OpenAP: From Open Data to Sustainable Aviation

Source: https://github.com/TUDelft-CNS-ATM/openap
Docs: https://openap.dev

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on behalf of Dr. Junzi Sun

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TU Delft

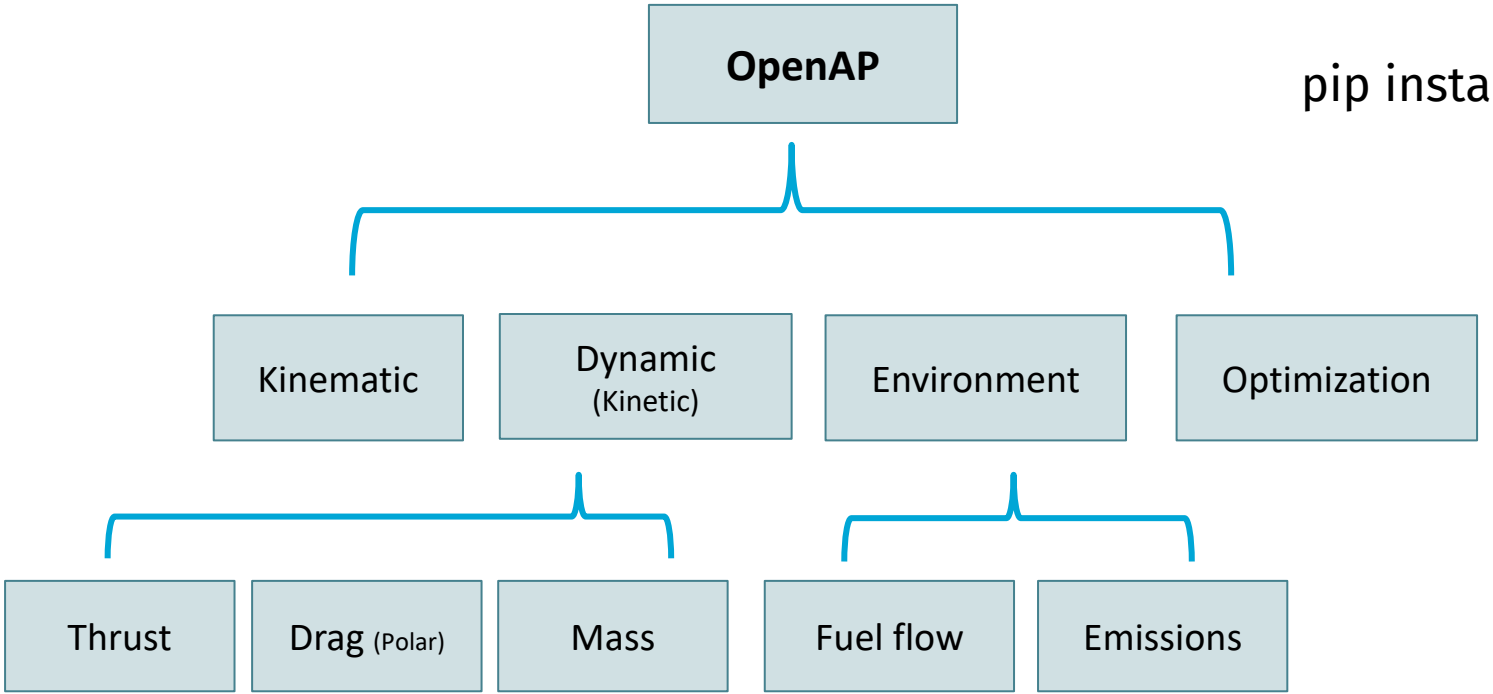
Origin story Open Aircraft Performance Models

- BlueSky Open ATM simulator started in 2013
- Also support for BADA implemented in BlueSky (2014), still compatible with BADA 3.12+
- Goal was to developing open aircraft performance models
- Started off as an MSc assignment in 2014 (Dr. Isabel Metz, now at DLR)
- In 2015 Dr. Junzi Sun started his PhD developing ADS-B based OpenAP
- Dr. Junzi Sun joined CNS-ATM in 2019 after his PhD defense, to continue on OpenAP and other open source initiatives
- OpenAP also split off as separate package
- Emission and fuel models added
- Trajectory optimizer added

Open Aircraft Performance Model (OpenAP)

Installation:

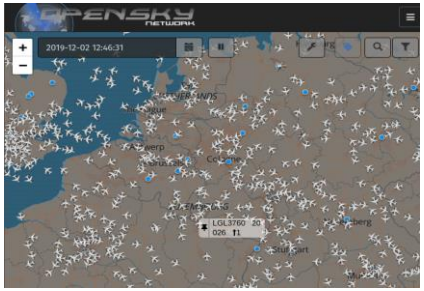
pip install openap



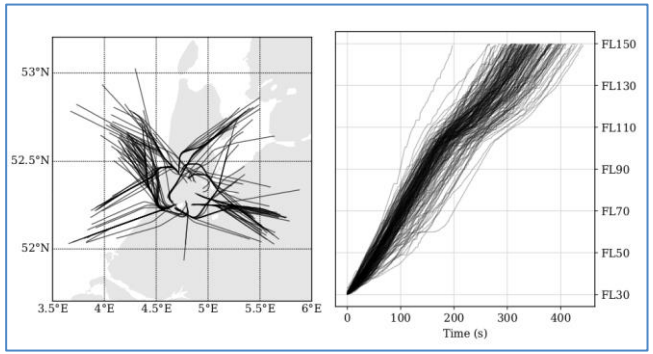
OpenAP: Built with open data (ADS-B / Mode S)

