Deep Learning Based Control for Autonomous Ornithopter

[M.Tech Thesis Defense]

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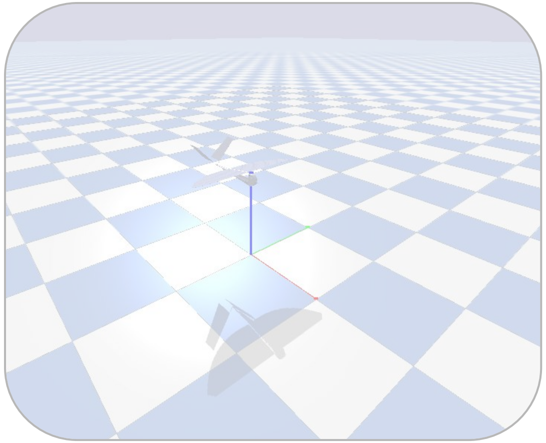
Unsteady Aerodynamics Lab

Department of Aerospace Engineering

IIT KANPUR
Indian Institute of Technology Kanpur

Motivation

- Natural Flying species are the result of millions of years of evolution and adaptation to flight.



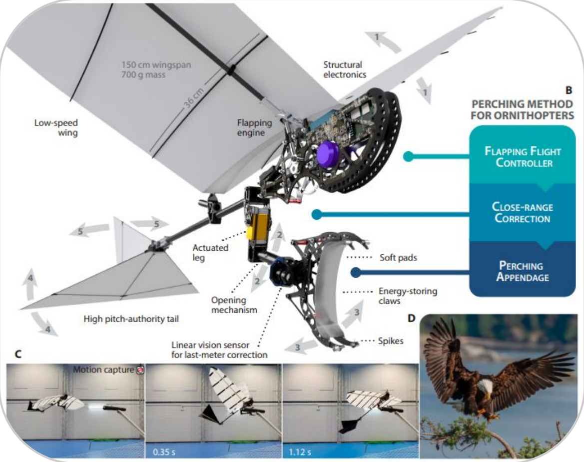
- Develop Autonomous Ornithopter

> Biomimicry is … the conscious emulation of life's genius.
>
> -- Janine Benyus

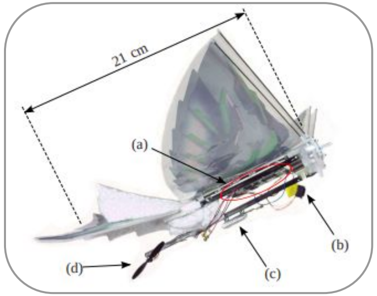
"Bird Probably don't solve Navier-Stoke Equation to Fly"

"Standing on the Shoulders of Giants"

