Flexibility with Flying
Replicable and Attachable Aerial Robot with Multi-Degree-of-Freedom

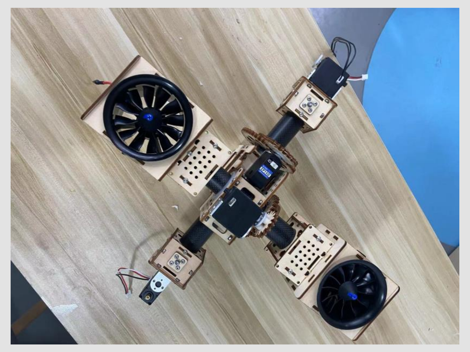
Abstract

This project, inspired by the movie Big Hero 6, attempts to create an aerial robot with muti-Degree-of-Freedom (DoF) in the air. Like microbots in Big Hero 6, it aims at creating a drone that could attach to and perform tasks with replicas of itself. Currently, most drones are the market are quadcopter drones with open propellers, losing DoF. This robot, however, created through two ducted fans, could transform shape when attached to replicas of itself. This allows the drone to increase its DoF and flexibility. The drone's mechanical design compost of a thrust rotor module, DoF-Joint Module, two ducted fans, and a Dual-Rotor Gimbal Module. The control uses Kalman Filters and PID, while the practicability of the idea is analyzed through Forward Kinematics (Kinematic Chains and D-H Convention) and classical Force Analysis. These combined, allowed the drone to achieve six DoF in air, with a maximum rotation of 120.73° in the x-direction and 114.22° in the y-direction, and a constant lift allowing the drone to hover in the air both alone and connected with a replica of itself.

Introduction

Despite being super happy when Hiro won, I thought the problem of running out of microbots could be solved if the microbots could fly. If they were able to fly, then Callaghan could simply be carried into the sky, and depending on the scenario, the flying-microbots could change in shape and form. So, my project started with an attempt to solve this problem.

This project was inspired by my all-time favorite movie: Big Hero 6. The idea of microbots, small robots that could transform in shape with almost a six degree of freedom, struck me as genius. The tiny flaw of this setup, however, was when it ran out and failed to push Callaghan into the sky, which resulted in Hiro winning. (YAY)

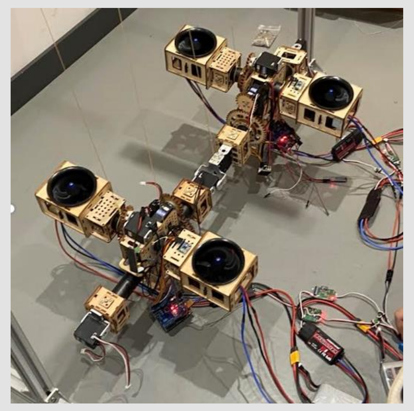


Most drones on the market right now are quadcopter drones with open propellers, and due to this form, they lack in flexibility. The goal of this project is to create a drone with 6 degrees of freedom, able of transforming in air, attachable to replicas of itself, and calculate its shape to overcome obstacles that could be in the air, providing flying with flexibility.

Mechanical Design

To Achieve 6 DoF in Air:

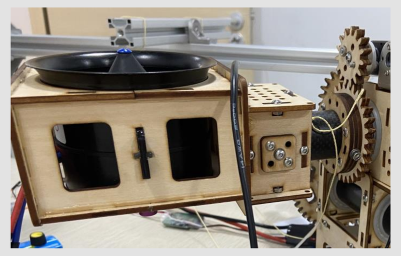
1) A rotor module controlled by two servos to produce 2DoF tilting
2) A rotor module controlled by a single servo to produce 1DoF tilting,
3) A fixed rotor configuration with different tilt directions



Why Ducted-Fans instead of Open Propellers:

1) High speed
2) With ideal hover case: $\frac{P_{df}}{P_{op}} = \frac{1}{2\Lambda}$

$$\frac{T_{df}}{T_{op}} = \sqrt[3]{2\Lambda}$$



Control

PID

Overall Formula:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{d}{dt} e(t)$$