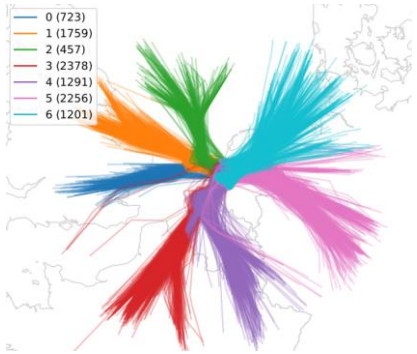
TU Delft data

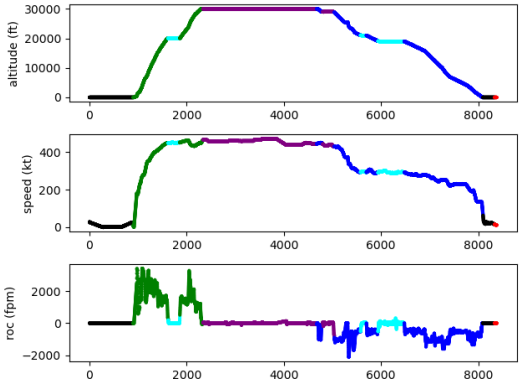
FlightRadar24



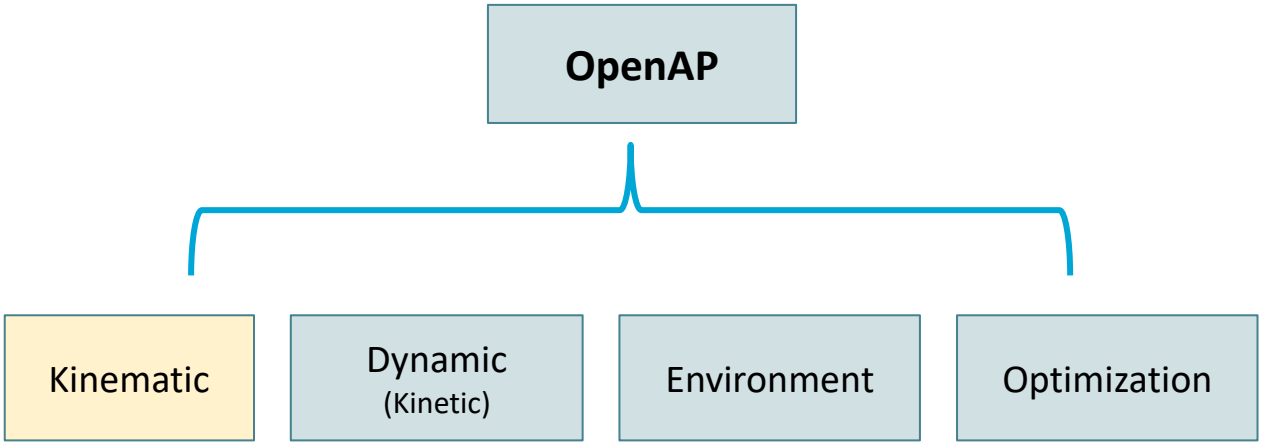
OpenSky







=> pymodes

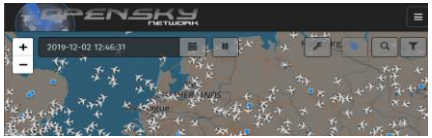

OpenAP
Kinematic
Dynamic
(Kinetic)
Environment
Optimization

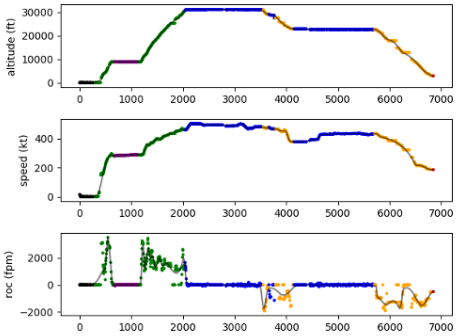
Constructing kinematics models

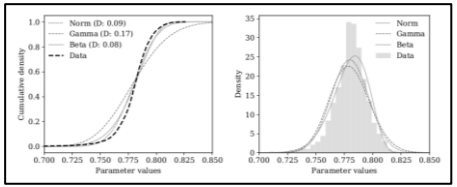
Local and global ADS-B Data

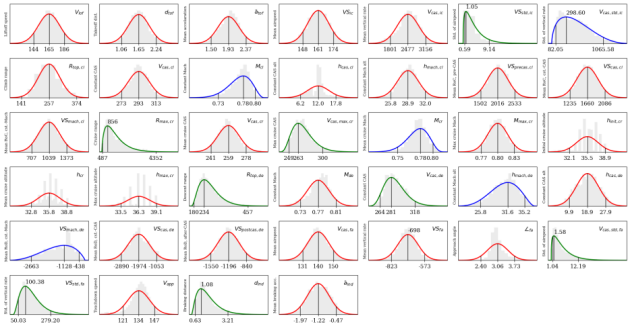
- Flight trajectory process,
- Flight phase identification
- Post-processing

Construct parametric model for key performance parameters (CAS, Mach, vertical rate, etc)









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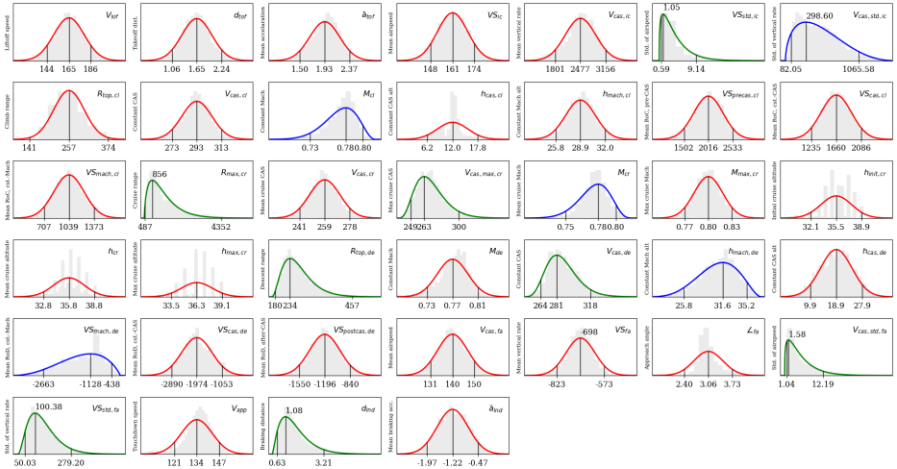
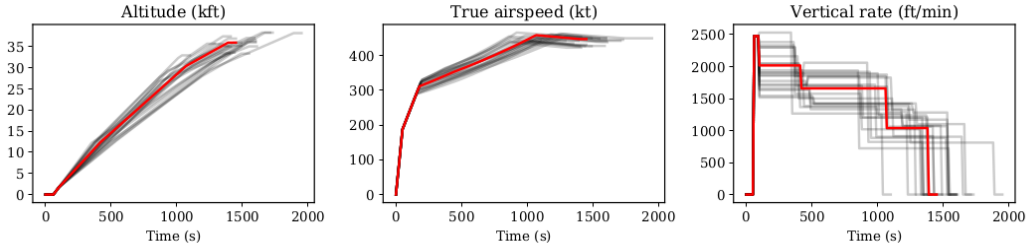
Trajectory generation



