UAV Test Benches for Hackathon #1

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Currently Captured eVTOL Concepts

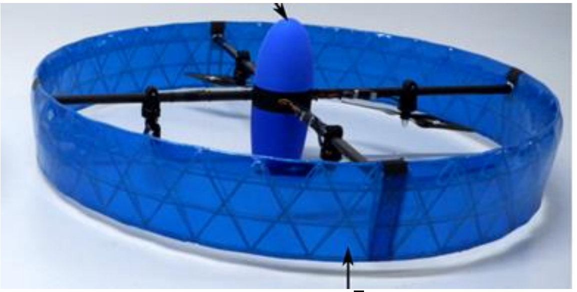
Commercial eVTOL Concepts

UAV eVTOL Concepts

Lift + Cruise

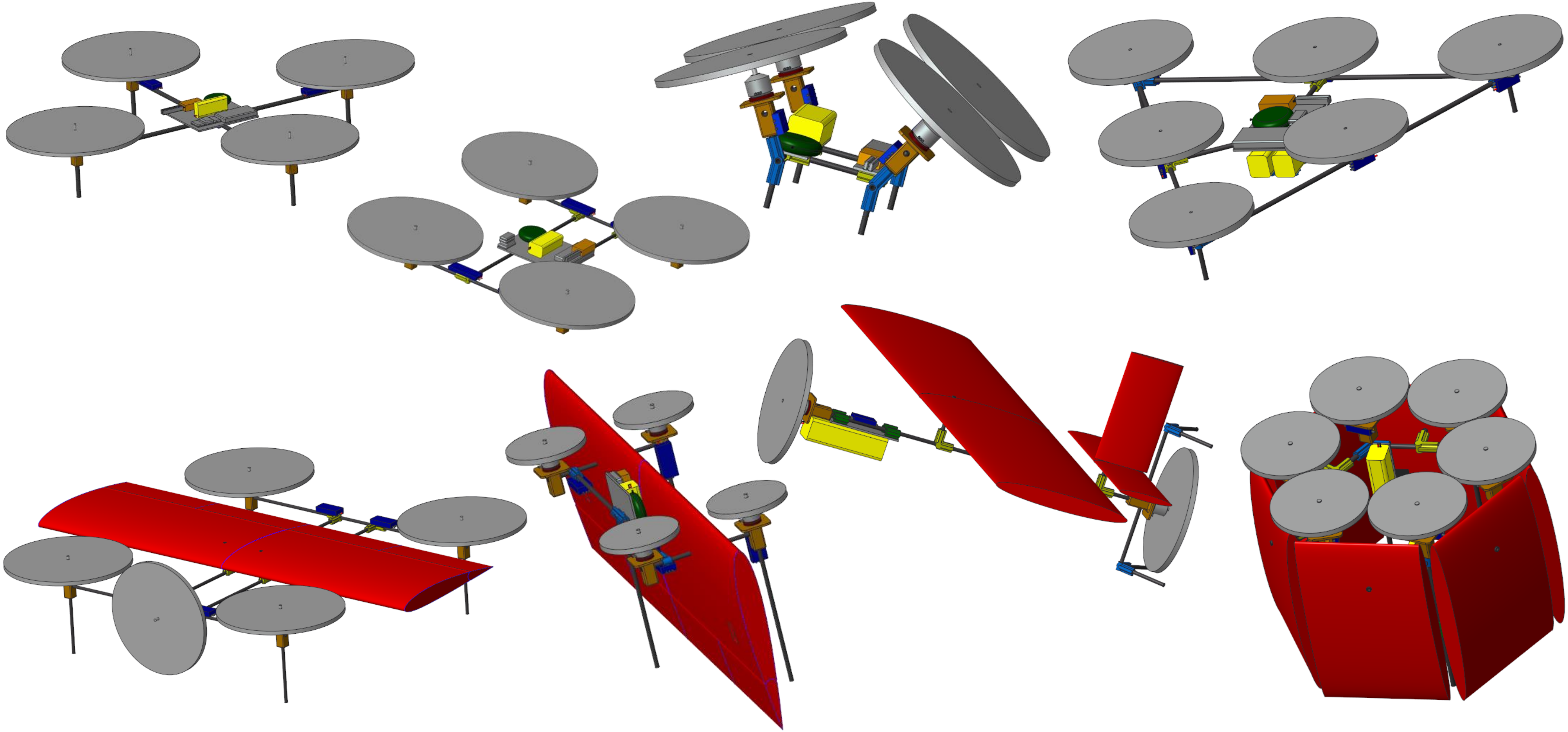
Multi-Copter

Transitional



Semi-Annular Wing

Some Examples



SwRI Flight Dynamics Model

SwRI Flight Dynamics Model

- We have a flight dynamics model written (full 6 DOF) in Fortran that will provide some test benches.
- There are two meaningful flight modes (analysis type 2 and 3).
- In type 2 it runs in a second. In type 3 it takes up to 10 seconds.
- i_analysis_type = 2 computes steady-flight cruise ("trim" state) for the design.
  - It tries to find a situation where all accelerations are zero for a specified speed and where the power is minimized.
    - It does this for lateral (straight line motion)
    - It also does it for two turning radii, right now 500 meters radius is of interest.
  - It determines control inputs to the motors and resulting pitch angle to achieve a specified speed the forward X direction (world frame) (U = given, V = W = 0).
  - Some warnings are printed to provide guidance on why it failed to find a trim state at a given speed.
  - At present it also computes a set of controls (if control%compute_A = .true.) – more about that later.
- i_analysis_type = 3 computes a flight along a defined path. There are currently 4 paths (1,3,4,5) (1 and 2 are essentially the same).
  - Computes all information seen in type 2 and then performs the flight.
  - Each one is scored and is worth around 300 to 500 points.
  - Total score is summed, but we require a positive score on path 4 or total score is zero (vertical rise and hover).
  - An autopilot (AP) is used and its controls are computed. We will discuss how to interact with the AP later.
- Main references:
  - Stevens, Lewis, Johnson, *Aircraft Control and Simulation: Dynamics, Controls Design, and Autonomous Systems*, 3rd Edition, Wiley, 2016.
  - Dreier, *Introduction to Helicopter and Tiltrotor Flight Simulation*, 2nd Edition, AIAA, 2018.

Input into the Model

- The OpenMETA/CREO CAD model are used to produce an input file for the aircraft.
  - Is in a Fortran name list format (.inp).
  - It is possible to change things directly in this file, though be aware that overall mass, moments of inertia, and projected area may also change. They are not computed internally but are inputs as computed by CREO. Thus, unless updated, they will be wrong. Submitted designs must in accordance with the CREO build.
  - Has categories: aircraft%, propeller%, wing%, battery%, control% to define the aircraft.
    - If interested in looking at the Fortran90 source for the FDM, look at include_parts.h for variables names and brief description.
- To see everything that went into the model, after the FDM internal values are set, look at the output file named “namelist.out”
  - In this there are many things that are not used – since the namelist feature is used to write it out, there currently are 50 wings and 50 propellers in the list, even if some (or all) are not used. The initial “aircraft” type declares the actual number of each object.
  - Again, to understand what is in this file, look at the include file “include_parts.h” which is well commented and describes what each Fortran type is and what is in it.