Proportion:

$$K_p e(t)$$
$$e(t) = 0° - \theta$$

Problem: Likely to be left in an oscillatory motion

Derivative:

$$K_d \frac{d}{dt} e(t)$$

Allows: System to stabilize quickly

Problem: Likely be left in an oscillatory motion

Integral:

$$K_d \frac{d}{dt} e(t)$$

Allows: Drone remain horizontal (Not necessary for this project)

Overall:

$$K_p = 2 \quad K_i = 0 \quad K_d = 0.2$$

$$u(t) = 2e(t) + 0.2 \frac{d}{dt} e(t)$$

Kalman Filter

Combine the actual measured results and the predicted results to estimate the system's true state.

Error: e_r $\quad e_r = x - \hat{x}$

Variable Predicted: x

Variable Measured: y

Input Value: u

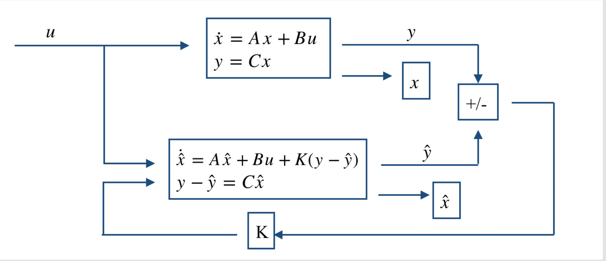
^ represents state estimate

Estimate Variable:

$$\dot{\hat{x}} = A\hat{x} + Bu + K(y - \hat{y})$$
$$\hat{y} = C\hat{x}$$

Assume:

$$\dot{x} = Ax + Bu$$
$$y = Cx$$



$$\dot{x} - \dot{\hat{x}}$$
$$= Ax + Bu - (A\hat{x} + Bu + K(y - \hat{y}))$$
$$y - \hat{y} = C(x - \hat{x})$$

Conclusion:

$$\dot{e}_r = (A - KC)e_r \longrightarrow e_r(t) = e^{(A-KC)t} e_r$$

If $(A - KC) < 1$, then

$e_r(t) \to 0$ as $t \to \infty$

Measuring Noise: v

$$x_k = Ax_{x-1} + Bu_k + w_k$$

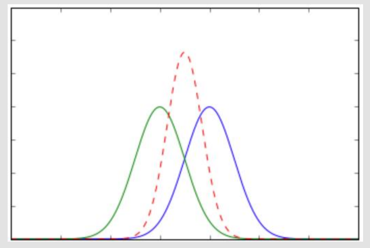
Processing Noise: w

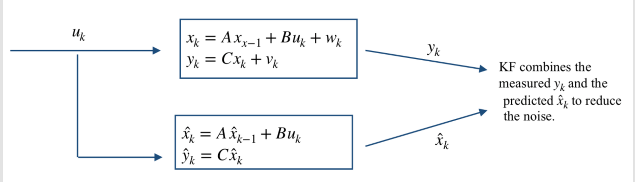
$$y_k = Cx_k + v_k$$

Gaussian:

$$v_k \sim N(0, R) \quad R: \sigma_v^2$$
$$w_k \sim N(0, Q) \quad Q: \sigma_w^2$$