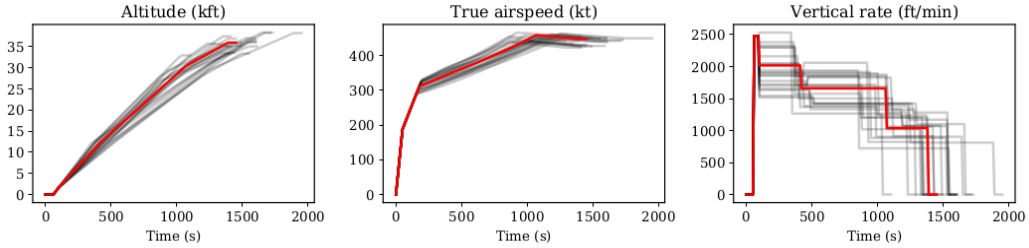


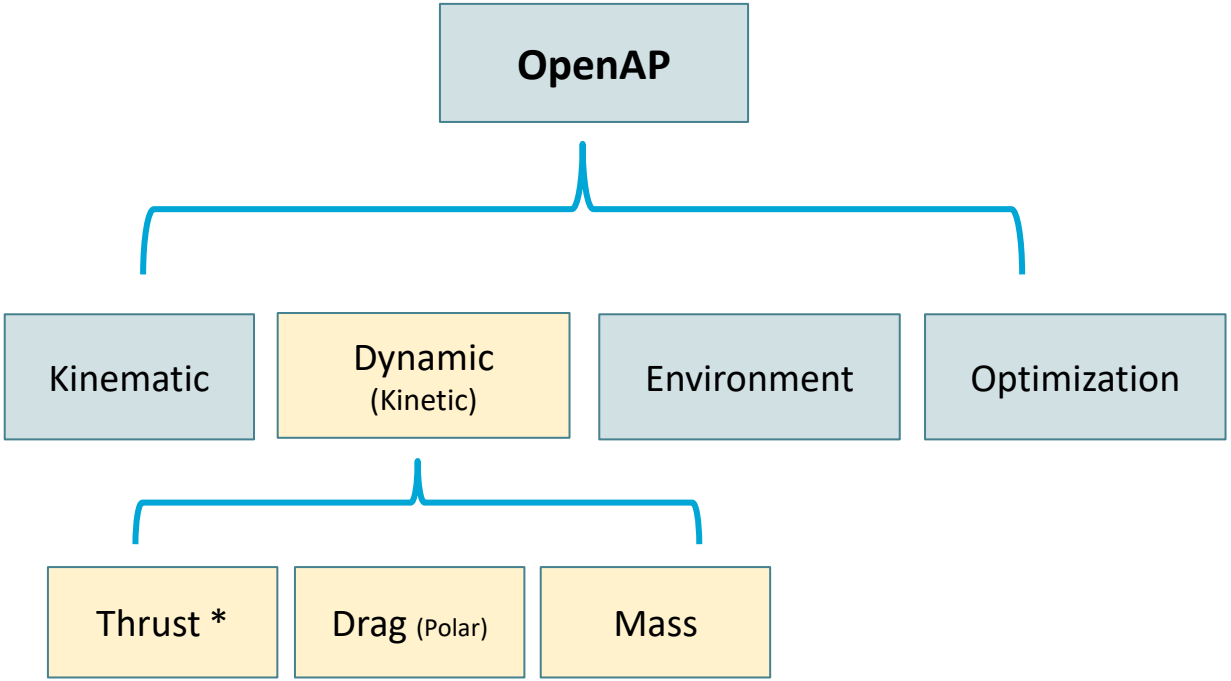
Trajectory:
Dictionary
with numpy arrays
‘t’,’h’,’v’,’s’,’vs’

Trajectory generation

Trajectory:
Dictionary
with numpy arrays
't', 'h', 'v', 's', 'vs'

```
from openap.traj import Generator

trajgen = Generator(ac='a320')

trajgen.enable_noise()    # enable Gaussian noise in trajectory data

data_cl = trajgen.climb(dt=10, random=True)  # using random paramerters
data_cl = trajgen.climb(dt=10, cas_const_cl=280, mach_const_cl=0.78, alt_cr=35000)

data_de = trajgen.descent(dt=10, random=True)
data_de = trajgen.descent(dt=10, cas_const_de=280, mach_const_de=0.78, alt_cr=35000)

data_cr = trajgen.cruise(dt=60, random=True)
data_cr = trajgen.cruise(dt=60, range_cr=2000, alt_cr=35000, m_cr=0.78)

data_all = trajgen.complete(dt=10, random=True)
data_all = trajgen.complete(dt=10, alt_cr=35000, m_cr=0.78,
                            cas_const_cl=260, cas_const_de=260)
```