Output from Test Bench

- When the test bench is run, it outputs a file with **a lot** of information in it.
  - In the next few slides we will look at the output file with some descriptions of what is there.
  - The intent is to provide information on the performance of the design.
- For analysis type 2
  - Aircraft controls are computed and printed to the output file per trim state speed
  - There is a summary table that it is helpful to examine.
  - At the very end of the output file, there are a list of # metrics on the trim states that could potentially be used to determine the goodness of mechanical design.
- For analysis type 3
  - Aircraft controls and autopilot controls are computed and printed to the output file per trim state speed.
  - Path performance over flight time is computed and printed to the output.
  - At the very end of the file are a list of #metrics that could potentially be used to determine the flight ability of the design.

Walk-through of Output File

Output: Propeller/Motor Analysis Section

Motor #	omega (rad/s)	omega (RPM)	Voltage (volts)	Thrust (N)	Torque (Nm)	Power (watts)	Current (amps)	Efficiency (%)	Motor: Max Power (watts)	Motor: Max Cur (amps)	Battery: Peak Cur (amps)	Battery: Cont Cur (amps)
Max Volt 1	916.61	8752.95	7.40	16.04	0.49	1047.29	141.53	44.95	326.00	29.00	150.00	75.00
Max Volt 2	916.61	8752.95	7.40	16.04	0.49	1047.29	141.53	44.95	326.00	29.00	150.00	75.00
Max Volt 3	916.61	8752.95	7.40	16.04	0.49	1047.29	141.53	44.95	326.00	29.00	150.00	75.00
Max Volt 4	916.61	8752.95	7.40	16.04	0.49	1047.29	141.53	44.95	326.00	29.00	150.00	75.00
Max Power 1	742.91	7094.24	4.78	13.23	0.24	343.16	71.85	55.77	326.00	29.00	150.00	75.00
Max Power 2	742.91	7094.24	4.78	13.23	0.24	343.16	71.85	55.77	326.00	29.00	150.00	75.00
Max Power 3	742.91	7094.24	4.78	13.23	0.24	343.16	71.85	55.77	326.00	29.00	150.00	75.00
Max Power 4	742.91	7094.24	4.78	13.23	0.24	343.16	71.85	55.77	326.00	29.00	150.00	75.00
Max Amps 1	455.70	4351.63	2.54	5.19	0.10	77.65	30.53	62.12	326.00	29.00	150.00	75.00
Max Amps 2	455.70	4351.63	2.54	5.19	0.10	77.65	30.53	62.12	326.00	29.00	150.00	75.00
Max Amps 3	455.70	4351.63	2.54	5.19	0.10	77.65	30.53	62.12	326.00	29.00	150.00	75.00
Max Amps 4	455.70	4351.63	2.54	5.19	0.10	77.65	30.53	62.12	326.00	29.00	150.00	75.00

- This is the beginning of the output file.
- We look at the propeller/motor/battery situation for a vehicle at rest (static).
  - Be aware that thrust decreases as the vehicle moves.
- If the current, for example, is roughly the same for each of the three computations (Max Volt, Max Power, Max Amps), for a motor #, then the propeller/motor/battery are well matched.
- Preliminary information to understand how a battery+motor+prop are performing together. Best matching is implied when the thrust values are similar for the three categories of Max Volt, Max Power, and Max Amps.

Output: Aerodynamic Table

Rought lift and drag forces for various angles of attack and flight speeds

Lift force (N)

Flight speed (m/s) / Angle of Attack alpha (deg)	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00	45.00	50.00
-15.098	-6.48	-25.92	-58.32	-103.69	-162.01	-233.29	-317.54	-414.74	-524.91	-648.03
-13.588	-5.75	-23.00	-51.75	-92.00	-143.75	-207.00	-281.75	-368.00	-465.75	-575.01
-12.078	-5.02	-20.08	-45.18	-80.32	-125.50	-180.71	-245.97	-321.27	-406.60	-501.98
-10.569	-4.29	-17.16	-38.61	-68.63	-107.24	-154.42	-210.19	-274.53	-347.45	-428.95
-9.059	-3.56	-14.24	-32.03	-56.95	-88.98	-128.13	-174.41	-227.79	-288.30	-355.93
-7.549	-2.83	-11.32	-25.46	-45.26	-70.73	-101.85	-138.62	-181.06	-229.15	-282.90
-6.039	-2.10	-8.40	-18.89	-33.58	-52.47	-75.56	-102.84	-134.32	-170.00	-209.88
-4.529	-1.37	-5.47	-12.32	-21.90	-34.21	-49.27	-67.06	-87.59	-110.85	-136.85
-3.020	-0.64	-2.55	-5.74	-10.21	-15.96	-22.98	-31.27	-40.85	-51.70	-63.83
-1.510	0.09	0.37	0.83	1.47	2.30	3.31	4.51	5.89	7.45	9.20
0.000	0.82	3.29	7.40	13.16	20.56	29.60	40.29	52.62	66.60	82.22
1.510	1.55	6.21	13.97	24.84	38.81	55.89	76.07	99.36	125.75	155.25
3.020	2.28	9.13	20.54	36.52	57.07	82.18	111.86	146.10	184.90	228.28
4.529	3.01	12.05	27.12	48.21	75.33	108.47	147.64	192.83	244.05	301.30
6.039	3.74	14.97	33.69	59.89	93.58	134.76	183.42	239.57	303.21	374.33
7.549	4.47	17.89	40.26	71.58	111.84	161.05	219.20	286.31	362.36	447.35
9.059	5.20	20.82	46.83	83.26	130.09	187.34	254.99	333.04	421.51	520.38
10.569	5.93	23.74	53.41	94.94	148.35	213.63	290.77	379.78	480.66	593.40
12.078	6.66	26.66	59.98	106.63	166.61	239.91	326.55	426.52	539.81	666.43
13.588	7.28	29.14	65.56	116.55	182.11	262.24	356.94	466.20	590.04	728.44
15.098	7.14	28.56	64.26	114.25	178.51	257.06	349.88	456.99	578.38	714.05

Drag force (N)

Flight speed (m/s) / Angle of Attack alpha (deg)	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00	45.00	50.00
-15.098	1.04	4.16	9.35	16.63	25.98	37.41	50.93	66.51	84.18	103.93
-13.588	0.83	3.31	7.46	13.25	20.71	29.82	40.59	53.01	67.10	82.83
-12.078	0.64	2.57	5.78	10.28	16.06	23.13	31.49	41.13	52.05	64.26
-10.569	0.48	1.93	4.34	7.71	12.05	17.35	23.62	30.85	39.04	48.20
-9.059	0.35	1.39	3.12	5.55	8.67	12.48	16.99	22.18	28.08	34.66
-7.549	0.24	0.95	2.13	3.78	5.91	8.51	11.59	15.13	19.15	23.65
-6.039	0.15	0.61	1.36	2.42	3.79	5.45	7.42	9.69	12.27	15.15
-4.529	0.09	0.37	0.82	1.47	2.29	3.30	4.49	5.87	7.42	9.17
-3.020	0.06	0.23	0.51	0.91	1.43	2.05	2.80	3.65	4.62	5.70
-1.510	0.05	0.19	0.43	0.76	1.19	1.71	2.33	3.05	3.86	4.76
0.000	0.06	0.25	0.57	1.01	1.58	2.28	3.11	4.06	5.13	6.34
1.510	0.10	0.42	0.94	1.67	2.61	3.76	5.11	6.68	8.45	10.43
3.020	0.17	0.68	1.53	2.73	4.26	6.14	8.35	10.91	13.81	17.05
4.529	0.26	1.05	2.36	4.19	6.55	9.43	12.83	16.76	21.21	26.18
6.039	0.38	1.51	3.41	6.05	9.46	13.62	18.54	24.22	30.65	37.84
7.549	0.52	2.08	4.68	8.32	13.00	18.72	25.48	33.29	42.13	52.01
9.059	0.69	2.75	6.18	10.99	17.18	24.73	33.66	43.97	55.65	68.70
10.569	0.88	3.52	7.91	14.07	21.98	31.65	43.08	56.26	71.21	87.91
12.078	1.10	4.39	9.87	17.54	27.41	39.47	53.72	70.17	88.81	109.64
13.588	1.31	5.25	11.81	21.00	32.81	47.25	64.31	84.00	106.31	131.25
15.098	1.36	5.43	12.21	21.71	33.92	48.85	66.49	86.84	109.91	135.69

- Only printed if design has a wing() defined
- Provides estimates of lift and drag over various angles of attack and flight speeds.
  - Useful for feedback on airfoil selection
- Computed without considering control surface deflection, meaning they will change in flight.

