has been done using ADAMS.

The way to proceed through this is through iterations with increasing complexity in every design. The first iteration included the simple analysis of a spring damper system with these systems placed at the end of the two base frames. Rough values of spring and damping coefficients are extracted.

The second iteration within the first design included using links to support the structure and distribute the load path in multiple directions to reduce the load on one part. This helps us to decrease the value of spring and damping coefficients.

The design (shown below) is a two-dimensional sketch in ADAMS of the modelled design. This includes applying a lock joint on the bottom part of chassis and applying a vertical prismatic joint to study the motion for the spring damping system and determining the response of the system subjecting to various loads.

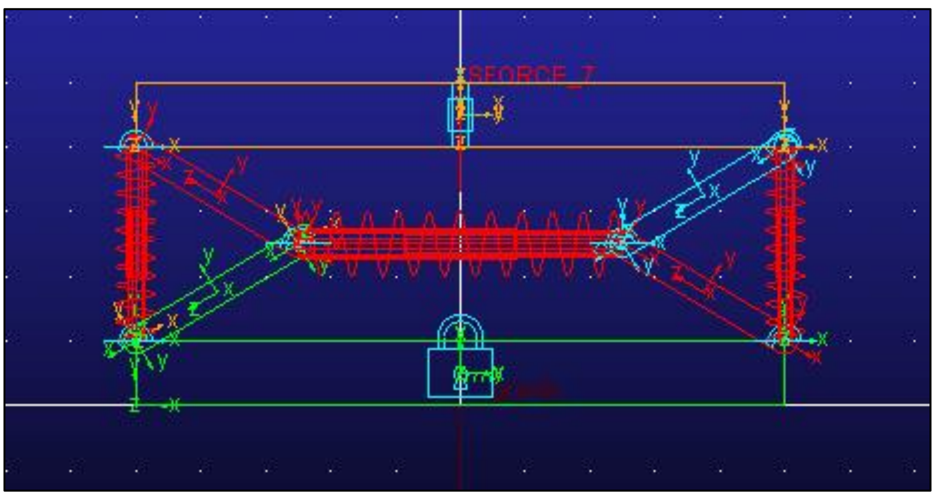

Fig 11 - 2D Spring-damper design modelled in ADAMS

The results for this spring damper system are shown as below.

External Vertical Downward Force - 2000N

Spring Constant - 20000 N/m

Damping Constant - 10 N-sec/m

Position Max Amplitude - 40mm

Velocity Max Amplitude - 2m/sec

Position Die-out Time - 2.3 sec

Velocity Die-out Time - 2.3 sec

Plots of deformation and velocity vs time follow.