Multiplication would result in the best estimate for $\hat{x}_k$





Movement Dynamics

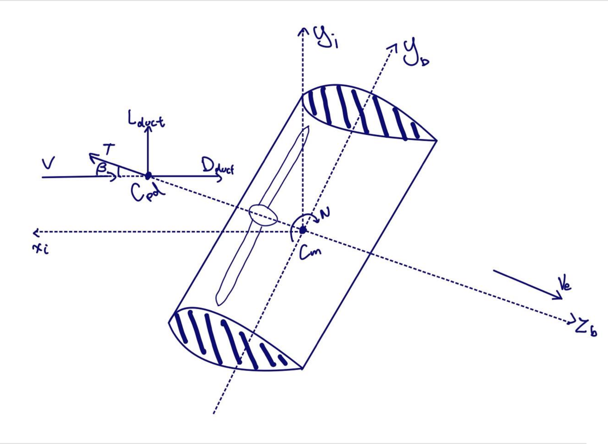
Force Analysis

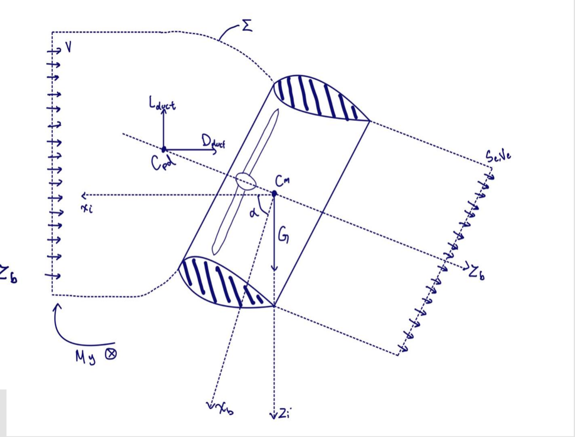
Aerodynamic Resistance

$$D = D_{duct}$$
$$D_{duct} = \frac{1}{2}\rho V^2 S(C_{D0d} + C_{D_\alpha d}\alpha)$$

Aerodynamic Lift

$$L = L_{duct}$$
$$L_{duct} = \frac{1}{2}mv^2 = \frac{1}{2}pSlv^2$$
$$W = \Delta KE = F\Delta x = Fl = L_{duct}$$
$$\frac{1}{2}pSlv^2 = Fl$$
$$L_{duct} = \frac{1}{2}\rho V^2 S C_{L_\alpha}\alpha$$





Gravity

$$G = mg$$

Precession Torque

$$M_{gyro} = \Omega \times J\omega$$

Yawing Torque

$$Y = Y_{duct} = \frac{1}{2}\rho V^2 S_d C_{Y_\beta d}\beta$$
$$N = (Y_{duct}cos(\beta) + D_{duct}sin(\beta))(z_{C_m} - Z_{C_p t})$$
$$N = Y_{duct}(Z_{C_m} - Z_{C_p t})$$

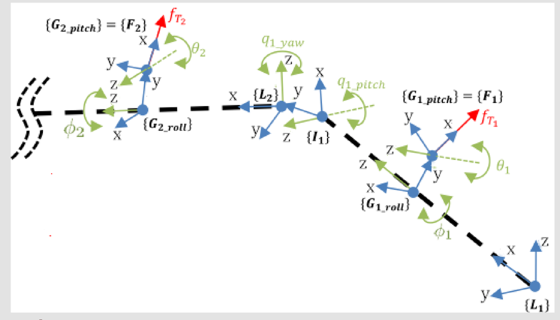
Fan Propulsion

$$T = \dot{m}(V_e + V) - \dot{m}V$$
$$= \rho S_e V_e (V_e + V)$$

Pitching Torque

$$M = F(l)$$
$$= \left(L_{duct}sin(\alpha) + D_{Duct}cos(\alpha)\right)\left(z_{C_m} - z_{C_p d}\right)$$
$$M = L_{duct}(z_{C_m} - z_{C_p d})$$

Kinematic Chains



i^{th} joint has only 1 DoF

Joint variable: q_i

$$(q_i = \theta_i)$$

Coordinating Frame: $o_i x_i y_i z_i$

Homogeneous Transformation Matrix: A_i

$$A_i = A_i(q_i) = A_i(\theta_i)$$

Transformation Matrix: T_j^i

$$T_j^i = A_{i+1}A_{i+2}A_{i+3}\ldots A_{j-2}A_{j-1}A_j \text{ if } i < j$$
$$T_j^i = 1 \text{ if } i = j$$

Matrix 6: o_n^1 and R_n^1

$$H_6 = T_n^1 = \begin{bmatrix} R_n^1 & o_n^1 \\ 0 & 1 \end{bmatrix}$$

$$A_{1+1}\ldots A_n = T_n^1 = \begin{bmatrix} R_n^1 & o_n^1 \\ 0 & 1 \end{bmatrix}$$

$$A_1 = \begin{bmatrix} R_1^{1-1} & o_1^{1-1} \\ 0 & 1 \end{bmatrix}$$

$$R_n^1 = R_{1+1}^1 R_{1+2}^{1+1}\ldots R_{n-1}^{n-2} R_n^{n-1}$$

$$o_n^1 = o_{n-1}^1 + R_{n-1}^1 o_n^{n-1}$$

Link	a	α	d	θ
1	a_1	90	0	θ_1
2	0	90	d_2	θ_2
3	a_3	90	d_3	θ_3
4	0	90	0	θ_4
5	a_5	90	d_5	θ_5

