Conceptual Study of Tube Launched Unmanned Aerial Vehicle (UAV)

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Abstract

Unmanned Aerial Vehicle Technology is used in the field of the military as well as in the commercial domain. Current paper deals with Tube Launched UAV, wherein the complete UAV must fit inside a cylindrical tube and launch from the tube in a very short time. Mainly mechanical design and analysis are carried out towards wing folding for fitting the folded UAV inside a tube of 6 inch diameter. In addition, Propulsion system sizing, catapult launch system design including comparative study of different ramp angles for launching the tube with encapsulated UAV is also highlighted. The main objective behind using Tube Launched Unmanned Aerial Vehicles is that they can be transported in compact spaces like tubes that can be carried in ships, helicopters, planes, and larger drones.

Keyword: *Drone, UAV, Design, Propulsion and ESC.*

1.0 Introduction

UAVs need to be transported and deployed at the necessary location and larger UAVs require runway to take off. In the modern era we need technologies which are efficient and consume less time for deployment. With the advancing technologies, UAVs have the capability of morphing shape that is useful for better flight performance. And one of the morphing vehicles is Tube Launched UAV (TLUAV)[1] which contains foldable wings and launched from tubular launcher. TLUAV with wings reduces the problem of space and it can be easily packaged and transported. TLUAV is best suitable for mission profiles where launching the UAVs by conventional means is difficult. The launching system of TLUAV can easily be carried by an aircrafts, larger drones, helicopters and or ships.

Applications of Tube Launched UAVs:

- Monitoring, Exploring and Military Missions.
- Search and Rescue (SAR) operations.
- Aerial mapping, aerial surveillance, atmospheric sensing.
- The exploration of the ocean resources.

For the current UAV an existing designed UAV configuration has been studied towards the requirement for Tube Integrated concepts concerning mainly the wing folding and unfolding apart from suitable sizing of the propulsion system with foldable propellers[2]. The conceptual study towards configuration has already been done and only mechanical studies towards tube integration and launching is explored in the current paper.

2.0 Propulsion Sizing

The process of designing a UAV is challenging and involves many complex steps to choose the correct components to achieve the desired properties, one of them being the

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propulsion system, for example, it is desired to have long-range or efficient performance irrespective of the external condition, etc. Different types of flights require different power requirements, similarly, mission profiles, and the altitude at which the UAV is flying must also be and hence becomes an appropriate substitute for IC engines. Important parameters of an electric motor considered while designing a propulsion system. The driving motor's main objective is to perform at the required efficiency level, provide good endurance, be reliable, and support and perform to the sudden changes in throttle responses.
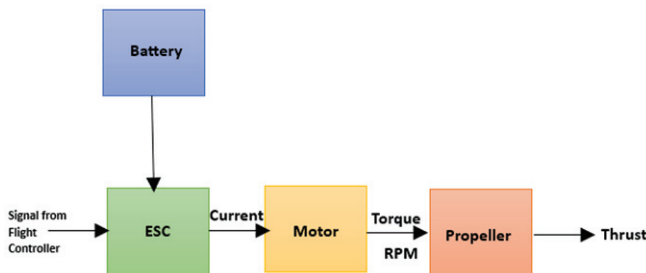

Figure 1: Components of electric propulsion system

There are various types of propulsion systems for a UAV:
1. IC Engines
    a. Nitro powered
        i. Methanol
        ii. Ethanol
        iii. Castor oil
    b. Petrol
    c. Diesel
2. Electric
    i. In Runner

In Runner motor spins only its shaft and the outer shell remains stationary.

    ii. Out Runner

The Out-Runner type motor spins its outer shell around its windings and these are extensively used in RC automotive and aircraft.
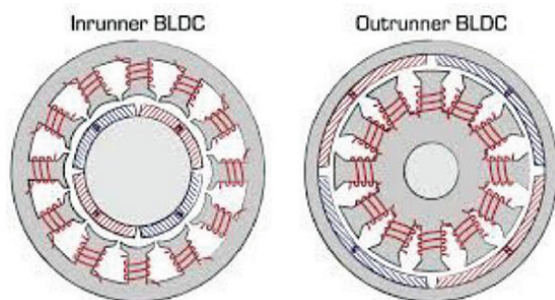

Figure 2: Electric propulsion classification

With the ease of maintenance and fewer vibrations leading to a simple design, the electric propulsion system is considered. Also, it is easily available, cost- effective, and hence becomes an appropriate substitute for IC engines.

Important parameters of an electric motor
- Stator diameter and height
- Number of poles
- Max power
- Operating voltages
- Max current draw
- KV rating

KV rating

It is defined as the RPM of the Motor per volt. Suppose a motor has 1450KV, then at unit volt it spins at 1450 RPM under no load. Higher KV rated motors will require smaller propellers and vice-versa. The ratio of power required to produce thrust increases with the motor KV rating, i.e., the greater the KV value, the greater the power required to produce the same thrust.

Motor and Propeller Selection Steps

If the weight of the UAV is known, then
i. Choose the thrust/weight ratio
ii. Calculate how much thrust required
iii. Deciding on the speed of the aircraft (slow or fast)
iv. Choose the correct KV value
v. According to the KV value found above, calculate Power/Thrust ratio
vi. With the required thrust, find the Power needed in Watts
vii. With the value of W, KV and thrust, finalize a motor from the data provided by the manufacturer
viii. Find the recommended propeller for this motor as per the data tables

2.1 Motor Selection

Thrust to weight ratio calculation:[1] We assume our UAV in the category of "sport and slow acrobatic" hence according to different RC pilots and users thrust to weight ratio is obtained as

$$\frac{T}{W} = 0.75 \qquad \qquad ...(1)$$

W = weight = 5000g

T = thrust = 3750g

Close to 50% throttle we are able to achieve a cruise speed of 25 m/s at the altitude of 2000m and the effective weight of the UAV is equal to lift generated, thus the thrust produced should compensate only the drag, due to this and other safety margins we are assuming to fly the UAV at 60% throttle and is chosen as criteria for motor selection.

