2024.12.13

Design and Development of a Lightweight, 3D-Printed VTOL Aircraft with Autonomous Flight Capabilities

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Contents

Introduction and Objectives

In this talk…

Overall development process of a fully 3D-printed VTOL with a 2m wingspan, built from scratch.

Focus 1. fully 3D-printed aircraft using lightweight PLA (pros and cons)

Focus 2. Design Features (modular design, access hatch, air cooler, print-in-place)

Focus 3. Simple aerodynamic analysis (OpenVSP) to estimate key flight parameters (cruise speed, C.G., etc.)

Focus 4. Autonomous flight missions (companion computer ↔ flight controller)

Our VTOL

This will be a light and broad seminar (more focus on HW)
- I hope you find it insightful!

Introduction and Objectives

Vertical Take-Off and Landing (VTOL) aircraft

Combined strengths of **fixed-wing** aircraft and **multicopter** : enabling long-range missions with vertical takeoff and landing capabilities

Recent developments on open-source firmware

Significantly simplified the implementation of autonomous flight missions for VTOL

Introduction and Objectives – Korea Robot Aircraft Competition

Advanced Air Mobility (AAM) Tech Challenge
One of the largest aerospace competition in Korea

1st place among 39 Teams

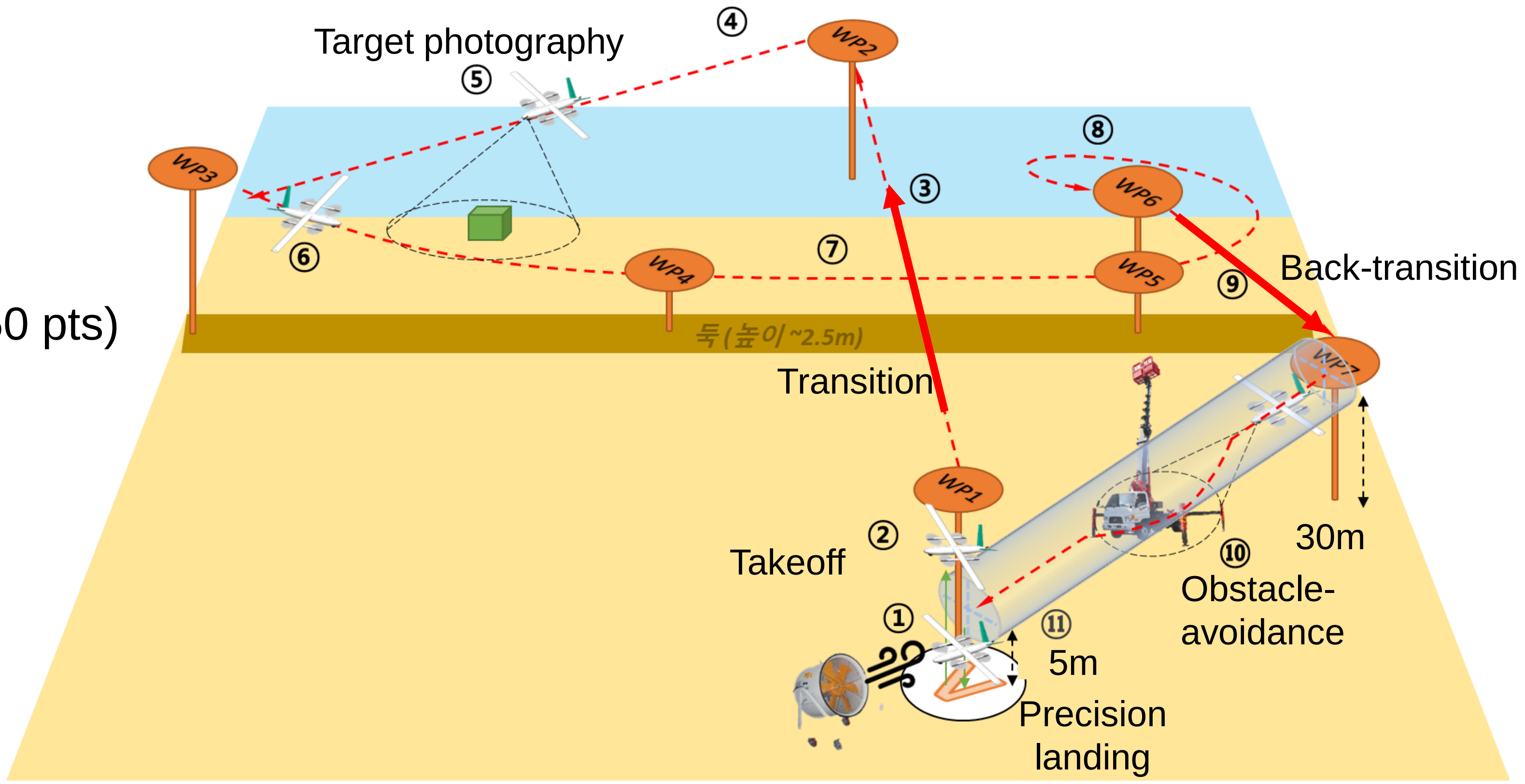
Introduction and Objectives – Korea Robot Aircraft Competition

Fully autonomous flight!!

Grades (Total 1000 points)

1. Waypoint Navigation (140 pts)
2. Transitions (150 pts)
3. Corridor Navigation (110 pts)
4. Low-Altitude Flight (50 pts)
5. Target Photography & Live streaming (50 pts)
6. Obstacle Avoidance (100 pts)
7. Precision Landing (100 pts)
8. Aircraft Design for AAM (200 pts)
9. Mission Time (50 pts)
10. Software Development (50 pts)

Scenarios for flight missions in urban environments



Required the integration of multiple components!

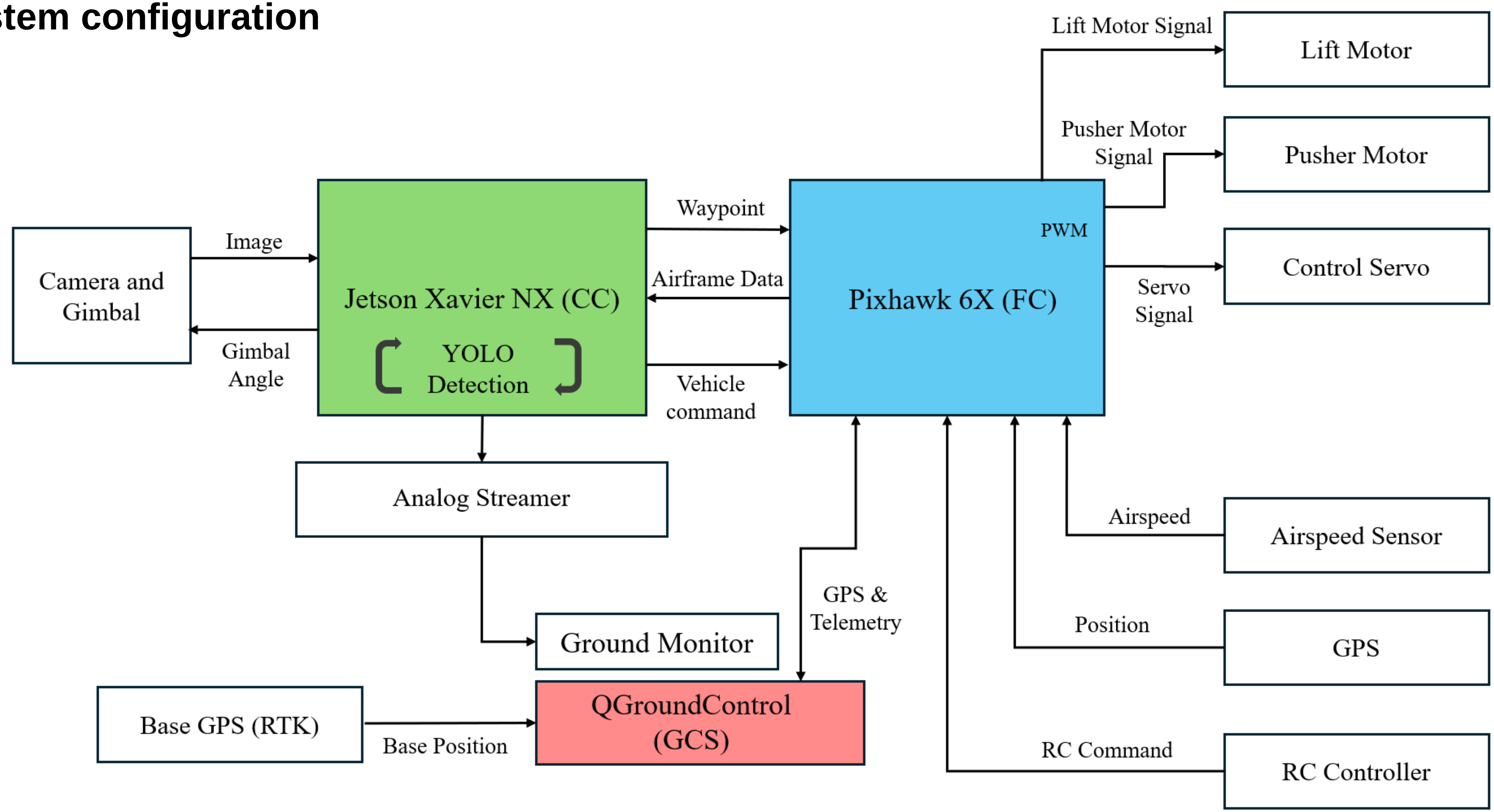
Overview of the Aircraft: BNB3402

Key features

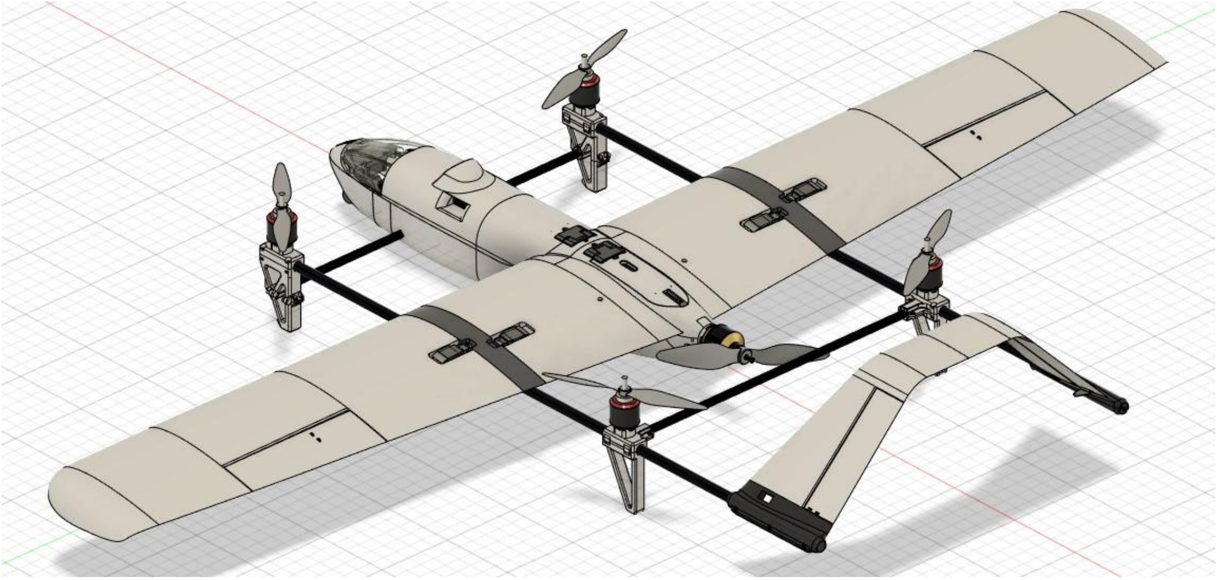
- **2m Wingspan, Quadplane A-tail VTOL**
- **4 lift motor and 1 pusher motor**
- **All components 3D-printed, Modular design**
- **Concept design for AAM (will be discussed)**
- **Detachable wings for transport**
- **Flight Controller** – Pixhawk 6X (with PX4)
- **Offboard Control** – CC: Nvidia Jetson Xavier
- **Gimbal Camera** – Siyi A8 mini
- **Obstacle Avoidance using YOLO**
- **Precision landing**
- **Live Streaming**

Overview of the Aircraft: BNB3402

System configuration



Overview of the Aircraft: BNB3402



< Specification >	
Takeoff weight	5.8 kg
Cruise Angle of Attack	$3°$
Cruise speed	17.72 m/s
Stall speed	11.03 m/s
Wingspan	2.02 m
Mean Aerodynamic Chord (MAC)	240 mm
Aspect ratio	8.55
Wing loading	12.2 kg/m^2
Maximum Lift-to-Drag Ratio (L/D)	18.79