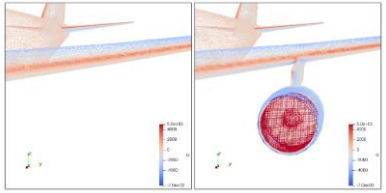


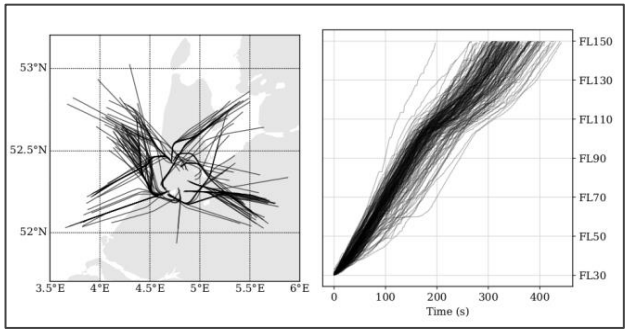


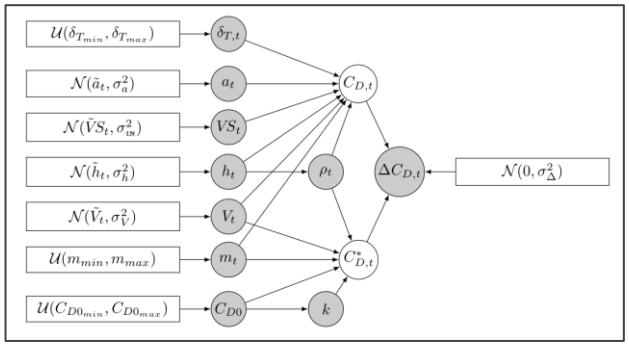
** Bartel, M., Young, T.M., 2008. Simplified thrust and fuel consumption models for modern two-shaft turbofan engines. Journal of Aircraft 45, 1450–1456.*

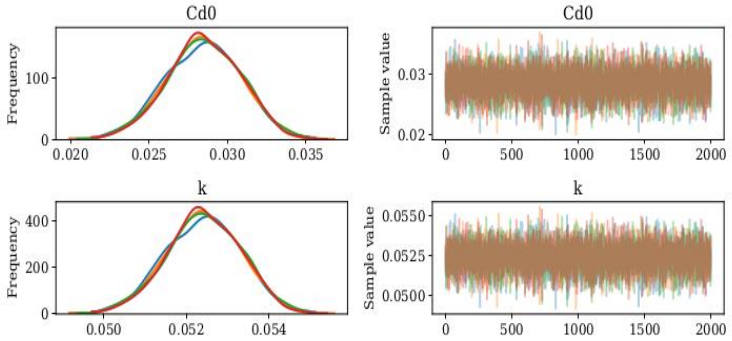
Drag polar estimation

Bayesian estimation / Markov chain Monte Carlo (MCMC) simulation





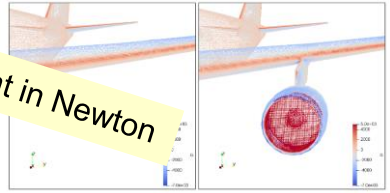


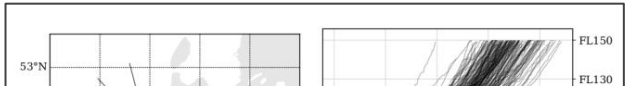


A milestone for the OpenAP model

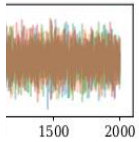
Drag polar estimation

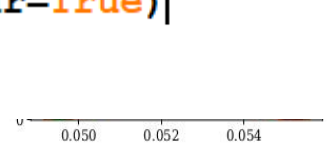
Bayesian estimation / Markov chain Monte Carlo (MCMC) simulati

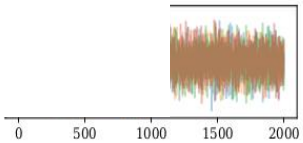


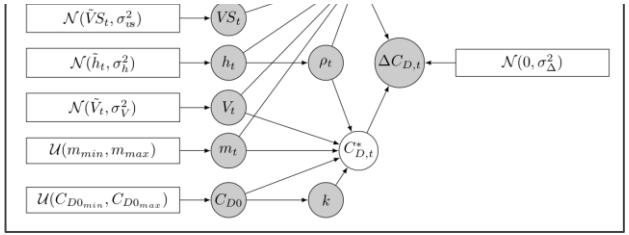



```
from openap import Drag

drag = Drag(ac='A320')

D = drag.clean(mass=60000, tas=200, alt=20000, path_angle=5)
D = drag.nonclean(mass=60000, tas=150, alt=100, flap_angle=20,
                  path_angle=10, landing_gear=True)
```