Denavit Hartenberg Convention

$$A_i = Rot_{z,\theta_i} Trans_{z,d_i} Trans_{x,a_i} Rot_{x,\alpha_i}$$

$$= \begin{pmatrix} c_{\theta_i} & -s_{\theta_i} & 0 & 0 \\ s_{\theta_i} & c_{\theta_i} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{\theta_i} & -s_{\theta_i} & 0 \\ 0 & s_{\theta_i} & -c_{\theta_i} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

a_i link length

α_i link twist

d_i link offset

θ_i joint angle

Results

Rotational Degree of Freedom Along X and Y Axis

Axis of Rotation	Direction	Maximum Angle	Change in Angle
x-axis	Forward	59.08°	120.73°
	Backward	-61.73°	
y-axis	Forward	57.79°	114.22°
	Backward	-56.43°	

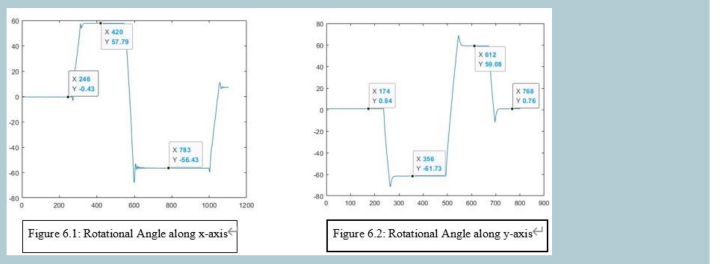


Figure 6.1: Rotational Angle along x-axis

Figure 6.2: Rotational Angle along y-axis

Such an angle of rotation would be enough for the drone to reach flexibility in the air.

Ducted Fan Lift Test

PWM	Wieght	PWM	Weight	PWM	Weight
1000	1463.9	1160	1067.3	1320	606.3
1020	1463.9	1180	997.8	1340	506.3
1040	1463.9	1200	942.7	1360	465.8
1060	1362.9	1220	873.3	1380	443.5
1080	1245.3	1240	812.3	1400	390.6
1100	1300.15	1260	766.8	1420	316.5
1120	1245.3	1280	706.3	1440	287.2
1140	1183.6	1300	648.7	1460	246.5

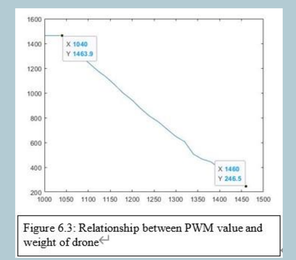


Figure 6.3: Relationship between PWM value and weight of drone

From the graph, we could see the linear relationship between the two and thus we could use determine the relationship as the two. When PWM value reaches 1060, the ducted fan would start and the linear relationship would be described as:

F=-2.888(PWM)+4417

F=mg-F_{lift}

In which F is the difference between gravity and lift, PWM as the duty ration, mg as the weight of the drone, and F_{lift} as the lift.

Further Application

Currently, the drone had reached the state of hovering either by itself or with another drone attached. It could also transform in shape with respect to another drone. Due to the limitations of time, the drone hasn't been able to recognize objects and transform their shape with regard to the object. However, the drone has all the functions to do so, and those functions had been tested. The practicability of the idea had also been tested and calculated through forward kinematics and force analysis. With more time, this drone, luckily, would be able to achieve all the intentions which I had for it, and the process with this project would not stop until its goals are reached. With such a drone, like microbots, it would be able to perform multiple functions of drones all in one, since it would be able to transform itself and perform at different needs.

Acknowledgements

Huge thanks to my school engineering teacher! He helped me throughout the mechanical design and allowed me many resources from textbooks to material!