Hardware Development

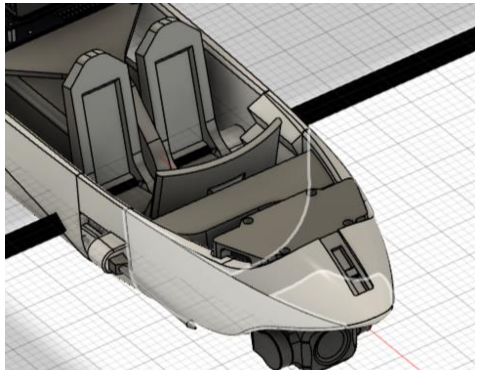
Hardware Development - Overview

Our goal: Design an aircraft tailored to the mission (no overspec)

1. Design and manufacturing

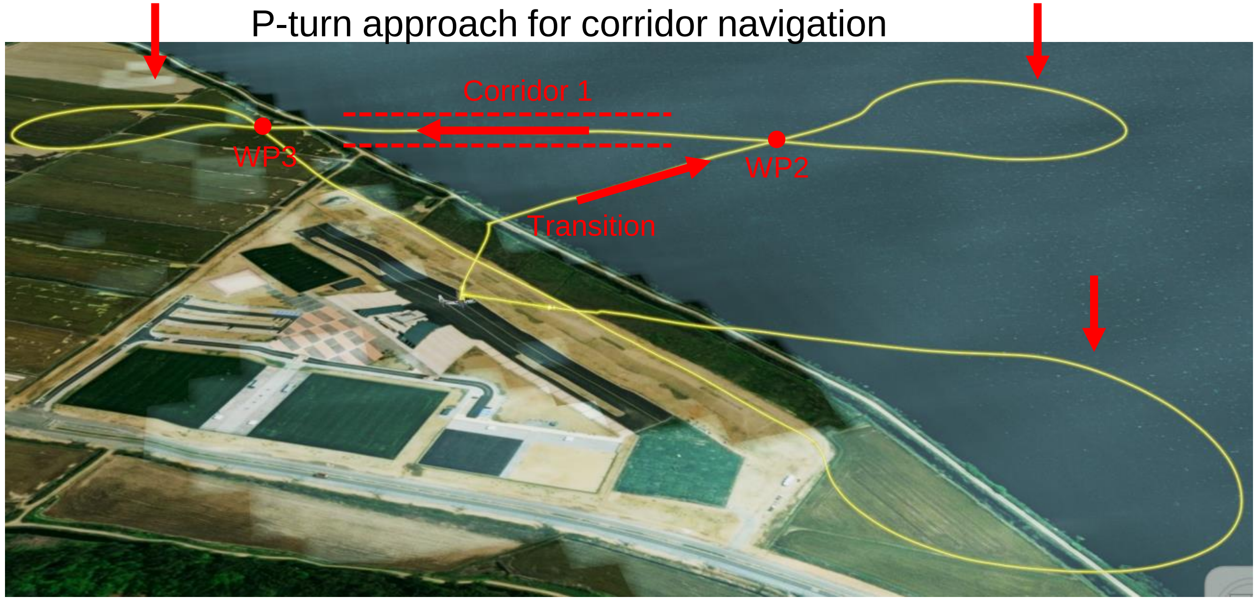

CAD rendering image

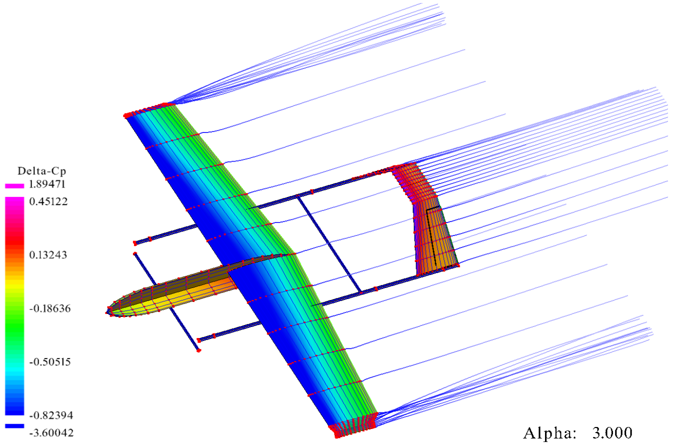

Gimbal Camera


Concept design for AAM

2. Stabilizing each flight phases

P-turn approach for corridor navigation





Hardware Development

Fully 3D-printed VTOL

- Efficiency in maintenance through modular design
- Use of lightweight PLA (LW-PLA)

<LW-PLA>

50% lighter than regular PLA

We used LW-PLA because…

- Continuous design improvements required
- VTOLs face less impact during takeoff and landing compared to fixed-wing aircraft

VS

Foam structure
Balsa wood
Composite Materials
- Carbon Fiber
- Glass Fiber

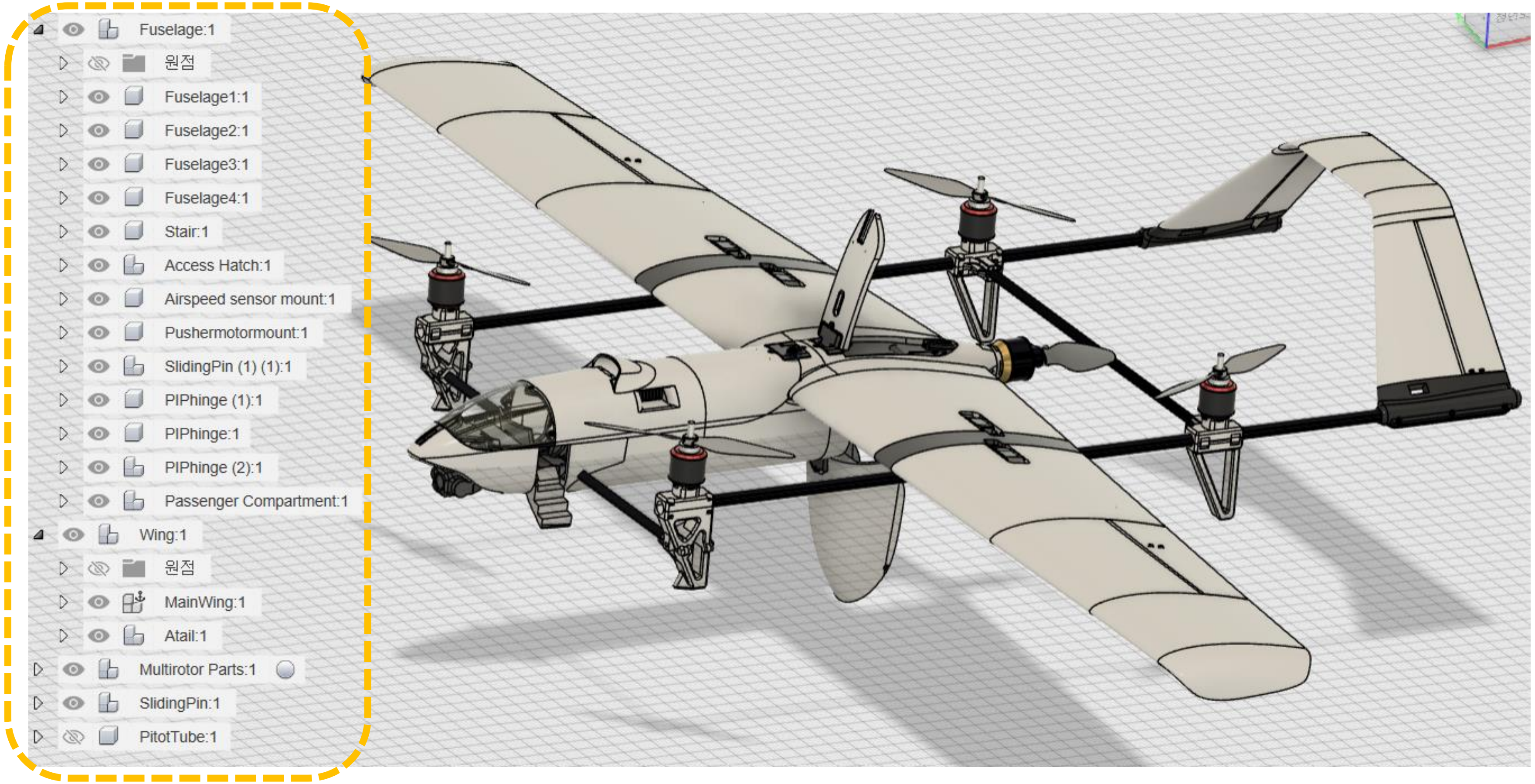
Carbon fiber

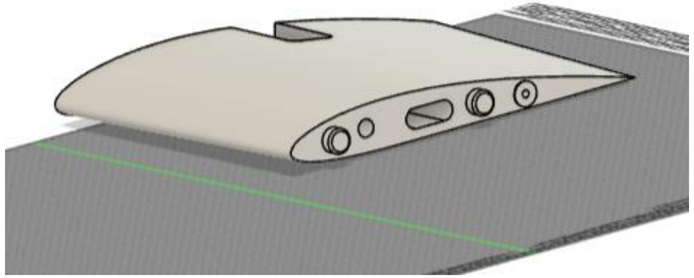
	3D printing (LW-PLA)	Composite Materials	Balsa wood	Foam structure
Pros	Design flexibility, Lightweight, Low cost, Ease of manufacturing	High strength, Durability	Lightweight, cheap	Lightweight, Impact absorption, cheap
Cons	Durability, Strength (inter-layer)	Complex processes, Reliance on hands-work, Difficult maintenance	Reliance on hands-work, Time-consuming, Limitations on producing complex 3D structure	Low quality, Limitations in producing complex 3D structures

