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Controllers auto-tuning for multirotors and fixed-wing vehicles

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Outline

1. **(Basic) Control theory**
    a. Block diagrams
    b. Controller tuning techniques
2. **Why do we need auto-tuning?**
3. **Auto-tuning and adaptive control**
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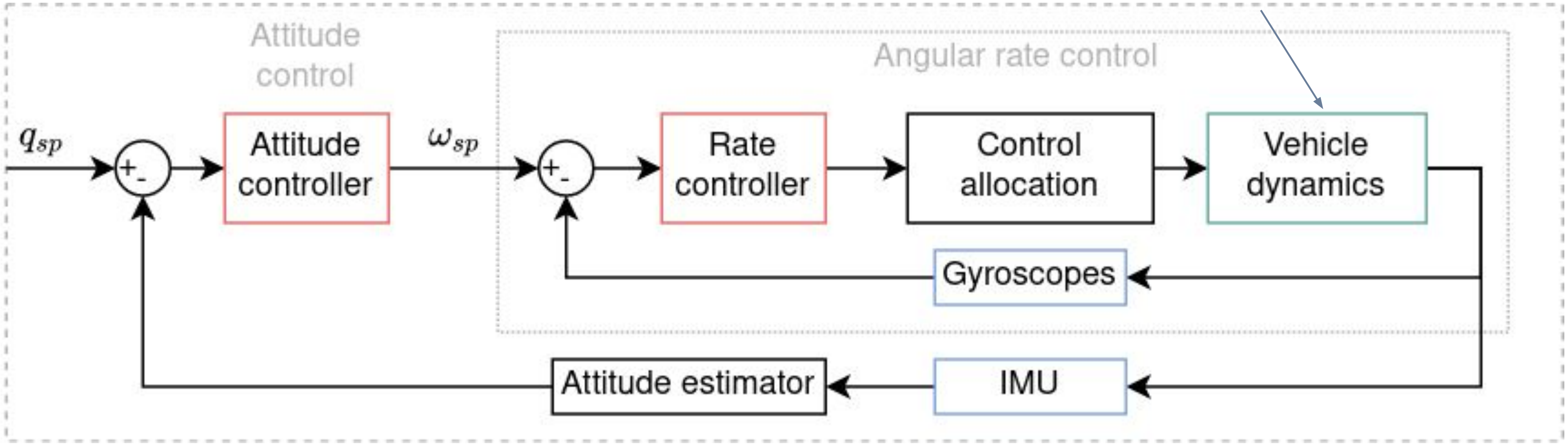
    b. Adaptive control → auto-tuning
4. **The strategy selected for PX4**
5. **Python prototyping**
6. **Onboard implementation (in PX4)**
7. **Flight test results**
8. **Conclusion**

1.a. Control theory - Block diagrams

Example: Cascaded attitude/rate controller

Set of (non)linear differential equations
"Converting" force → motion

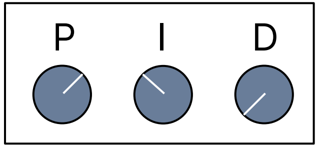


1.b. Control theory - Controller tuning

No model required:

- manual PID tuning
- Ziegler-Nichols → too dangerous for aircrafts
- Auto-tuning (~adaptive control)

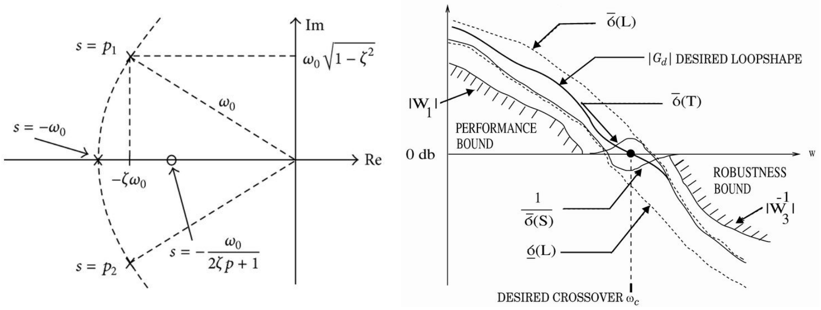
Widely used in industrial projects



Model required:

- Loop-shaping
- H-infinity
- Pole placement
  - Internal model control
  - Minimum variance control
  - Model reference control
- ...

