UAV Wing Structure with 3D Printed PLA Filament Wing Spar

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***Abstract*— Polylactic Acid (PLA) filament is one of the organic polymers that commonly wide-used in making a model by using a 3D Print method. This material can be applied on the UAV wing structure, by using semi-monocoque structure concept. The sizes of the wing structure components are determined by the forces acting on the wing itself, and derived into shear and bending moment stresses, so it created an optimum semi-monocoque structure to carry the load. This paper discusses the use of 3D printed PLA filaments for spars on the acrobatic UAV in order to optimize vehicle weight.**

***Index Terms*— UAV, semi-monocoque wing structure, Polylactic Acid filament, 3D print, lightweight structure**

I. INTRODUCTION

A flying vehicle has limits in various ways, one of them is the limitation of structural strength. This boundary is represented by a diagram called flight envelope, which is derived from the maximum limit of the UAV flight condition. Thereby, the flight envelope act as the benchmark to determine loads withstood by the UAVs structure.

The wing is the main part of a fixed-wing UAV that carries large structural loads. Aerodynamic force, weight, and propulsion force are the main forces that happened when the UAV is in flying condition. Therefore, those type of forces creates various type of internal loads such as bending moment, shear force, and torsional load. This paper is intended toget an optimum wing structure for fixed wing UAV with an optimum weight.

The racing plane division of the AKSANTARA ITB has designed an acrobatic UAV vehicle that has been flown at 2018 Indonesian Flying Robot Contest. The designed vehicle has the following specifications, as shown in Fig. 1, Table I, and Table II:

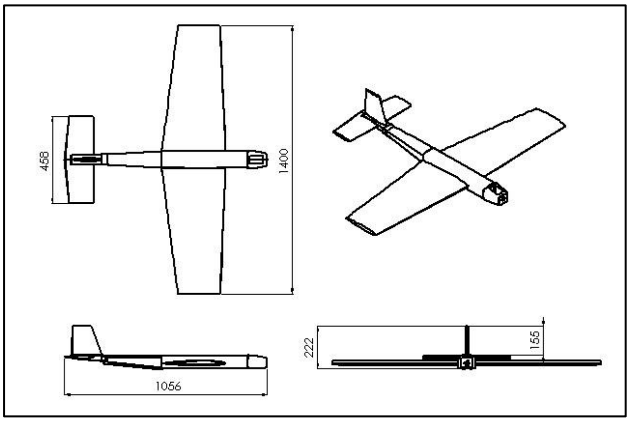

Figure 1. Racing Plane UAV 3 View Drawing

TABLE I. RACING PLANE SPECIFICATIONS

No	Parameters	Input	Unit
1	Length	1.02	m
2	Height	0.22	m
3	MTOW	3	kg
4	Airframe Weight	0.89	kg
6	Cruise speed	70	m/s
7	Propulsion System	3400-Watt GoolRC Brushless motor	

TABLE II. RACING PLANE WING PARAMETER

No	Parameters	Input	Unit
1	Airfoil	MH54	-
2	Wing Area	0.392	m^2
3	Wing Aspect Ratio	5.0	m^2/m^2
No	Parameters	Input	Unit
4	Wing Taper Ratio	1.545	m/m

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5	Chord Root	0.333	m
6	Wing span. B	1.308	m

The UAV has 4 main speed conditions, which are Stall Speed (Vs), Maneuver Speed (Va), Cruise Speed (Vc), and Dive Speed (Vd). Those 4-speed conditions are shown in Table III:

TABLE III. SPEED CONDITIONS OF UAV

Speed Condition	Speed (m/s)
Maneuver Speed (Va)	31.5
Stall Speed (Vs)	11.3
Cruise Speed (Vc)	70
Dive Speed (Vd)	87.5

From the specifications and speed conditions, the flight envelope is shown in Figure 2 as follows:

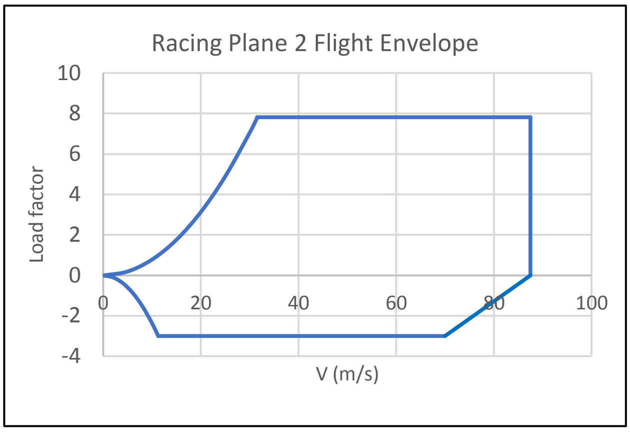

Figure 2. Racing Plane flight envelope

II. DESIGN CONCEPT

A. Wing Configuration

The UAV wing design is a semi-monocoque structure, thus it has an internal structure to help the wing endure the loadings. The components that included in internal structures are spar, skin, and ribs.

B. Material Properties

Polylactic Acid (PLA) filament is one of the most widely researched and utilized biodegradable and renewable aliphatic organic polymer material. PLA filament has many advantages, some of them are easy to produce and biodegradable. PLA filament can create many variations of difficult shape and geometry, by using 3D Print manufacture process.

The material's mechanical properties [2] used for the spar in this paper are tabulated in Table IV.

TABLE IV. MECHANICAL PROPERTIES OF PLA

Property	Unit	Value
Polymer density	kg/m^3	1210-1250
Tensile Strength	N/m^2	$21\text{-}60 \times 10^6$
Tensile Modulus	GPa	0.35-3.5
Specific Tensile Strength	kNm/kg	16.8-48
Specific Tensile Modulus	kNm/kg	280-2800
Melting Temperature	°C	150-162

Based on the Table IV about the PLA Filament mechanical properties, this type of polymer has a low density compared to other commonly used polymer, such as polycarbonate/PET polyester (1.47 gr/cm^3) [3] and polyvinyl dichloride/PVDC (1.78 gr/cm^3) [4]. PLA filament only has ultimate tensile strength, meaning that this material is brittle, since there's no yield strength and no plasticity region. PLA filament can also be categorized as thermoplastic polymer, a kind of polymer that soften when heated and harden when cooled [5].

III. MAIN WING LOAD AND INITIAL SIZING

A. Lift Distribution

To determine the lift distribution, we use Schrenk Method theory and half-span of main wing divided into 6 sections [6]. Here is the equation to approximate the lift distribution along the wing half-span, from root to tip.

$$Le(y) = \frac{4L}{\pi b}\sqrt{\left(1-\left(\frac{2y}{b}\right)^2\right)} \quad (1)$$

$$Lt(y) = \frac{2L_r}{(1+\lambda)b}\left(1+\frac{2y}{b}(\lambda-1)\right) \quad (2)$$

$$Schrenk\ Lift = \frac{Le+Lt}{2} \quad (3)$$

Whereby,
Le = Elliptical Lift Distribution (N/m)
Lt = Trapezoidal Lift Distribution (N/m)
Lr = Lift at wing root section (N)
y = Location of each section (m)
b = Wingspan (m)
λ = Wing Taper Ratio

Table V and Figure 3 shows the result from lift distribution calculation.

TABLE V. LIFT DISTRIBUTION FOR EACH SECTION

Section	Le (N/m)	Lt (N/m)	Schrenk Lift Distribution (N/m)
1	208.7	192.2	200.45

2	204.5	179.2	191.85
3	191.3	166.1	178.7
4	166.9	153.1	160
5	125.2	140.1	132.65

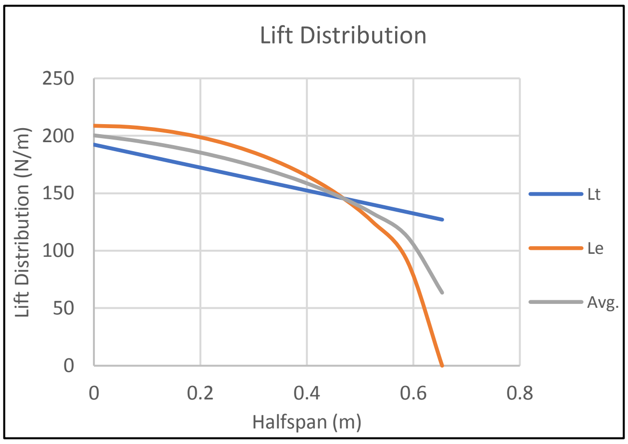

Figure 3. Main wing lift distribution.