Table 1: Speed comparison for lift generation

Cl max	1
ρ	1.006
Spam for Canard	90
Chord of Canard	1196
Spam of rear wing	1534
Chord of rear wing	88
Actual lift of Canard	24.525
Actual life of wing	24.525

Quantity	in mm^2	in m^2
Area of Chanard	107640	0.10764
Area of rear wing	134992	0.134992

Table 2 : Speed required at Throttle

Throttle percentage	RPM	RPS	Velocity (m/s)
12	800	13.333	6.26533
18	1200	20	9.398
24	1600	26.667	12.53066
30	2000	33.333	15.6633
36	2400	40	18.796
42	2800	46.667	21.92866
48	3200	53.333	25.06133
54	3600	60	28.194
61	4000	66.667	231.3266
67	4400	73.333	34.45933
74	4800	80	37.592
81	5200	86.667	40.72466
88	5600	93.333	43.85733
95	6000	100	46.99
100	6300	105	49.3395

Velocity = Pitch of the propeller (m) x rotation in RPS

Four motors-E-Flite Power 60(400KV), E-Flite power 90(325KV)[2], T-motor 450KV[3], and AXi 5325-308KV, are capable of providing 3750g of thrust. Thus on performing the analysis on ecalc software we conclude that AXi 5325-308KV has the highest efficiency at 60% throttle, thereby providing higher endurance at optimum.

2.2 ESC Selection

An electronic speed control (ESC) is an electronic circuit that controls and regulates the speed of an electric motor. It may also provide reversing of the motor and dynamic braking. ESC receives signals from the flight controller and provides control of the throttling of the propulsion system.

ESC needs to be sized according to the maximum current flowing to the motor.

According to the AXI motor company's specification, ESC (electronic speed controller) should have the following specification: 90-Amp 25V BL, 20amp BEC. Fig.4.
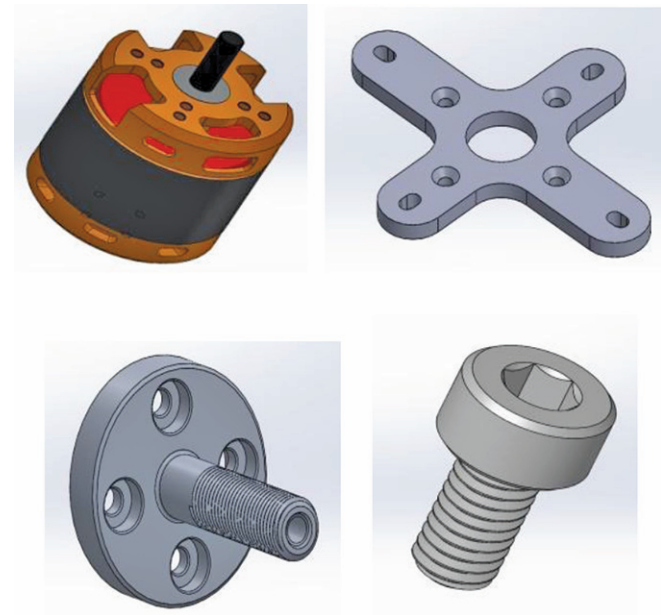

Figure 3. Motor components

Table 3: Comparison of different Motors

Parameters	E-Flite power 60(400KV)	E-Flite power 90(325KV)	T-motor (450KV)	Axi 5325-308KV
Efficiency at 60% throttle	79	86.8	86.4	87.5
Thrust/Weight	0.9:1	0.86:1	0.94:1	1.21:1
Temperature	75 ° C	38 ° C	50 ° C	51 ° C
Endurance	38-46 min	59-72 min	43-54 min	45-55 min
Current	14.7 A	12.5 A	16.6 A	16.2 A
Weight	380 g	450 g	408 g	595 g

2.3 Propeller Selection

According to ecalc software, the propeller is chosen to be Aeronaut 18.5×12, where 18.5 inches represents the diameter of the propeller and 12 inches is the pitch of the propeller.

Figure 4. ESC

2.4 Battery

From the Table 4 we can finalize Lipo because of its high energy density, less charging time and less maintenance. To operate the UAV at the required endurance, the following battery is been selected and it has the following specifications

Battery Specification: 8000mAh 3S 35C/70C (7.4V) lithium polymer battery pack

No of batteries: 2 (connected in series)

Dimension: 52mm × 43mm × 137mm

Figure 5. Propeller dimensions

Figure 6. Propeller spinner

Figure 7. Battery

3.0 Material selection

The primary objective of sizing the UAV was to limit the weight to 5kg. Different types of materials have been analyzed theoretically and validated using Solid works software and carbon fiber material has been chosen with the following properties:

Density = 1780 kg/m^3

Young's modulus = 231 Gpa

Yield tensile strength = 4410 MPa

Poisson ratio = 0.37

Bulk modulus = 296.15 GPa

Shear modulus = 84.307 GPa

Filament diameter = 6.9um

Shear strength = 124 Mpa

Flexural modulus = 128 GPa

3.1 Center of Gravity Estimation

It is determined by adding weight and moment of each weighing point to determine the total weight and total moment. For structural center of gravity i.e., excluding the battery, payload, flight control systems and avionics, the C.G is found out using the below equation:

$$C.G = \frac{(d_F*W_F)+(d_C*W_C)+(d_W*W_W)+(d_S*W_S)}{Weight} \quad \text{... (2)}$$

Where the subscripts F,C,W and S refer to Fuselage, Canard, Wings and Stabilizer respectively.