Mainly used in academia or in research projects



Left: pole placement, Right: loop shaping (Mathworks.com)

2. Why do we need auto-tuning?

Manual tuning

- Need good pilot (and a 2nd operator)
- Understand the control parameters
- Tuning experience
- A lot of flight time (iterations)
- Everyone has a different standard
- Limited to simple controllers (e.g.: PID)
- ...

Total: expensive for every bringup

Auto-tuning

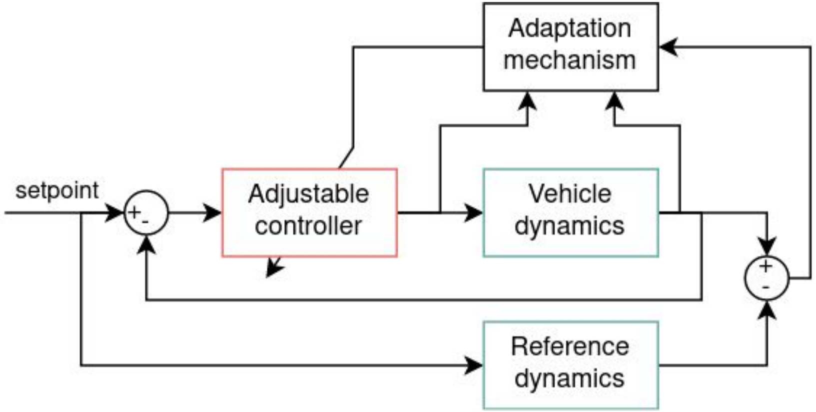
- Can be used by everyone
- High-level understandable criteria
- No tuning experience required
- Fast
- Generates a good base tuning on all drones
- Can be used to tune simple and advanced controllers

Total: expensive to develop but then almost free

3. Auto-tuning and adaptive control

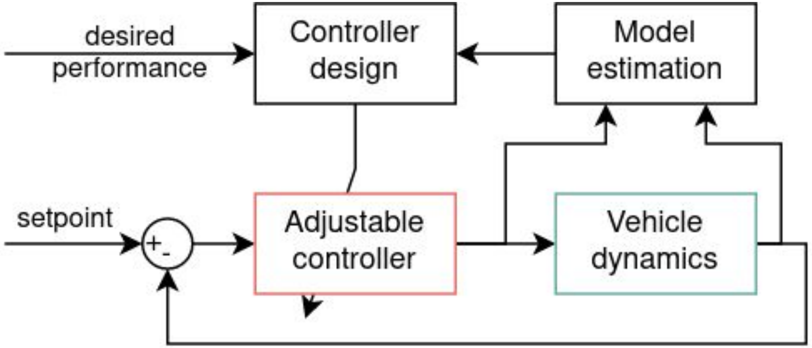
Direct adaptive control

Adjust the controller to track the desired reference dynamics (e.g.: MRAC)



Indirect adaptive control

1. Estimate the vehicle dynamic model
2. Adjust the controller using model-based tuning techniques (e.g.: loop shaping, pole placement, ...)