From the Figure 3, the highest value of lift distribution is located at the wing root, which has value of **200.45 N/m** and the smallest value is located at wing tip which has value of **63.5 N/m.**

B. *Shear Force and Bending Moment Distribution*

Lift force and structural weight created shear force and bending moment. Here are Table VI and Figure 4 which shown the shear force and bending moment distribution.

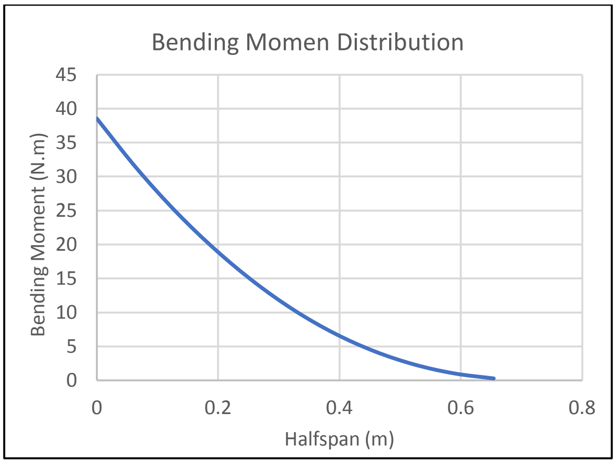

Figure 4. Diagram of bending moment distribution.

TABLE VI. SHEAR FORCE AND BENDING MOMENT DISTRIBUTION

Section	Shear Force Distribution (N)	Bending Moment Distribution (N.m)
1	-116.7	38.6
2	-89.82	24.7
3	-65.5	14.3
4	-41.97	6.9
5	-21.12	2.3

C. *Initial Sizing*

1) Spar initial sizing.

From bending moment diagram in Figure 4, the highest value of bending moment is located at wing root, which has value of 40.35 N.m. To analyze the stresses acting on the spar, wing box structure is idealized as a perfect rectangle, as shown in Figure 5. The location of the spar is between 25% to 75% of chord length [7]. By using the formula of bending stress, the value of beam cross-section area can be identified.

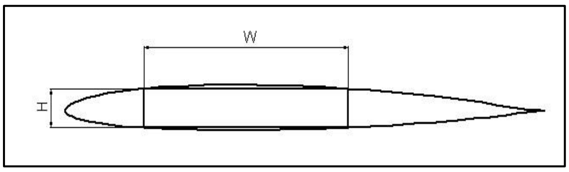

Figure 5. Idealized wing box cross-section.

$$\sigma = \frac{My}{I} \tag{4}$$

Whereby,
M = Bending Moment (N.m)
y = Location of point of interest (m)
I = Beam cross-section Inertial Moment (m^4)
σ = Bending Moment Stress (MPa)

Based on the idealized wing box structure, bending moment load is equally distributed on each spar, depends on the number of the spar. Each spar cross-section uses I-beam shape. Here is Table VII that shown the spar initial sizing data :

TABLE VII. 3 SPAR CONFIGURATION INITIAL SIZING

3 Spar Configuration	
Section	Root
Bending Moment each spar (N.m)	12.87
Material $\sigma_{tensile}$ (MPa)	59
f.s.	1.3
h (m)	0.028
y (m)	0.014
I (m^4)	3.18×10^{-9}
One Spar Cross-section Area (mm^2)	36

Based on Table VII the conclusion is 3 spar configuration has lower total cross section area (number of spar x cross-section area) for each wing, it means that

3 spar configuration has lighter mass compared to 2 spar configurations. This caused by the lesser the number of spars, the higher will be the load held by each spar. The ratio between h_s and w_s is 2. The dimension of I-beam cross-section is shown by Fig. 6 below

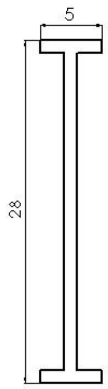

Figure 6. I-beam cross-section.