IIT K

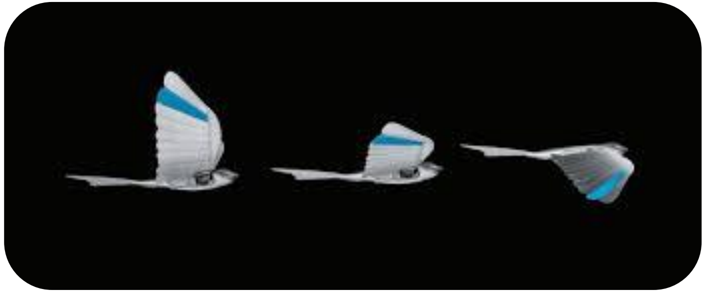


Nature



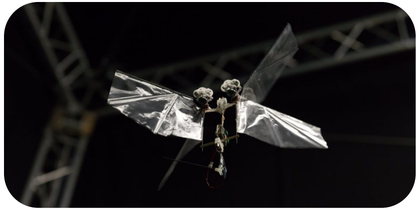
UC Berkley

Stanford



Festo

MIT Phonix



TU Delft

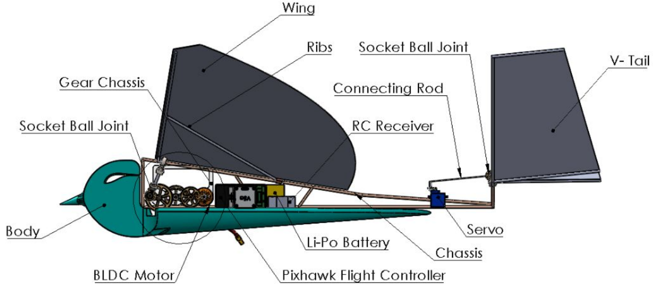
Design Development of Ornithopter

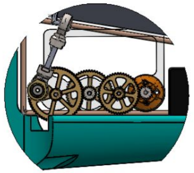
Improvement of Flapping Wings

Improvement of Kinematics Mechanism

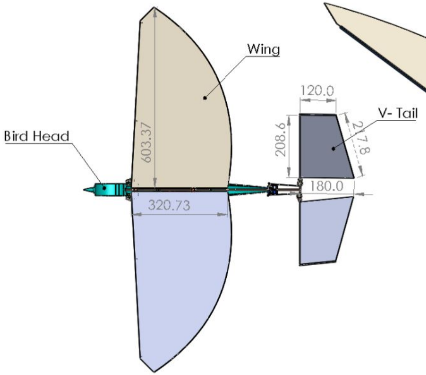
Development of RNN Controller

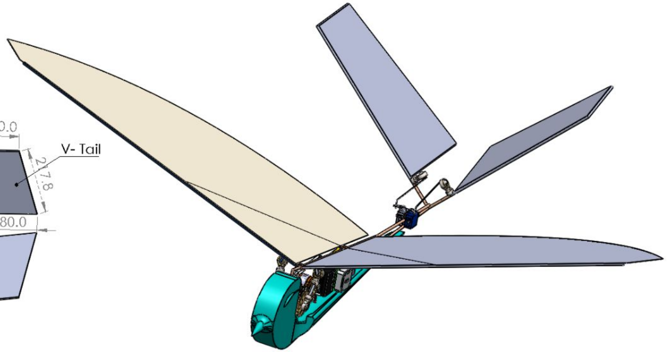
Overview of Ornithopter

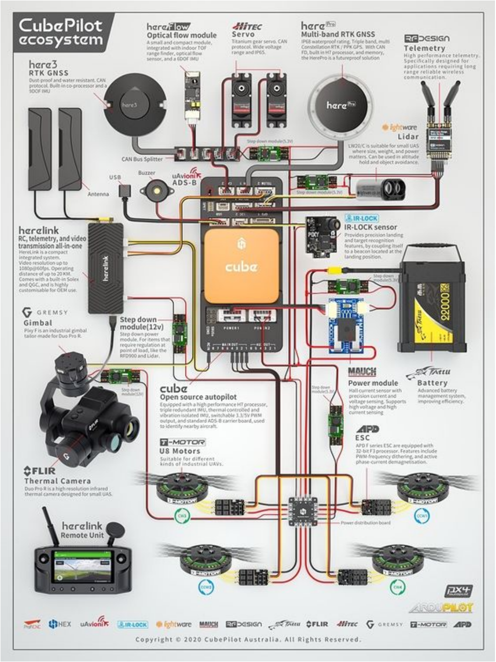




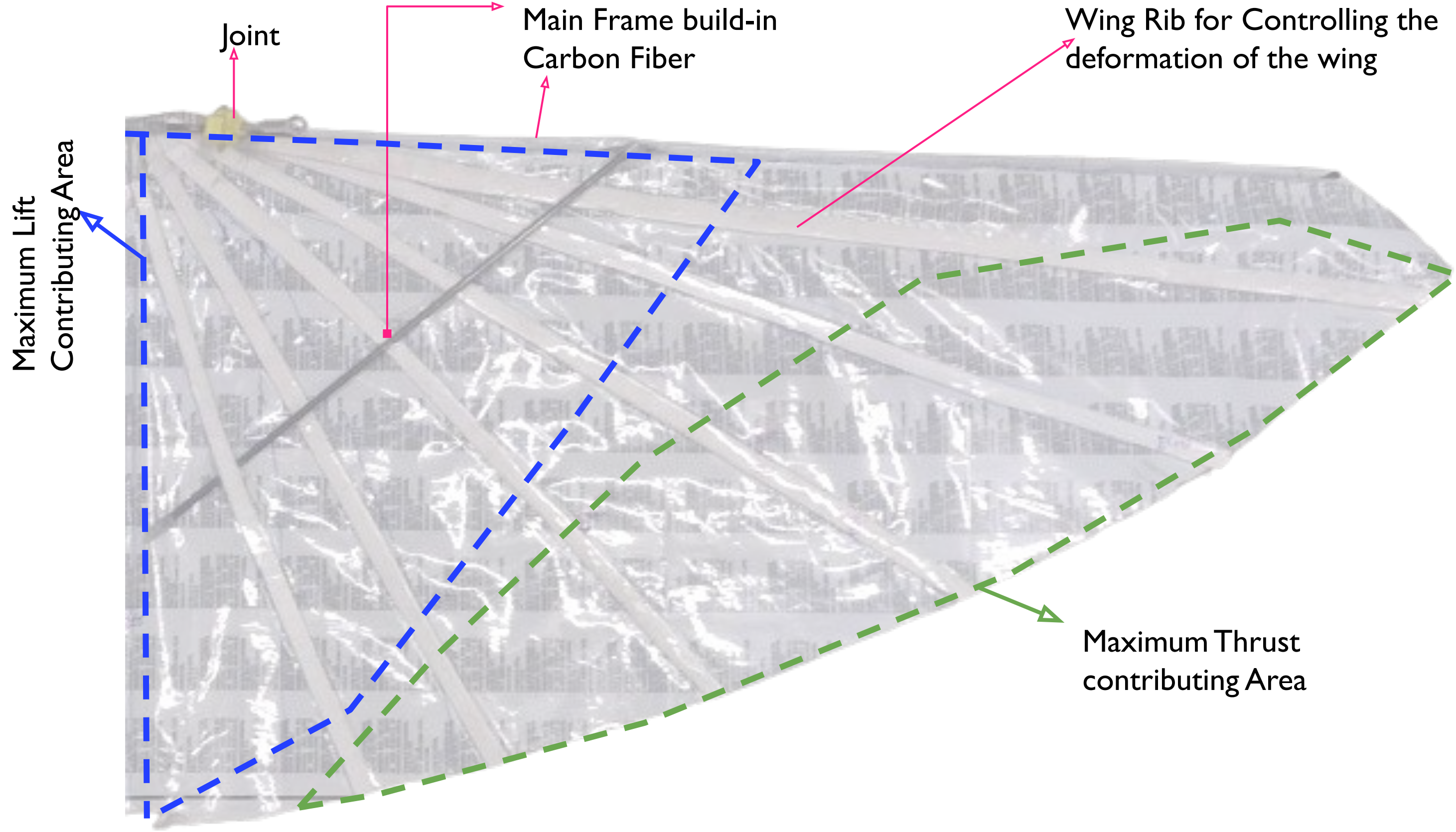
DETAIL B
SCALE 2 : 5







Design Principle of Wings



- W. Yang, L. Wang, and B. Song. Dove: A biomimetic flapping-wing micro air vehicle. International Journal of Micro Air Vehicles, 10(1):70–84, 2018b.

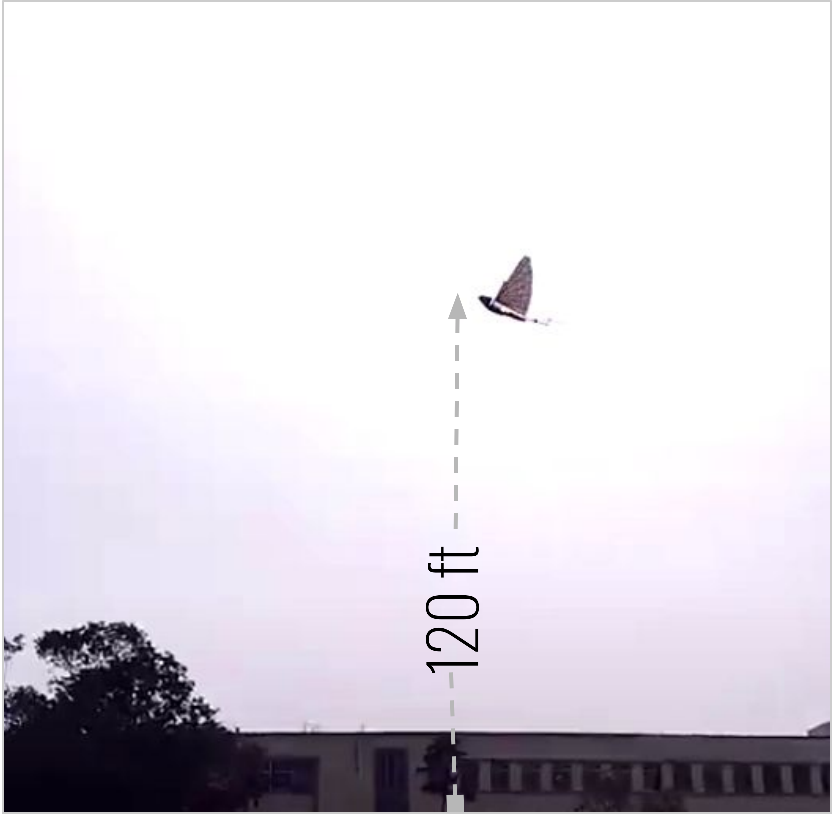
Building Components

Component	Description
Fuselage Material	High-density styrofoam
Wing Design	Semi-elliptical shape with laminated low-density polythene
Gear Material	PLA, ABS, Nylon (0.8 module)
Gearbox	Three-stage gear reduction with 3D printed gears
Motor	Brushless DC (BLDC) motor
Power Source	Li-Po (Lithium Polymer) Battery
Flight Controller	Pixhawk PX4
Receiver	Fr-Sky X8r 8-channel multi-protocol receiver

Specification

Component	Description
Total mass	450 g
Wingspan	150 cm
Flap frequency	3-6 Hz
Speed	5-8 m/s
Endurance	40 min
Operating Range	Ideally 25 km
Power Source	Li-Po battery, 2S
Control	Manual

Building Manual Ornithopter for Flight Test



Design Development of Ornithopter

Improvement of Flapping Wings

Improvement of Kinematics Mechanism

Development of RNN Controller

Articulating Wing

Fig 1a: Up Stroke

FIg1b:Down Stroke

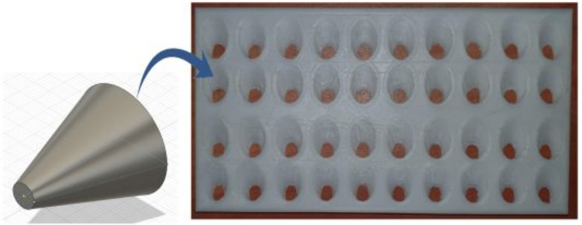
Twisting Wing

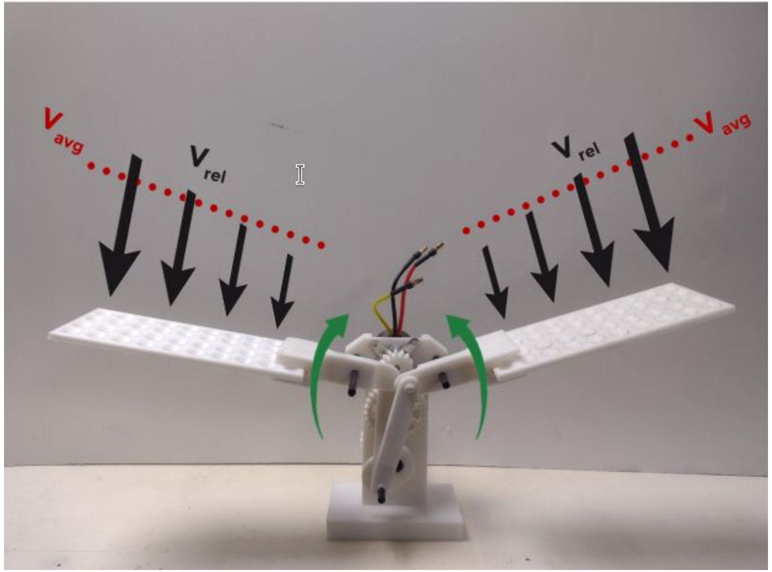
Fig 2a: Up Stroke

Fig 2b: Down Stroke

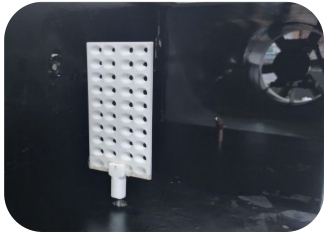
1. JCVdude (2011), "birds flying at 240fps slow motion - grace and beauty", available at: https://www.youtube.com/watch?v=PSikfcJezy4
2. SmarterEveryDay (2012), "MACAWS in SlowMotion! Rainforest Research! Smarter Every Day 60", available at: https://youtu.be/VTVigNA3KCY

Experimental Setup

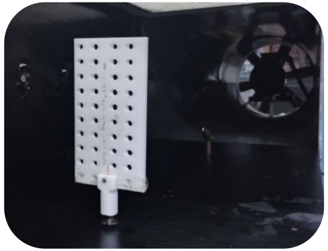




Experimental Setup



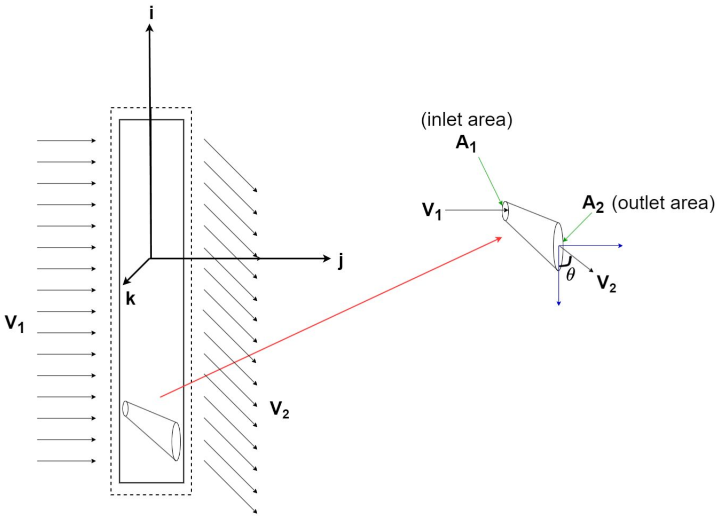
Up-Stroke (FF)