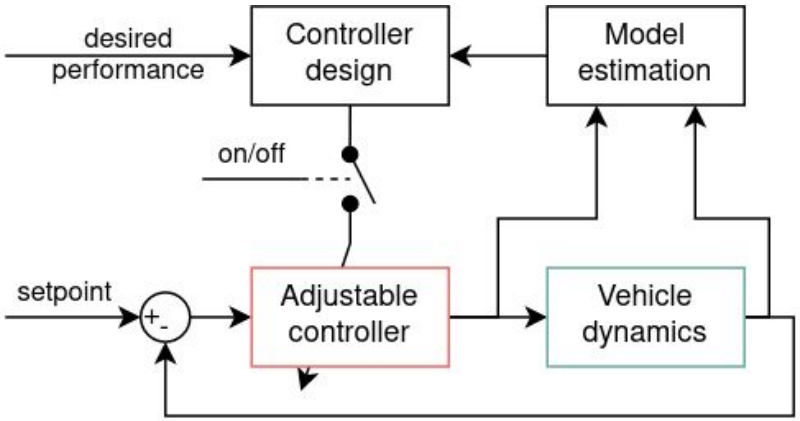


Ref: A.Karimi, Robust and Adaptive control, epfl

3. Auto-tuning and adaptive control

Adaptive control: Continuously adjust the controller as the parameters change

Auto-tuning: Temporarily enable the control adaptation algorithm to tune the controller



4. The strategy selected for PX4

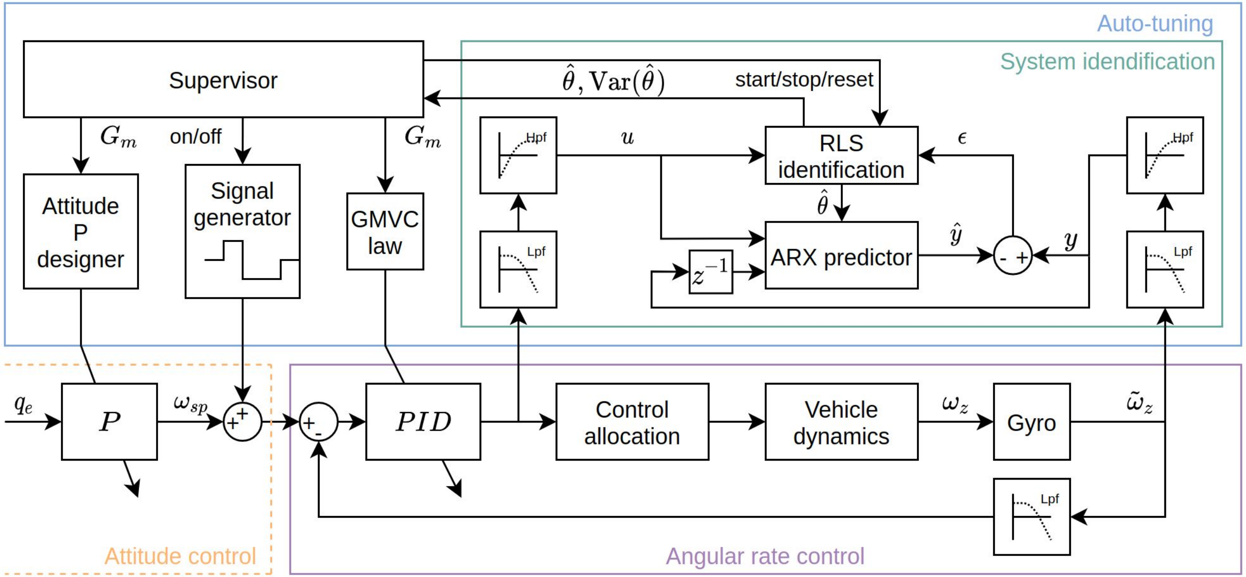
Indirect adaptive control

System identification:

- Efficient Recursive Least-Squares (RLS) algorithm (no matrix inversion)
- Linear optimization
- Fixed structure

Attitude and rate control tuning:

- Closed-form solution



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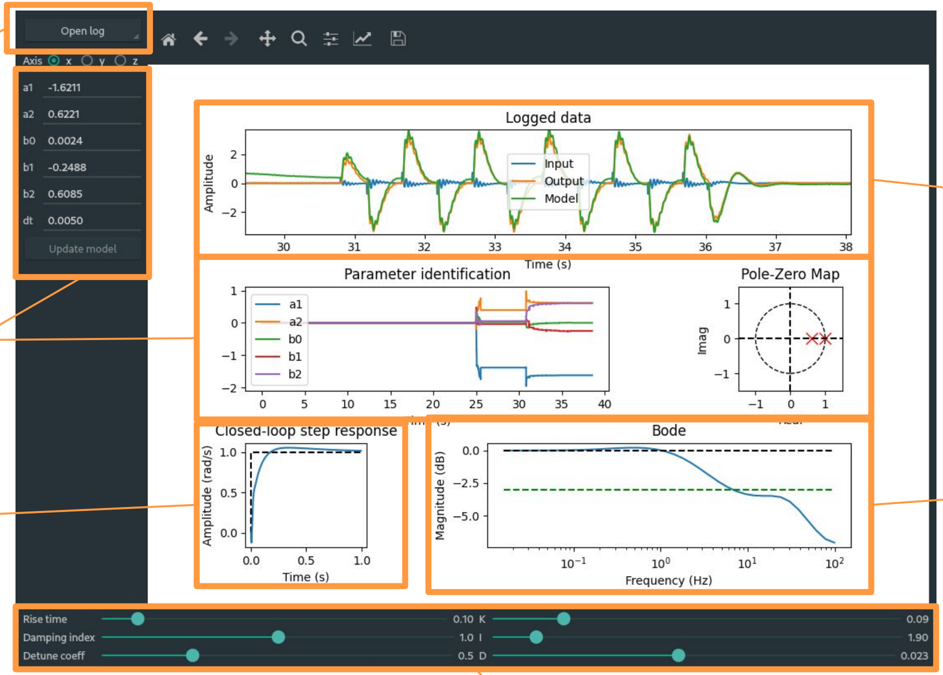
5. Python prototyping

Input: high-rate *.ulg* flight logs

Discrete-time model identification

Closed-loop (controller + identified model) step response



Simulates model output based on identified model and logged inputs

Closed-loop bode plot (frequency response)

Sliders for auto-tuning meta-parameters and PID gains

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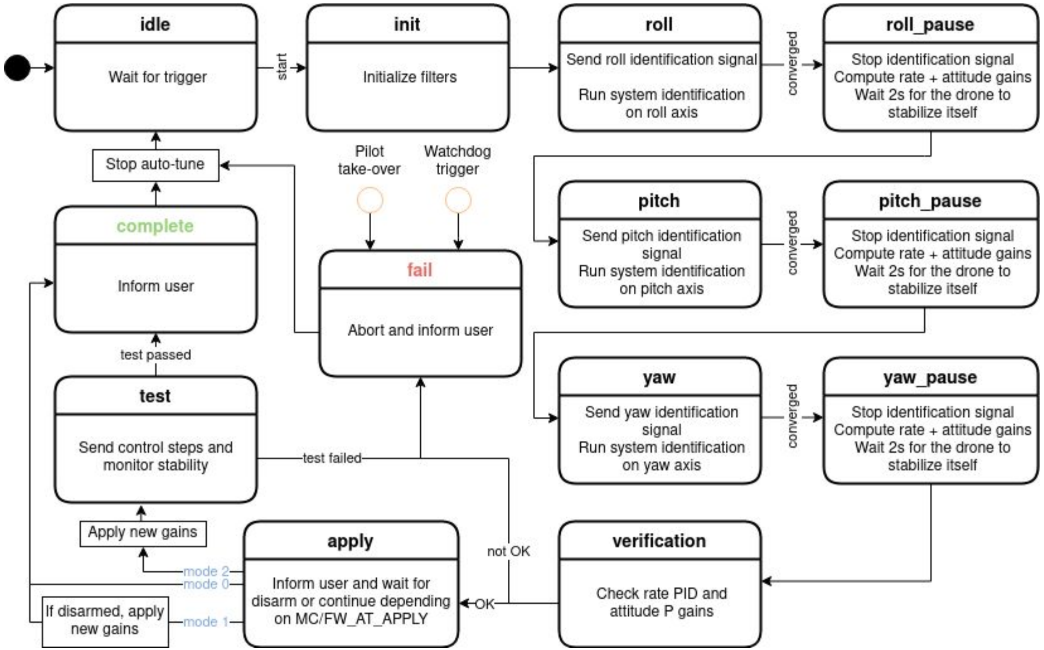
6. Onboard implementation (in PX4)