2) Wing structure final assembly.

After initial sizing process has done, 3D drawing of spar and ribs by using CAD Software, SOLIDWORKS. These two parts are assembled together and created a complete semi-monocoque wing structure assembly as shown in Fig. 7.

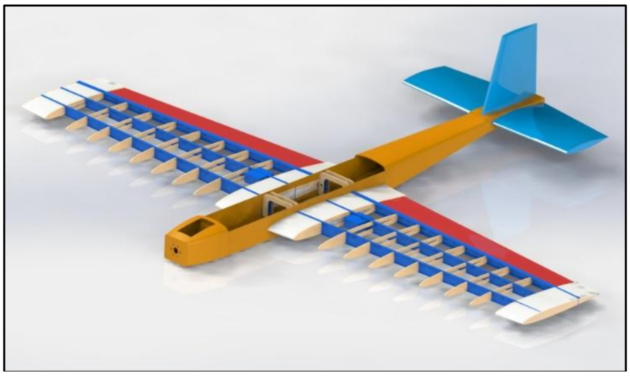

Figure 7. Main Wing structure final assembly.

The 3 spars that have been calculated in initial sizing process is located at 25%, 50%, and 72.4% chord length [4]. This decision made to minimize the effect of torsional load that caused by lift force, provide enough space for control surfaces, and give enough space for wiring system inside the wing box.

IV. Finite Element Analysis

A. Load Case and Boundary Condition

In ABAQUS/CAE 6.14 the CAD Model of the spar was imported then analyzed. For the analysis of the finite element model, the physical and material properties of the model is needed. The loading of the wing has been calculated prior in chapter 3.2, whereby the load applied on the half- wing is from the integration of line equation to approximate Schrenk lift distribution. Equation 5 below obtained from the trendline approach of the lift distribution, *L(x)*.

$$L(y) = \int_{y1}^{y2} (-33300y^6 + 55678y^5 - 35025y^4 + 10064y^3 - 1414.9y^2 + 7.3868y + 200.39)\ dy \qquad (5)$$

The value of a and b respectively are the initial and final point of each section. Since the wing assembly divided into 5 sections, the location of each load are located in the centroid of each section, and the x location of centroid (x_c) can be obtained by the integration of the function *L(x)*.

$$y_c = \frac{\int_a^b y(L(y)-g(y))\ dy}{\int_a^b (L(y)-g(y))\ dy} \qquad (6)$$

By defining the location and the magnitude of the load that shown in Table VIII, Figure 8 shows the load and boundary condition of the wing model in finite element analysis :

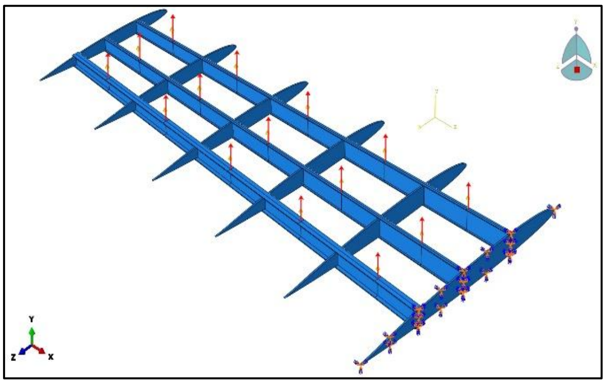

Figure 8. Loading condition of the wing assembly.

TABLE VIII. Wing Loading

Load Case	Section	Load Applied (N)	Load Location from Root (m)
Lift Load	1	25.56	0.065
	2	24.12	0.195
	3	22.14	0.325
	4	19.2	0.455
	5	14.46	0.58

Supporting boundary condition is also applied in the model. The boundary condition for the model is set to point where the spar is attached to the fuselage, so fixed boundary condition is given on the root section of the spar, so there is no any degree of freedom.