Hardware Development - Design

Design for manufacture– modular design, access hatch, print-in-place

1) Modular design





Damaged parts can be reprinted individually for repair

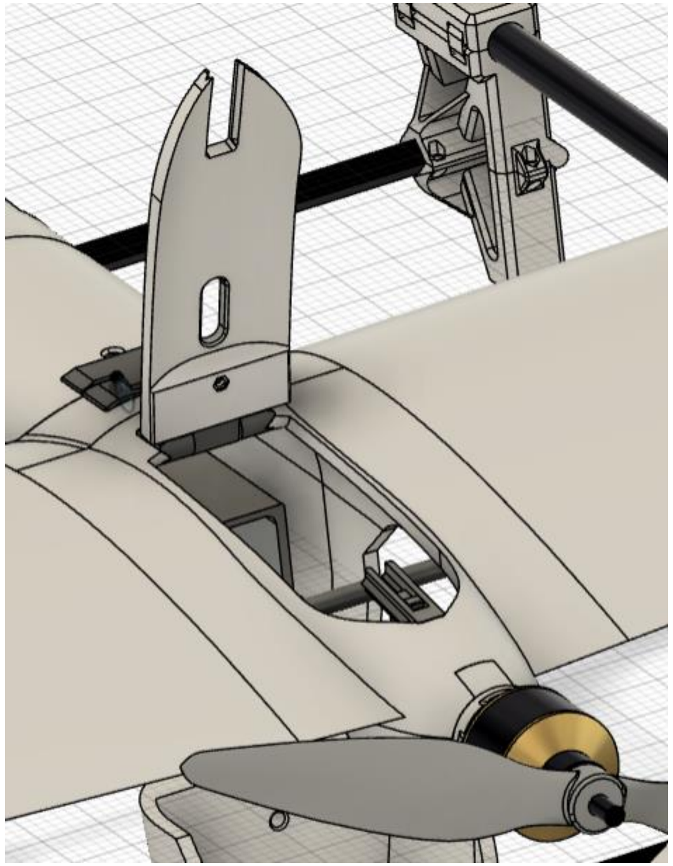
Hardware Development - Design

Design for manufacture– modular design, access hatch, print-in-place

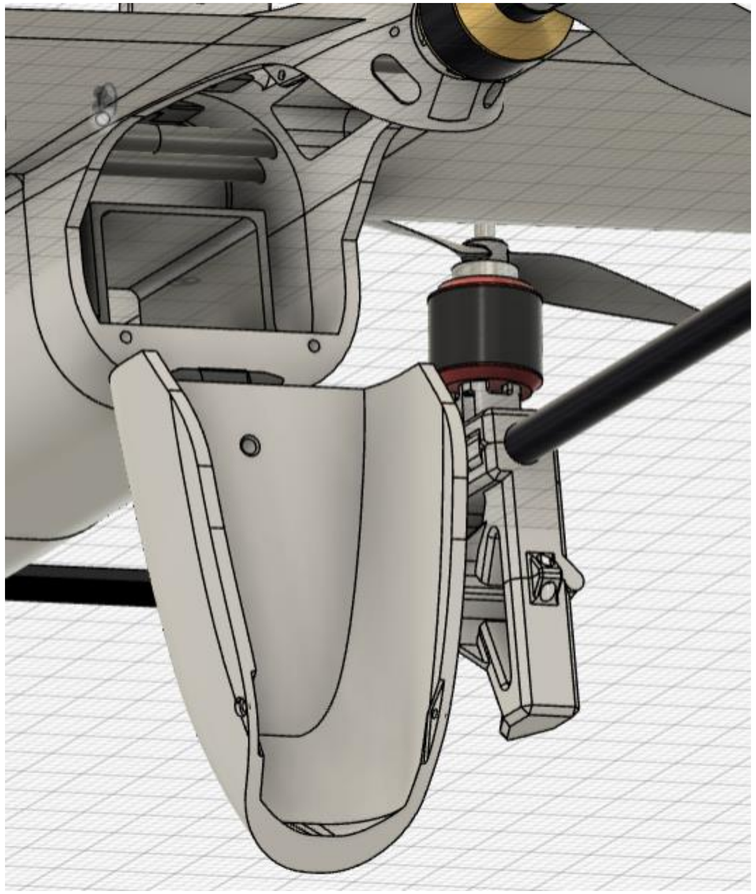
2) Access Hatch

Access hatch enables easy internal wiring and maintenance

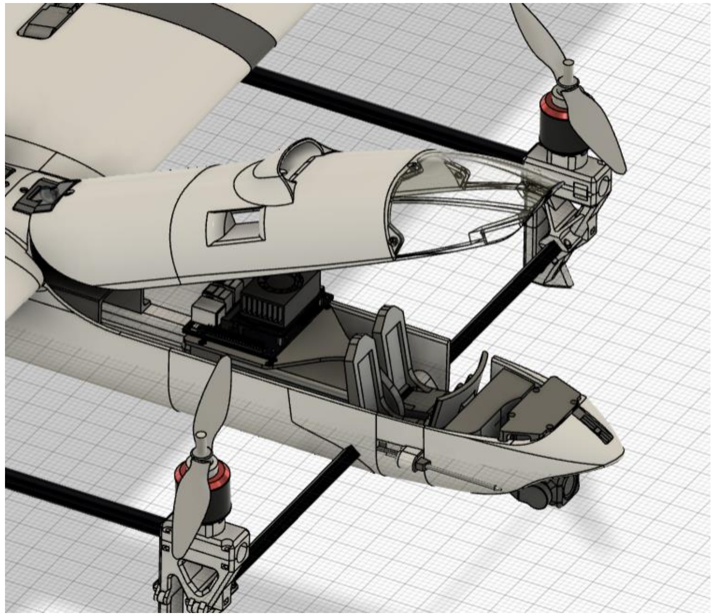
① Rear upper section



② Rear lower section



③ Front canopy

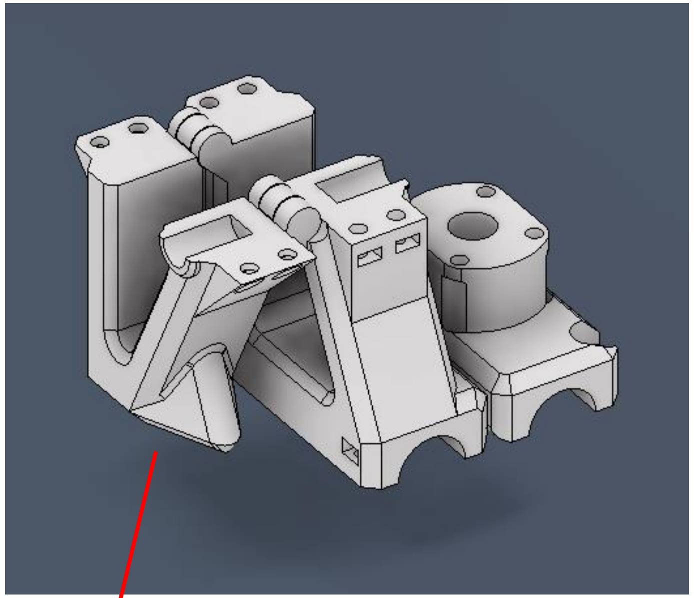


Hardware Development - Design

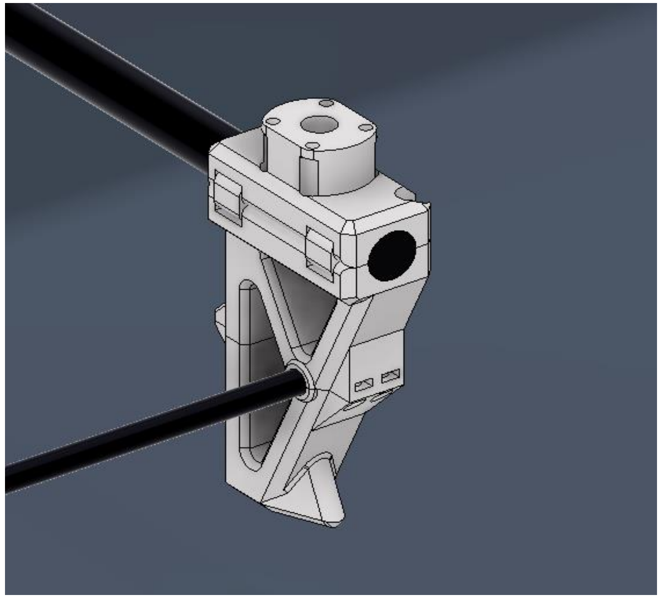
Design for manufacture– modular design, access hatch, print-in-place

3) Print-in-place & Design for printing

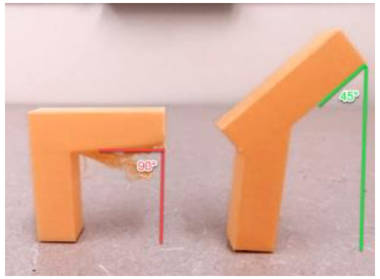
print-in-place design for 3D printing pre-assembled parts

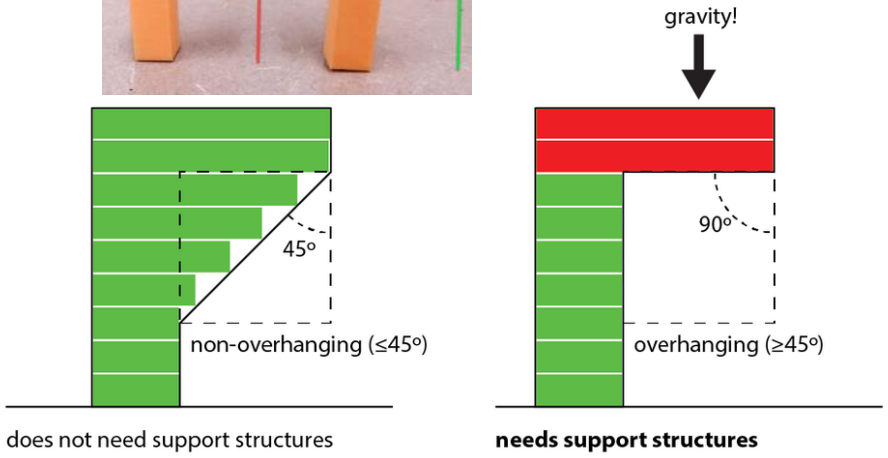


Right after printed



After assembly



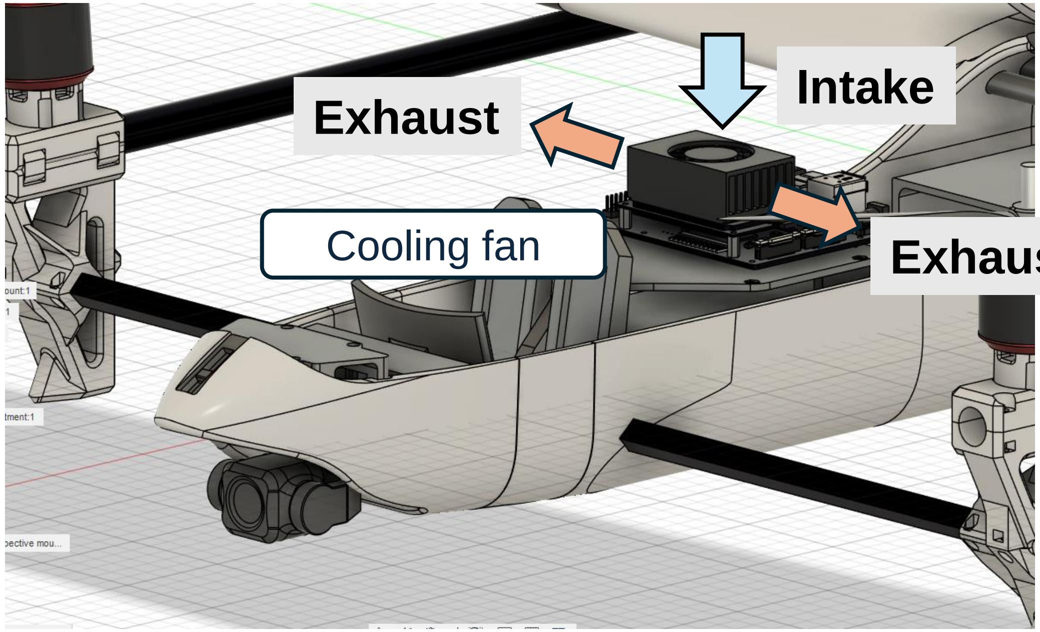


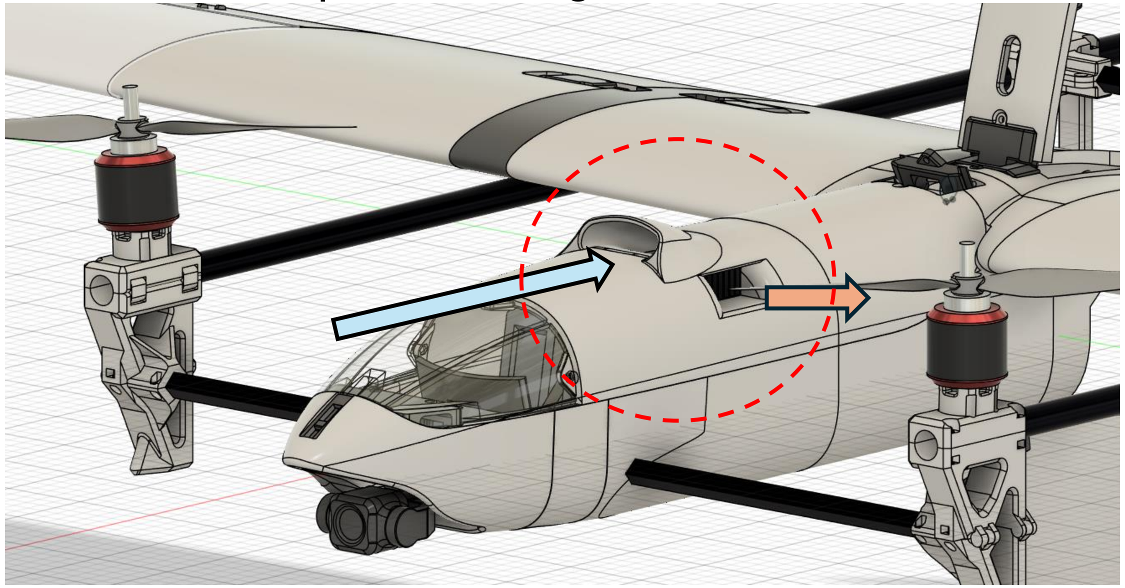
Carefully design to make overhang angles below 45°, printing can be done without support, minimizing manual effort!

Heat management design

Overheating causing significant issues (especially in summer)
1. Reduced power efficiency due to thermal resistance
2. Computational throttling

During fixed-wing flight, natural airflow through the computer cooling fan enables effective air cooling.