Down-Stroke (BF)

Flat Plate (FF)

Result
Theoretical



- Momentum Conservation
- 2D Potential flow

$$F_y = -\rho {V_1}^2 A_{total} + N\rho {V_2}^2 A_2(sin^2\theta)$$

$$F_x = -N\rho {V_2}^2 A_2 sin\theta cos\theta \quad -$$

Result

Simulation

Simulation Settings

- 3D pressure based simulation
- SIMPLE (Semi-Implicit Method for Pressure Linked Equations) Algorithm
- Boundary Conditions
  - Velocity inlet
  - Out -Flow boundary
  - Stationary No Slip wall
- Free stream velocity 4 m/s
- Unstructured Mesh size 0.005 mm

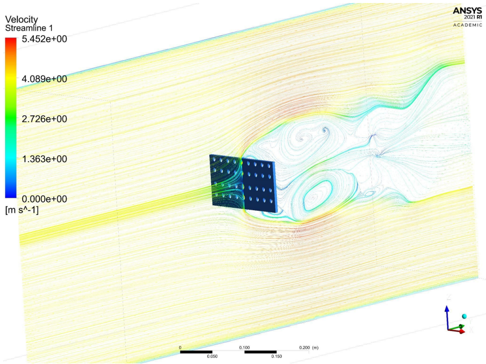


Fig a: Isometric View

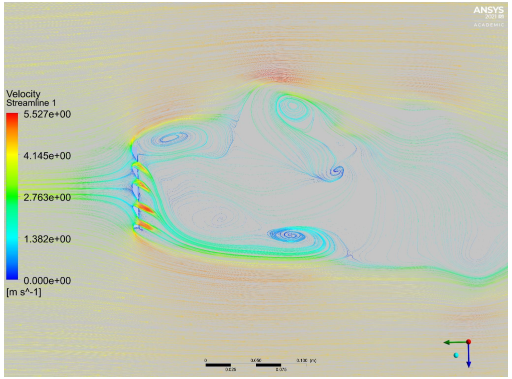


Fig b: Up-Stroke

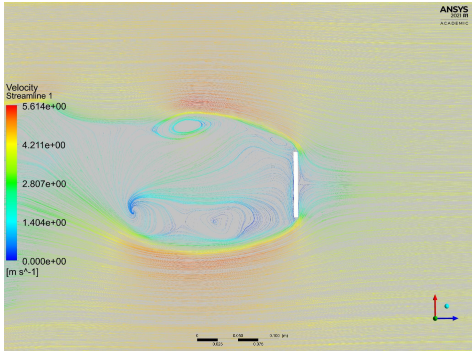


Fig c: Flat Plate

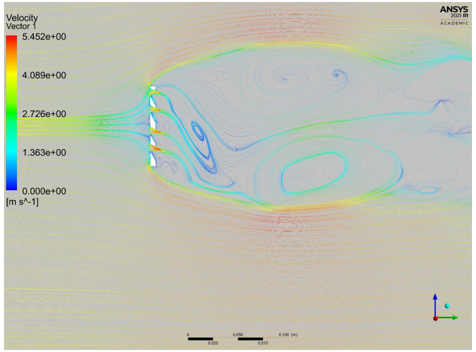


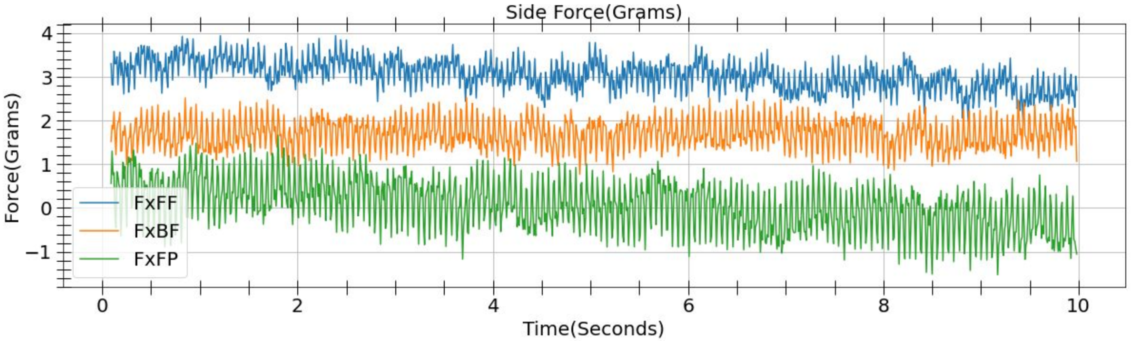
Fig d: Down-Stroke

Result

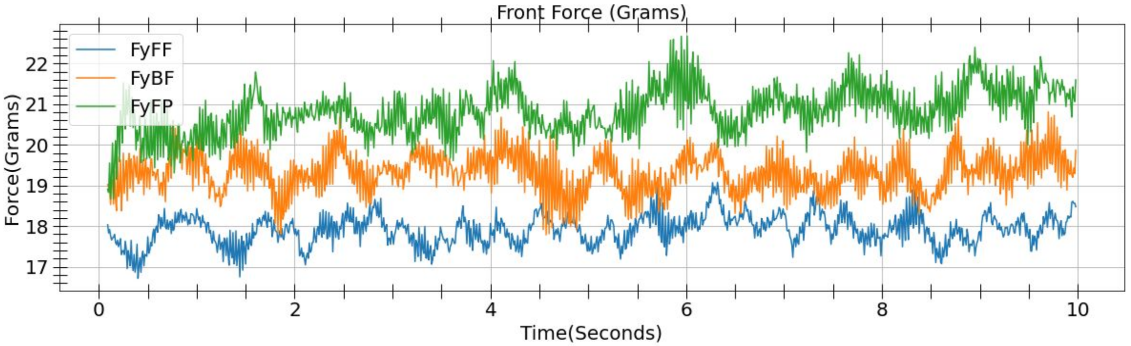
Experimental

Force Transducer Settings

- Sampling Frequency 100 hz
- ATI gamma load cell with 95% of confidence
- Least count 0.1 grams

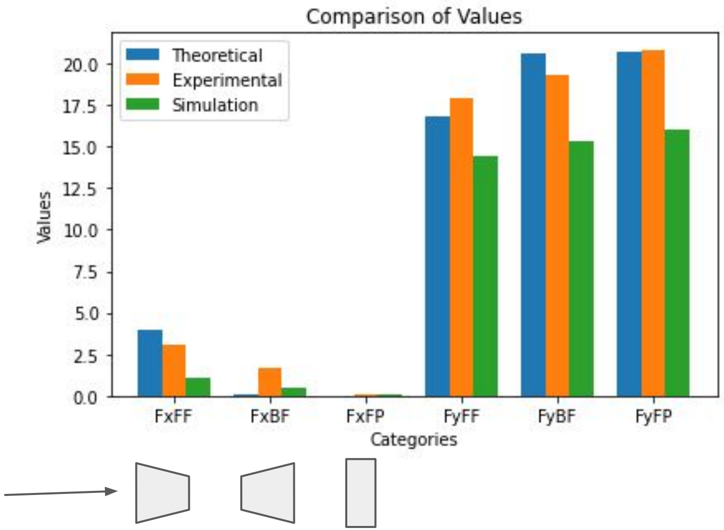


Thrust Force



Lift Force

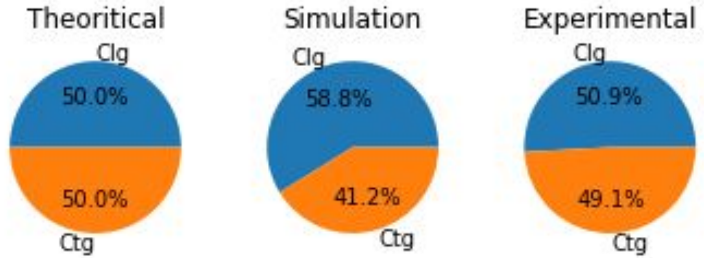
Validation



$$Clg = \frac{\textit{Net lift gain in a cycle with respect to benchmark case}}{0.5 * \rho A v^2} = \frac{|FyBF - FyFF|}{0.5 * \rho A v^2}$$

$$Ctg = \frac{\textit{Net lift gain in a cycle with respect to benchmark case}}{0.5 * \rho A v^2} = \frac{|FxFP - FxBF|}{0.5 * \rho A v^2}$$

Net Lift & Thrust 13%



- D. Poddar, A. Gangwar, and D. Das.Bio-inspired perforated flapping wings.International Conference on Intelligent Unmanned Systems, 2023