Output: Trim State Calculation Parameters

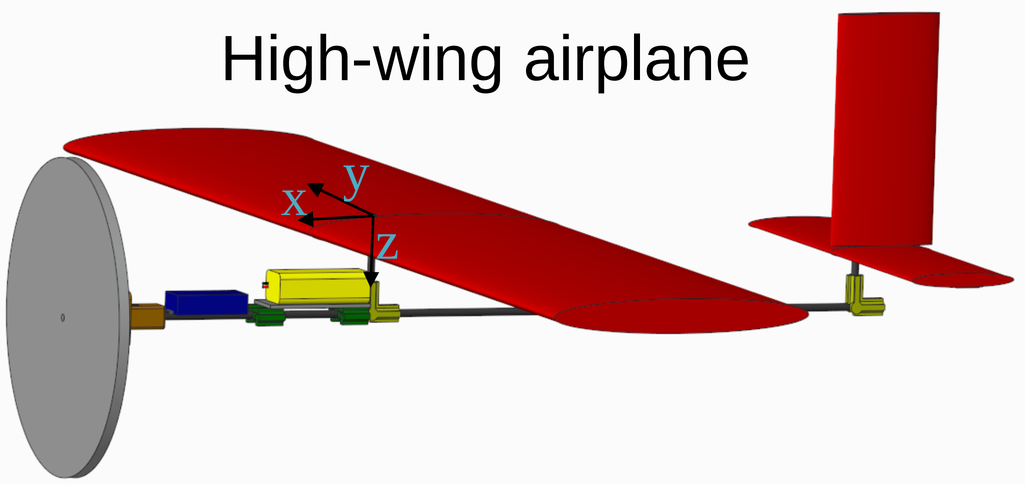
```
 The body  frame is frd: x forward, y right, z down (down is positive)
 The world frame is ned: X north,   Y east,  Z down (down is positive, so altitude (up) is negative)

Number of state variables x: xdim =  18
    x( 1 -  3) is velocity in body frame: U forward, V right, W down (m/s)
    x( 4 -  6) is angular velocity in body frame: P about x (roll rate), Q about y (pitch rate), R about z (yaw rate) (radians/s)
    x( 7 - 10) is quaternion connecting world frame to body frame: q0, q1, q2, q3
    x(11 - 13) is world frame displacement:  X north, Y east, Z down (m)
    x(14 - 17) is motor angular speed (one for each motor) (radians/s)
    x(18 - 18) is battery charge (one for each battery) (amp seconds)
Number of controls uc (0 <= uc <= 1): udim =   6
    uc( 1 -  6) are control channels
               Propeller motor  1 controlled by uc channel  1 and powered by battery  1
               Propeller motor  2 controlled by uc channel  2 and powered by battery  1
               Propeller motor  3 controlled by uc channel  3 and powered by battery  1
               Propeller motor  4 controlled by uc channel  4 and powered by battery  1
               Wing  1 servo 1 controlled by uc channel  5 with bias  0.500
               Wing  1 servo 2 controlled by uc channel  6 with bias  0.500
               Wing  2 servo 1 controlled by uc channel  5 with bias -0.500
               Wing  2 servo 2 controlled by uc channel  6 with bias  0.500

 Downward force (N) = mg =    10.8944054
```

- Explains some convention, like axis directions and state variables
- Useful for checking motor and wing control channel and control information
  - For example, motor 1 could be controlled by uc channel 4. It does not matter to the FDM, but must be kept in mind when reading output file

Output: Trim States



- Consider a high-wing conventional airplane with a single motor (1), wing with ailerons and flaps (2,3), elevator (4), and rudder (5)
- This trim state is for a forward speed of 10 m/s

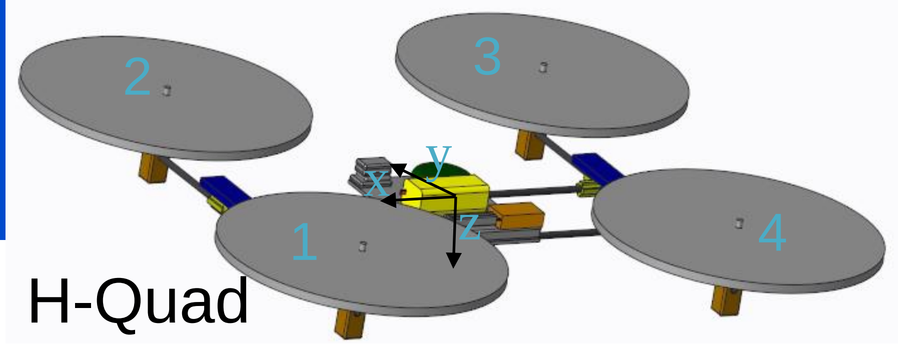
- The aircraft is rotated 5.95 degree about the y axis, which will tend to increase main wing lift (negative is upward lift)
- Here, forward thrust and drag are equal and opposite
- Aileron, flap, elevator, and rudder are in a neutral position at UC = 0.5 if deflection angled are symmetric

```
Objective steady state speed is UVW world =    10.00    0.00    0.00 m/s =    22.37    0.00    0.00 miles per hour
 Finished lmdif1 call; info =  3 (should be 1, 2 or 3; see MINPACK documentation)
 UVW world, body    (m/s)     10.00000000     0.00000000     0.00000000     9.94600013     0.00000000     1.03782534
 UVWdot,PQRdot (m|r/s^2)     -0.00000008     0.00000003     0.00000000    -0.00000000    -0.00000000     0.00000000
 Pitch angle theta (deg)      5.95702753
 Thrust world, body   (N)     0.75968473     0.00000000    -0.07927006     0.76380929     0.00000000     0.00000000
 Lift world, body     (N)     0.00000000     0.00000002    -7.17842414     0.74499505     0.00000002    -7.13966074
 Drag world, body     (N)    -0.75968478    -0.00000000     0.01226301    -0.75685518    -0.00000000    -0.06664523
 Controls     1 -  5          0.24322267     0.49170401     0.13156518     0.08004890     0.49999999
 Motor RPM    1 -  1       3258.62458151
 Motor Amps   1 -  1          8.55937789
 Battery # 1 Current =     8.559 amps,  Time to 20% charge remaining =  504.7 s,  Flight distance =   5047.096 m
```

This row being ~zero is what defines a “trim” state

Motor | Aileron | Flap | Elevator | Rudder

Output: Trim States



- Consider a H configuration quadcopter with no aerodynamic controls
- This trim state is for a forward speed of 10 m/s