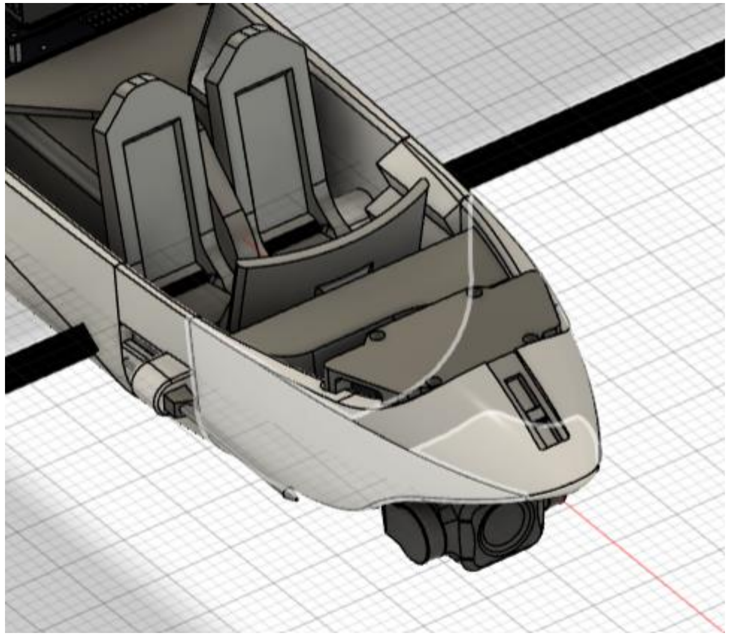
Companion Computer (Nvidia Jetson)
Flight Controller (Pixhawk 6X)
Gimbal Camera (SIYI A8 Mini)
Pusher Motor … etc

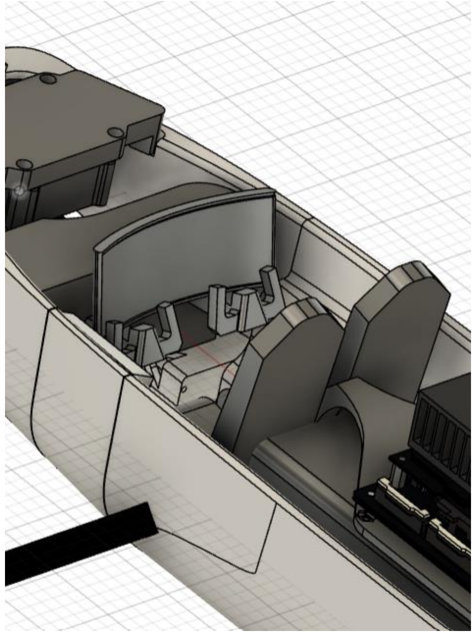
Motivated by Air-intake in fighter aircraft

Hardware Development - Design

Concept Design for AAM – Passenger transport

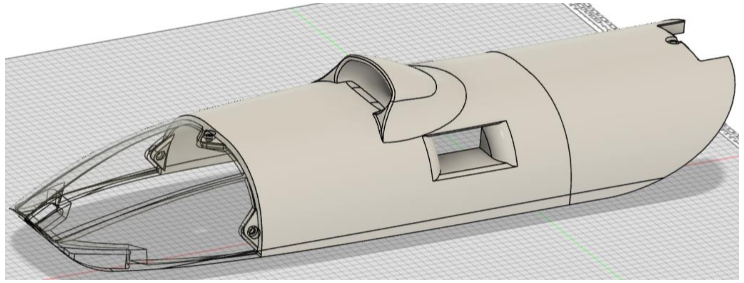
1) Seals



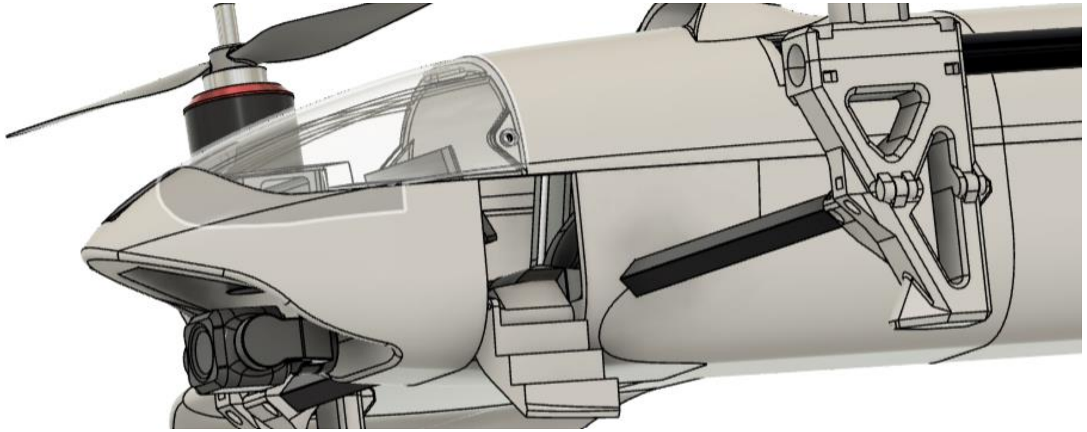


Cockpit: Equipped with seats for two passengers and a monitor.

2) Transparent canopy – created using a Lesin printer



3) Passenger entry door and boarding stairs



Hardware Development – stabilizing each flight phases

Our biggest mistake

- Initially lacking a systematic approach, leading to numerous trials, errors, and wasted time

Successful stabilization of VTOL autonomous flight missions required a **systems engineering** process and **basic aerodynamic analysis** (It may sound obvious, but it’s often overlooked at the RC-scale)

Especially when building your vehicle from scratch or modifying a purchased one!

Hardware Development – stabilizing each flight phases

Fixed-wing phase

1. Our first flight (Manual flight)

Takeoff

Transition
(Multicopter to Fixed-wing)

Problems:
1. Significant **altitude drop** during transition
2. **Weight** (at the time both general PLA and LW-PLA were used)

Hardware Development – stabilizing each flight phases

Fixed-wing phase

2. After some improvements… (reduced weight)

Issue: Insufficient speed, resulting in flight at a 10° angle of attack.

→ Revised PX4 fixed-wing flight parameters
Cruise speed, AOA, and many more
→ Adjusted center of gravity

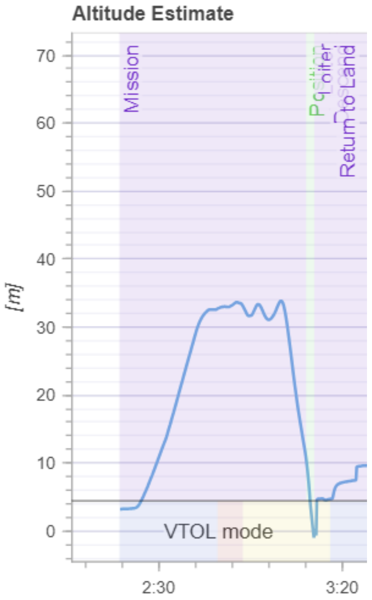
Hardware Development – stabilizing each flight phases

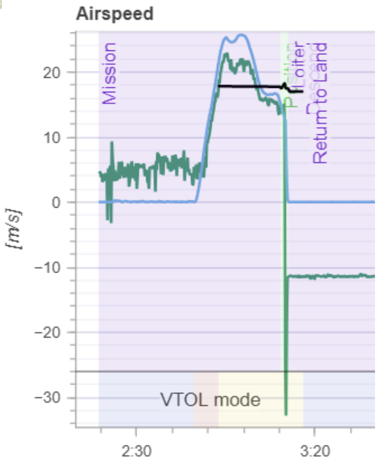
Fixed-wing phase

There are still many issues:

① Altitude drop during transition

② Voltage drop & Lack of flight time





At this point, we realized that without a systematic approach and aerodynamic analysis, completing this complex mission would not be possible

We started from the beginning

1. Redesign: increased wing size by 20% to address insufficient lift
2. High power pusher motor & Increased propeller pitch angle
3. Battery: 4-cell 12,000mAh to 6-cell 10,000mAh

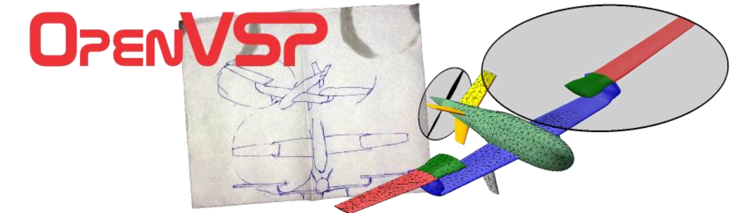
<u>Each decision requires a reason (mission profile)</u>

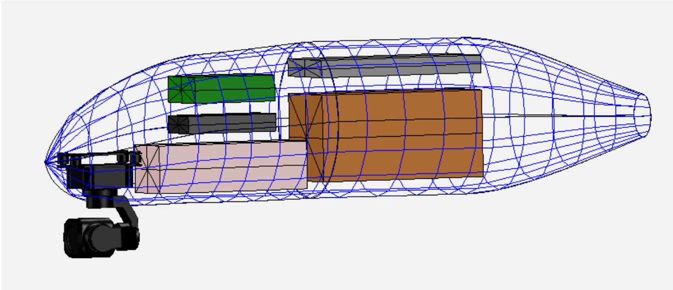
Performed aerodynamic analysis after redesign

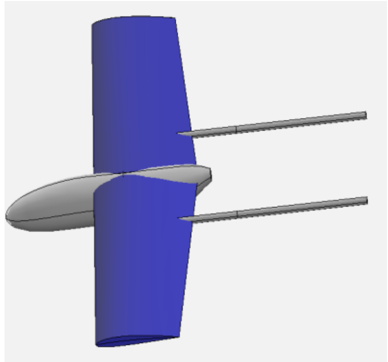
	storage (mAh)	Cell (S)	Discharge Rate(C)	Max current(A)	Continous power(W)	Energy(J)	Weight(g)	Energy/weight	Total aircraft weight(g)	Flight power (hovering, conservative)	expected hovering time(min)
LiPo	6300	6	45	283.5	6293.7	503496	880	572.1545455	5380	1307.34	6.418835192
	16000	6	30	480	10656	1278720	2000	639.36	6500	1579.5	13.49287749
	16000	6	30	480	10656	1278720	2000	639.36	6500	1579.5	13.49287749
	12000	6	25	300	6660	959040	1532	626.0052219	6032	1465.776	10.90480401
current	12000	4	100	1200	17760	639360	1030	620.7378641	5530	1343.79	7.929810461
	8000	6	35	280	6216	639360	1055	606.028436	5555	1349.865	7.894122746
	8200	6	45	369	8191.8	655344	975	672.1476923	5475	1330.425	8.209707424
4cell	5800	4	55	319	4721.2	309024	520	594.2769231	5020	1219.86	4.22212385
6cell	5200	6	50	260	5772	415584	722	575.601108	5222	1268.946	5.4583883
Li-ion 18350	14300	6	6.682653551	95.56194578	2121.475196	1142856	3900	293.04	8400	2041.2	9.331569665
BYD	18000	6	4.410551344	79.38992419	1762.456317	1438560	1800	799.2	6300	1530.9	15.66137566
Sony vtc6	21000	6	3.675459453	77.18464852	1713.499197	1678320	1957.2	857.5107296	6457.2	1569.0996	17.82678423
Molicel P28A	14000	6	6.563320452	91.88648633	2039.879996	1118880	1500	745.92	6000	1458	12.79012346
Molicel P42A	16800	6	5.250656362	88.21102688	1958.284797	1342656	1728	777	6228	1513.404	14.78626989
Samsung INR	16000	6	6.432054043	102.9128647	2284.665596	1278720	1728	740	6228	1513.404	14.0821618

Hardware Development – stabilizing each flight phases

Aerodynamic analysis - OpenVSP







You can easily draw your aircraft

A program specialized in aircraft design and analysis:

- Automatically generates 3D wing models based on inputs like span and chord length.
- Developed by NASA and released as open-source in 2012.
- Enables simple aerodynamic and structural analysis during conceptual design.

We used OpenVSP's VSPAero tool for aerodynamic analysis (lift, drag, and moment)

It is ideal for early-stage conceptual design!

You can easily estimate key parameters (e.g., cruise speed, center of gravity, cruise angle of attack)
We need to put some of these parameters into PX4-Autopilot or Ardupilot.

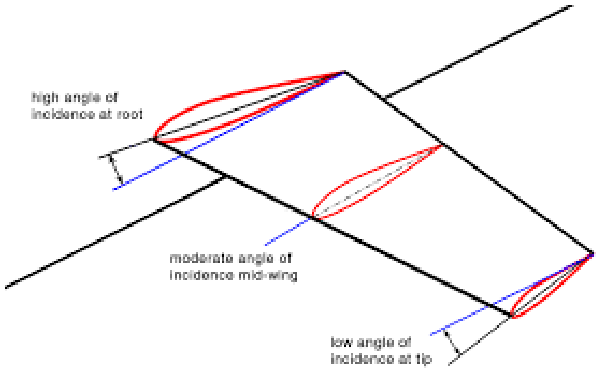
I highly recommend conducting this step, even if your background is not in aerospace engineering - especially when building your plane from scratch or modifying a purchased one (e.g., when adding more mission equipment)

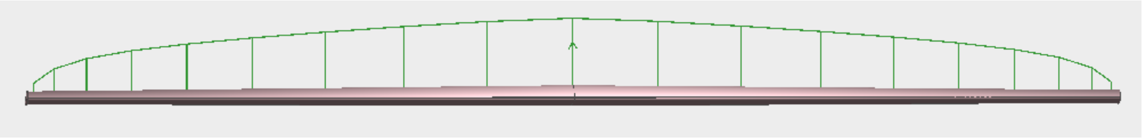
Hardware Development – stabilizing each flight phases

Fixed-wing phase

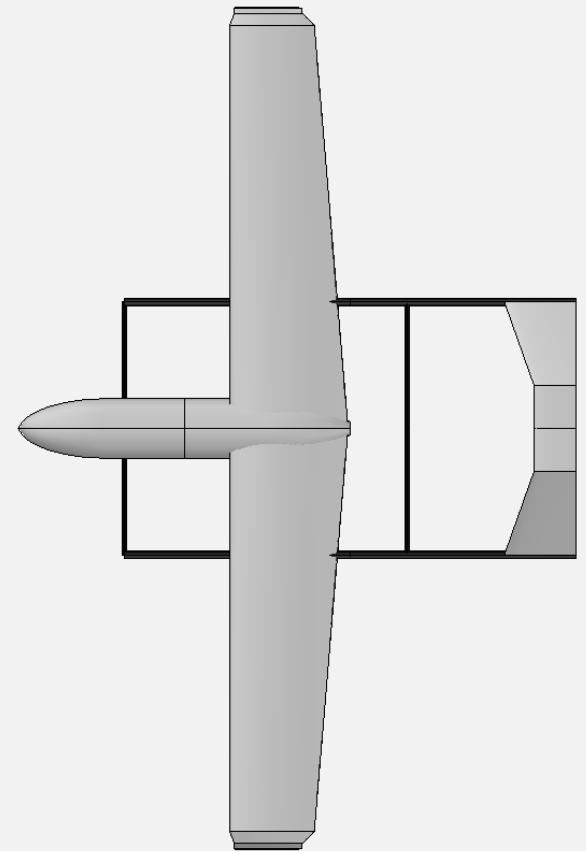
To reduce drag:

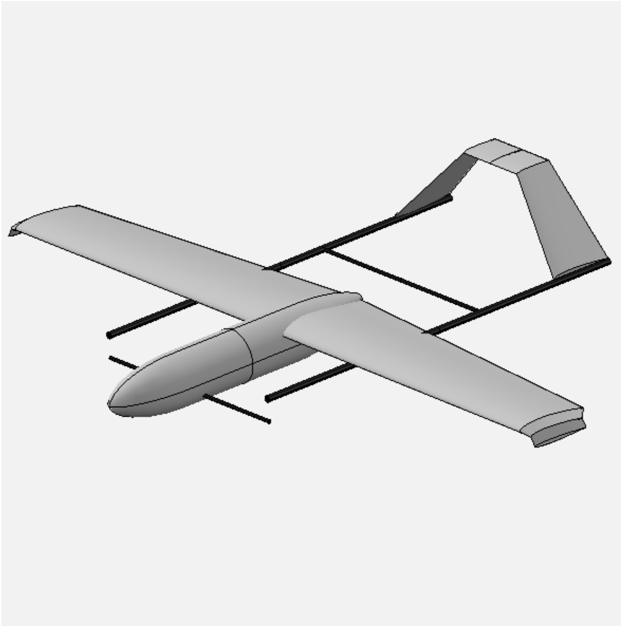
- Designed the wing to achieve an elliptical lift distribution
- Used a higher-lift airfoil at the wing root (root: NACA 4412, tip: NACA 2412)
- Incorporated a 1° washout angle, increasing the AOA at the root

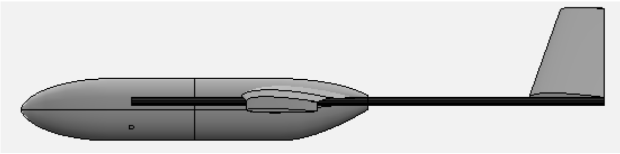


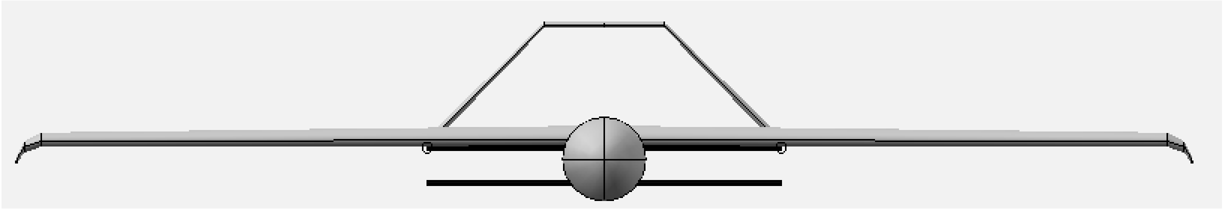


elliptical lift distribution





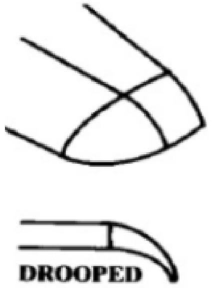


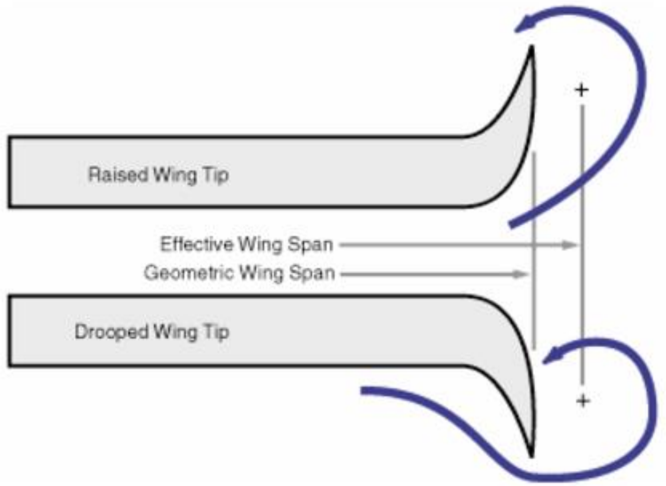


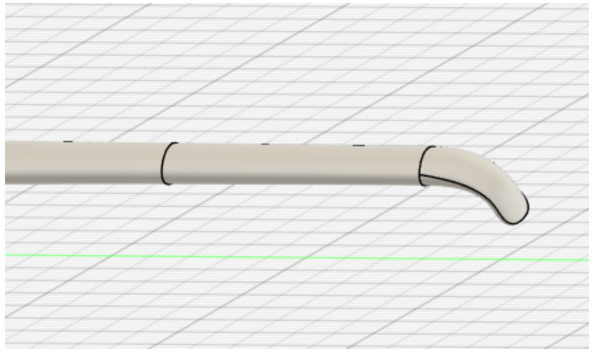
Hardware Development – stabilizing each flight phases

Fixed-wing phase

Winglet Design :drooped wingtip







Upward winglets can encounter vortices from lift rotors during transition, causing wing vibrations
→ Adopted a downward drooped winglet design to avoid this issue

Known to provide similar benefits (increased lift and reduced drag)

Hardware Development – stabilizing each flight phases

Fixed-wing phase

<VSPAero>

Analysis Method : Vortex Lattice Method (VLM)

Reynolds Number : 230,000

Analysis Range: Angle of attack (-5° to 14°)

Predefined cruise angle of attack at 3° and determined the corresponding lift coefficient.

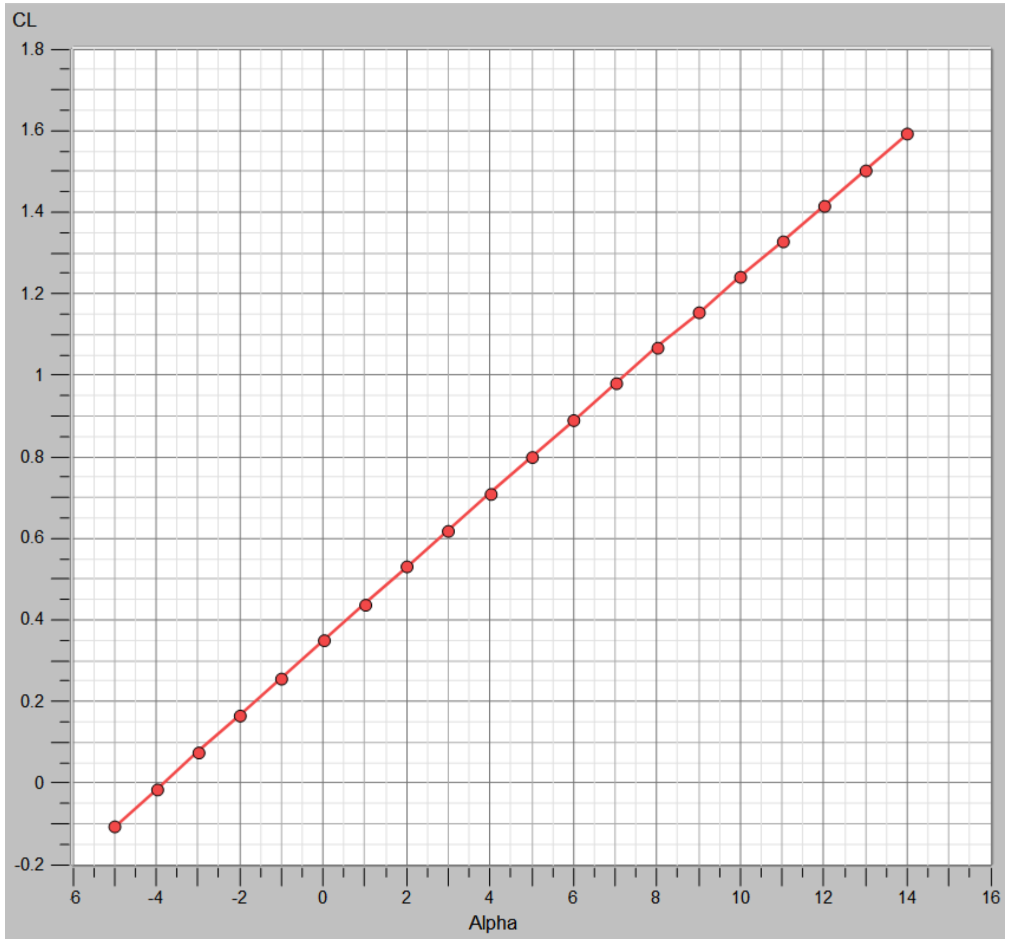
$$at \ \ AOA \ \ 3°, \qquad C_L = 0.62$$

Based on a takeoff weight of 5.8 kg,

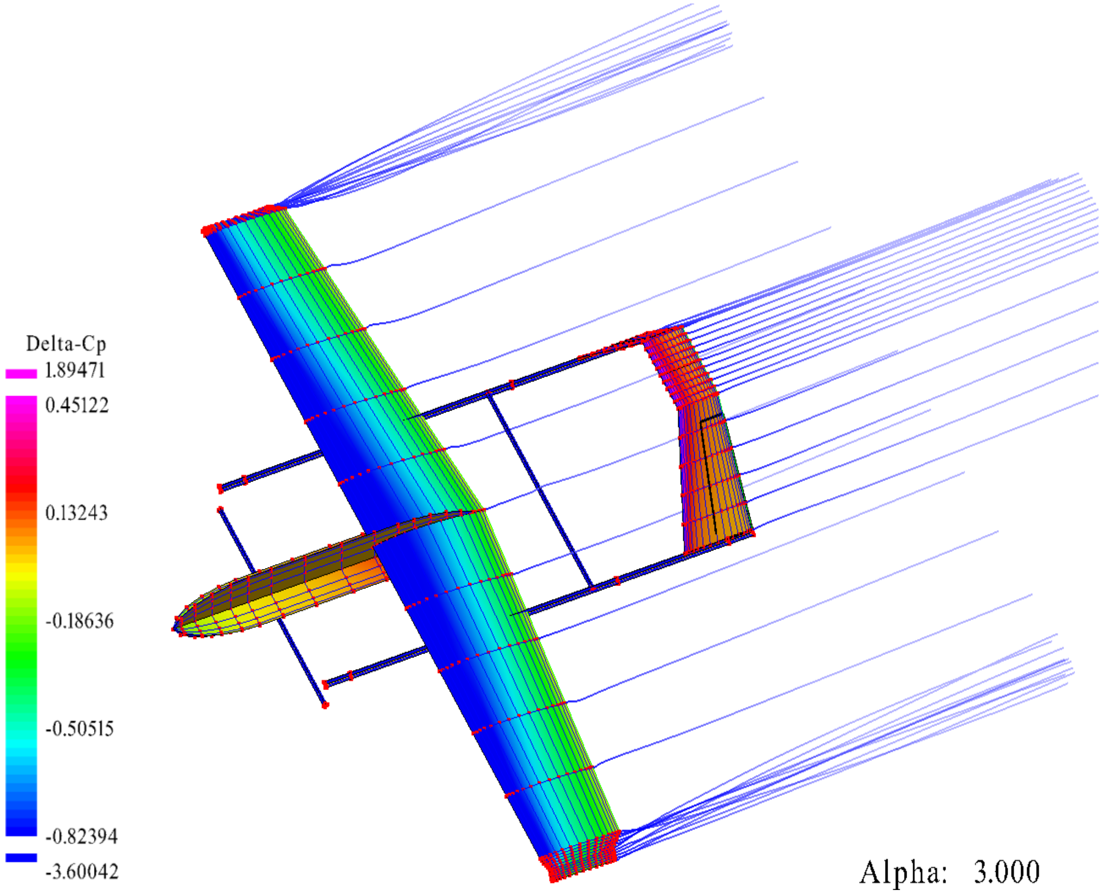
the cruise speed was calculated using the above lift coefficient.

$$V_{cruise} = \sqrt{\frac{2W}{\rho S C_L}} = 17.72 \ m/s$$

For autonomous flight mission, we need to put this parameter to PX4 or Ardupilot!