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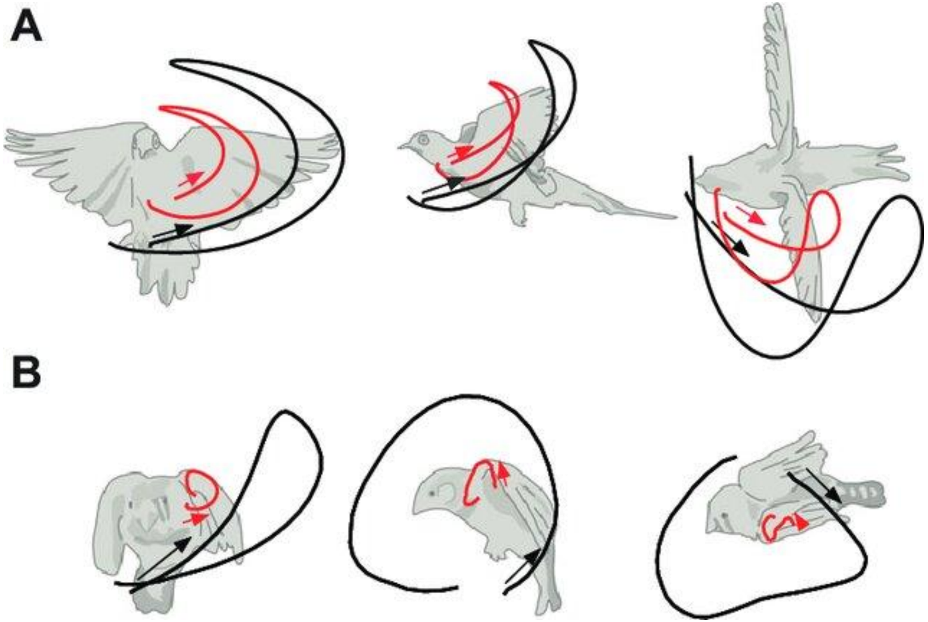
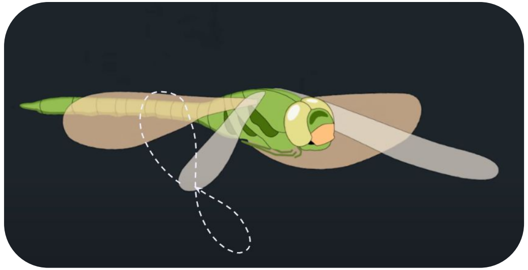
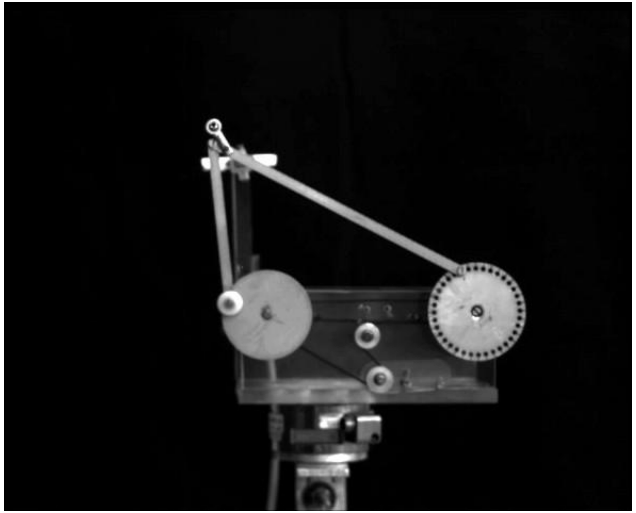
Kinematics of WingTip Motions

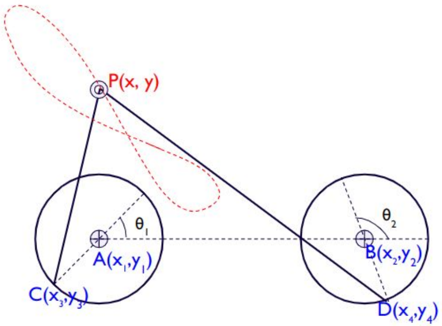




- Crandell, Kristen E., and Bret W. Tobalske. "Kinematics and aerodynamics of avian upstrokes during slow flight." *The Journal of experimental biology* 218.16 (2015): 2518-2527.

Experimental vs Theoretical





Algorithm 1 Locus of P(x,y) of Linkage Calculation

procedure CALCULATE TRAJECTORY($\phi, \omega, L, R_1, R_2, L_1, L_2, t_{start}, t_{end}, t_{step}$) ▷ Parameters: linkage geometry, angular velocity, time range, step size

  Define symbolic variables x, y, t

  Define crank trajectories:

   $X1(t) = R_1 \cos(\omega t - \pi)$

   $Y1(t) = R_1 \sin(\omega t - \pi)$

   $X2(t) = R_2 \cos(\omega t + \phi - \pi) + L$

   $Y2(t) = R_2 \sin(\omega t + \phi - \pi)$

  Define floating link constraints:

   $(x - X1(t))^2 + (y - Y1(t))^2 = L_1^2$

   $(x - X2(t))^2 + (y - Y2(t))^2 = L_2^2$

  $t\_vals \leftarrow t_{start} : t_{step} : t_{end}$ ▷ Generate time values

  Initialize empty lists $x\_intersect$, $y\_intersect$

  for t in t_vals **do**

   sol = SolveSystem($(x - X1(t))^2 + (y - Y1(t))^2 = L_1^2$,

    (x - X2(t))$^2 + (y - Y2(t))^2 = L_2^2$)

   for i in 1 to 2 **do** ▷ Handle two possible solutions

    if $sol.x(i)$ is real **then**

     $x\_intersect.append$(double(subs(sol.x(i), t)))

     $y\_intersect.append$(double(subs(sol.y(i), t)))

    end if

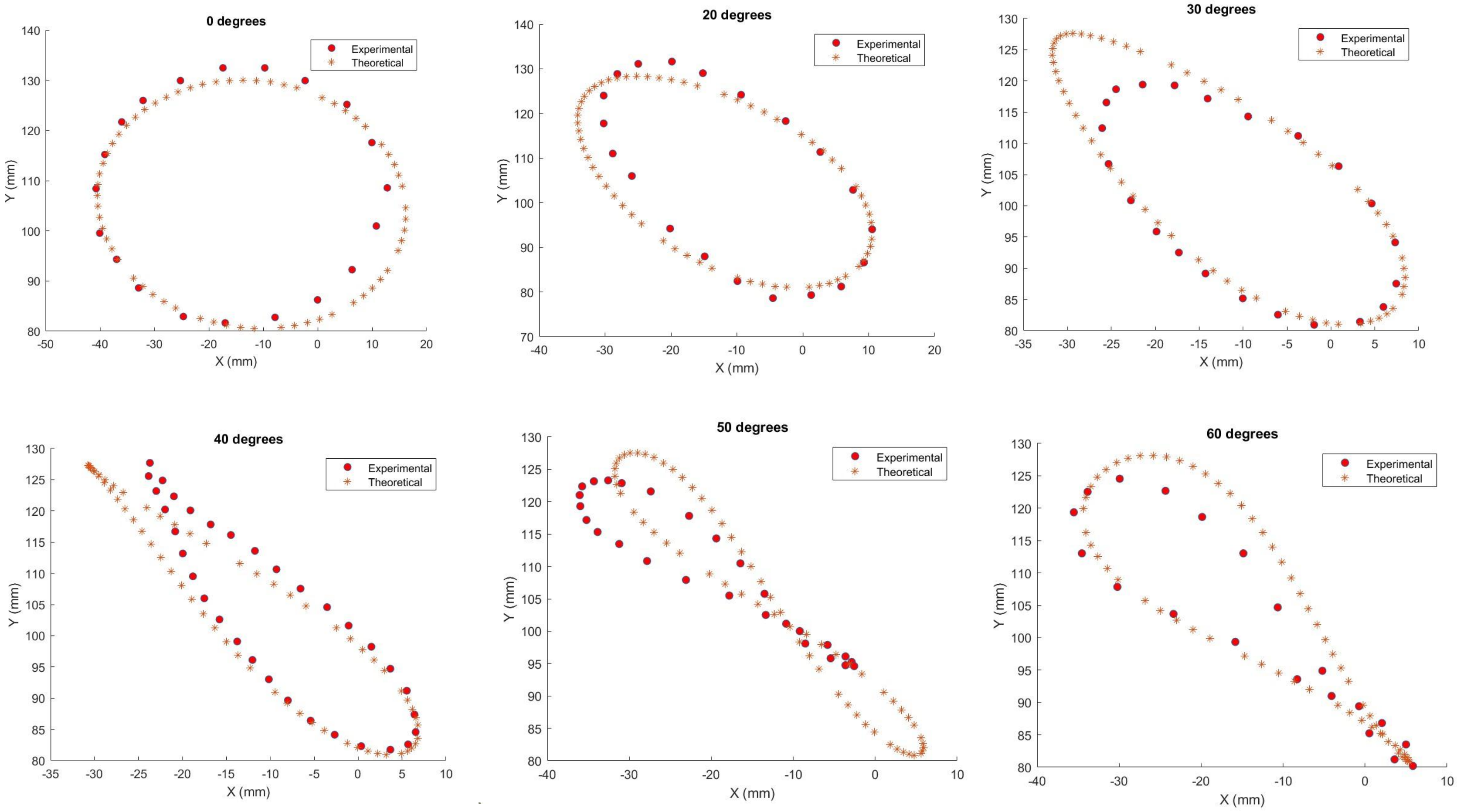
   end for

  end for

  return $x\_intersect$, $y\_intersect$

end procedure

- Submitted to AIAA


0 degrees
20 degrees
30 degrees
40 degrees
50 degrees
60 degrees
Experimental
Theoretical
X (mm)
Y (mm)

