Flight Simulation of a MAKO UAV for Use in Data-Driven Fault Diagnosis

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Technology getting smaller

Small drones get more capable

New application areas and new users

incidences
privacy
safety
concerns

Safe integration of drones into airspace

- System wise safety
  - UTM, seperation

- Component wise safety
  - Design of safer drones

. Parimal Kopardekar, Joseph Rios, Thomas Prevot, Marcus Johnson, Jaewoo Jung, and John E Robinson III. Unmanned aircraft system traffic management (utm) concept of operations. In 16th AIAA Aviation Technology, Integration, and Operations Conference. AIAA Aviation, 2016

Approaches Towards Safe Aircraft Design

Fail Operational Systems

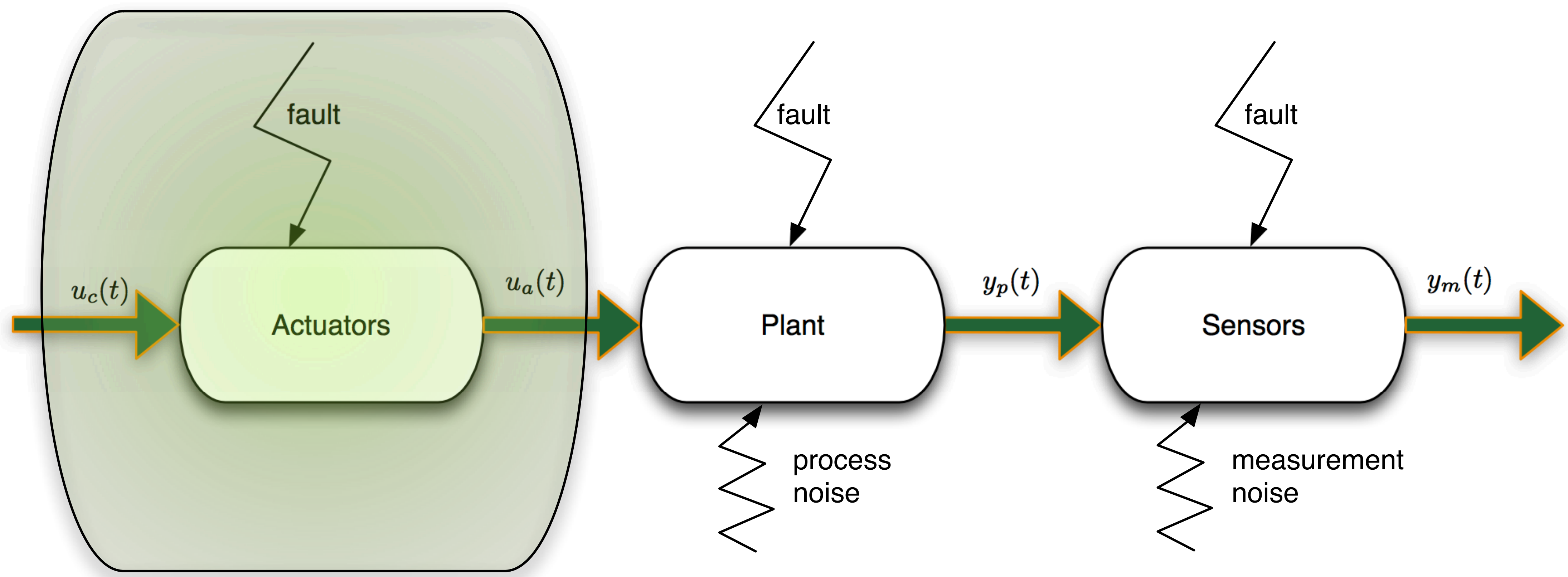
- Higher reliability components > cost, weight
- redundancy > cost, weight
  - but UAS are expected to cost less