Using equation (2), the moments of individual components are evaluated from the reference point (i.e., from

Table 4: Comparison of different batteries

Characteristics	NiCd	NiMH	Lead acid	Li-ion	Li- Polymer	Resuable alkaline	Li-Fe
Energy density (Wh/Kg)	45-80	60-120	30-50	110-160	100-130	80	100-265
Fast charge time (h)	1	2 to 4	8 to 16	2 to 4	2 to 4	2 to 3	NA
Nominal voltage (V)	1.2	1.2	2	3.6	3.6	1.5	3.3
Fully charged (V)	1.3	1.5 - 1.66	2.1	4.1	4.2	1.7	3.6
Minimum safe charge (V)	1	1	1.8	3.4	3.4	1.2	3
Maintenance requirement	30-60 days	60-90 days	3-6 months	Not required	Not required	Not required	3-6months

Table 5: Center of gravity

C.G. x	0.5851
C.G. y	0.0025
C.G. z	0.0023

Table 6: Mass budget

Components	Quantity	Mass (kg)
Battery	2	0.870
Fuselage Nose	1	0.228
Propeller	2	0.060
Motor	1	0.595
Fuselage	1	0.423
Wing	2	0.482
Canard	2	0.368
Rudder springs	2	0.003
Wing Springs	4	0.169
Fuselage Tail	1	0.125
Rudder	2	0.120
Spring Shaft	2	0.045
Cap Canard	2	0.054
Cap Wing	2	0.052
T Nut	10	0.002
Screw	8	0.0067
2 Press fitConnector	4	0.0003
Spar	4	0.035
Washer	10	0.0012
Total Weight		3.6401

the nose tip of UAV) and further, the center of gravity is as shown in Table 5.

3.2 Mass Budget

The total mass has been calculated using Solidworks software with Hexcel AS4C type carbon fiber. As shown in Table 3, the overall weight of the TLUAV excluding the payload, avionics and control surfaces is evaluated to be 3.6kg, which fulfills the criteria of the overall weight of TLUAV to be well under 5kg. The remaining weight allocation can be given for payload and recovery systems.

4.0 Wing Deployment Designs

Various concepts were studied towards wing deployment like
   (a)   Telescopic wing mechanism
   (b)   Roll out solar array (ROSA)
   (c)   Multi Hinge solar array deployment
   (d)   Outrider wing release mechanism

A spring-based mechanism was considered. Considering hard drawn steel spring wire of tensile limit (min) =1900 MPa. Assuming the spring geometry to meet the load requirement without exceeding 60% of the material tensile limit at 90° rotation. The full spring length should be about 20 mm and the spring to be inserted with a 25 mm rod. The internal diameter must clear the rod by 15 %. The spring is required as part of an assembly to counter the 20N load at 365 mm.

Equations used:

$$T = F * r \qquad \qquad ... (3)$$
$$\sigma = 32*T*d3 \qquad \qquad ... (4)$$

Table 7: Structural Mass

		Density of CF=1780 kg/m3				
		X axis	Y axis	Z axis	Volume of shell	Mass (kg)
Canard	Left	222.5	-299	43	0.000306176	0.545
	Right	222.5	299	33		
Main wing	Left	903.97	-337.5	-31	0.0003726	0.663
	Right	903.97	337.5	-45		
Fuselage	Middle body	591	0	0	0.000204288	0.363
	Payload	114	0	0	0.00004279477513	0.076
	Dome	37.4	0	0	0.00003034987943	0.054
	Tail	1036.66	0	0	0.00001598023463	0.028
Stabilizer	Left	983.75	50	95	0.00002584	0.091
	Right	983.75	50	95		
	Total				0.0009980288892	1.822

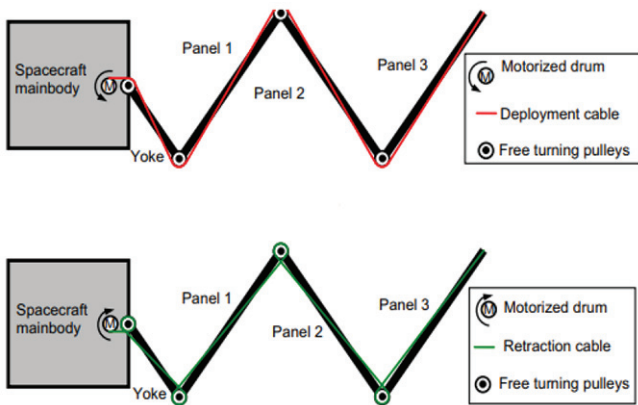Figure 8. Roll out solar array (ROSA)

Figure 9. Multi hinge solar array deployment

Figure 10. Outrider wing release mechanism

$$K = \frac{F}{\theta} \qquad \ldots (5)$$

Stress correction

$$D_i = D_{rod} * 115\% \qquad (6)$$

$$D_o = D_i + 2d \qquad (7)$$

$$c = Dd \qquad (8)$$

Actual stress

$$\sigma = \frac{32*T}{\pi*d^3} X \frac{4c^2 - c - 1}{4c*(c-1)} \qquad \ldots (9)$$