- The aircraft is rotated -4.5 degree about the y axis, which will allow the quad to propel forward
- Here, forward thrust and drag are equal and opposite
- The front two motors are throttled up more than the rear two motors, but all are similar
- There is no lift and vertical thrust is equal to the weight of the quad

```
Objective steady state speed is UVW world =    10.00     0.00     0.00 m/s =     22.37     0.00     0.00 miles per hour
 Finished lmdif1 call; info =  1 (should be 1, 2 or 3; see MINPACK documentation)
 UVW world, body    (m/s)     10.00000000      0.00000000      0.00000000      9.96877300     -0.00000000     -0.78966121
 UVWdot,PQRdot (m|r/s^2)     -0.00000006      0.00000000      0.00000010     -0.00000000     -0.00000035      0.00000001
 Pitch angle theta (deg)     -4.52914070
 Thrust world, body   (N)      1.00448649      0.00000000    -12.68075180      0.00000000      0.00000000    -12.72047402
 Lift world, body     (N)      0.00000000      0.00000000      0.00000000      0.00000000      0.00000000      0.00000000
 Drag world, body     (N)     -1.00448658      0.00000000      0.00088839     -1.00127971      0.00000000      0.08020603
 Controls     1 -  4           0.56445961      0.56443321      0.56091502      0.56095685
 Motor RPM    1 -  4        4120.32173708   4120.13862064   4095.73441786   4096.02466390
 Motor Amps   1 -  4           5.77495981      5.77451303      5.71512639      5.71583086
 Battery # 1 Current =   22.980 amps,  Time to 20% charge remaining =  376.0 s,  Flight distance =   3759.721 m
```

All motors

Output: Trim States Summary

```
Trim states: 16 found by MINPACK,  4 found by nonlinear simplex.
Control states found by RICPACK solving the Algebraic Riccati Equation (ARE): 13

Summary of no-warning steady state trims (thrust, lift, and drag are vector magnitudes).  Frac amp is the ratio of the current in the
motor divided by the maximum allowed current, then the maximum is taken over all the motors.  Frac pow is the same thing for motor power.
Frac current is the battery current divided by maximum allowable battery current, taken over all the batteries.
These Frac values should be less than 1.  Max uc is the max control variable uc (or throttle).
```

Lateral speed (m/s)	Distance (m)	Flight time (s)	Pitch angle (deg)	Max uc (-)	Thrust (N)	Lift (N)	Drag (N)	Current (amp)	Total power (watt)	Frac amp (-)	Frac pow (-)	Frac current (-)	
0.00	0.00	79.54	90.00	0.90	10.87	0.00	0.00	54.31	373.17	0.508	0.526	0.483	MINPACK
1.00	79.53	79.53	88.92	0.70	10.87	0.00	0.21	54.32	373.43	0.513	0.531	0.483	SIMPLEX
2.00	159.26	79.63	85.82	1.00	10.83	0.06	0.79	54.25	373.15	0.525	0.544	0.482	SIMPLEX
3.00	240.98	80.33	81.01	0.67	10.67	0.31	1.67	53.78	368.69	0.541	0.560	0.478	MINPACK
4.00	330.57	82.64	74.64	1.00	10.24	0.95	2.71	52.27	353.65	0.555	0.575	0.465	MINPACK
6.00	659.77	109.96	52.03	0.79	6.95	5.30	4.28	39.29	236.66	0.529	0.548	0.349	SIMPLEX
21.00	1984.25	94.49	1.28	0.68	6.39	10.85	6.39	45.72	322.87	0.693	0.718	0.406	MINPACK
22.00	1894.99	86.14	1.17	0.70	6.99	10.85	6.99	50.15	358.94	0.730	0.756	0.446	MINPACK
23.00	1816.37	78.97	1.07	0.72	7.61	10.85	7.61	54.70	399.29	0.769	0.797	0.486	MINPACK
24.00	1746.19	72.76	0.98	0.74	8.27	10.85	8.27	59.37	443.44	0.810	0.839	0.528	MINPACK
25.00	1683.21	67.33	0.91	0.76	8.95	10.85	8.95	64.16	491.47	0.852	0.883	0.570	MINPACK
26.00	1625.67	62.53	0.84	1.00	9.66	10.86	9.66	69.09	543.58	0.897	0.929	0.614	MINPACK
27.00	1573.04	58.26	0.78	0.81	10.41	10.86	10.41	74.15	599.45	0.941	0.975	0.659	MINPACK

```
Of all cases, maximum no-warning distance was at speed 21.0 m/s with distance   1984.253 m
Of all cases, maximum no-warning speed was a speed of  27.0 m/s with distance   1573.042 m
```

- Summary of important trim state information, per flight speed
- Trim states shown here are for lateral, steady flight
- Distance is dependent on energy consumption and battery capacity
- Displays which solver found the trim state

MINPACK Versus SIMPLEX Trim Stats Solvers

- The trim state minimizes a weighted sum of the squares of the translational accelerations, the rotational accelerations, and the total power.
  - The hope was that this would make the states unique, but the solvers can find different states.
- MINPACK – minimization uses derivative information - faster
- Nonlinear SIMPLEX – a search algorithm - slower
- It has been our experience that, in general, both yield very similar in performance UC (control channel) solutions
- However, by default, SIMPLEX is only called **if MINPACK fails** to find a trim state
  - In these cases, SIMPLEX typically finds a “more creative” UC solution
  - This can result in unusual UC values or unusual behavior
- It is more common for SIMPLEX to provide the UC solutions at the extremes of trim states found. i.e. lowest or highest velocity trim states

Output: Trim State #Metrics

```
#Metrics
Max_Hover_Time_(s)    79.5444489
Max_Lateral_Speed_(m/s)    27.0000000
Max_Flight_Distance_(m)    1984.25317
Speed_at_Max_Flight_Distance_(m/s)    21.0000000
Max_uc_at_Max_Flight_Distance    0.680050015
Power_at_Max_Flight_Distance_(W)    322.871002
Motor_amps_to_max_amps_ratio_at_Max_Flight_Distance    0.692933619
Motor_power_to_max_power_ratio_at_Max_Flight_Distance    0.717879236
Battery_amps_to_max_amps_ratio_at_Max_Flight_Distance    0.406399757
Distance_at_Max_Speed_(m)    1573.04175
Power_at_Max_Speed_(W)    599.445862
Motor_amps_to_max_amps_ratio_at_Max_Speed    0.941339970
Motor_power_to_max_power_ratio_at_Max_Speed    0.975228250
Battery_amps_to_max_amps_ratio_at_Max_Speed    0.659105182
```

- Condensed summary
- Intended to provide quick outputs for the user to quantify aircraft performance

Autopilot and trim states

- The autopilot uses trim states and to do the flight paths you need to know something about them.
- The output file lists trim state solutions for
  - Lateral or straight line flight
  - Turning flight with radius 500 meters, turning clockwise (from above)
  - Turning flight with radius 300 meters turning counterclockwise (from above), currently not used.
- When you state a lateral speed for a trim state, it needs to have found a trim state for that speed. You can see if it has by looking in the output file.
  - If there is no appropriate trim state with controls found, you will get printouts saying something to that effect.
  - You can tell if a found trim state has controls by looking for the controls in the detail printout section or the initials ARE at the end of the summary list.

Example lateral trim state/control summary

Trim states: 26 found by MINPACK, 0 found by nonlinear simplex.