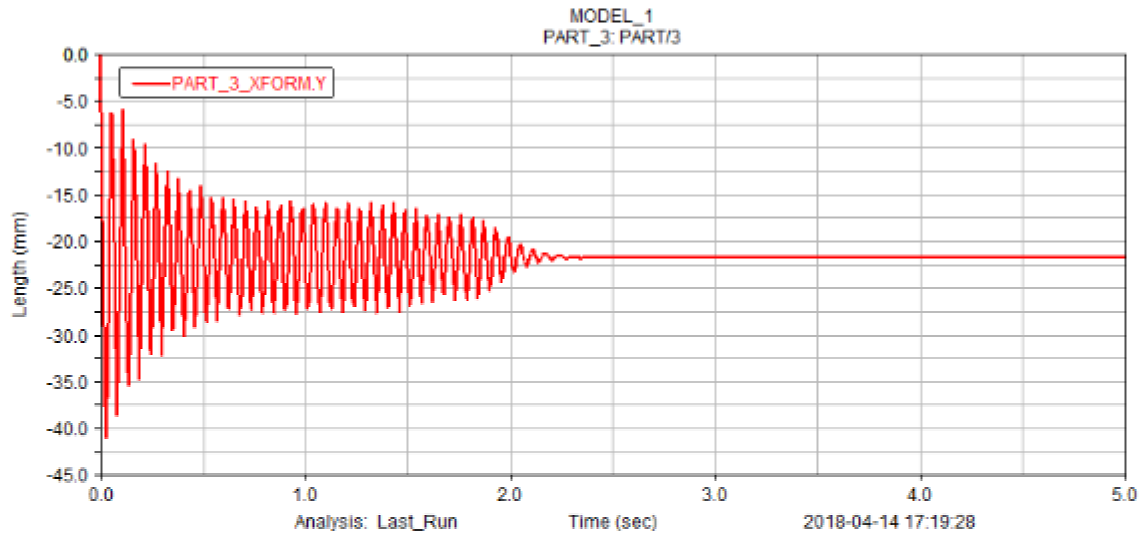

Fig 12 - Deformation in Y direction with respect to time

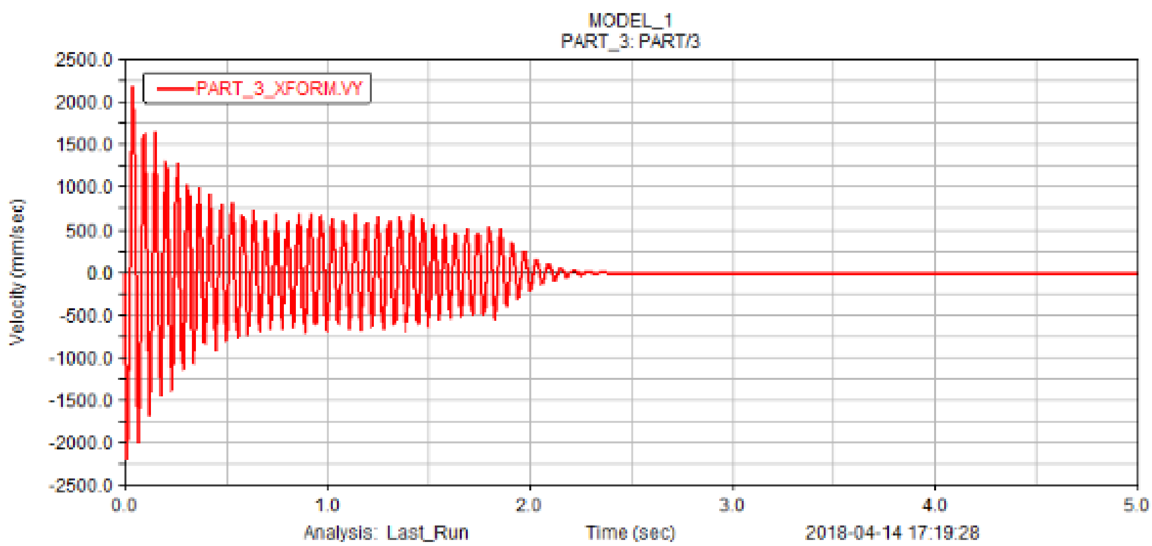

Fig 13 - Velocity in Y direction with respect to time

The loading conditions here includes the worst-case scenario where the force is considered to be maximum on the top part of the dynamic systems. For a general dynamic analysis, the system during landing will have a load less than the total weight of the chassis.

Further scope of work includes importing SolidWorks geometry of the dynamics space frame. Using a 3-Dimensional sketch the load path can be further improved and symmetric distribution of load ensures better dynamic characteristics of the system.

7. Battery Management System (BMS)

The requirement of this Battery Management System is to monitor cell voltage, pack voltage, and pack temperature. Each cell needs to be kept within a certain voltage through cell balancing. The cells need to be protected from cell over-voltage (COV) and cell under-voltage (CUV) by performing the necessary tasks depending on the statuses of the cells. This system also needs to mitigate the effects of fires in the cells by shutting the system down if there are thermal excursions beyond the set temperature limits.

Firstly, we will focus on the characteristics of batteries' charge and discharge. Knowing what currents are needed and what voltages are expected at every step in the charge and discharge is important when developing the BMS. Secondly, we will be focusing on different BMS chips by connecting them to a n-cell battery (n: varies according to the configuration) pack and to monitor the cells and control the cell balancing as needed. Thirdly, we will be creating a fully functional BMS as per our battery configuration (discussed below) that can monitor the cells and display the measurements to an LCD screen for the user to see.

7.1. Motor configuration

The motors we use to drive the propellers should provide enough mechanical output to drive the propellers at the required rpm to generate the thrust. Now at the hovering state the thrust required is 20kg and the max thrust expected is 26kg.

According to the 27x13E propeller data, the required rpm values and motor mechanical power output is shown below.

Hovering state:	RPM of motor shaft	5290 RPM
	Mechanical Power output of motor	4.211 kW
Max. Thrust state:	RPM of motor shaft	6230 RPM
	Mechanical Power output of motor	6.253 kW

Table 6 - Power and RPM for hovering case and maximum thrust case

Note that these values are slightly different from previous calculations because we will be using a 12S battery configuration to power the motor instead of 14S. This is because 6S batteries are easily available whereas 7S are not (so it is difficult to attain a 14S config.).