Hardware Development – stabilizing each flight phases



<Aerodynamic Analysis at 3° Angle of Attack>

(Contoured pressure coefficient and visualized wake with streamlines)

Observed vortex formation at the wingtip

< Specification >	
Takeoff weight	5.8 kg
Cruise Angle of Attach	3°
Cruise speed	17.72 m/s
Stall speed	11.03 m/s
Wingspan	2.02 m
Mean Aerodynamic Chord (MAC)	240 mm
Aspect ratio	8.55
Wing loading	12.2 kg/m^2
Maximum Lift-to-Drag Ratio (L/D)	18.79

Hardware Development – stabilizing each flight phases

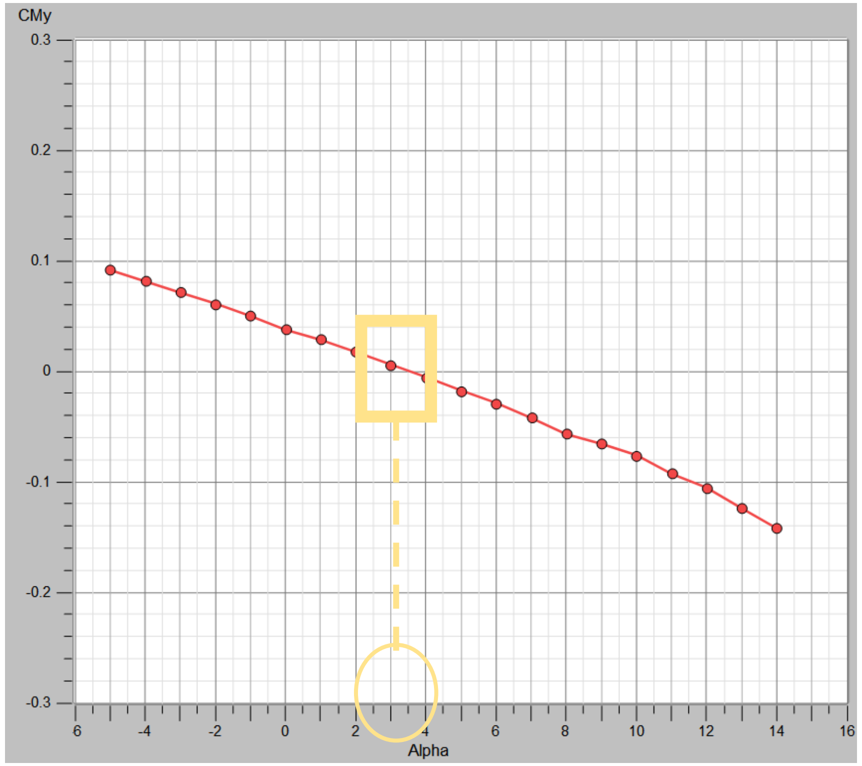
Fixed-wing phase

< Finding the Center of Gravity (C.G.) point>

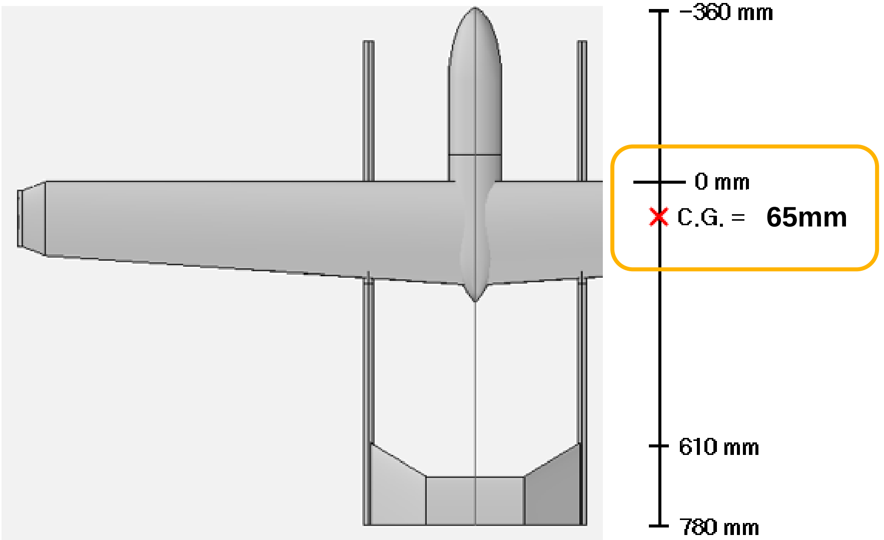
Since the cruise AOA is set to 3°, the moment coefficient graph must satisfy $C_m = 0$ at $AOA = 3°$, and the slope must be negative (stability condition)

In VSPAero, you can check the graph for the specified C.G. point.

Adjust the position iteratively to find the point that satisfies the above conditions—this is the optimal C.G. point.



It was confirmed that a point 65mm from the wing's leading edge achieves a moment coefficient of 0 at a 3° angle of attack.

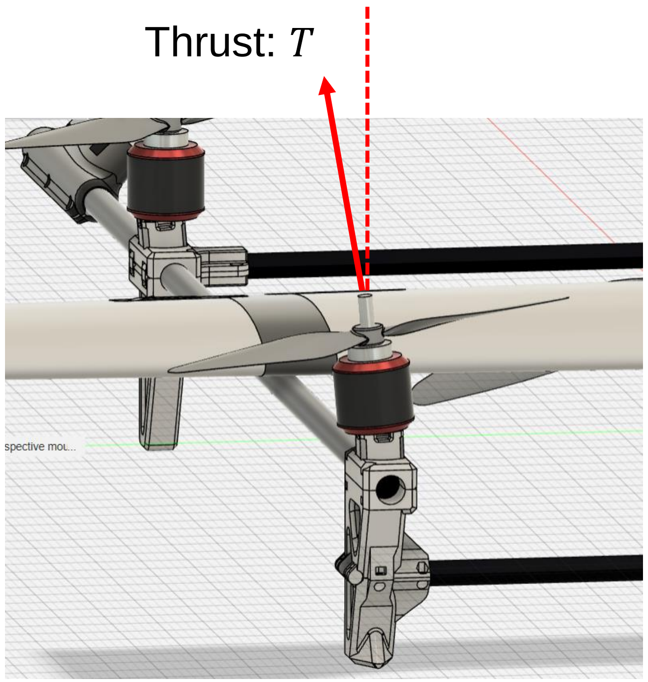


Hardware Development – stabilizing each flight phases

Multirotor phase

Issue: Insufficient yaw control in strong wind conditions (a common problem in VTOLs due to larger wing, tail.. etc)

Direction alignment required for transition

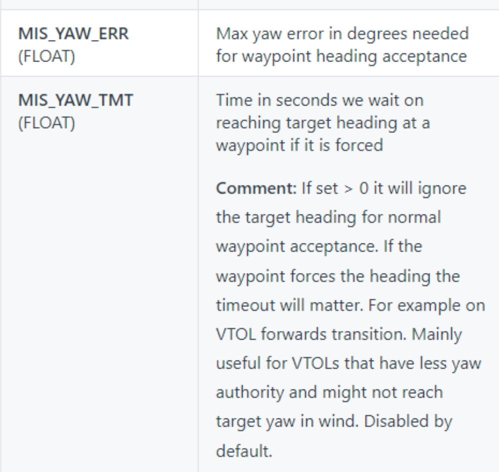


Tilted the lift motors outward by 5° to improve yaw control using thrust.

If motor is tilted by θ, Vertical thrust will be $T\cos\theta$.
Then the Thrust loss will be $T(1-\cos\theta)$

If motor generates $15N$ of thrust and is tilted by $5°$,

$$T_{vertical} = 15\cos 5 = 14.94\text{N}$$
$$Thrust\ loss = 0.057N$$



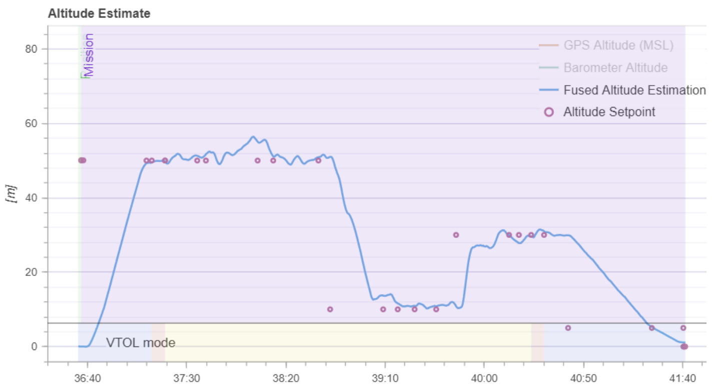
MIS_YAW_ERR (FLOAT)	Max yaw error in degrees needed for waypoint heading acceptance
MIS_YAW_TMT (FLOAT)	Time in seconds we wait on reaching target heading at a waypoint if it is forced **Comment:** If set > 0 it will ignore the target heading for normal waypoint acceptance. If the waypoint forces the heading the timeout will matter. For example on VTOL forwards transition. Mainly useful for VTOLs that have less yaw authority and might not reach target yaw in wind. Disabled by default.

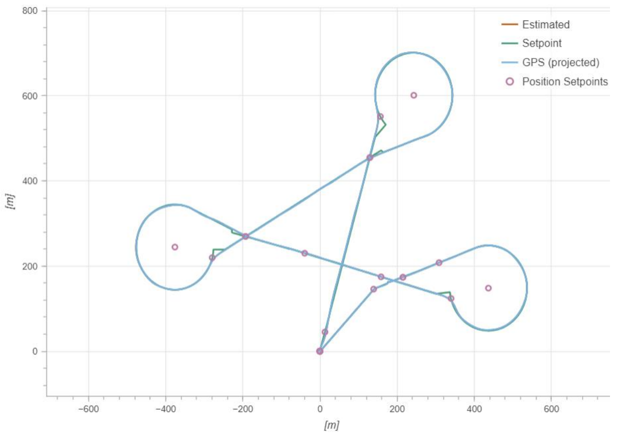
PX4 Parameters Related to Yaw Error tolerance

Hardware Development – stabilizing each flight phases

After all refinements:

1. No altitude drops during transition phase
2. Approximately 2 minutes of flight time remained after completing the entire mission





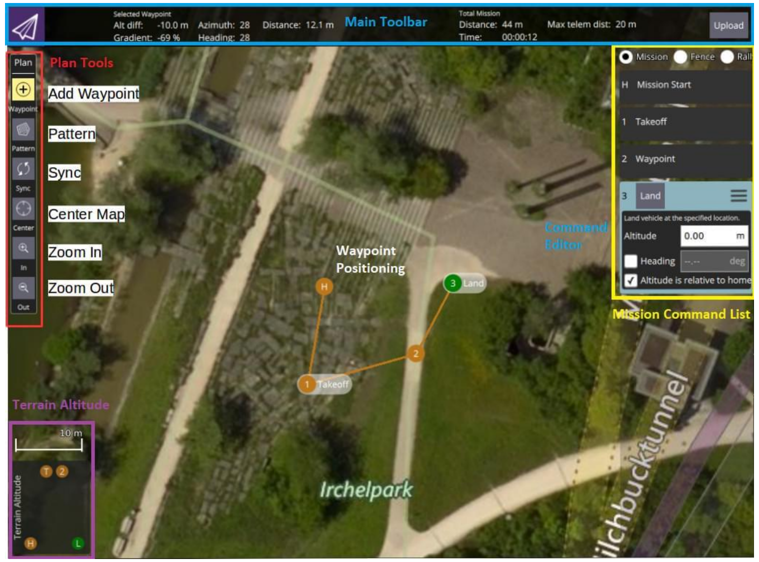
Software Development

Software Development

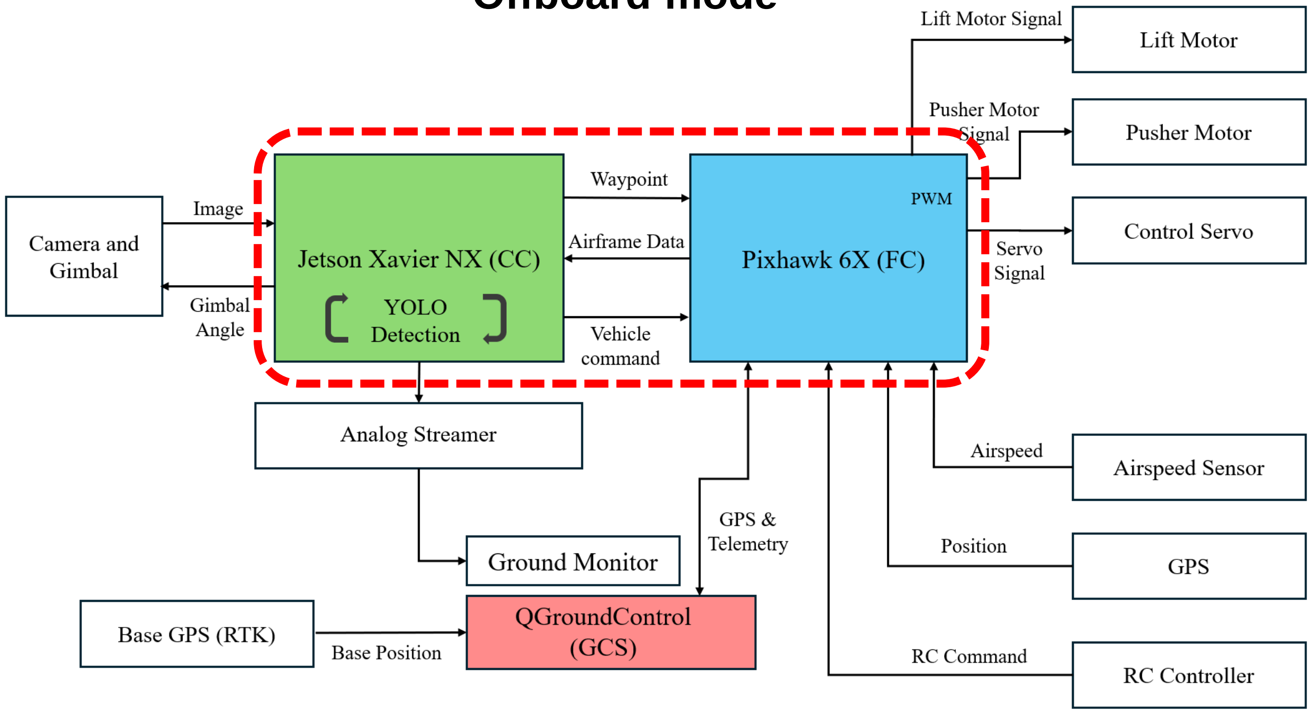
1. Autonomous flight missions

Difference between Mission & Offboard mode in PX4

Mission mode



Offboard mode



Predefined missions are stored on the FC's SD card.
Can be easily planned using GCS (e.g., QGroundControl).
However, they cannot adapt to real-time information, limiting flexibility.