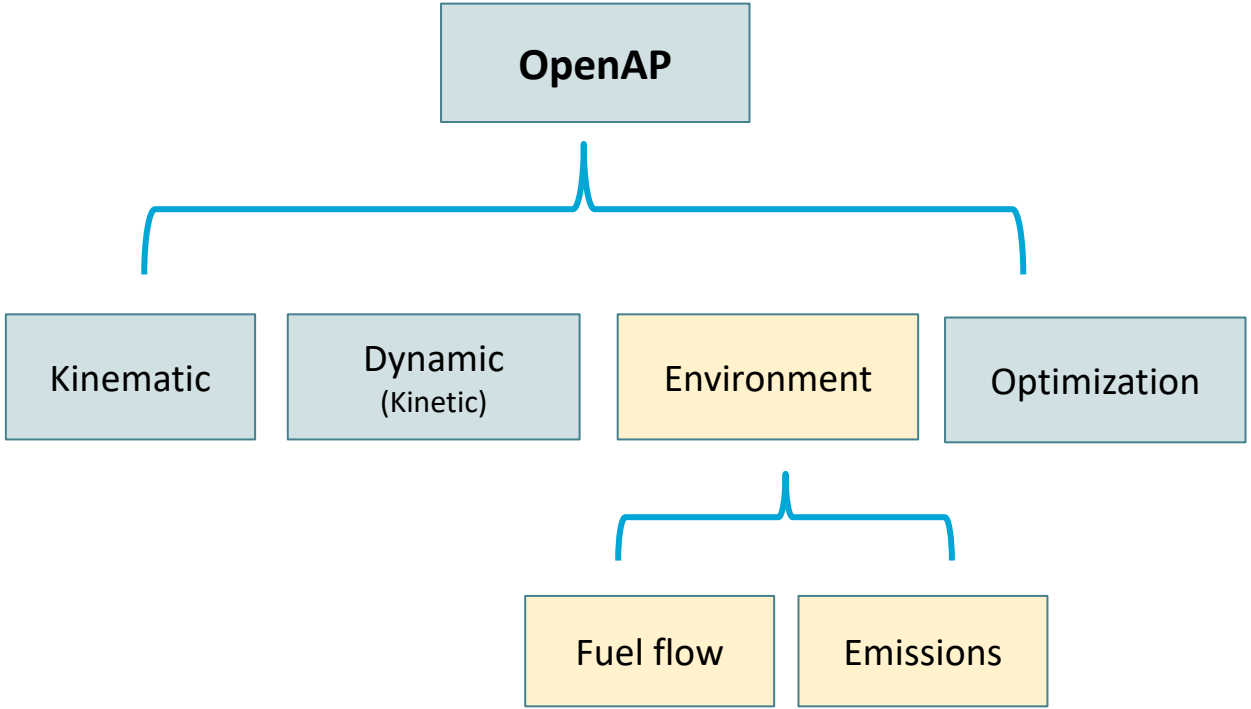








A milestone for the OpenAP model


OpenAP
Kinematic
Dynamic
(Kinetic)
Environment
Optimization
Fuel flow
Emissions

OpenAP fuel module

ICAO ENGINE EXHAUST EMISSIONS DATA BANK

SUBSONIC ENGINES

ENGINE IDENTIFICATION:	CFM56-5B1	BYPASS RATIO:	5.7
UNIQUE ID NUMBER:	2CM012	PRESSURE RATIO (π_{oo}):	30.2
ENGINE TYPE:	TF	RATED OUTPUT (F_{oo}) (kN):	133.45

REGULATORY DATA

CHARACTERISTIC VALUE:	HC	CO	NOx	SMOKE NUMBER
D_p/F_{oo} (g/kN) or SN	7.1	49.7	67.7	13.5
AS % OF ORIGINAL LIMIT	36.1 %	42.1 %	67.4 %	61.7 %
AS % OF CAEP/2 LIMIT (NOx)			84.3 %	
AS % OF CAEP/4 LIMIT (NOx)			100.4 %	
AS % OF CAEP/6 LIMIT (NOx)			114.0 %	
AS % OF CAEP/8 LIMIT (NOx)			134.0 %	

DATA STATUS

- PRE-REGULATION
x CERTIFICATION
- REVISED (SEE REMARKS)

TEST ENGINE STATUS

x NEWLY MANUFACTURED ENGINES
- DEDICATED ENGINES TO PRODUCTION STANDARD
- OTHER (SEE REMARKS)

EMISSIONS STATUS

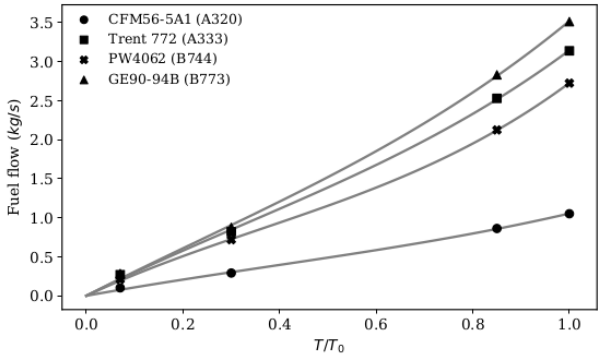
x DATA CORRECTED TO REFERENCE (ANNEX 16 VOLUME II)

CURRENT ENGINE STATUS

(IN PRODUCTION, IN SERVICE UNLESS OTHERWISE NOTED)
x OUT OF PRODUCTION (DATE: -)
- OUT OF SERVICE

MEASURED DATA

MODE	POWER SETTING (%F_{oo})	TIME minutes	FUEL FLOW kg/s	EMISSIONS INDICES (g/kg) HC	CO	NOx	SMOKE NUMBER
TAKE-OFF	100	0.7	1.359	0.1	0.5	35.1	8.6
CLIMB OUT	85	2.2	1.113	0.1	0.5	27.2	10.5
APPROACH	30	4.0	0.364	0.12	1.57	10.8	0
IDLE	7	26.0	0.117	3.21	28.4	4.6	0
LTO TOTAL FUEL (kg) or EMISSIONS (g)			474	617	5423	7783	-
NUMBER OF ENGINES				1	1	1	1
NUMBER OF TESTS				3	3	3	3
AVERAGE D_p/F_{oo} (g/kN) or AVERAGE SN (MAX)				4.6	40.5	58.4	10.5
SIGMA (D_p/F_{oo} in g/kN, or SN)				0.29	0.34	0.7	1.4
RANGE (D_p/F_{oo} in g/kN, or SN)				4.28-4.86	40.1-40.8	58.0-59.2	8.9-11.4



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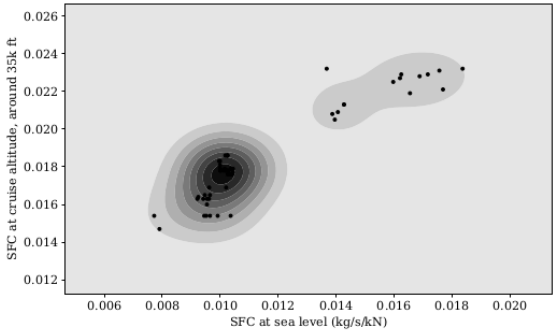
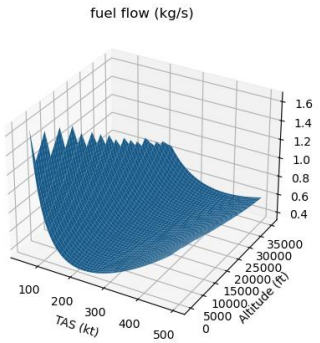
Fuel flow correction model