Same algorithms used in python prototype script (same results are confirmed by unit tests)

Additional supervisor state machine and error handling logic



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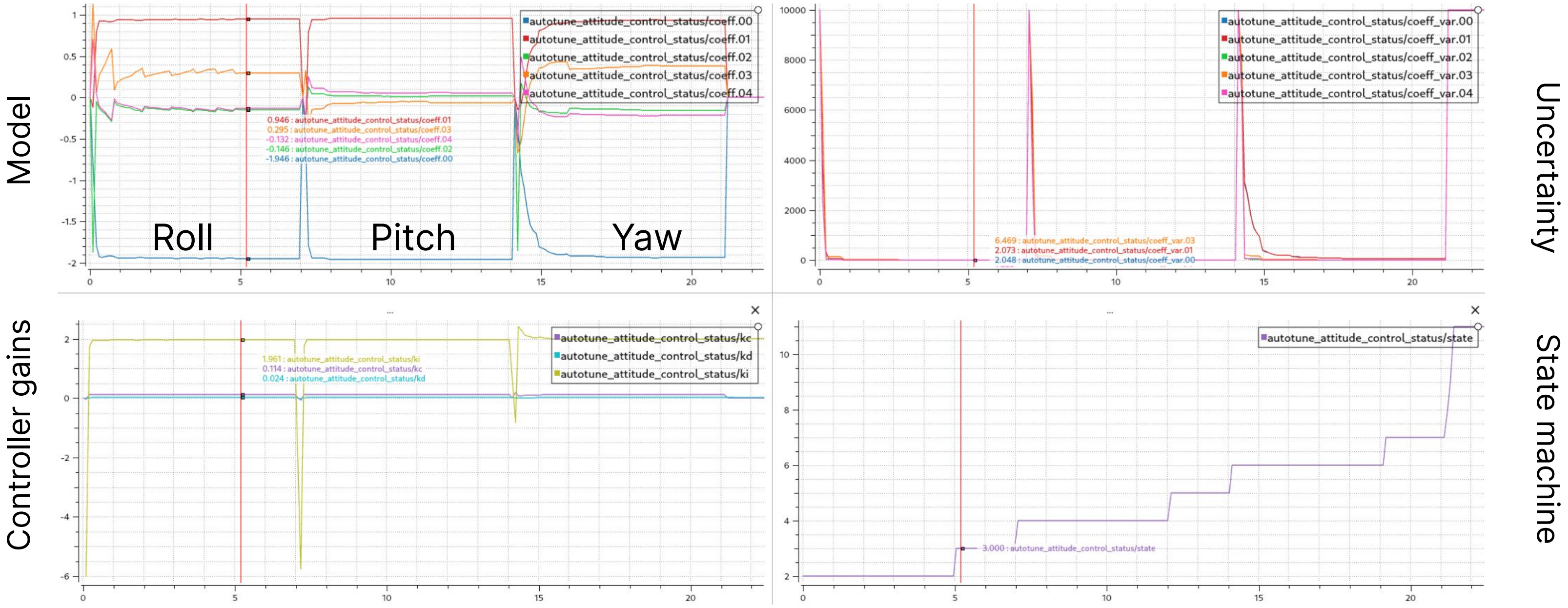
7. Flight test results

Example: X500 Quadrotor



8. Conclusion

Benefits

Speeds-up initial bringup

Complicated trial and error tuning → single click

No control theory knowledge required

Provides a dynamic model (can be used in sim of offline controller design)

Limitations

Cannot tune all drones with same meta-parameters

The drone needs to fly decently before starting the auto-tune algorithm

Struggles to tune UAVs with flexible body or large actuator delays (unmodeled dynamics)

Does not fix the hardware problems

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Questions?

Thank you!