Fail Safe Systems

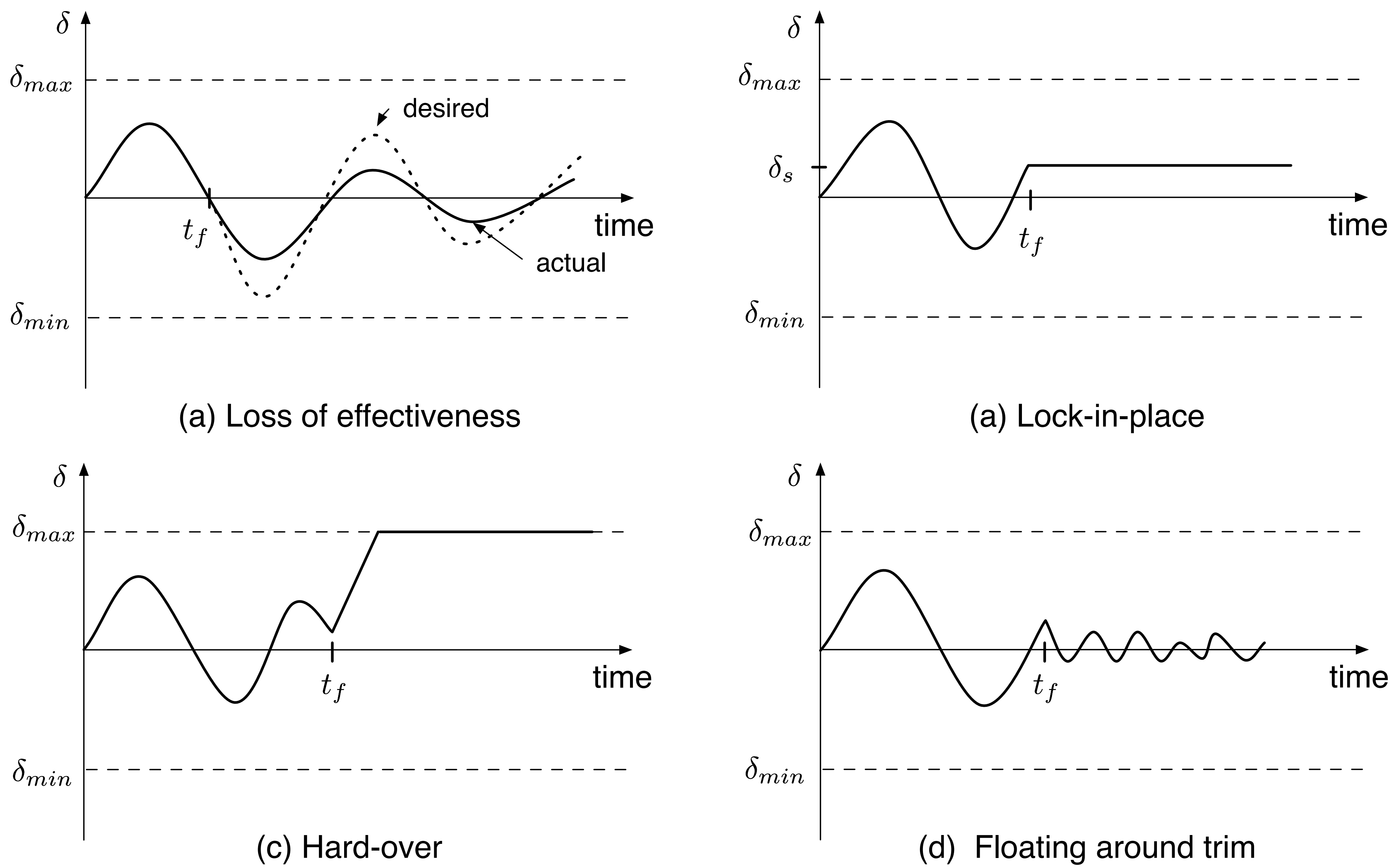
Fault Tolerant Control Systems

- To utilize intelligent software that monitors the state of the systems and acts if needed