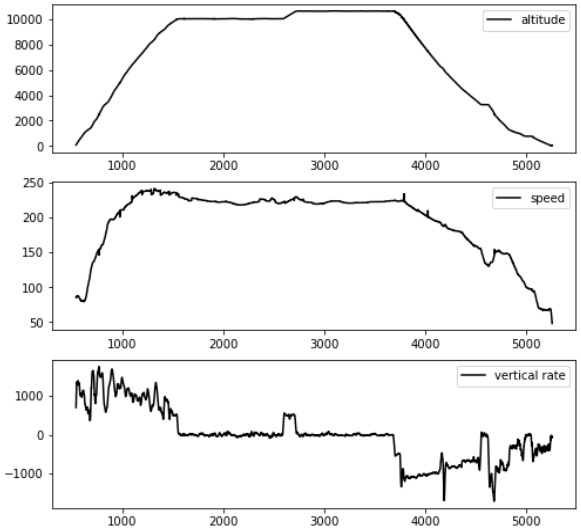


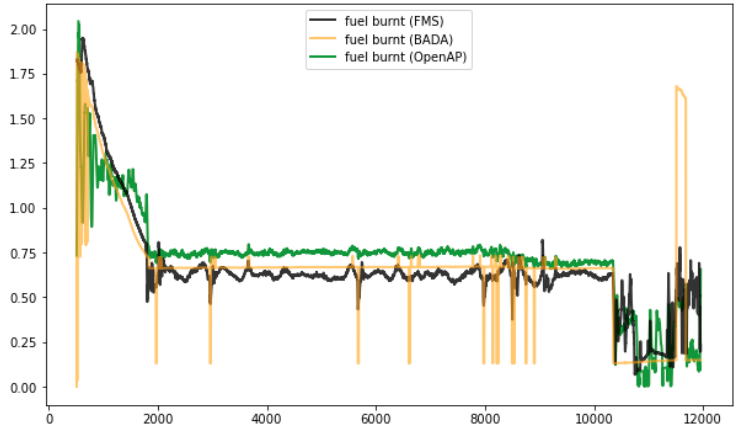
TUDelft

OpenAP fuel & emission module

- Fuel flow model enables calculation of fuel consumption directly from trajectory data
- Simplified APIs for calculating fuel consumption

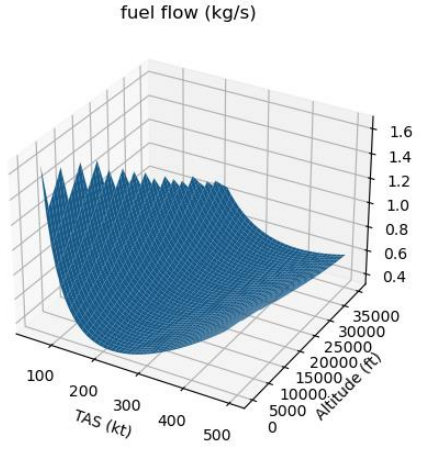


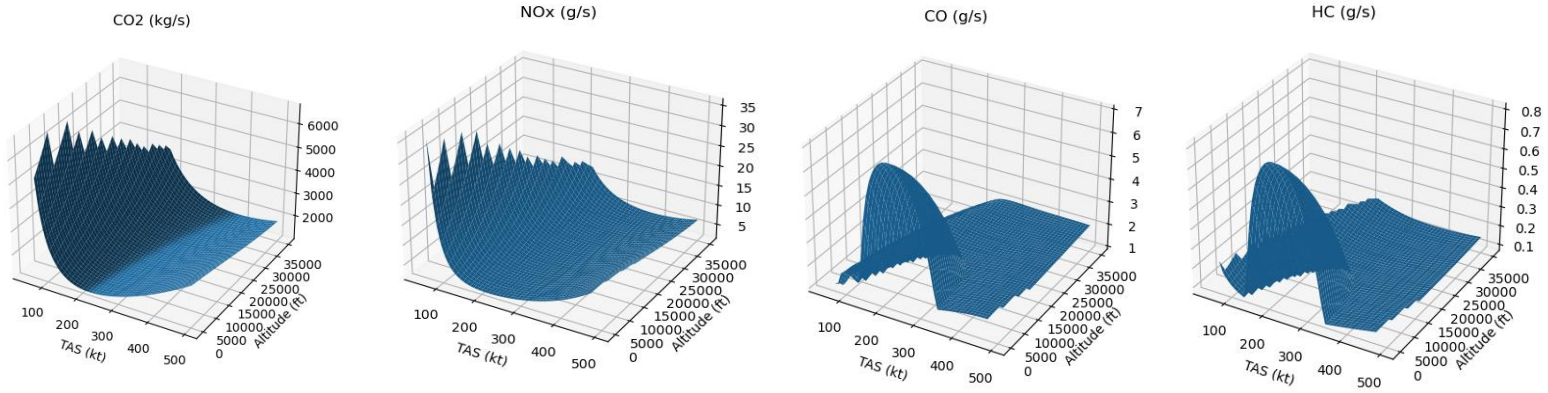




OpenAP fuel & emission module

- Based on Boeing Fuel Flow Method (BFFM2)
- Simplified APIs for calculating different pollutant emission (CO2, H2O, CO, NOx, HC) from trajectory data



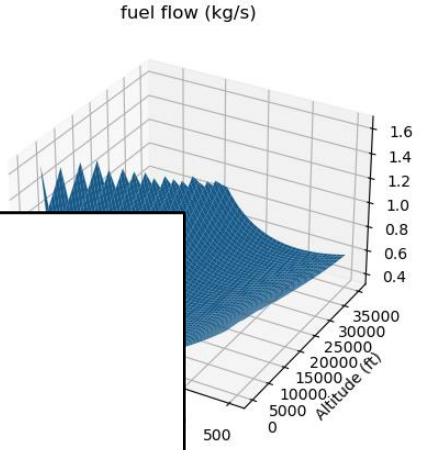


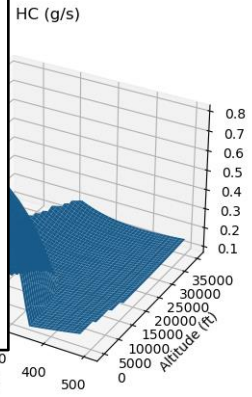
DuBois, D. and Paynter, G., ""Fuel Flow Method2" for Estimating Aircraft Emissions," SAE Technical Paper 2006-01-1987, 2006, https://doi.org/10.4271/2006-01-1987.*