$$N_a = \frac{E*d^4}{10.8*D*K} \qquad \ldots (10)$$

Contribution from ends

$$N_e = \frac{L1 + L2}{3*D*\pi} \qquad \ldots (11)$$

$$N_b = N_a - N_e \qquad \ldots (12)$$

Spring length at free state

$$L_{fs} = (N_a + 1) * d \qquad \ldots (13)$$

Spring length at loaded state

$$L_{ls} = (N_a + 1 + 0.25) \times d \qquad \ldots (14)$$

Table 8: Spring result table for vertical stabilizer

Rates and torques	
Rate per degree	2.109 N-mm/deg
Spring rate	759.288 N-mm/360
Max torque	183.180 N-mm
Physical dimension	
Diameter of spring wire, d	1.079 mm
Outer diameter of spring, Do	13.658 mm
Inner diameter of spring, Di	11.5 mm
Mean diameter of spring, D	12.579 mm
Number of active coils, Nn	2.718
Body length	4.012 mm
Length of arm1	95 mm
lengthh of arm2	95 mm
Total arm length	190 mm
Direction of wind	Left hand
Spring index, C	11.658
Material type	
Music wire ASTM A228	
Weights and measures	
Weight of 1 spring, M	0.0021 Kg
Length of wire required to make 1	297.4102 mm
Stress factors	
Shear Modeulus, G	80483.5482 Pa
Maximum shear stress, tmax	5245.9733 Pa
Wahl Correct factor, w	1.1231

The following results were finalized after iterating with different standard spring materials.
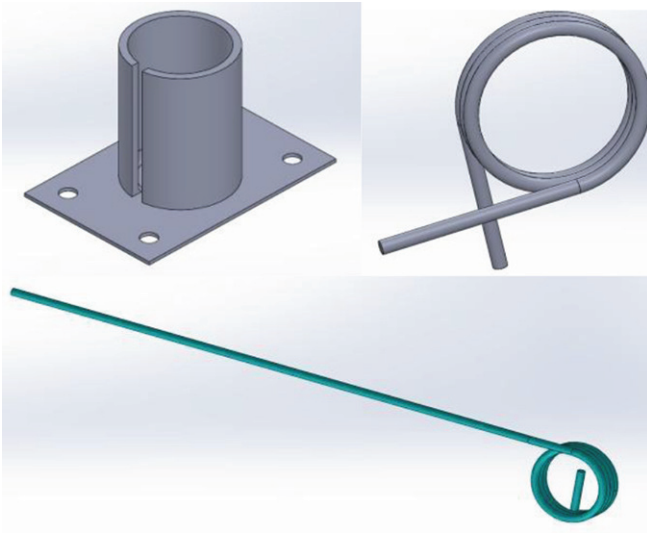
4.1. Wings and Fuselage Assembly
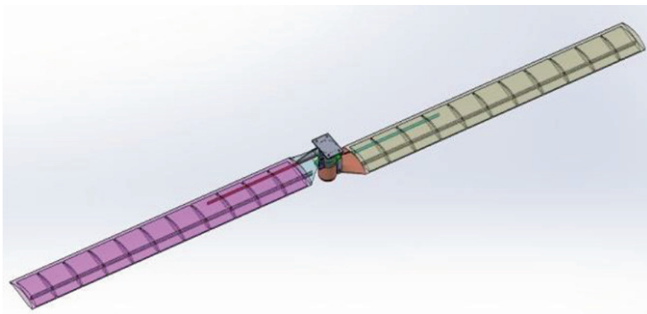

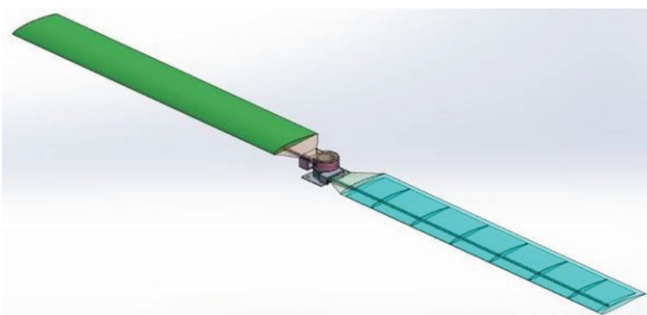Figure 11. Spring and shaft assembly

Figure 12. Wing assembly

Figure 13. Canard Assembly

5.0 Catapult Launch Design

Similarly, towards design of primary launch system, many existing concepts were studied along with their relative merits.

Table 9: Spring result table for wings

Rates and Torques	
Rate per degree	56.148 N-mm/deg
Spring rate	20226.318 N-mm/360 deg
Max Torque	4049.836 N-mm
Physical Dimension	
Diameter of spring wire, d	3.237 mm
Outer diameter of spring, Do	35.225 mm
Inner diameter of spring, Di	28.751 mm
Mean diameter of Spring, D	31.988
Number of active coils, Nn	3.25
Body length	13.757 mm
Length of arm1	240 mm
lengthh of arm2	240 mm
Total arm Length	480 mm
Direction of wind	Left hand
Spring Index, C	9.882
Material Type	
Music Wire ASTM A228	
Weights and measures	
Weight of 1 spring, M	0.0522 kg
Length of wire required to make 1	806.603 mm
Stress Factors	
Shear Modeulus, G	80483.5482 Pa
Maximum shear stress, tmax	11152.6202 Pa
Wahl Correct factor, w	1.1467

(a) Weight and pulley launchers
(b) Spring launchers
(c) Pneumatic/hydraulic launchers
(d) Electro-magnetic launchers
(e) Bungee powered catapult launch

For our requirements, a bungee powered catapult system is considered for further investigation towards requirements.

5.1 Positive Ramp Angle Catapult Analysis

This analysis is done about positive ramp angle catapult design.