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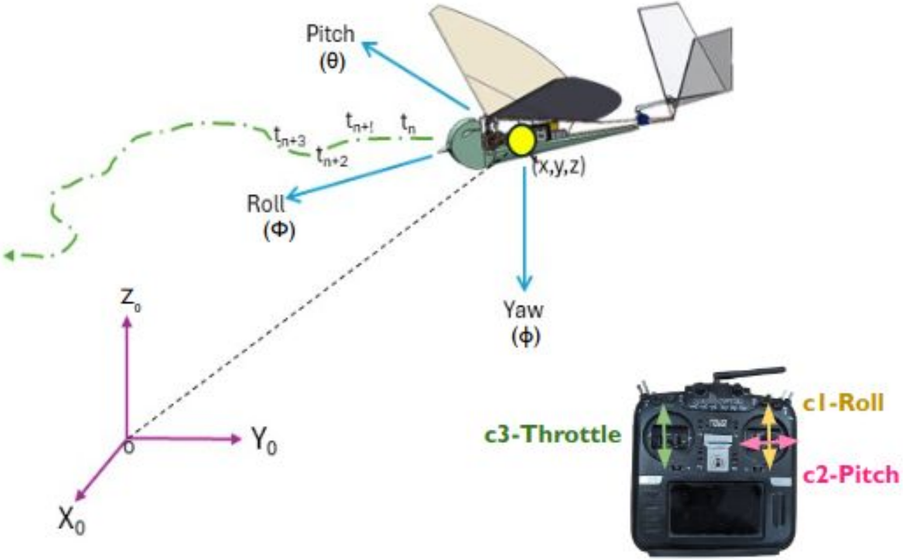
Data Preprocessing



$X=[x, y, z, \Phi, \theta, \Psi, t]$

$y=[c1,c2,c3]$

Sensors	Sampling Rate	Resampling Rate
GPS	1 Hz	10 Hz
Gyroscope	20 Hz	10 Hz
IMU	50 Hz	10 Hz
Transmitter	10 Hz	10 Hz

Algorithm 4 Data Normalization

▷ Calculate range for attitude angles

$Roll_{max} \leftarrow \text{MAX}(df['roll'])$

$Roll_{min} \leftarrow \text{MIN}(df['roll'])$

$Pitch_{max} \leftarrow \text{MAX}(df['pitch'])$

$Pitch_{min} \leftarrow \text{MIN}(df['pitch'])$

$Yaw_{max} \leftarrow \text{MAX}(df['yaw'])$

$Yaw_{min} \leftarrow \text{MIN}(df['yaw'])$

▷ Calculate range for control signals

$C_{min} \leftarrow 900$ ▷ Adjust if needed

$C_{max} \leftarrow 2100$ ▷ Adjust if needed

▷ Normalize attitude angles

$df['roll'] \leftarrow \dfrac{df['roll'] - Roll_{min}}{Roll_{max} - Roll_{min}}$

$df['pitch'] \leftarrow \dfrac{df['pitch'] - Pitch_{min}}{Pitch_{max} - Pitch_{min}}$

$df['yaw'] \leftarrow \dfrac{df['yaw'] - Yaw_{min}}{Yaw_{max} - Yaw_{min}}$

▷ Normalize control signals

$df['c1\_roll'] \leftarrow \dfrac{df['c1\_roll'] - C_{min}}{C_{max} - C_{min}}$

$df['c2\_pitch'] \leftarrow \dfrac{df['c2\_pitch'] - C_{min}}{C_{max} - C_{min}}$

$df['c3\_throttle'] \leftarrow \dfrac{df['c3\_throttle'] - C_{min}}{C_{max} - C_{min}}$

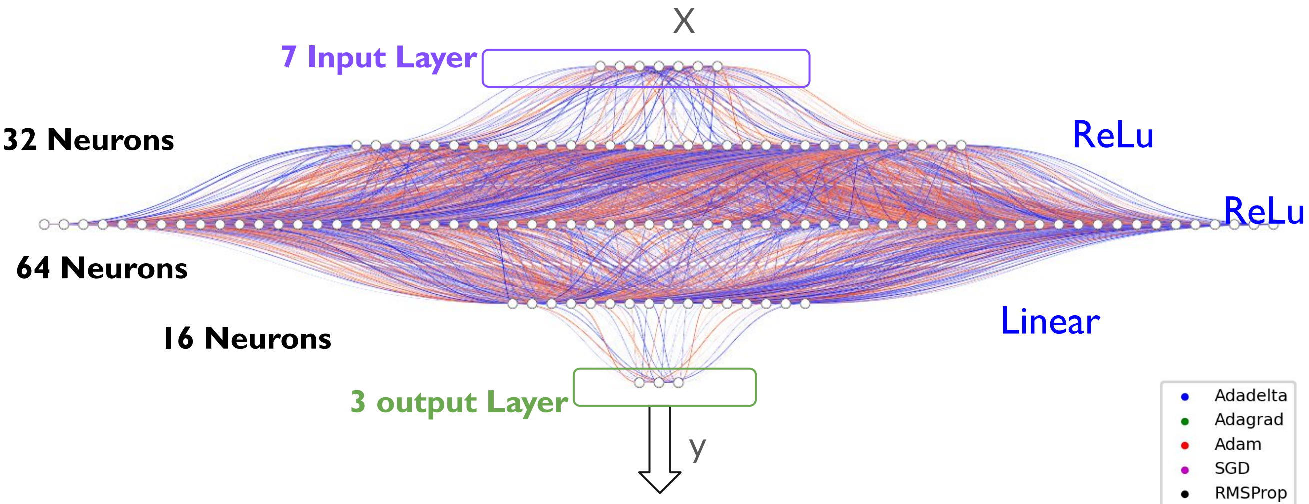
▷ Additional normalizations as needed ...

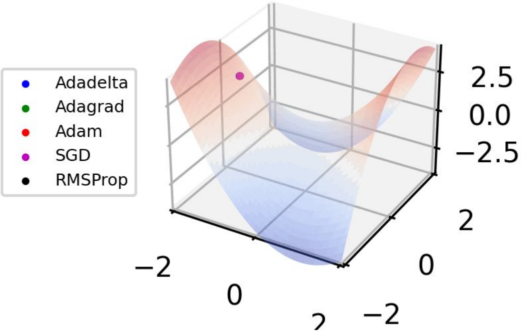
Using DNN

$$\delta_j^l = \begin{cases} \frac{\partial L}{\partial a_j^L} \sigma'(z_j^L) & \text{if } l = L \text{ (output layer)} \\ \sum_k w_{kj}^{l+1} \delta_k^{l+1} \sigma'(z_j^l) & \text{otherwise (hidden layers)} \end{cases}$$

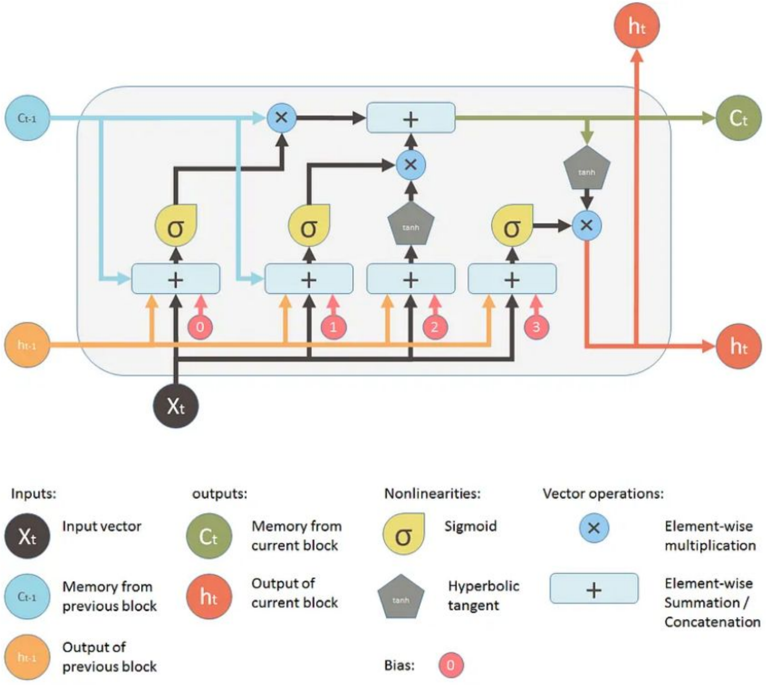
$$w_j^l = w_j^l - \eta a_j^{l-1} \delta_j^l$$