OpenAP fuel & emission module

- Based on Boeing Fuel Flow Method (BFFM2)
-

```
from openap import FuelFlow, Emission

fuelflow = FuelFlow(ac='A320', eng='CFM56-5B4')
emission = Emission(ac='A320', eng='CFM56-5B4')

TAS = 350
ALT = 30000

FF = fuelflow.enroute(mass=60000, tas=TAS, alt=ALT) # kg/s

CO2 = emission.co2(FF) # g/s
H2O = emission.h2o(FF) # g/s
NOx = emission.nox(FF, tas=TAS, alt=ALT) # g/s
CO = emission.co(FF, tas=TAS, alt=ALT) # g/s
HC = emission.hc(FF, tas=TAS, alt=ALT) # g/s
```





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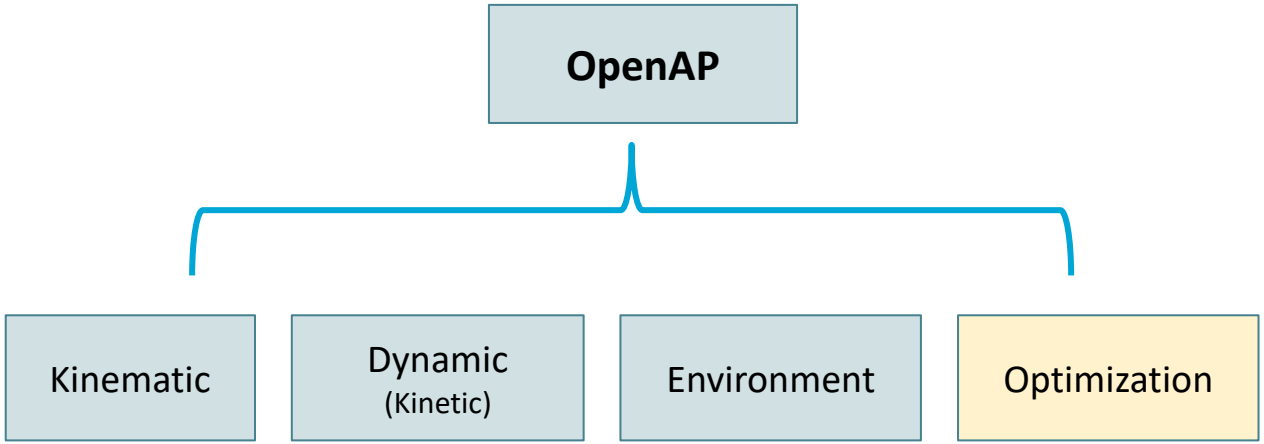
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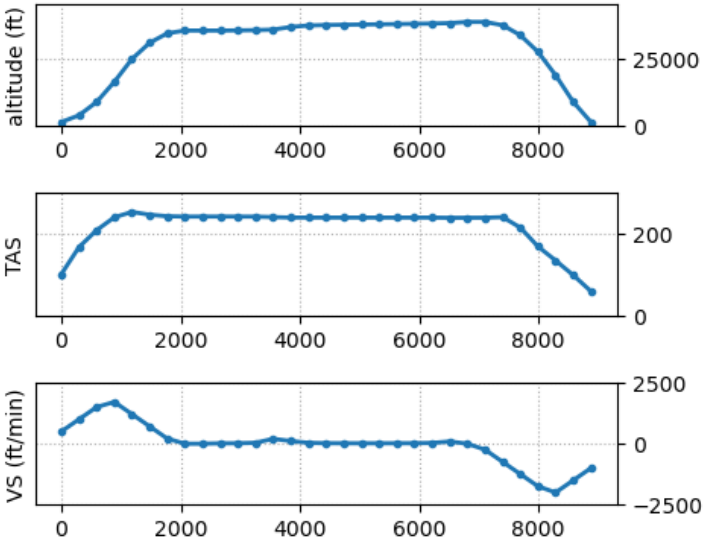
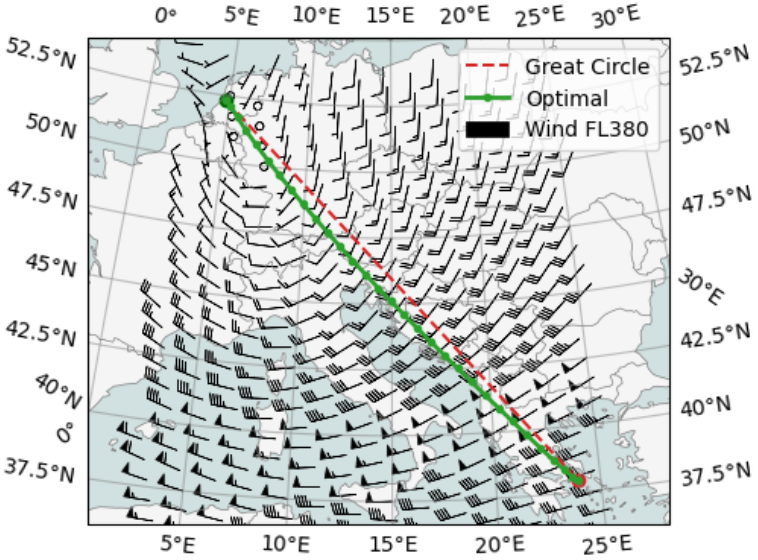
Optimization

Trajectory optimization

- Separate package: pip install openap-top
- Rapid generation of 4D optimal trajectories Different objective functions, focusing on minimizing environmental impacts