Control states found by RICPACK solving the Algebraic Riccati Equation (ARE): 26

Summary of no-warning steady state trims (thrust, lift, and drag are vector magnitudes). Frac amp is the ratio of the current in the motor divided by the maximum allowed current, then the maximum is taken over all the motors. Frac pow is the same thing for motor power. Frac current is the battery current divided by maximum allowable battery current, taken over all the batteries. These Frac values should be less than 1. Max uc is the max control variable uc (or throttle).

Lateral speed	Distance	Flight time	Pitch angle	Max uc	Thrust	Lift	Drag	Current	Total power	Frac amp	Frac pow	Frac current		
(m/s)	(m)	(s)	(deg)	(-)	(N)	(N)	(N)	(amp)	(watt)	(-)	(-)	(-)		
0.00	0.00	391.39	0.00	0.56	12.68	0.00	0.00	22.08	135.62	0.233	0.116	0.098	MINPACK	ARE
1.00	391.37	391.37	-0.05	0.56	12.68	0.00	0.01	22.08	135.63	0.232	0.116	0.098	MINPACK	ARE
2.00	782.53	391.26	-0.18	0.56	12.68	0.00	0.04	22.08	135.68	0.232	0.116	0.098	MINPACK	ARE
3.00	1172.90	390.97	-0.41	0.55	12.68	0.00	0.09	22.10	135.81	0.229	0.114	0.098	MINPACK	ARE
4.00	1561.70	390.43	-0.73	0.55	12.68	0.00	0.16	22.13	136.08	0.229	0.114	0.098	MINPACK	ARE
5.00	1947.67	389.53	-1.14	0.55	12.68	0.00	0.25	22.18	136.54	0.229	0.115	0.099	MINPACK	ARE
6.00	2329.13	388.19	-1.64	0.55	12.68	0.00	0.36	22.26	137.23	0.230	0.115	0.099	MINPACK	ARE
7.00	2703.94	386.28	-2.23	0.56	12.68	0.00	0.49	22.37	138.22	0.231	0.116	0.099	MINPACK	ARE
8.00	3069.48	383.68	-2.91	0.56	12.68	0.00	0.64	22.52	139.60	0.233	0.117	0.100	MINPACK	ARE
9.00	3422.92	380.32	-3.68	0.56	12.70	0.00	0.81	22.72	141.44	0.235	0.118	0.101	MINPACK	ARE
10.00	3759.72	375.97	-4.53	0.56	12.72	0.00	1.00	22.98	143.90	0.239	0.119	0.102	MINPACK	ARE
11.00	4078.44	370.77	-5.47	0.57	12.76	0.00	1.22	23.30	146.95	0.242	0.121	0.104	MINPACK	ARE
12.00	4379.63	364.97	-6.49	0.57	12.84	0.00	1.45	23.67	150.53	0.246	0.123	0.105	MINPACK	ARE
13.00	4624.50	355.73	-7.58	0.58	12.95	0.00	1.72	24.29	156.67	0.253	0.127	0.108	MINPACK	ARE
14.00	4825.86	344.70	-8.75	0.59	13.12	0.00	2.02	25.06	164.68	0.262	0.131	0.111	MINPACK	ARE
15.00	4983.92	332.26	-9.99	0.61	13.36	0.00	2.36	26.00	174.71	0.272	0.136	0.116	MINPACK	ARE
16.00	5099.00	318.69	-11.28	0.62	13.70	0.00	2.78	27.11	186.89	0.284	0.142	0.120	MINPACK	ARE
17.00	5151.37	303.02	-12.63	0.65	14.15	0.00	3.29	28.51	202.95	0.299	0.150	0.127	MINPACK	ARE
18.00	5122.70	284.59	-14.02	0.67	14.75	0.00	3.93	30.36	225.07	0.318	0.159	0.135	MINPACK	ARE
19.00	5035.42	265.02	-15.46	0.71	15.52	0.00	4.72	32.60	253.21	0.342	0.171	0.145	MINPACK	ARE
20.00	4904.15	245.21	-16.91	0.74	16.49	0.00	5.71	35.24	288.11	0.370	0.185	0.157	MINPACK	ARE

Example turning trim state/control summary

Trim states: 25 found by MINPACK, 0 found by nonlinear simplex.

Control states found by RICPACK solving the Alegraic Riccati Equation (ARE): 25

Summary of no-warning steady state trims (thrust, lift, and drag are vector magnitudes). Frac amp is the ratio of the current in the motor divided by the maximum allowed current, then the maximum is taken over all the motors. Frac pow is the same thing for motor power. Frac current is the battery current divided by maximum allowable battery current, taken over all the batteries. These Frac values should be less than 1. Max uc is the max control variable uc (or throttle).

Turning radius 500.00 m (positive means clockwise looking down)

Tangent speed	Distance	Flight time	Pitch angle	Roll angle	Max uc	Thrust	Lift	Drag	Current	Total power	Frac amp	Frac pow	Frac current		
(m/s)	(m)	(s)	(deg)	(deg)	(-)	(N)	(N)	(N)	(amp)	(watt)	(-)	(-)	(-)		
1.00	391.35	391.35	-0.05	0.01	0.55	12.68	0.00	0.01	22.08	135.62	0.228	0.114	0.098	MINPACK	ARE
2.00	782.49	391.24	-0.18	0.05	0.55	12.68	0.00	0.04	22.08	135.67	0.228	0.114	0.098	MINPACK	ARE
3.00	1172.90	390.97	-0.41	0.11	0.55	12.68	0.00	0.09	22.10	135.81	0.229	0.114	0.098	MINPACK	ARE
4.00	1561.70	390.42	-0.73	0.19	0.55	12.68	0.00	0.16	22.13	136.08	0.229	0.115	0.098	MINPACK	ARE
5.00	1947.64	389.53	-1.14	0.29	0.55	12.68	0.00	0.25	22.18	136.54	0.229	0.115	0.099	MINPACK	ARE
6.00	2329.08	388.18	-1.64	0.42	0.55	12.68	0.00	0.36	22.26	137.23	0.230	0.115	0.099	MINPACK	ARE
7.00	2703.83	386.26	-2.23	0.57	0.56	12.68	0.00	0.49	22.37	138.23	0.231	0.116	0.099	MINPACK	ARE
8.00	3069.26	383.66	-2.91	0.75	0.56	12.69	0.00	0.64	22.52	139.62	0.233	0.117	0.100	MINPACK	ARE
9.00	3422.53	380.28	-3.68	0.95	0.56	12.70	0.00	0.81	22.72	141.47	0.235	0.118	0.101	MINPACK	ARE
10.00	3759.08	375.91	-4.53	1.17	0.56	12.72	0.00	1.00	22.98	143.93	0.238	0.119	0.102	MINPACK	ARE
11.00	4077.45	370.68	-5.47	1.42	0.57	12.77	0.00	1.22	23.31	147.01	0.241	0.121	0.104	MINPACK	ARE
12.00	4378.29	364.86	-6.49	1.69	0.57	12.84	0.00	1.45	23.68	150.60	0.245	0.123	0.105	MINPACK	ARE
13.00	4622.61	355.59	-7.58	1.99	0.58	12.95	0.00	1.72	24.30	156.76	0.251	0.126	0.108	MINPACK	ARE
14.00	4823.40	344.53	-8.75	2.32	0.59	13.13	0.00	2.02	25.08	164.81	0.260	0.130	0.111	MINPACK	ARE
15.00	4980.92	332.06	-9.99	2.67	0.61	13.37	0.00	2.36	26.02	174.86	0.270	0.135	0.116	MINPACK	ARE
16.00	5095.39	318.46	-11.28	3.05	0.62	13.71	0.00	2.78	27.13	187.09	0.283	0.141	0.121	MINPACK	ARE
17.00	5148.24	302.84	-12.63	3.46	0.64	14.17	0.00	3.29	28.53	203.13	0.298	0.149	0.127	MINPACK	ARE
18.00	5120.38	284.47	-14.02	3.89	0.67	14.77	0.00	3.92	30.37	225.21	0.318	0.159	0.135	MINPACK	ARE
19.00	5034.41	264.97	-15.46	4.36	0.71	15.54	0.00	4.71	32.61	253.25	0.343	0.172	0.145	MINPACK	ARE
20.00	4904.75	245.24	-16.91	4.87	0.74	16.50	0.00	5.68	35.23	288.01	0.372	0.186	0.157	MINPACK	ARE