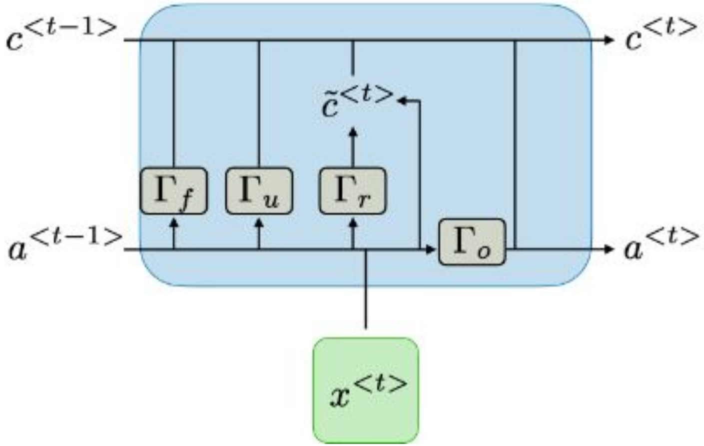
$$b_j^l = b_j^l - \eta \delta_j^l$$





RNN-LSTM Unit Cell

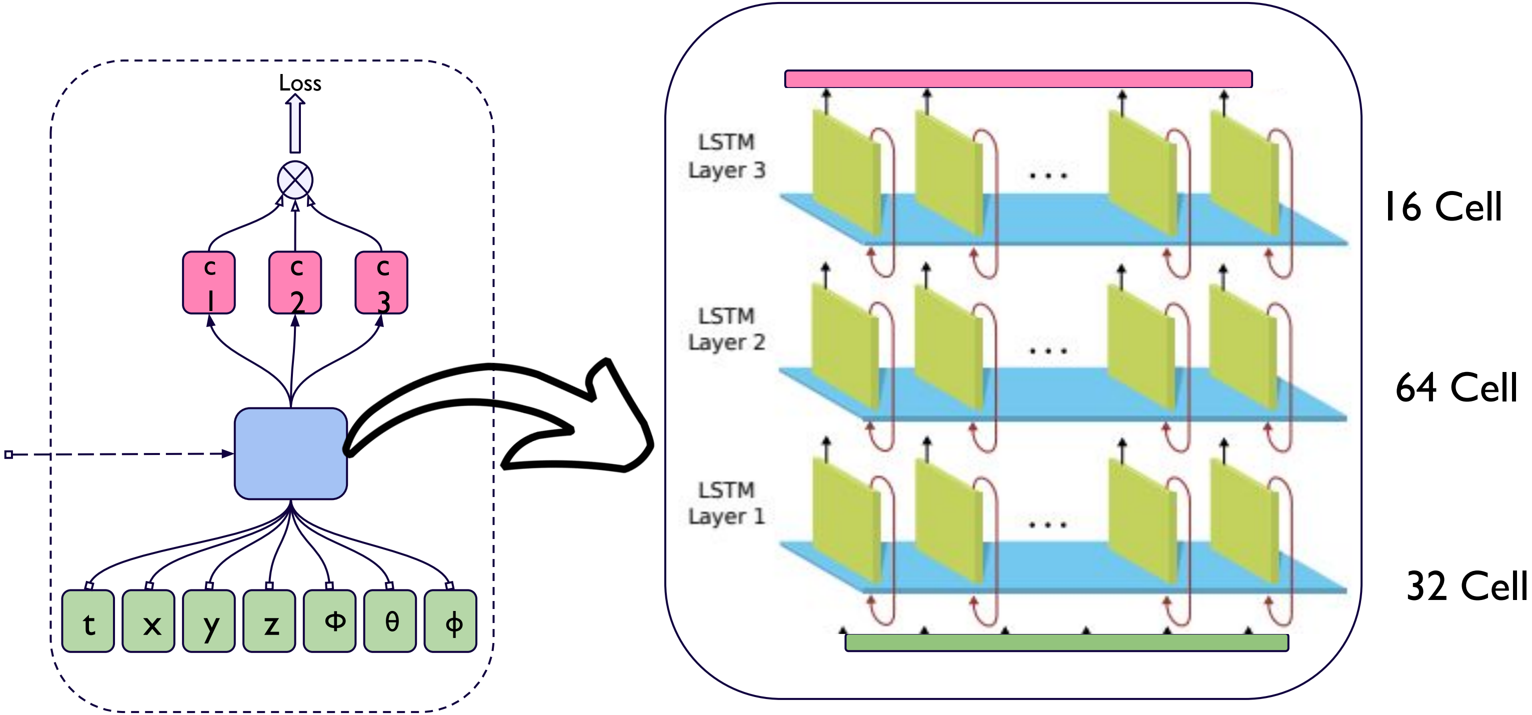




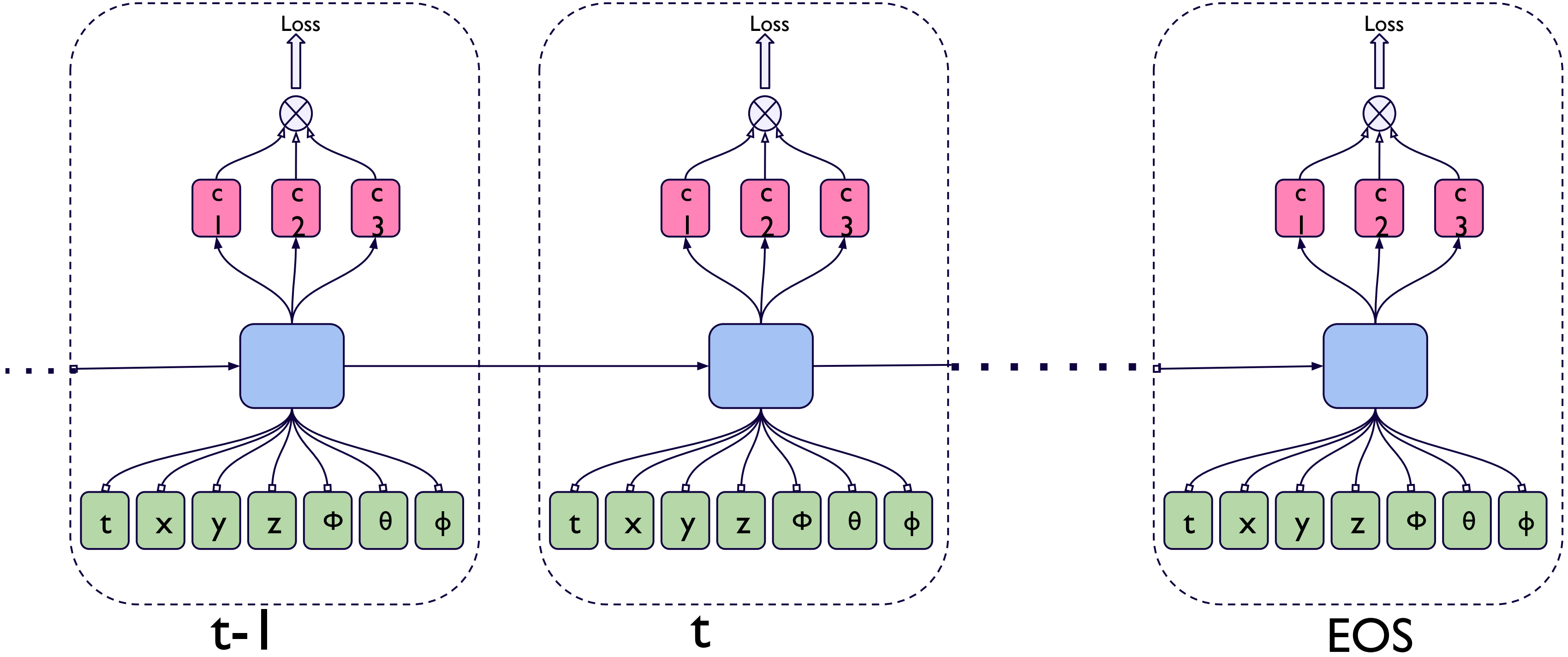
$\tilde{c}^{<t>}$	$\tanh(W_c[\Gamma_r \star a^{<t-1>}, x^{<t>}] + b_c)$
$c^{<t>}$	$\Gamma_u \star \tilde{c}^{<t>} + \Gamma_f \star c^{<t-1>}$
$a^{<t>}$	$\Gamma_o \star c^{<t>}$

Source:[Medium] and [Stanford.edu]

RNN-LSTM Neural Stack



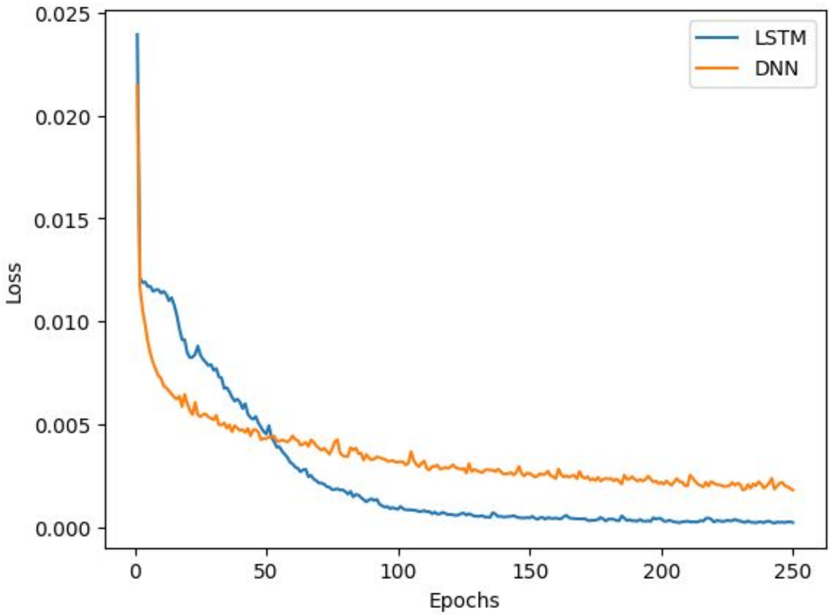
Time Sequence RNN-LSTM Stack



$$\mathcal{L}(\hat{y}, y) = \sum_{t=1}^{T_y} \mathcal{L}(\hat{y}^{<t>}, y^{<t>})$$

$$\frac{\partial \mathcal{L}^{(T)}}{\partial W} = \sum_{t=1}^{T} \frac{\partial \mathcal{L}^{(T)}}{\partial W}\Bigg|_{(t)}$$