Trajectory optimization

- Separate package: pip install openap-top
- Rapid generation of 4D optimal trajectories Different objective functions, focusing on minimizing environmental impacts

	ts	xp	yp	h	lat	lon	alt	mach	tas	vs	heading	mass	fuel
0	0.0	-652999.321758	834923.636025	457.200000	52.316620	4.746300	1500.0	0.30	197.42	500.0	129.51	66300.0	242.307282
1	495.0	-614487.871534	803170.971554	1714.979740	52.072871	5.359326	5627.0	0.50	324.28	700.0	136.92	66047.0	271.304510
2	990.0	-558662.916386	743475.056260	3474.631769	51.591841	6.257091	11400.0	0.70	444.52	1200.0	136.92	65771.0	375.278102
3	1486.0	-482790.960282	662342.060174	6492.063560	50.927484	7.449811	21299.0	0.82	501.12	1000.0	136.92	65403.0	389.360710
4	1981.0	-397078.421340	570686.125050	9007.623018	50.162845	8.760018	29553.0	0.82	484.18	500.0	136.92	65025.0	333.832365
5	2476.0	-313590.147398	481408.687763	10265.402719	49.404290	9.999234	33679.0	0.82	475.48	-0.0	136.92	64695.0	291.345349
6	2971.0	-230856.502150	392938.205904	10265.402679	48.639828	11.192213	33679.0	0.82	475.48	-44.0	136.92	64404.0	287.655101
7	3466.0	-148055.606310	304395.810227	10154.524565	47.862635	12.352211	33315.0	0.82	476.26	12.0	136.92	64116.0	291.663965
8	3962.0	-65206.030982	215801.359576	10185.205885	47.073466	13.479867	33416.0	0.82	476.04	13.0	136.92	63825.0	291.052710
9	4457.0	17605.483824	127247.608603	10217.282758	46.273738	14.574960	33521.0	0.82	475.82	13.0	136.92	63534.0	290.397531
10	4952.0	100378.046963	38735.510244	10249.404142	45.464062	15.638483	33627.0	0.82	475.59	13.0	136.92	63244.0	289.742513
11	5447.0	183111.593551	-49734.866114	10281.557682	44.645030	16.671425	33732.0	0.82	475.37	13.0	136.92	62954.0	289.088061
12	5942.0	265806.066099	-138163.458997	10313.743398	43.817221	17.674762	33838.0	0.82	475.14	13.0	136.92	62666.0	288.434183
13	6437.0	348461.406891	-226550.206689	10345.961512	42.981207	18.649450	33943.0	0.82	474.92	13.0	136.92	62377.0	287.782114
14	6933.0	431077.530780	-314895.018137	10378.256766	42.137546	19.596423	34049.0	0.82	474.69	48.0	136.92	62090.0	289.590364
15	7428.0	513600.238559	-403139.935904	10499.431368	41.287346	20.516002	34447.0	0.82	473.85	127.0	136.92	61801.0	294.066220
16	7923.0	595853.980125	-491097.237062	10818.877960	40.432988	21.407251	35495.0	0.82	471.60	-373.0	136.92	61508.0	257.387872
17	8418.0	678482.040998	-579454.813215	9880.544826	39.568291	22.277925	32416.0	0.70	408.19	-873.0	136.92	61248.0	198.841922
18	8913.0	750610.723598	-656584.973336	7684.431935	38.808582	23.018417	25211.0	0.50	300.71	-1373.0	136.92	61045.0	121.268546
19	9409.0	804096.501379	-713779.510284	4230.539286	38.242498	23.556079	13880.0	0.30	188.74	-1500.0	129.51	60921.0	74.760340
20	9904.0	841941.757884	-744982.898488	457.200000	37.923510	23.943260	1500.0	0.10	65.81	-1627.0	122.09	60849.0	142.261908

Thank you and for questions:

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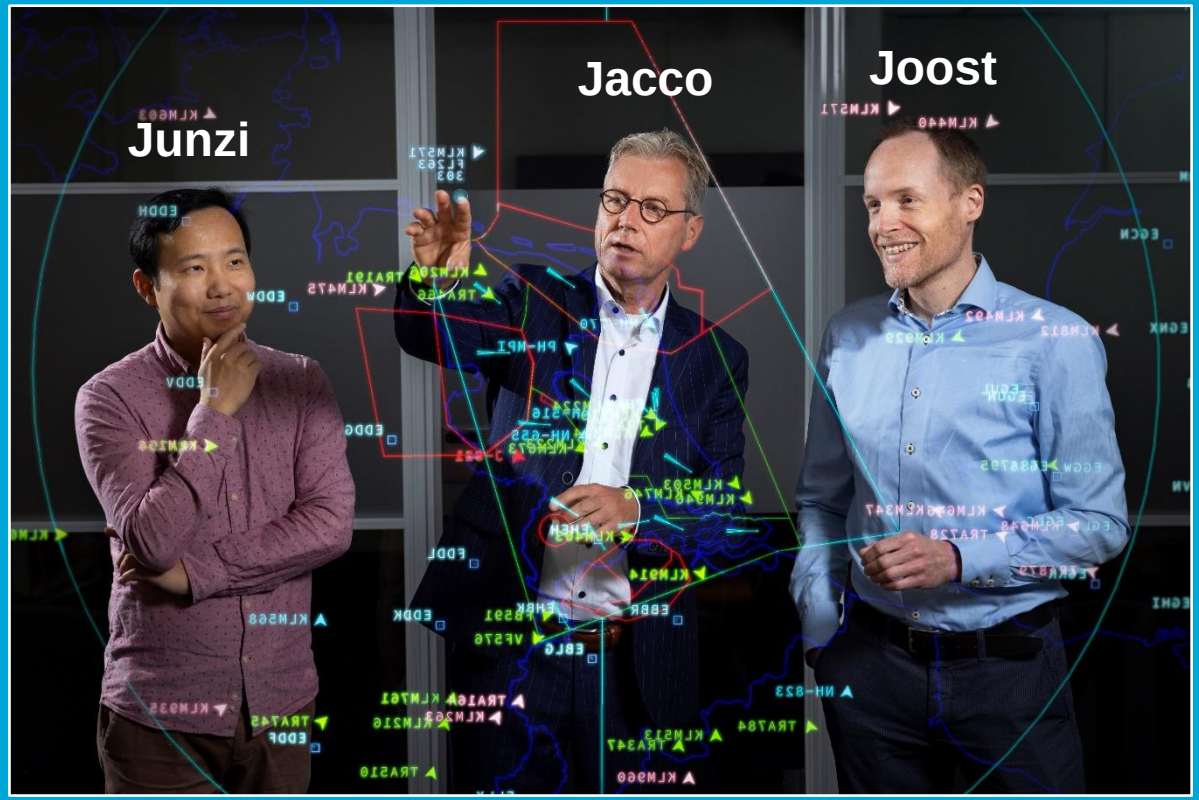

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Keep an eye on: https://github.com/TUDelft-CNS-ATM

Thank you!

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