Test Benches: Picking a Flight Path Output

```
Hackathon              1
Path performance, flight path              1
Initialized to lateral trim state            20

Downward force (N) = mg =     12.6798639
```

time (s)	phi (deg)	theta (deg)	psi (deg)	Unorth (m/s)	Veast (m/s)	Wdown (m/s)	Xnorth (m)	Yeast (m)	Zdown (m)	Vt (m/s)	alpha (deg)	beta (deg)	Thrust (N)	Lift (N)	Drag (N)
0.001	-0.000	-16.914	0.000	20.000	-0.000	0.000	0.020	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
1.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	20.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
2.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	40.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
3.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	60.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
4.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	80.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
5.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	100.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
6.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	120.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
7.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	140.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
8.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	160.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
9.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	180.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708
10.000	-0.000	-16.914	0.000	20.000	-0.000	0.000	200.000	-0.000	-200.000	20.000	-16.914	-0.000	16.486	0.000	5.708

- You pick a flight path and a lateral speed – it displays which flight path and the requested lateral speed
  - In this case, flight path 1 for this first hackathon
  - Trim state 20 indicates it found a lateral trim state corresponding to a requested 20 m/s
- If the simulation end time is long enough and the aircraft flies well, you should see a long table with many rows about the aircraft state over time
- If the table is short, check the aircraft%time_end is sufficient to allow the aircraft to complete the path. Otherwise, the input aircraft could not fly the path.

Output: Flight Path ‘Success’ Criteria

```
Calculation completed at time    314.160004      due to course completion.

The following information is about electrical performance.
 Battery  1 fraction capacity used     0.6567 and fraction max continuous amperage used     0.1094
 Motor  1 fraction max amps reached     0.4698 and fraction max power reached     0.1648
 Motor  2 fraction max amps reached     0.3726 and fraction max power reached     0.1377
 Motor  3 fraction max amps reached     0.4200 and fraction max power reached     0.1668
 Motor  4 fraction max amps reached     0.5548 and fraction max power reached     0.1955

Wind speed (m/s)    0.00000000       0.00000000       0.00000000
Air density (kg/m^3)    1.22500002

Path performance, flight path           3

Maximum distance error (measured perpendicularly) from flight path was    4.85936451      m
The full circle was flown, so 300 points are initially awarded
Score is now deducted for inaccuracy by 50 * maximum lateral error   -242.968231
Final score (rounded) =    57.0000000

Measures of flight path performance (distance in meters, time is seconds, speed in meters per second)

Flight path was successfully traversed.
```

If the maximum distance error from the flight path is large, it is likely the aircraft did not fly the course – that is, the autopilot could not keep it on the flight path. Typically results in zero score.

- Show if course was completed and how much time passed
- Show electrical performance
  - Often if the flight fails, this table indicates why
    - Battery is less than 0.8
    - Max amps/power less than 1
- Shows a break down of the scoring
- Displays if the flight path was successfully flown
  - Only ‘successful’ flights result in a nonzero score!

Output: Flight #Metrics

```
#Metrics
Flight_distance    3161.09985
Time_to_traverse_path    314.160004
Average_speed_to_traverse_path    10.0620699
Maximimum_error_distance_during_flight    4.85936451
Time_of_maximum_distance_error    51.3199997
Location_of_maximum_distance_error    258.950897       427.720032       0.00000000
Velocity_at_time_of_maximum_distance_error    -8.55440044       5.17901802       0.00000000
Spatial_average_distance_error    2.51225734
Maximum_ground_impact_speed    0.00000000
Path_traverse_score_based_on_requirements    57.0000000
Input_LQR_weights_Qp_Qv_Qav_Qang_R    1.00000000       0.00000000       0.00000000       1.00000000       0.200000003
```

- Short summary to provide users quick information on flight path performance
- Contains the flight path score, which will be used in the hackathon
- Notice on the last line, it displays the autopilot Q and R values defined in the input file
  - The values of these are important and dictate the ability of the aircraft to maintain the path
  - They are the way you communicate with the autopilot and affect the cyber aspect of the design.

Autopilot

The Autopilot

- We have developed an autopilot that can fly most aircraft. We've tried it out on quadcopters, octacopters, decacopters, planes, etc.
- You do not need to identify the control channel connections, the autopilot will figure it out. (You do need to identify control channels as with the trim FDM calculations, but you don't need to provide any additional information.)
- The autopilot is based on the linear quadratic regulator (LQR) solution and trim states. To fly, you need a trim state. The LQR helps you get back to the trim state. Flying is not the same as a trim state, as you will discover by setting a quadcopter in a fixed trim state and letting it go.
- The only allowable speeds right now are integers in meters per second.
- A current weakness in our autopilot is that we are having difficulty changing from one type a trim state to another – e.g., lateral to turning.
  - Thus, for now, some vehicles cannot take curves very fast. It depends on your design – some can. (Hopefully in the future this will be addressed.) More on this later.