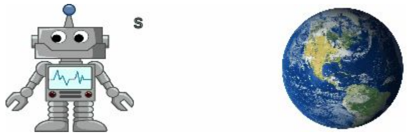
DNN vs RNN-LSTM



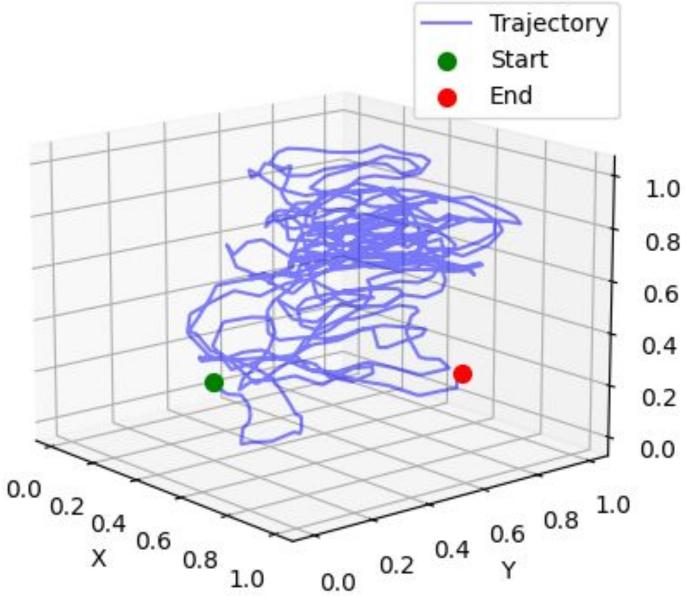
DNN Accuracy: 89%

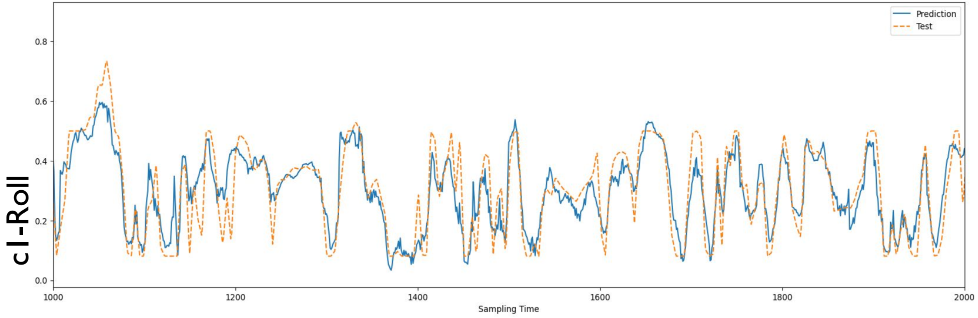
LSTM Accuracy: 93%

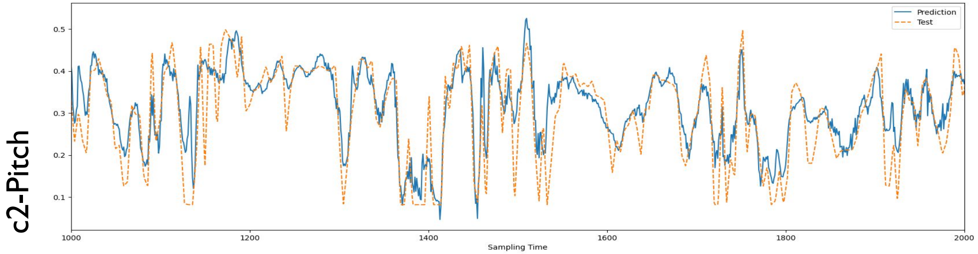
Validation of Prediction Model

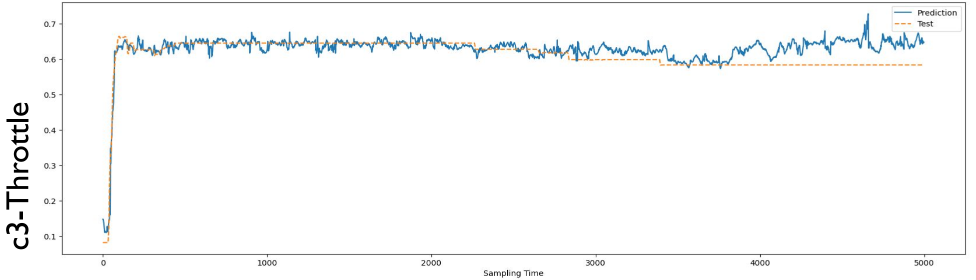


Training…

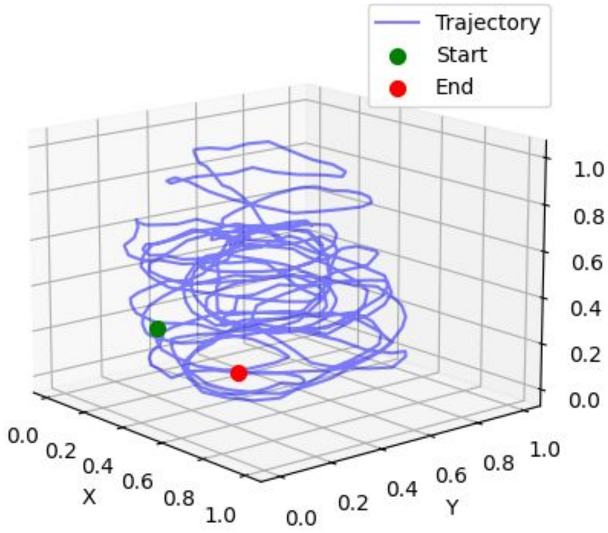




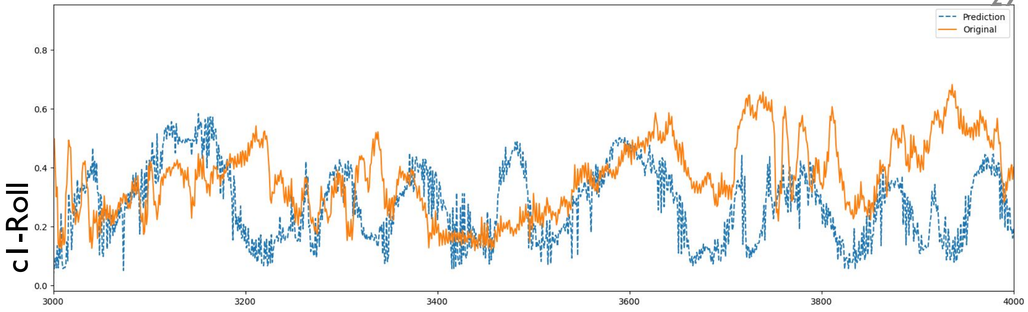


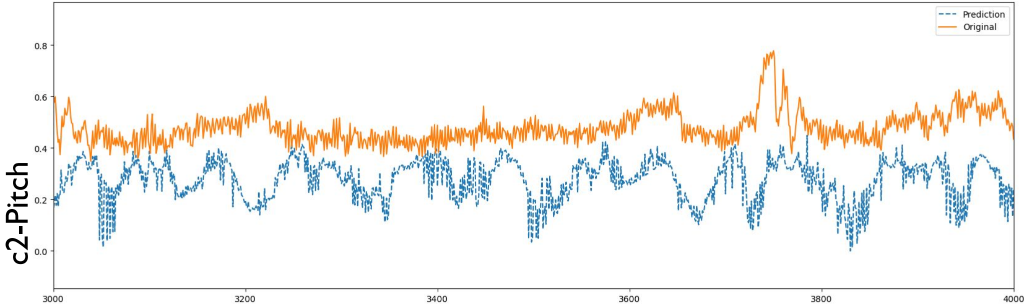


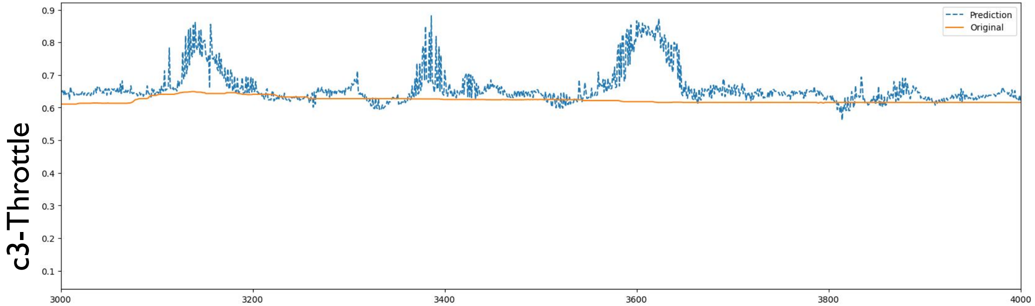
Testing!