The elastic cord is connected to the cradle by one of its ends and then enwrapped over a system of rollers. By the other end, it is firmly attached to the rail body. The elastic cords are tensioned by moving the cradle to the start position where it is locked. After releasing, the force of the elastic

Table 10: Comparisons of wing release deployment mechanism

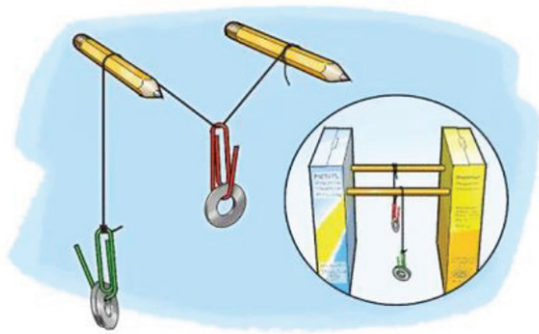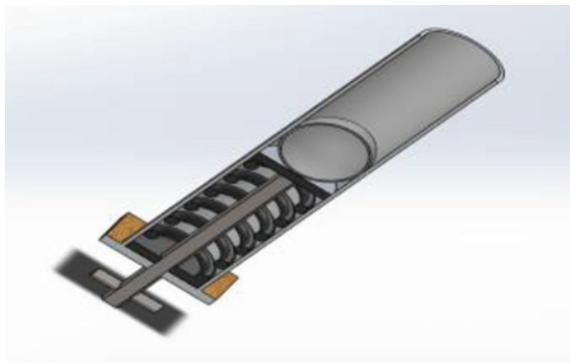| Wing deployment mechanisms	Advantages	Disadvantages
Telescopic Wing Deployment	- Compact and simple. - Very large wingspan could be folded in small structure	- Uniform thickness of the wing cannot be obtained. - Consumes power. - Heavy.
Roll out Solar Array (ROSA)	- Light weight - Compact - Uniform wing width obtained - Scalable	- Moving parts involved - Temperature constraints
Multi Hinge Solar Array Deployment	- Simple - Compact - Uniform width of wing obtained	- Temperature constraints - Chance of failure atmechanical joints
Outrider Wing Release Mechanism	- Simple - Proven technology	- Non uniform width

Figure 14. Weight and Pulley Launchers

Figure 16. Pneumatic/Hydraulic Launcher
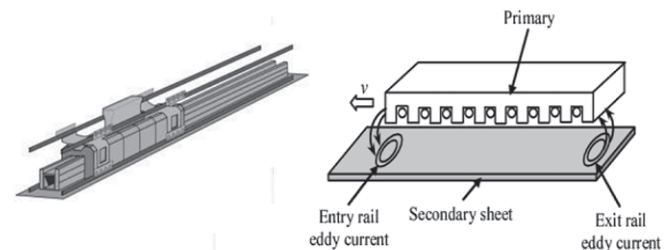

Figure 15. Spring Launchers

Figure 17. Electromagnetic Launchers

cords accelerates the cradle to a maximum speed at the end position where the damper stops it. After the cradle stops, the forward momentum causes the UAV to continue forward and takes over the flight with its propulsion assistance.

The front roller can only rotate and can't move, but the rear one can rotate and has linear displacement. This linear displacement is used to pre-tension the cord.

5.1.1 Mathematical model

Assumptions
- The mass of the elastic cords is neglected.
- The mass of the rollers is neglected.
- Direction of the force of the elastic cords that tow the cradle with the UAV is coplanar to the inclined plane.

Figure 18. Bungee Powered Catapult Launchers

Load (in N) to give extension of :-				
Diameter	30%		75%	
(mm)	Min (N)	Max(N)	Min(N)	Max(N)
5	29	38	50	65
6.5	58	76	100	130
8	88	116	150	196
9.5	120	170	210	280
12.5	210	280	370	480
16	350	460	500	600
19	500	650	850	1100
22	660	880	1150	1500
26	930	1250	1600	2100
28	1080	1425	1850	2425
32	1410	1875	2425	3200

Figure 19. Bungee cord specifications

- The friction force of the elastic cords over the rollers is neglected.
- Stiffness of the elastic cords is constant.
- It is considered that the UAV propeller pulling force T is constant.
- Elastic cords force Fe is linear to elongation.
- The UAV drag forces are neglected.
- Time = 0.9 sec

Specification
- Considering Thrust from propeller; T = 250N
- Ramp length L = 5 m
- Bungee cord length (non-elongated) b = 8 m
- Ramp angle = α
- Bungee cord stiffness (N/m) = K
- Length of the bungee cord at any instant = x
- Total initial elongation including (with elongation of 1.5 m) x0=14.5m

Balancing Force at equilibrium

X-axis: $Mg \sin\alpha - Fe + F\mu - T = 0$ ... (15)

Y-axis: $Mg \cos\alpha - N = 0$ ... (16)

From newton's 2nd law we know that

$F_{NET} = M*a = Mx''$ ... (17)

$M = m_{UAV} + m_{Tube} + m_{cradle}$ ... (18)

Elastic force $F_e = k\ (x - b)$ ... (19)

Frictional Force $F\mu = \mu N = \mu Mg \cos\alpha$ ... (20)

$Mx'' = Mg \sin\alpha - k(x-b) + \mu Mg \cos\alpha - T$ ... (21)

$Mx'' + kx = Mg \sin\alpha + kb + \mu Mg \cos\alpha - T$ ... (22)

$X'' + x\dfrac{k}{M} = g\ (\sin\alpha + \mu \cos\alpha) + b\dfrac{k}{M} - \dfrac{T}{M}$ ... (23)

Table 11: Launch Systems

Launch Systems	Advantages	Disadvantages
Weight and Pulley Launchers	- Simple and easy to implement.	- High launching velocity can not be achieved - Occupy large volume - System becomes bulky if scaled up
Spring Launcher	- Simple and easy to implement	- Over a long duration the spring might lose its elasticity - System becomes bulky if scaled up - High exit velocity can not be obtained
Pneumatic/Hydraulic Launch Systems	- Heavier UAV can be launched - High take off velocity	- Requires Power supply - Bulky and difficult to transport - Noisy - Not feasible for launching from aircraft
Electro-magnetic Launcher	- It accelerates UAV smoothly, putting less stress on their airframes. - Require less maintenance	- Consumes power - Expensive
Bungee Powered Catapult Launcher	- No energy is consumed - More reliable - Cost-effective - It can be scaled up or down according to the requirement	- Very high launch velocity cannot be achieved - Upon the multiple usagesthe bungee cord would lose its desired stiffness - Heavier aircraft are difficultto launch using catapult system