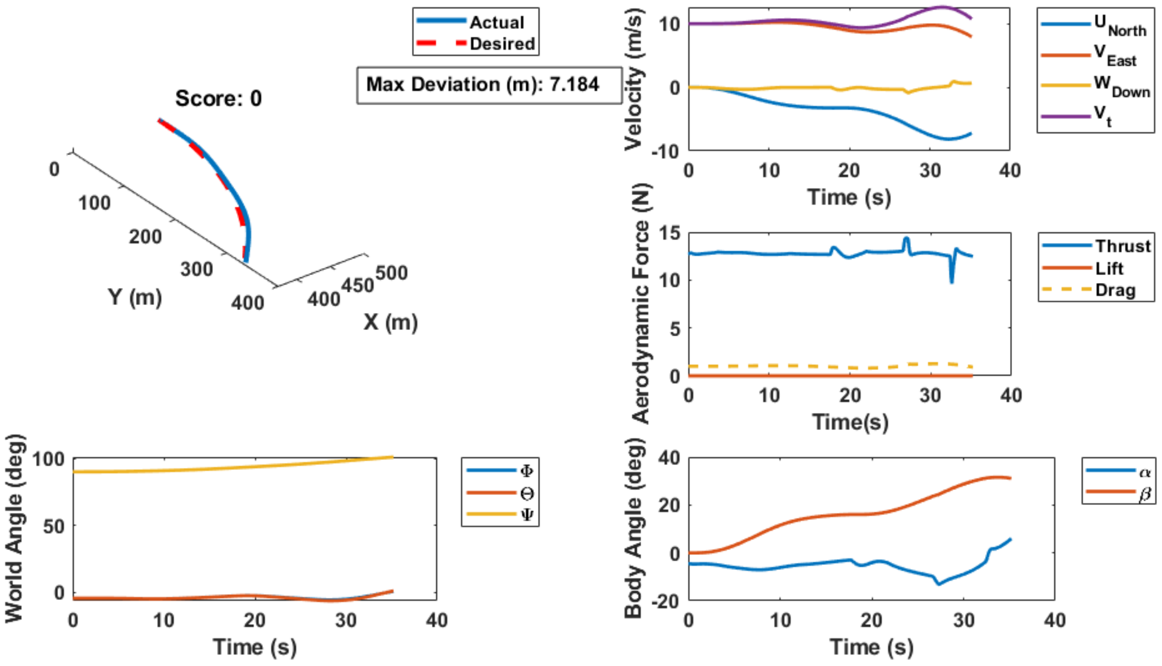
More on the Autopilot

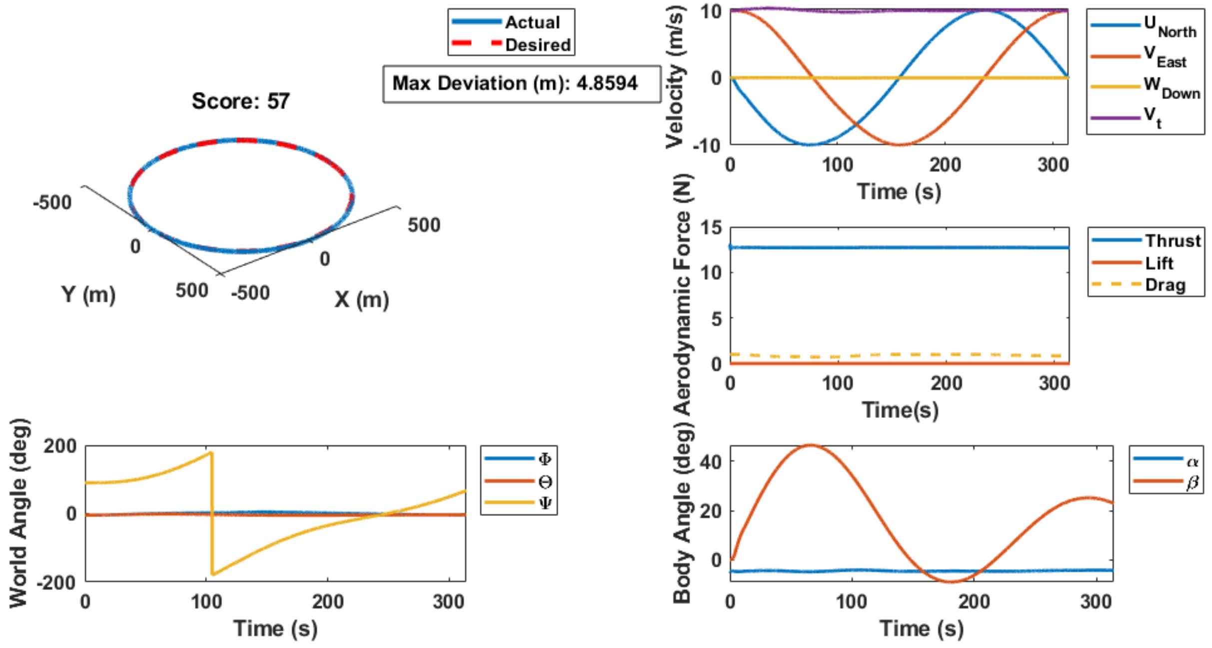
- You can influence the autopilot through five input variables. These variables, in the .inp file, are
  - control%Q_position ! The XYZ deviation weight (world frame)
  - control%Q_velocity ! The UVW deviation weight (body frame, but makes no difference)
  - control%Q_Angular_velocity ! The PQR deviation weight (body frame; same as world frame)
  - control%Q_angles ! The quaternion connection world to body frame deviation weight
  - control%R ! The weight on the control variables.
- We compute a linearization around the trim state, and then solve the LQR problem, minimizing the time integral from 0 to infinity of $x^TQx + u^TRu$. Our Q above are along the diagonal and R is the constant R times the identity.
- We have a matrix K of controls so that $u = u_{trim} + K(x - x_{trim})$, where x is the state vector (U V W P Q R q1 q2 q3 X Y Z) (we drop q0).
- The values of Q and R are only relative to each other, and the values can/do affect the results

Autopilot Control Values (Qs and R)

- Default weights are somewhat robust but likely not perfect for every design
  - Q_position = 1, Q_velocity = 1, Q_Angular velocity = 0, Q_angles = 1, R = 1
- Some guidance:
  - Setting all = 0 is not a valid solution and will be rejected
  - Are relative to each other
  - Should be positive
  - At least one Q must be greater than zero
  - Currently, Q_velocity and Q_Angular velocity seem to be less important than the others (can be zero)
  - Q_position is important for turns
  - R (control channel weights) must be greater than zero

Example of Autopilot Improvement





- Path 3 is a circle.
- Left is with default: Q_position = 1, Q_velocity = 1, Q_Angular velocity = 0, Q_angles = 1, R = 1
- Right is with Q_position = 1, Q_velocity = 0, Q_Angular velocity = 0, Q_angles = 1, R = 0.25
- If a flight significantly less distance than predicted by the static trim state calculation, it is likely the problem is with the autopilot and the Q need to be changed.

Scored Test Benches

Dynamic Test Bench 1: Rise and Hover

- This test bench examines control during vertical flight of the vehicle as it rises from 0 to 150 meters and then hovers.
- The goal speed for rise is 2 m/s, but we do not include the actual speed in the score.
  - This means control%requested_vertical_speed = -2 (since Z is down)
- You need to reach 150 meters, otherwise no points (you need to be at 150 plus or minus 2 meters altitude when you complete).
- The objective is to do this and hover (rise time counts) for 200 seconds: that's 200 points.
- If you can go for another 200 seconds you can get one point per second, up to 400 points. That's the max.
- You are done hovering when one battery reaches 20% charge left.   (Sorry, don't know how else to do it for multiple batteries: your time is up when the first battery reaches this state.)
- control%i_flight_path = 4
- Success on this test best is required: zero points here means zero points overall.

Test Bench 1 Example Output: Rise and Hover

```
 Calculation completed at time    381.394012      due to an electrical issue.

 The following information is about electrical performance.
  Battery  1  fraction capacity used     0.8000 and fraction max continuous amperage used     0.1861
  Motor   1 fraction max amps reached     0.4263 and fraction max power reached     0.1285
  Motor   2 fraction max amps reached     0.4371 and fraction max power reached     0.1346
  Motor   3 fraction max amps reached     0.4277 and fraction max power reached     0.1293
  Motor   4 fraction max amps reached     0.4386 and fraction max power reached     0.1353

 Wind speed (m/s)    0.00000000       0.00000000       0.00000000
 Air density (kg/m^3)    1.22500002

 Hackathon            1
 Path performance, flight path            4

 Maximum distance error (measured perpendicularly) from flight path was    9.14964767E-05  m
 Since minimum flight time of 200 s was achieved and final vehicle height was within 2 m of specified hover height, score is flight time with max 400 pts.
 Final height (-Z) =    150.000000     m;  flight time =    381.394012     s
 Final score (rounded) =    381.000000

 Measures of flight path performance (distance in meters, time is seconds, speed in meters per second)

 Flight path was successfully traversed.

#Metrics
etc = they don’t fit on this page
```