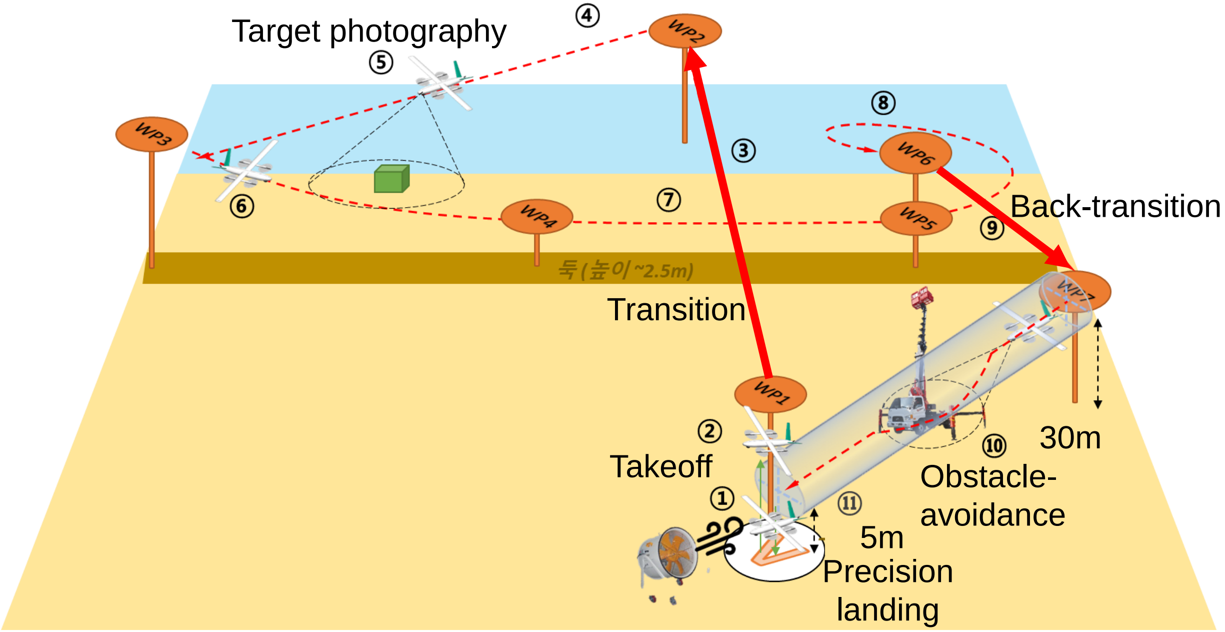
The Companion Computer (CC) integrates all information, manages the phase, and sends trajectory setpoints and vehicle commands to the FC.
Compared to Mission mode, this approach offers greater flexibility as the CC can process real-time information.

Software Development

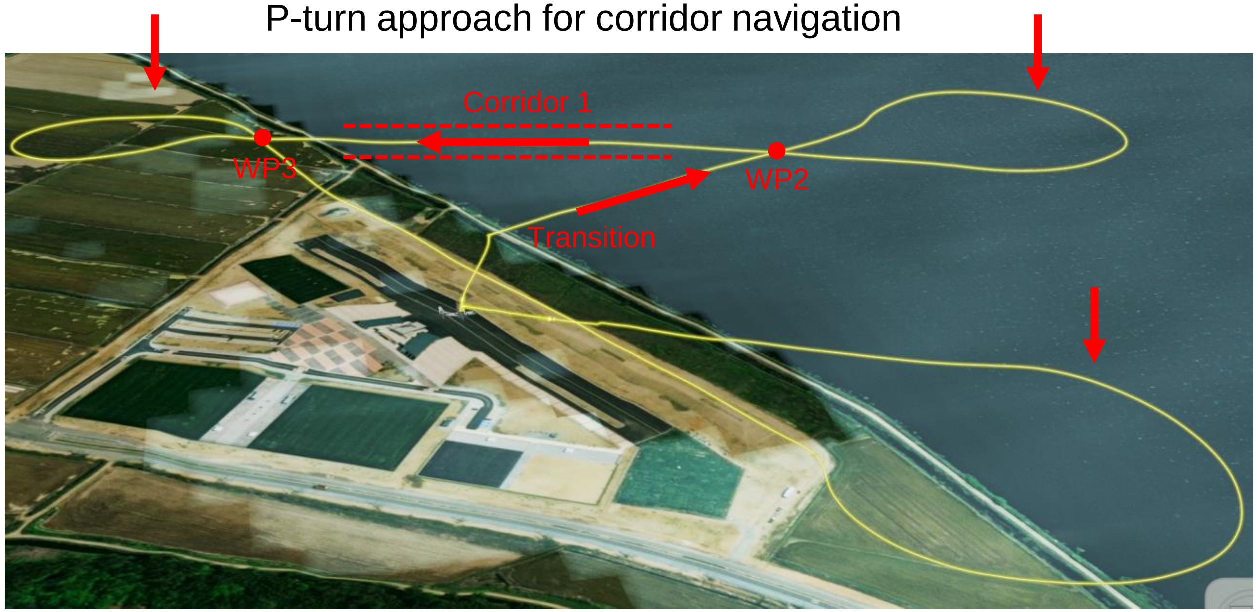
1. Autonomous flight missions

Mixed use of PX4 Offboard + Mission Mode (At the time, fixed-wing Offboard mode was not supported)

- Recently, our team resolved errors in the fixed wing Offboard mode and merged to the PX4 main branch
- Full Offboard mode is now available in both multirotor and fixed-wing phase
- Additionally, there are many updates in VTOL in PX4 this year. Please check the latest codes if you are interested



P-turn approach for corridor navigation



Software Development

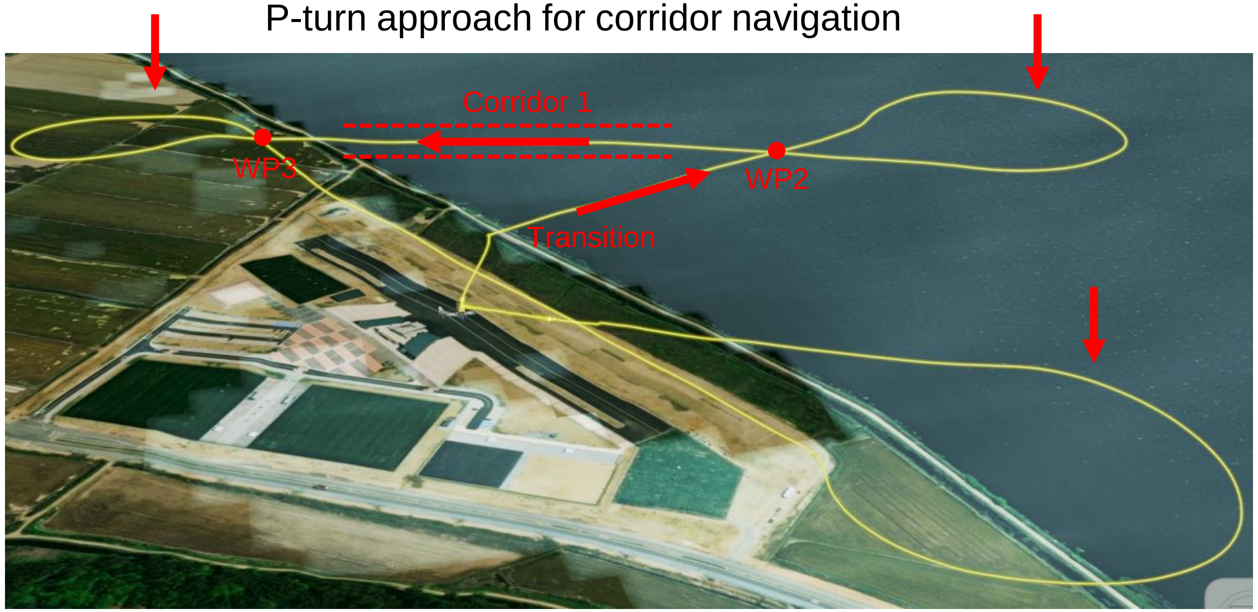
1. Autonomous flight missions

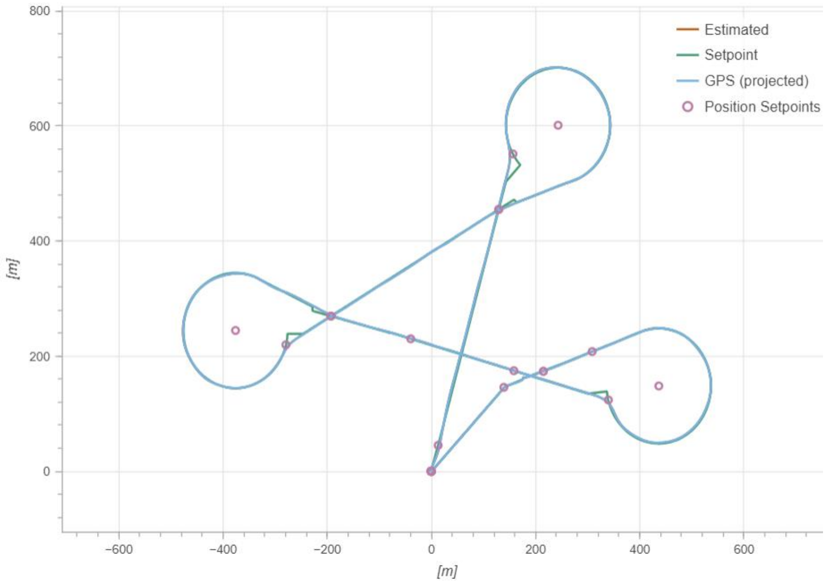
Things we need to consider for the mission planning

Unlike quadrotors, fixed-wing aircraft do not always fly directly to waypoints as commanded. Must carefully design the flight path.