B. Result

The finite element analysis results of the spar for Maximum-Minimum Principal Stress are shown in Fig. 9 and Fig. 10.

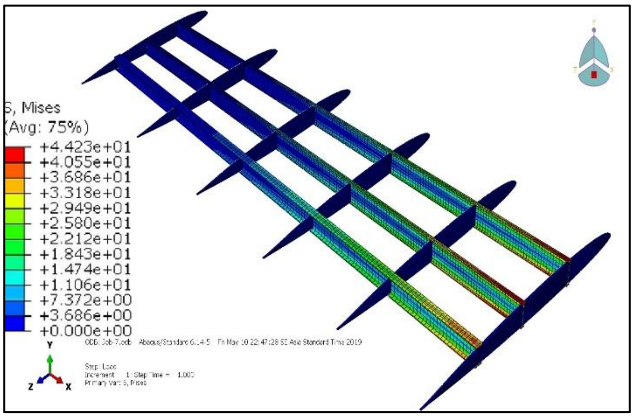

Figure 9. Von mises stress on spar.

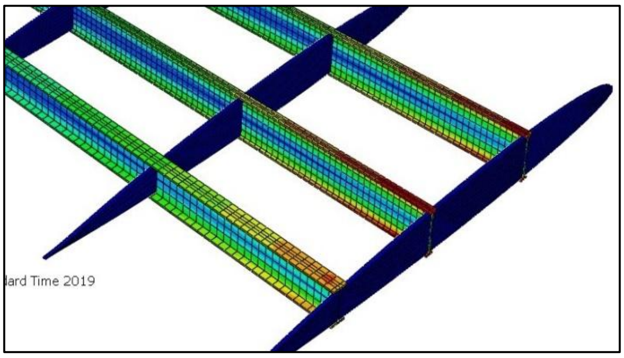

Figure 10. Maximum stress location.

The red area indicates maximum stress and the blue surface indicates minimum stress. The maximum stress occured near from the wing root, at the upper and lower part of the spar beam, which bear compression and tension. The stress distribution in spar model is having the maximum value of Von Mises Stress of $\boldsymbol{\sigma_{VonMises}}$ = **44.23 MPa**.

C. Margin of Safety

To ensure that the material of the spar doesn't fail when load is applied throughout the structure, margin of safety (MOS) [8] can be calculated with the equation below

$$M.O.S = \left(\frac{\sigma_{tensile}}{\sigma_{Von\ Mises}}\right) - 1 \tag{7}$$

Since the tensile strength of PLA is approximately 60 MPa, the value of margin of safety for the wing spar is **0.35**. Meaning that the structure can withstand the applied loads without any material failure since the value of margin of safety is above zero.

V. Conclusion

Polylactic Acid (PLA) filament can be applied as Racing plane UAV wing structure component. It has been proven by the result of the finite element method analysis, which shows that the applied limit load value is still below the material tensile strength and the structure has margin of safety of **0.35** at maximum lift condition applied on the UAV.

Conflict of Interest

The authors declare no conflict of interest.

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Mohammad Alif Maarif Mabbrur was born in Jakarta, 2nd August 1998. He graduated from 61 Senior Highschool Jakarta in 2016, after 3 years studied in natural science course. After finished the highschool, he continues his education programme into university in 2016. He currently study in Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung (ITB) and majoring in Aerospace Engineering.

From 2016 until 2018, he was a team member in an urban car team which called CIKAL ITB Urban Car Team as a Car Design Engineer. This team is focusing on create an highly efficient urban car, that compete in Shell Eco Marathon Asia competition. He also was the part of FTMD Nano Aerial Vehicle (NAV) research team in 2018. He took part as an Design Engineer in NAV airframe design division. This airframe was made of 3D printed PLA filament that has only 6 grams of weight.

Mr. Mabbrur joined into Aksantara ITB since 2018, one of the ITB's team that focuses on competition, research, and development of Unmanned Aerial Vehicle (UAV) and serves as the Staff of Research and Development Department and focus on UAV structre optimization. His achivements is when in Shell Eco Marathon Asia. He and his team got 1st place in Ethanol Poweresd Urban Car category (2017) and Finalist in Internal Combustion Engine Urban Car category (2018) in Singapore.