Dynamic Test Bench 2: Fly a Straight Line

- This test bench examines control during level steady flight of the vehicle as it flies north.
- You begin in a trim state of your choice (from the integral trim states) at an initial 200 meters altitude (Z = -200) and then you fly north (X direction).
- You pick your lateral speed: control%requested_lateral_speed = 20. e.g.
- Your flight ends when one battery reaches 20% charge.
- You need to fly at least 2 kilometers, otherwise no points.
- The number of points is meters/10 up to 400 points (i.e., you will get 0 points or 200 to 400 points) minus 10 times your lateral error in meters.
  - So if you wander off the flight path by 10 meters you lose 100 points (however, if you wander off this far you will likely wander off a lot more and end up with zero points).
- control%i_flight_path = 1

Test Bench 2 Example Output: Straight Line

```
Calculation completed at time    245.207993      due to an electrical issue.

 The following information is about electrical performance.
  Battery  1  fraction capacity used     0.8000 and fraction max continuous amperage used     0.1566
  Motor   1 fraction max amps reached     0.3702 and fraction max power reached     0.1378
  Motor   2 fraction max amps reached     0.3702 and fraction max power reached     0.1378
  Motor   3 fraction max amps reached     0.3575 and fraction max power reached     0.1305
  Motor   4 fraction max amps reached     0.3576 and fraction max power reached     0.1306

 Wind speed (m/s)    0.00000000       0.00000000       0.00000000
 Air density (kg/m^3)    1.22500002

 Hackathon            1
 Path performance, flight path             1

 Maximum distance error (measured perpendicularly) from flight path was    4.44130492E-05  m
 Score is distance flown / 10 =    490.416016      since minimum flight distance of 2 km achieved
 The maximum score on flight distance is 400 so score is =    400.000000
 Score is now deducted for inaccuracy by 10 * distance error   -4.44130506E-04
 Final score (rounded) =    400.000000

 Measures of flight path performance (distance in meters, time is seconds, speed in meters per second)

 Flight path was successfully traversed.

#Metrics
etc = they don't fit on this page
```

Dynamic Test Bench 3: Fly a Circle

- This test bench examines control during level steady flight of the vehicle as it traverses a circle of diameter 1 km (so you need to fly 3.15 km to get points).
- You begin in a trim state of your choice (from the integral trim states) at an initial 250 meters altitude (Z = -250) and then you fly the circle clockwise (from above).
- You get to pick your speed (i.e., the trim state of your choice).
  - If available, it will use a turning trim state
  - If not, it will use a lateral trim state
- Your flight ends when one battery reaches 20% charge or you finish the circle.
- If you fly the circle you get 300 points minus 50 times your lateral error in meters (so the idea here is accuracy in flying the circle).
- control%i_flight_path = 3

Test Bench 3 Example Output: Straight Line

```
Calculation completed at time    157.080002      due to course completion.



 The following information is about electrical performance.
 Flight termination due to electrical issues was turned off.
  Battery  1  fraction capacity used     0.5124 and fraction max continuous amperage used     0.1566
  Motor  1 fraction max amps reached     0.3645 and fraction max power reached     0.1345
  Motor  2 fraction max amps reached     0.3531 and fraction max power reached     0.1280
  Motor  3 fraction max amps reached     0.3727 and fraction max power reached     0.1392
  Motor  4 fraction max amps reached     0.3720 and fraction max power reached     0.1388

 Wind speed (m/s)    0.00000000       0.00000000       0.00000000
 Air density (kg/m^3)    1.22500002

 Hackathon            1
 Path performance, flight path            3

 Maximum distance error (measured perpendicularly) from flight path was    2.77841859E-03  m
 The full circle was flown, so 300 points are initially awarded
 Score is now deducted for inaccuracy by 50 * maximum lateral error  -0.138920933
 Final score (rounded) =    300.000000

 Measures of flight path performance (distance in meters, time is seconds, speed in meters per second)

 Flight path was successfully traversed.

#Metrics
etc = they don’t fit on this page
```

Dynamic Test Bench 4: Racing Oval

- This test is a racing oval. You are 500 meters in the air (Z = -500). You go 750 m to the north, then fly a 600 meter diameter half circle counterclockwise, then travel 750 meters to the south, then fly a 600 meter diameter half circle counterclockwise, back to the starting point, and you are done. This course is 3.38 km long.
- You begin in a lateral trim state of your choice (from the integral trim states) by picking your lateral speed.
- Your flight ends when one battery reaches 20% charge or you finish the course.
- Finishing the course is 200 points. For every second less than 350 seconds you get a point.
  - If you go 9 m/s or less you end up with 200 points.
  - If you go 10 m/s you end up with 211 points.
  - If you go 20 m/s you end up with 381 points.
- If you depart from the course path by 10 meters (laterally), you get zero points.
- This test bench is the most challenging due to control issues.
- control%i_flight_path = 5

Test Bench 4 Example Output: Racing oval (not successful – runs out of power before completing course)

```
 Calculation completed at time    393.466003      due to an electrical issue.

 The following information is about electrical performance.
  Battery  1  fraction capacity used     0.8000 and fraction max continuous amperage used     0.1045
  Motor   1 fraction max amps reached     0.3947 and fraction max power reached     0.1516
  Motor   2 fraction max amps reached     0.4277 and fraction max power reached     0.1711
  Motor   3 fraction max amps reached     0.3952 and fraction max power reached     0.1519
  Motor   4 fraction max amps reached     0.4242 and fraction max power reached     0.1697

 Wind speed (m/s)    0.00000000       0.00000000       0.00000000
 Air density (kg/m^3)    1.22500002

 Hackathon            1
 Path performance, flight path            5

 Maximum distance error (measured perpendicularly) from flight path was    1.12133420      m
 Zero points since complete oval not flown
 Stayed with 10 m of flight path (otherwise no points would have been awarded)
 Final score (rounded) =    0.00000000

 Measures of flight path performance (distance in meters, time is seconds, speed in meters per second)

 Flight path was not successfully traversed.

#Metrics
etc = they don't fit on this page
```

Test Bench 4 Example Output: Racing oval (not exactly what you would see, but for clarity)

```
Calculation completed at time    846.239014      due to course completion.

The following information is about electrical performance.
Flight termination due to electrical issues was turned off.
 Battery  1  fraction capacity used     1.7143 and fraction max continuous amperage used     0.1342
 Motor   1 fraction max amps reached     0.5776 and fraction max power reached     0.2696
 Motor   2 fraction max amps reached     0.4712 and fraction max power reached     0.1973
 Motor   3 fraction max amps reached     0.5713 and fraction max power reached     0.2648
 Motor   4 fraction max amps reached     0.4708 and fraction max power reached     0.1977

Wind speed (m/s)    0.00000000       0.00000000       0.00000000
Air density (kg/m^3)    1.22500002

Hackathon            1
Path performance, flight path            5

Maximum distance error (measured perpendicularly) from flight path was    1.98551989      m
Complete oval being flown gives 200 pts.
Every second less than 350 seconds gives one additional point; flight time =    846.239014
Stayed with 10 m of flight path (otherwise no points would have been awarded)
Score ignoring electrical issues    200.000000
However, score set to 0 because of electrical issue.
Final score (rounded) =    0.00000000

Measures of flight path performance (distance in meters, time is seconds, speed in meters per second)

Flight path was not successfully traversed.

#Metrics
etc = they don't fit on this page
```

- End of Slides