Differential Equation Solution

(Initial conditions at t = 0, x = 0 and x' = 0)

$$x(t) = \left(x_0 + \frac{T}{k} - \frac{Mg\,(sin\alpha + \mu\,cos\alpha)}{k} - b\right)$$

$$Cos\left(\sqrt{\frac{k}{M}}\,t\right) + \frac{Mg\,(sin\alpha + \mu\,cos\alpha)}{k} + b - \frac{T}{k} \qquad \ldots (24)$$

$$x(t)' = \left(x_0 + \frac{T}{k} - \frac{Mg\,(sin\alpha + \mu\,cos\alpha)}{k} - b\right)\sqrt{\frac{k}{M}}\,sin\left(\sqrt{\frac{k}{M}}\,t\right) \ldots (25)$$

$$x(t)'' = -\left(x_0 + \frac{T}{k} - \frac{Mg\,(sin\alpha + \mu\,cos\alpha)}{k} - b\right)\frac{k}{M}Cos\left(\sqrt{\frac{k}{M}}\,t\right) \ldots (26)$$

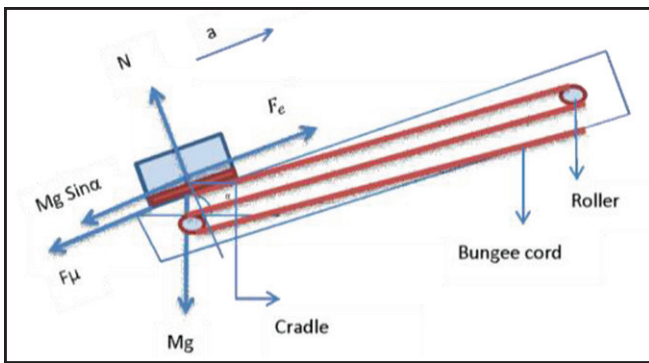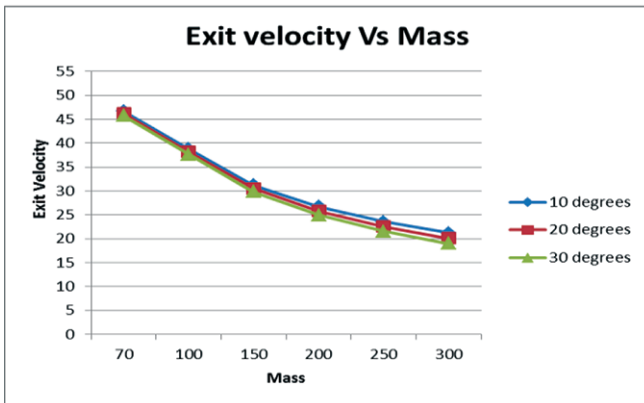
Figure 20. Free body diagram for positive launch angle

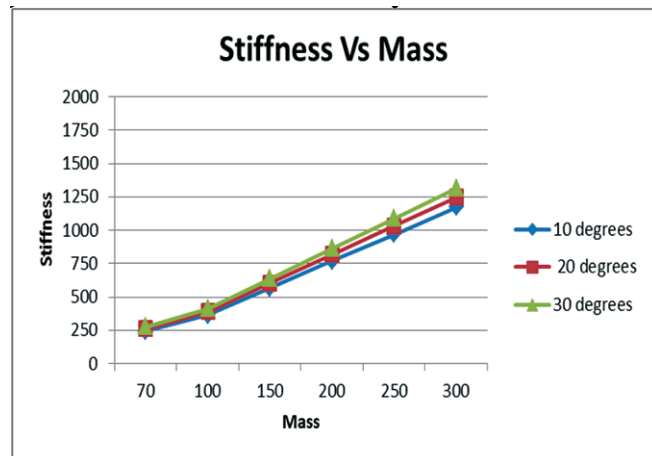Plotting exit velocity VS Mass graph at different ramp angles At constant stiffness K = 800 N/m

Graph 1: Velocity VS Mass at different angles

Plotting stiffness VS Mass graph at different ramp angle at constant Exit velocity V = 21.7 m/s. (Graph 2)

In the case of plotting exit velocity vs mass graph at different ramp angles at constant stiffness following observation was made

- As mass increases the exit velocity decreases for given ramp angle
- As the ramp angle increases exit velocity for given mass decreases

Graph 2 Stiffness VS Mass at different angles

In the case of plotting stiffness VS mass graph at different ramp angles at constant exit velocity following observation was made

- As mass increases the required stiffness of bungee cord increases for given ramp angle
- As the ramp angle increases the stiffness of the bungee cord increases for a given mass.

5.2 Negative Ramp Angle Catapult Analysis

This analysis is done for following ramp design.
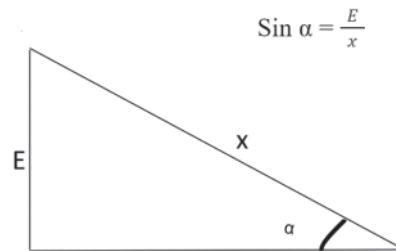

$$Sin\,\alpha = \frac{E}{x}$$

Figure 21. Ramp design

The elastic cord set is connected to the tube by one of its ends and by the other end it is firmly attached to the rail body. The elastic cords are tensioned by moving the UAV to the start position where it is locked. After releasing, the force of the elastic cords accelerates the tube along the launching rail to the end position. The tube reaches a maximum speed at the end position where the damper stops it. After that tube stops, the forward momentum causes the UAV to continue forward and launch it.