The kv rating of the motor is 150 RPM/V. This means for the above range (hovering to max thrust), the average voltages will be in the range of 35 to 42 V.

Now from the efficiency data of the motor (shown in the figure that follows) we see that the motor efficiency is maintained to be above 85% for the above voltage regions.

Current(A) \ Voltage (V)	10V	20V	30V	40V	50V
20	75.5	70.2	64.4	58	
30	82.8	79.3	76	72.3	68
40	85.3	83.7	81.5	78.7	74.9
50	86.5	85.9	84.5	82.3	79.3
70	86.9	87.8	87.1	85.9	83.9
100	85.5	87.7	88.2	87.8	86.4
130	77.9	87	87.5	88	86.8
160	75	81	84	86.5	86
190	72	78	82	85	84

Table 7 - Efficiency (in %) of the motor at various current and voltage values

Thus, we get the motor characteristics for the hovering state and max thrust state as,

	Hovering state	Max Thrust state
RPM of shaft	5290 rpm	6230 rpm
Power output at shaft	4.211 kW	6.253 kW
Power input to motor	4.954 kW	7.35 kW
Motor Terminal Voltage	35.3 V	41.5 V
Motor Current	141 A	177 A

Table 8 - Motor characteristics for hovering state and max thrust state

7.2. Battery configuration

The battery of the system supplies power to all the motors through the ESC. Thus the terminal Voltage of the battery must be sufficent to drive the motors at our required rpms. Since the maximum voltage we require at motor terminals is 41.5V , we choose a 12s configuration (44.4 V) for the batteries.

Also the Time of flight must be greater than 20 minutes. Thus the total energy content of the batteries can be calculated as 20 kWh. For this energy content using the lipo batteries mentioned in the battery selection, we need a total of atleast 56 cells. We thus use 60 individual batteries in a 2s30p configuration (2 in series and 30 such series combinations in parallel).

Thus, the total battery specs which can be calculated from the individual cell data.

Cell Configuration	2s30p
Terminal Voltage	44.4 V
Capacity	480 Ah
Max continuous discharge current	>7000 A
Energy Content	21.3 kWh

Table 9 - Battery specifications

Here we can see the current requirement by the motors is well below the maximum discharge current of the battery with a safety factor of 3. Thus, even with the reduction in current supply capability with discharge, the battery will still be able to supply enough current with a generous margin.

In the actual design, we have divided the batteries into ten smaller blocks each with 6 cells connected in 2s3p configuration. This is done so that if one of the batteries overheat or fail , then the failed battery can be individually shut down and since there is a safety factor of 3 , we can use the remaining blocks of batteries to safely run the device.

Image

7.3. Battery placement on the chassis

We have to accommodate 60 batteries into the chassis design shown above to meet the required specifications. The dimension of the battery we are using are 22.6*12.4*7.9 centimeters. The size of the bottom chassis is 100*100*25 centimeters. We divided the battery in three layers (24 + 24 + 12), layer with 12 batteries being the bottom most layer. We decided to keep it flat on the 22.6cm*7.9cm layer, thus we have 2 layers of height 12.4 cm, which correlates nicely with the distance between 2 layers of the bottom chassis (~25cm). In that configuration we could fit 24 batteries in one layer as shown in figure below. The third layer accommodating 12 batteries can be fit at the bottom of the two layers, also keeping them flat on 22.6cm*7.9cm. As a result, the third layer will increase the length of our structure. In the most optimal arrangement, the horizontal component of clearance from the propeller blades were 4.03cm on one side, 4.17cm on the other side, and 3.82 cm from the corner.