Hafidz El Amien NP was born in Sleman, Indonesia, on July 18th, 1998. He went to SMAN 1 Yogyakarta taking natural science course and graduated after three years of studying. He continued his school journey in Institut Technology Bandung (ITB) and majoring in aerospace engineering.

In the second year in campus, he joined Aksantara ITB, one of the ITB's team that focuses on competition, research, and development of Unmanned Aerial Vehicle (UAV) and serves as the Head of Manufacturing Department. He and his team also won the 2nd place in the Indonesia Flying Robot 2018 for fixed wing category.

He has great interest in everything that involves airplanes, composites, and mechanical structures.

Novia Sari Syaifer was born on August 23, 1998, in Bukittinggi, West Sumatra. She grew up in Bukittinngi until 2013. At the age of 15, she continued her high school education in Padang Panjang city, at SMA N 1 West Sumatra, and after 3 years continued her tertiary education at Bandung Institut Technology in aerospace engineering departement up until now. She was especially interested in aerospace, lightweight structure, art and craft.

In the second year of her undergraduate program, she joined the Aksantara ITB team, a team that focused on UAV research and development and pursued on UAV manufacturing. She also joined the martial arts community on her campus. In addition, she was a private tutor for science subjects for middle school until high school students.

Ms Syaifer also joined the national volunteer community, called Indonesia's Smile Volunteers, she also volunteered for a development of isolated region program organized by ITB in the Cianjur districts. Besides that, she won the women's singles category martial arts competition for her class.

She and her team of Aksantara ITB also won 2nd place in the Indonesia Flying Robot 2018 for fixed wing category.

Arif Hidayat was born in Padang, September 5th, 1998. After several years living, he took high school education in Padang Panjang, on SMAN 1 Padang Panjang, class of 2016 focusing on natural science course. After that, he makes decision to continue his education far from his hometown, Bandung. Arif entering Bandung Institute of Technology on 2016, majoring Mechanical Engineering on Faculty of Mechanical and Aerospace Engineering, and focusing on Conversion Energy course.

In the second year of college life, he desired to join AKSANTARA ITB, one of ITB's team focusing on research and development of Unmanned Aerial Vehicle (UAV). On his team, he is the member of Manufacturing department in Technology Development Division, division that focusing to develop latest technology on UAV. On that year, they're developing Tube launch UAV with Coordinated Air Relay System, that aims to make uav that easy to launch anywhere and everywhere. And also, it proposed to expand the communication network using that uav. He and his team got 2nd place winner on Indonesia Flying Robot 2018 for Technology Development category

He has a great interest on UAV, especially on manufacturing UAV, and also all about mechanical engineering such as conversion energy, strength of material, dynamics, and others

Sayyid Fawwaz Nadzir was born in the city of Jakarta, 13th November 1997, but he was raised in Bekasi, a crowded town near Jakarta. There, he attended some educational levels from kindergarten until senior high school, from 2002 until 2015. His senior high school was SMA Islam Al-Azhar 4 Kemang Pratama. After 3 years of studying, he graduated from there with a satisfying result. Then, he continued his education to ITB, Bandung Institute of Technology in 2016. Because he interested in engine and cars, he went to mechanical engineering major.

Since junior high school, Fawwaz has been engaged in some communal parties and events. One of them was OSIS (Organisasi Siswa Intra Sekolah) - Organization of students that runs in a school. Later, in his college life, he has taken some responsibilities in an organizations/teams. For example, in 2016, he joined an Aksantara ITB, a UAV research group in ITB. He has become a member since then. Aksantara gave him a chance to join a team that takes a part in KRTI 2017 (Kontes Robot Terbang Indonesia 2017), UAV competition in Indonesia. This competition was attended by students from universities in Indonesia. He got an award of 'Best Complexity System'. Now, he has become a project manager of Aksantara ITB. He manages four teams that have a goal to win KRTI this year. Mr. Fawwaz has won 3rd place in a paper competition in PNJ (Politeknik Negeri Jakarta).