5.2.1 Mathematical model

Assumptions:

- The mass of the elastic cords is neglected.

- Direction of the force of the elastic cords that tow the cradle with the UAV is coplanar to the inclined plane.
- Stiffness of the elastic cords is constant.
- Elastic cords force Fe is linear to elongation.
- The UAV drag forces are neglected.
- Time = 0.5 sec

Specification:
- Ramp elevation = α
- Bungee cord length = b
- Elongation of cord = 20-80%
- Friction coefficient μ = 0.25
- Height of ramp = E
- Ramp length = x =1.75*b
- Length of the bungee cord at any instant = x

Balancing Force at equilibrium

X axis: Mg sinα + Fe - Fμ=0   ... (27)

Y axis : Mg cosα - N=0   ... (28)

From newton's 2nd law we know that

F_{NET} = M*a=Mx"   ... (29)

M = m_{UAV} + m_{Tube} + m_{cradle} ... (30)

Elastic force Fe = k (x − b)   ... (31)

Frictional Force Fμ = μN = μMg cosα ... (32)

M x(t)" = Mg sinα + k(x−b) −μMg cosα ... (33)

x(t)"−xkM = g(sinα − μ cosα) − bkM   ... (34)

Differential Equation Solution
(Initial conditions at t = 0, x = 0 and x' = 0)

$$x(t)= \frac{(Mg\ sin\alpha - kb - \mu Mg\ cos\alpha)}{2k} e^{t\sqrt{\frac{k}{m}}} +$$
$$\frac{(Mg\ sin\alpha - kb - \mu Mg\ cos\alpha)}{2k} e^{-t\sqrt{\frac{k}{m}}} - \frac{Mg\ sin\alpha}{k}$$
$$+ \frac{\mu Mg\ cos\alpha}{k} + b \quad\quad ... (35)$$

$$x(t)'= \frac{(Mg\ sin\alpha - kb - \mu Mg\ cos\alpha)}{2k}\left(\sqrt{\left(\frac{k}{m}\right)}\right) e^{t\sqrt{\frac{k}{m}}} +$$
$$\frac{(Mg\ sin\alpha - kb - \mu Mg\ cos\alpha)}{2k}\left(-\sqrt{\left(\frac{k}{m}\right)}\right) e^{-t\sqrt{\frac{k}{m}}} \quad\quad ... (36)$$

$$x(t)''= \frac{Mg\ (sin\alpha - \mu\ cos\alpha) - bk}{2m} e^{t\sqrt{\frac{k}{m}}}$$
$$+ \frac{Mg\ (sin\alpha - \mu\ cos\alpha) - bk}{2m} e^{-t\sqrt{\frac{k}{m}}} \quad\quad ... (37)$$
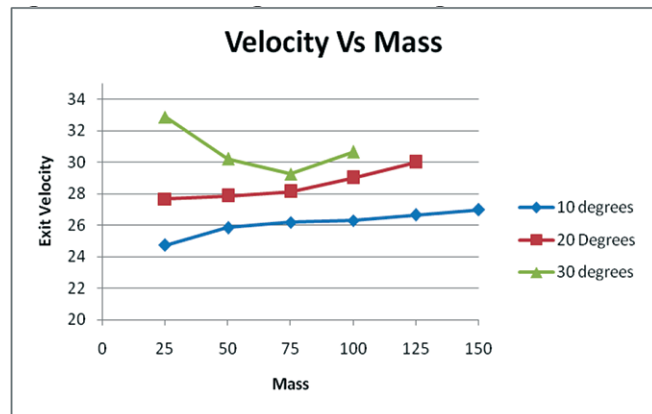
Plotting exit velocity vs Mass at different ramp angles at 75% elongation of bungee cord. (Graph 3)
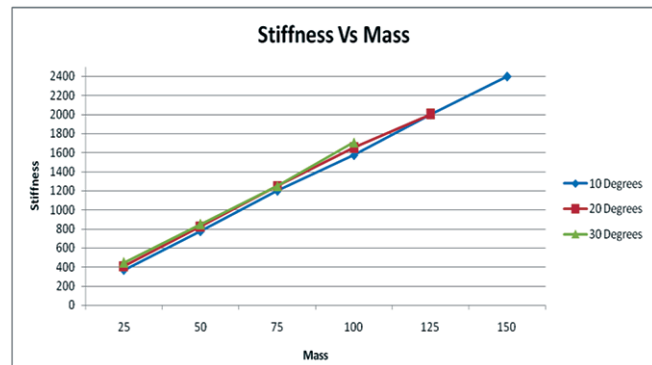
Plotting Stiffness vs Mass at different ramp angles at 75% elongation of bungee cord. (Graph 4)

From the analysis following observation is made:
- As the mass increases the exit velocity and stiffness of the bungee cord increases.

Graph 3 Velocity VS Mass at different angles
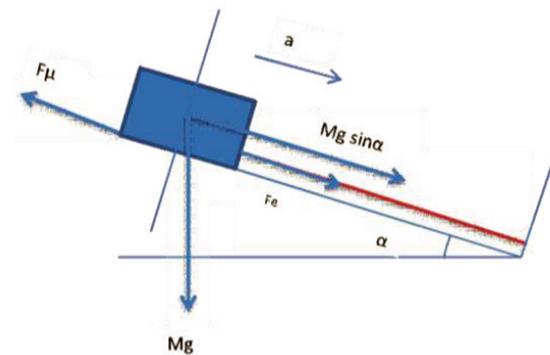

Graph 4 Stiffness VS Mass at different angles

Figure 22. Free body diagram for negative launch angle

- As the ramp angle increases exit velocity increases.