- The vehicle's speed must remain above the stall speed
- Minimum radius of turn (can be determined using flight log or equations)

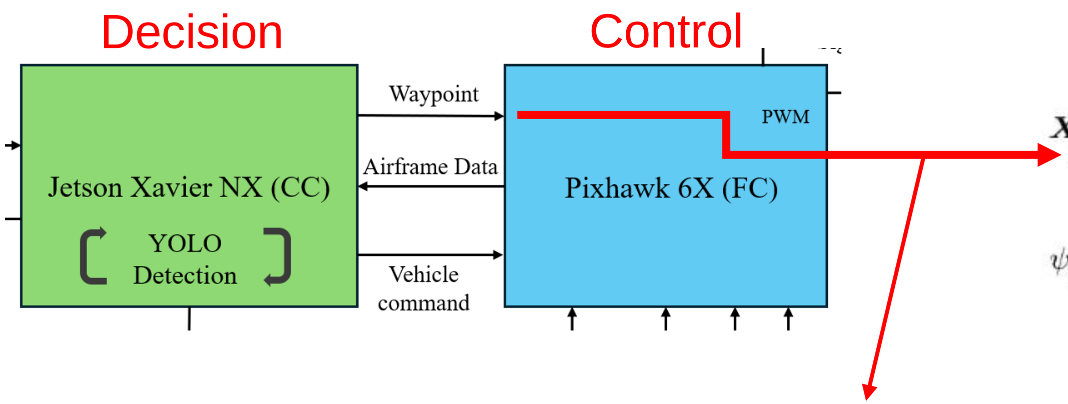
P-turn approach for corridor navigation

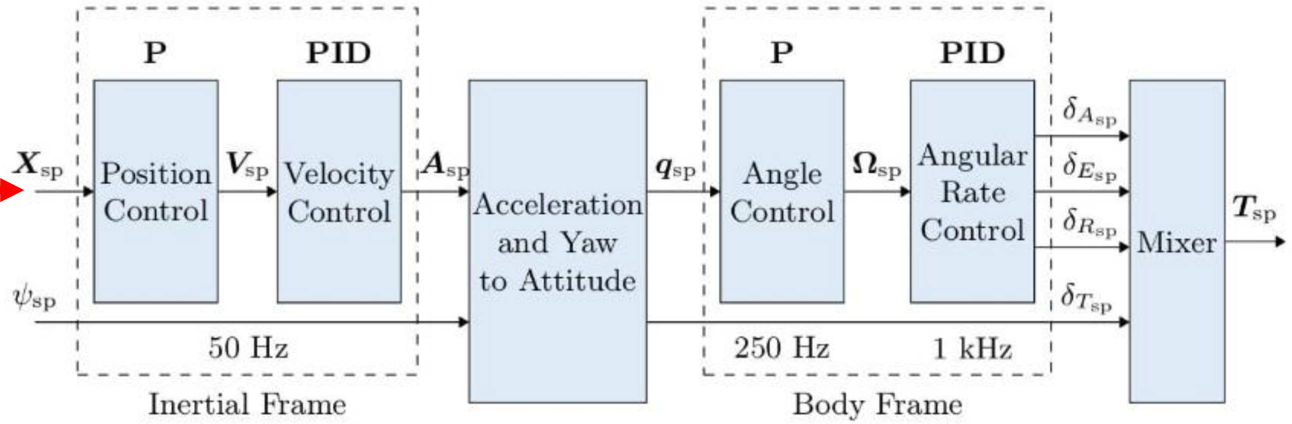




2. Multicopter guidance using Bezier curves

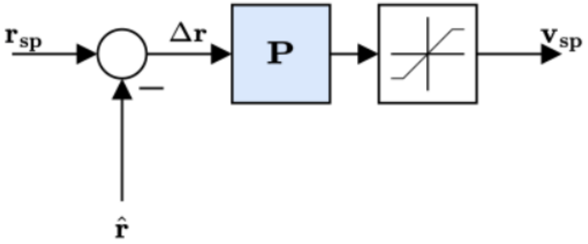
We send trajectory setpoints (position) from the CC to the FC. While it is possible to send velocity commands or lower-level attitude and rate commands, this is not recommended due to input delays.
Instead, these low-level commands and controllers should be implemented directly within PX4 and uploaded to FC.





PX4 multicopter control architecture

If the current vehicle position is (0, 0, 0) m
and CC send a position command of (10, 0, 0) m



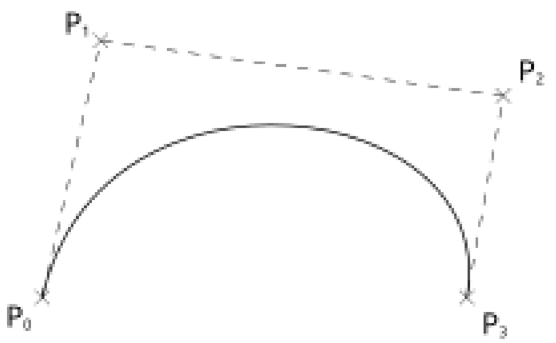
Position P-controller

With this simple P-controller, the vehicle will accelerate rapidly due to the large positional error.

We want to avoid this rapid behavior, especially when carrying passengers.

2. Guiding multicopter using Bezier curves

Using Bezier curves, we can generate list of trajectory setpoints enabling smooth behavior



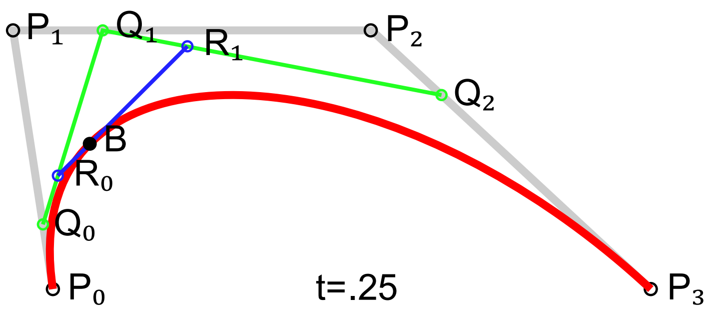
$$\mathbf{B}(t) = (1-t)^3\mathbf{P}_0 + 3(1-t)^2 t\mathbf{P}_1 + 3(1-t)t^2\mathbf{P}_2 + t^3\mathbf{P}_3,\ 0 \le t \le 1$$

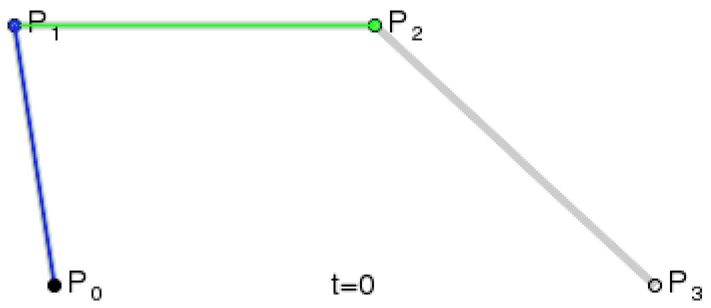
$$\mathbf{B}'(t) = 3(1-t)^2(\mathbf{P}_1 - \mathbf{P}_0) + 6(1-t)t(\mathbf{P}_2 - \mathbf{P}_1) + 3t^2(\mathbf{P}_3 - \mathbf{P}_2)$$

T	: Travel time
Vinit	: Initial velocity vector
Vfinal	: Final velocity vector
P0, P3	: Start and destination position vectors

P0 = P0
P1 = P0 + (T/3) * Vinit
P2 = P3 - (T/3) * Vfinal
P3 = P3

The initial and final velocity match the desired velocities

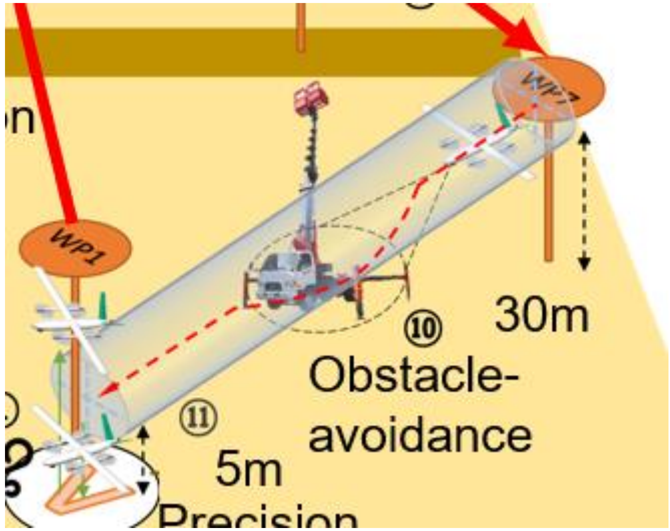




Software Development

3. Obstacle Avoidance

We need to avoid the ladder truck within a 3-meter radius.



We made ladder truck datasets, and used YOLO object detection model
Q. Why not use advanced sensors? Stereo camera, Lidar ,, etc
A. The mission was straightforward, we focused only on left and right avoidance

Training data we made

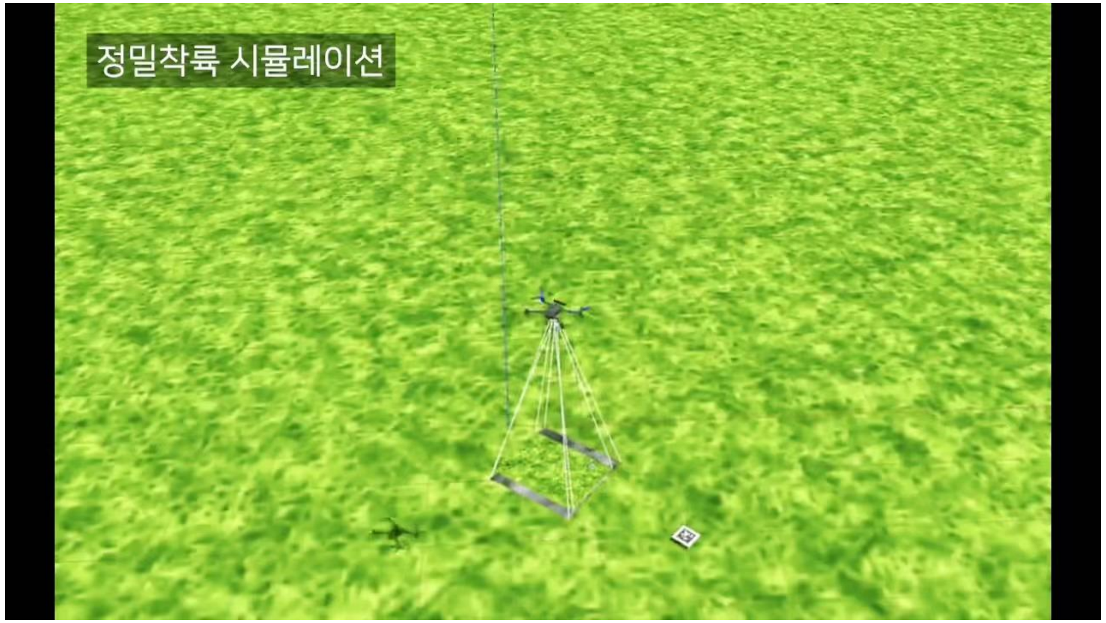
Photo from competition

Software Development

4. Precision Landing

Using markers with known shapes and sizes (April Tag), the 3D pose of the vehicle is estimated for precise landing

- Enable camera-based landing in environments where GPS accuracy is insufficient (e.g., indoors, forests, near buildings)
- Enable landing on the moving platform (e.g., Ship, truck)



SITL & preliminary test on small quadrotor

It may sound simple, but the real-world implementation wasn't easy

1. Tags became unrecognizable at close distances. We resolved this by adding a smaller tag at the center of the main tag

2. The system occasionally returned noisy data, requiring us to average multiple data for accuracy

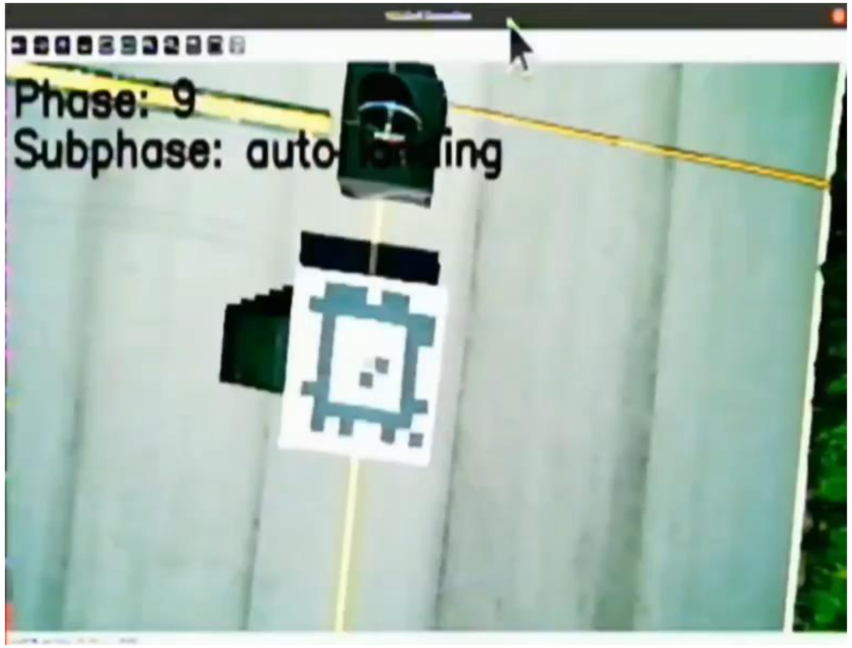
3. The landing path was continuously updated during the descent

4. Tuning was needed, such as determining how frequently to update the path and the optimal descent speed

Software Development

4. Precision Landing

- Enable camera-based landing in environments where GPS accuracy is insufficient (e.g., indoors, forests, near buildings)
- Enable landing on the moving platform (e.g., Ship, truck)



During the competition, the initial recognition quality was poor, but fortunately, the landing ended up centered

Landing on the moving truck – implemented on large Quadrotor

Summary

1. Importance of Systems Engineering and Aerodynamic analysis

2. Application of lightweight PLA-based 3D printing techniques for RC-scale VTOL aircraft (in our case, 2m wingspan)

- Unlike fixed-wing aircraft, VTOLs land using multicopter, reducing concerns about durability from impact during landing
- For single-use missions (e.g., suicide drones), is it necessary to invest significant effort in manual assembly?

3. With open-source firmwares like PX4 and ArduPilot, anyone can now build VTOL aircraft and conduct autonomous flight

- Easily start with Mission mode
- Advanced features using Offboard mode

Q&A

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