Parameters	MSE	MAE	RMSE
C1-Roll	0.042	0.166	0.207
C2-Pitch	0.076	0.2412	0.276
C3-Throttle	0.014	0.086	0.118







Publications

1. **D. Poddar**, A. Gangwar, and D. Das. Bio-inspired perforated flapping wings. **International Conference on Intelligent Unmanned Systems**, 2023.
2. **D. Poddar**, N. Kumar, J. Mohd., and D. Das. Aerodynamics of flapping fin inspired from manta ray. In Fluid Mechanics and Fluid Power, Volume 2, pages 513–523, Singapore, 2024. **Springer Nature** Singapore. ISBN 978-981-99-5752-1.
3. G. Wadhwa, A. Tambe, J. Mohd, **D. Poddar**, R. Rajan, G. Mandal, P. Kadam, S. Saha, and D. Das. Regime transitions in a laminar film flowing over a cylinder. Bulletin of **the American Physical Society**, 2023
4. R. Rajan, B. P. Akherya, J. Mohd., **D. Poddar**, G. Wadhwa, S. Saha, and D. Das. Flow falling from slit and circular hole over a horizontal cylinder. In Fluid Mechanics and Fluid Power, Volume 6, pages 261–271, Singapore, 2024. **Springer Nature** Singapore. ISBN 978-981-99-5755-2

Patents and Copyright

1. Design Software Architecture for Virtual Ecosystem for Enabling Revenue, Open Platform.
   Copyright Reg.No-**L145397/2024**
2. A Biomimicry Scout Camera System for Monitoring Activities of Objects.
   Patent No. **IN 480305**
   Featured in **Dainik Jagran** newspaper for invention.
3. Modular Design of a Mechanism for Neutralizing Flying Objects. (Submitted)
4. Modular Design of a Mechanism for Ejection of a Neutralizer. (Submitted)

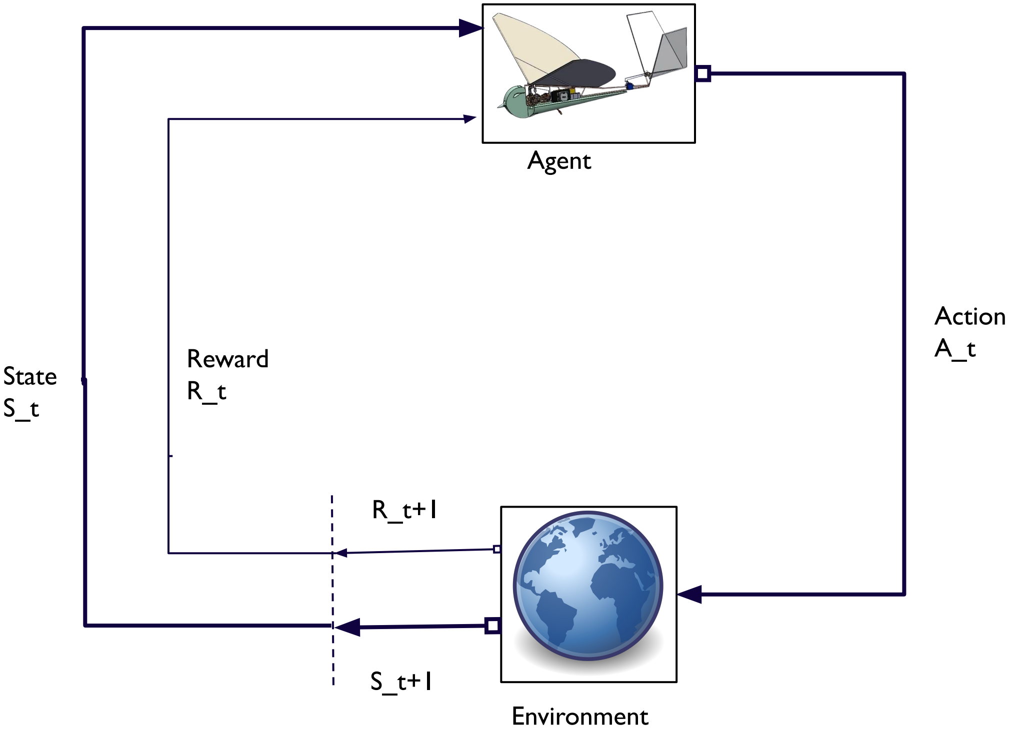
Achievements and Awards

1. Selected for grant from **STPI** (Software Technology Parks of India, Government Ministry) in the FinBlue Startup Challenge by TiE Chennai
2. Selected by **IIM B-NSRCEL** for Startup LP-25
3. Head Maintenance Secretary Award , for outstanding dedication & service,Hall-7, IIT-K
4. Selected for ”Future Green Aviation Technologies Seminar for Young Scientists and Specialists” at TSAGI, Moscow, Russia.
5. Mentorship award for HAL 44th batch Training Program
6. Mentorship award for HAL 45 Th batch Training Program.

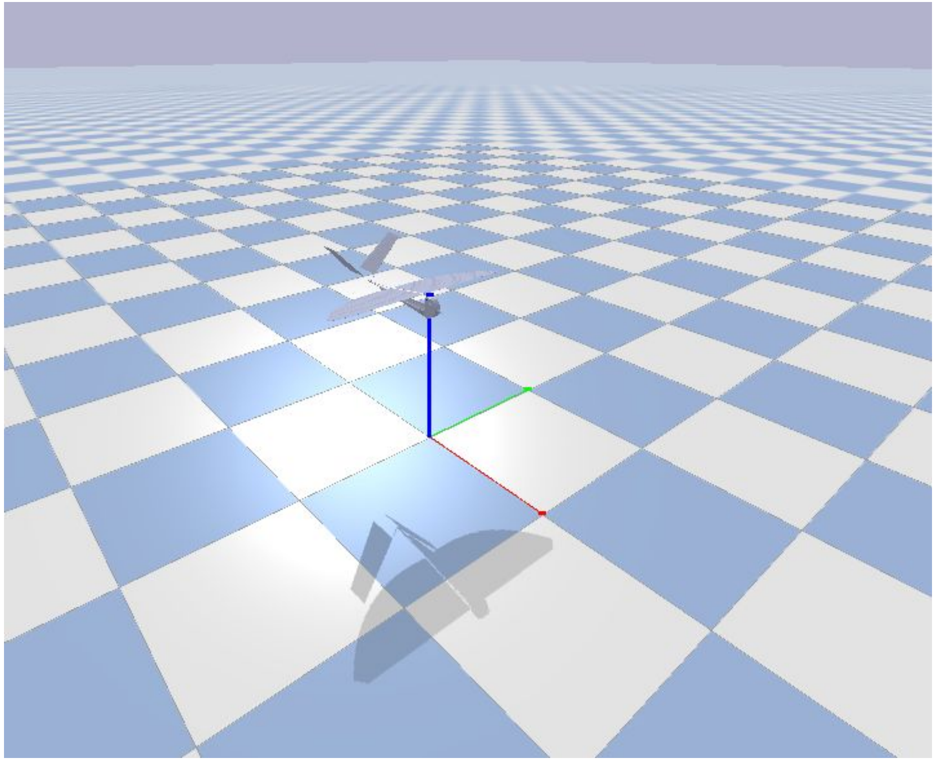
Thanks :)

"think_Uthinkable"

RL Framework



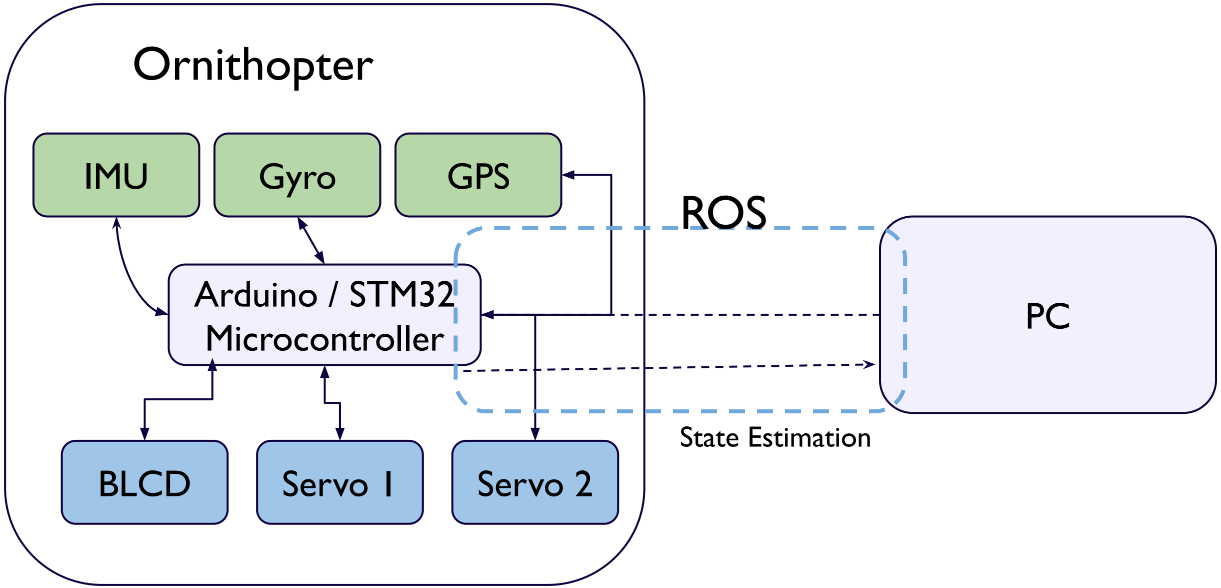
Pybullet ENV



Unsteady Aerodynamics Lab

IIT KANPUR
Indian Institute of Technology Kanpur

Sim to Real


Ornithopter
IMU
Gyro
GPS
Arduino / STM32
Microcontroller
BLCD
Servo 1
Servo 2
ROS
PC
State Estimation