Therefore, from the above results we can conclude that the optimal launching ramp angle for a lighter UAV would be 30°.

5.3 TL-UAV Launch System

Launching the TL-UAV along the negative ramp angle with total mass to 7 kg (for 5 kg TUAV with 2 kg tube) given below are the acceleration, velocity, and stiffness of cord at different ramp angles.

Table 12: Parameters at 10⁰ Ramp angle

TRIAL 1	AT 75% ELONGATION		K RANGE FROM 36.73-2350.78	
μ	0.25			
α	0.17452		FROM DIFFERENTIAL EQ	
M	7	V	26.25	
g	9.81	a	108.09	
b	1.815	FROM MOTION EQ		
k	110	V	26.242	
TIME Sec	0.5			
E RAMP HEIGHT		0.551		
S RAMP LENGTH		3.173		

Table 13: Parameters at 20⁰ Ramp angle

TRIAL 2	AT 75% ELONGATION		K RANGE FROM 35.27-2257.49	
μ	0.25			
α	0.17452		FROM DIFFERENTIAL EQ	
M	7	V	27.216	
g	9.81	a	113.78	
b	1.89	FROM MOTION EQ		
k	114	V	26.49	
TIME Sec	0.5			
E RAMP HEIGHT		1.136		
S RAMP LENGTH		3.32		

Table 14: Parameters at 30⁰ Ramp angle

TRIAL 3	AT 75% ELONGATION		K RANGE FROM 32.36-2071.19	
μ	0.25			
α	0.17452		FROM DIFFERENTIAL EQ	
M	7	V	30.65	
g	9.81	a	131.09	
b	1.815	FROM MOTION EQ		
k	120	V	30.73	
TIME Sec	0.5			
E RAMP HEIGHT		1.801		
S RAMP LENGTH		3.6		

From the above trials, it can be seen that when a 5kg UAV is launched at a ramp angle of 30°, the maximum exit velocity is obtained.

6.0 Results and Discussions

Primary objective being fitting the UAV into a 6inch diameter tube with max length arrived from earlier preliminary study being 1.13m. A suitable wing foldable mechanism is designed and analyzed along with a foldable propeller mechanism with an electric propulsion system. UAV can fit inside the tube with some clearance spaces, therefore friction between UAV and tube is low.

Since the structural weight of the UAV is less than 30% of 5 kg, we propose carbon fiber material for the TLUAV and it serves the purpose of reducing the weight drastically unlike aluminium or stainless steel. The final design of the TLUAV consists of 4 torsional springs for wing folding, 6 ribs in the Canard and 10 ribs in the rear wing. Each of these ribs are connected with a 5mm spar which is a hollow rod made up of Carbon fiber to decrease the overall weight of the TLUAV. the following Fig. shows the complete design
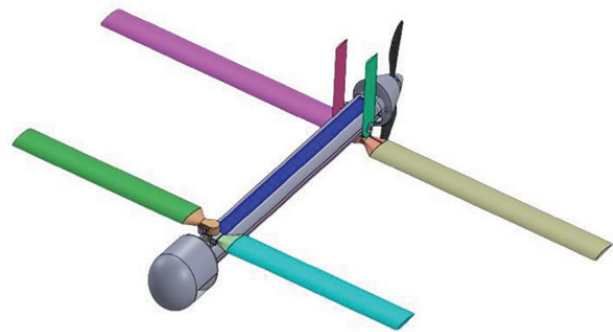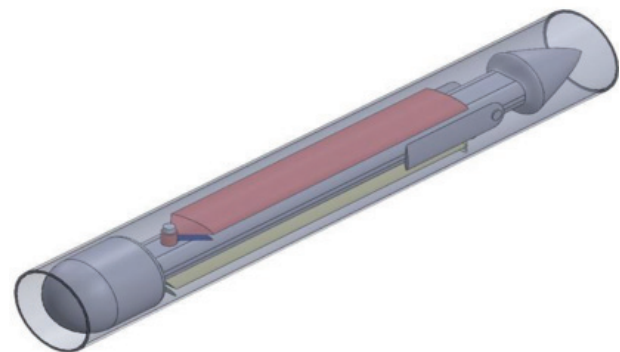

Figure 23. Final design of TLUAV

Figure 24. Wings in folded condition (inside the tube)

7.0 Conclusions

Unmanned Aerial Vehicle design has been carried out with an objective of Tube Launched UAV, wherein the complete UAV must fit inside a cylindrical tube and launch from the tube in a very short time. Mainly mechanical design and analysis are carried out towards wing folding for fitting the folded UAV inside a tube of 6 inch diameter and length of 1.13m. In addition, Propulsion system sizing, catapult launch system design including comparative study of different ramp angles for launching the tube with encapsulated UAV is also highlighted.

The main advantage of using Tube Launched Unmanned Aerial Vehicles is that they can be transported in compact

spaces like tubes that can be carried in ships, helicopters, planes, and larger drones.

Some areas of the current paper which have further scope for improvement and have not been analyzed are Control surface sizing, Vertical Stabilizer etc. which will be taken up later. Current paper focused only on wing folding and catapult system design aspects apart from electric propulsion sizing.

Abbreviations

RPM	Rotation per minute
W	Watts
KV	constant velocity of motor
RC	Remote control
T	Thrust
k	Elastic stiffness
x_0	Initial displacement
D_{rod}	Shaft diameter
N_e	Contribution from end
N_a	Number of active coils
θ	Deflection
c	Spring index
D	Mean diamter
d	Wire diameter
E	Young's modulus
σ	Stress

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