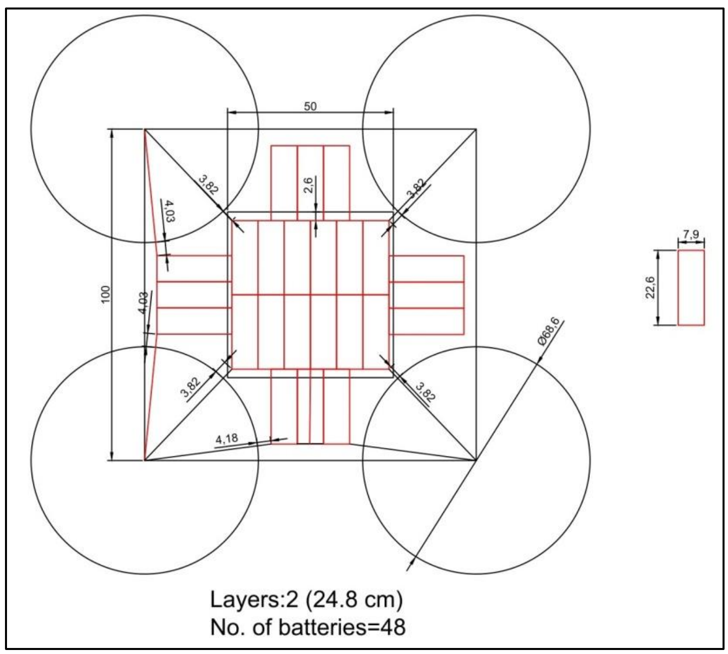

Fig 14 - Battery placement with respect to the chassis

8. Final specifications

Maximum device dimension	: 7 ft
Device weight	: 150 kg (40 kg thrusters + 20 kg chassis + 90 kg batteries)
Maximum available thrust	: 312 kg
Hovering thrust	: 240 kg
Top speed	: 120 km/hr or 65 knots
Cruising speed	: 60 km/hr or 32 knots

Maximum power consumption	: 88.2 kW;	Maximum power output	: 75 kW
Hovering power consumption	: 59.5 kW;	Hovering power output	: 50.5 kW

Maximum estimated noise level (50 feet away from the device) : 80 dB

9. Concluding remarks and unique features of our design

From all the analysis we have done, we can confidently say that our device meets all the criteria as specified by GoFly. It can lift a 90 kg person, has a flight time of 20 minutes, and its size is well within the limits to call it a personalized flying vehicle.

Listed below are some features of the device which we think are unique to our design and make the device different than most existing conventional personalized flying machines.

1. We are not giving the passenger a remote control to operate the device. We are giving one the freedom to mechanically move the upper propellers to specify the direction in which they want to go. This makes flying our device much more intuitive and will give a feel and thrill of flying, than just using a remote control.
2. The user can start and fly the device in less than a minute (if we exclude wearing a fire-retardant suit). One just has to enter the device, strap up and they are ready to fly. That's comparable to starting any regular road vehicle – enter, buckle up and drive.
3. It is an all-electric device. There are only a few (if not none) personalized flying vehicles in the market that are completely electric. Most are combustion based or hybrid. The challenge in an all-electric device is the low energy density of batteries as compared to any fuel. But we were able to get a configuration where we could get the entire device weight to just 150 kg (including the thrusters and power source).
4. We will still have a control board in front of the passenger. If the user is not comfortable doing the maneuvers mechanically, they can use this board.
5. We will have an override option at some ground control station. This can be used in cases of emergencies. For example, if the passenger suddenly feels giddy or unwell and is unable to control the device properly, then we can override the control to a ground station which can bring the device back to the ground.

9.1. The Electrical vs. Combustion dilemma

We felt this was an important discussion that we could not address in any of the previous sections. So, we will be showing a comparison table and concluding why we chose an electrically powered device over a combustion one.

Parameter	Electric	Combustion
Power Density of motors or engine (small scale)	3,000 W/kg	2,500 W/kg
Energy Density (best one)	300 Wh/kg	10,000 Wh/kg
Noise level (scale – one passenger device)	Low	High
Energy source associated risk	Low	High
Level of innovation	Relatively low	Quite high (been a century)
Level of challenge	High	Moderate

Table 10 - Electric vs. Combustion based systems - A comparison

From table 10, at a first glance, one would want to go for the combustion option for that sole parameter 'energy density' which reduces the weight beyond imagination. The level of research and development of combustion based systems is also quite high, owing to the fact that they have been around for more than a century now.

But, the electric industry is continuously developing and researching on battery technology, motors, and use of exotic materials among other innovations. This is an excellent motivator to venture into the field of electrically powered flying machines. Electrical cars have claimed their worth and soon, all IC engine cars will be replaced by electric ones.

Our hope for personalized flying machines is a similar one. Though that day might be much further away, we are willing to strive to promote and innovate in this field so that this wish may one day be fulfilled with a utopia of green personalized flying machines.

ExoFly is a step in that direction.

Fig 15 - ExoFly with an average sized human inside it

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