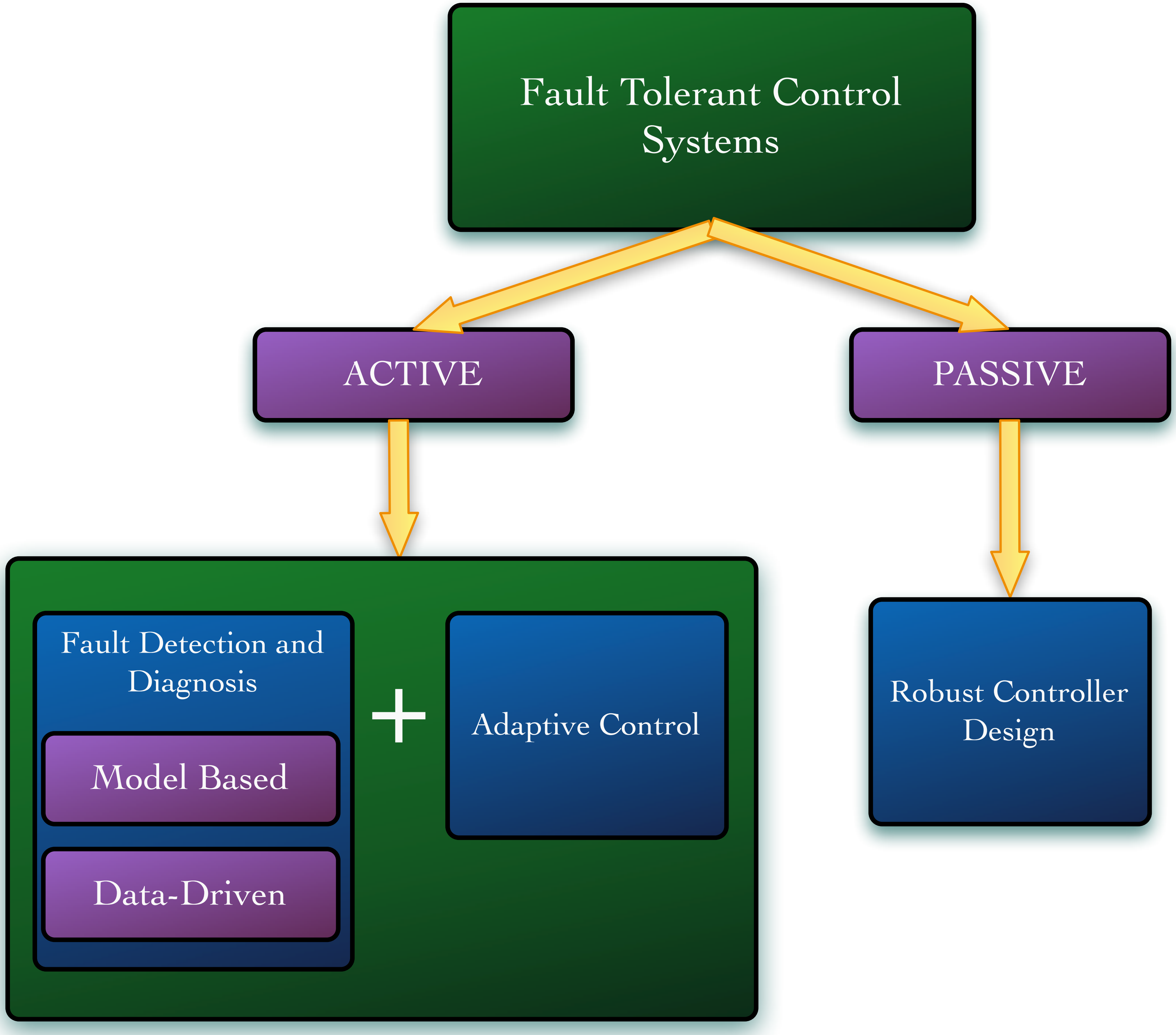
Possible Faults



Actuator Faults



FTCS


Fault Tolerant Control Systems
ACTIVE
PASSIVE
Fault Detection and Diagnosis
Model Based
Data-Driven
+
Adaptive Control
Robust Controller Design

Ideal FDD

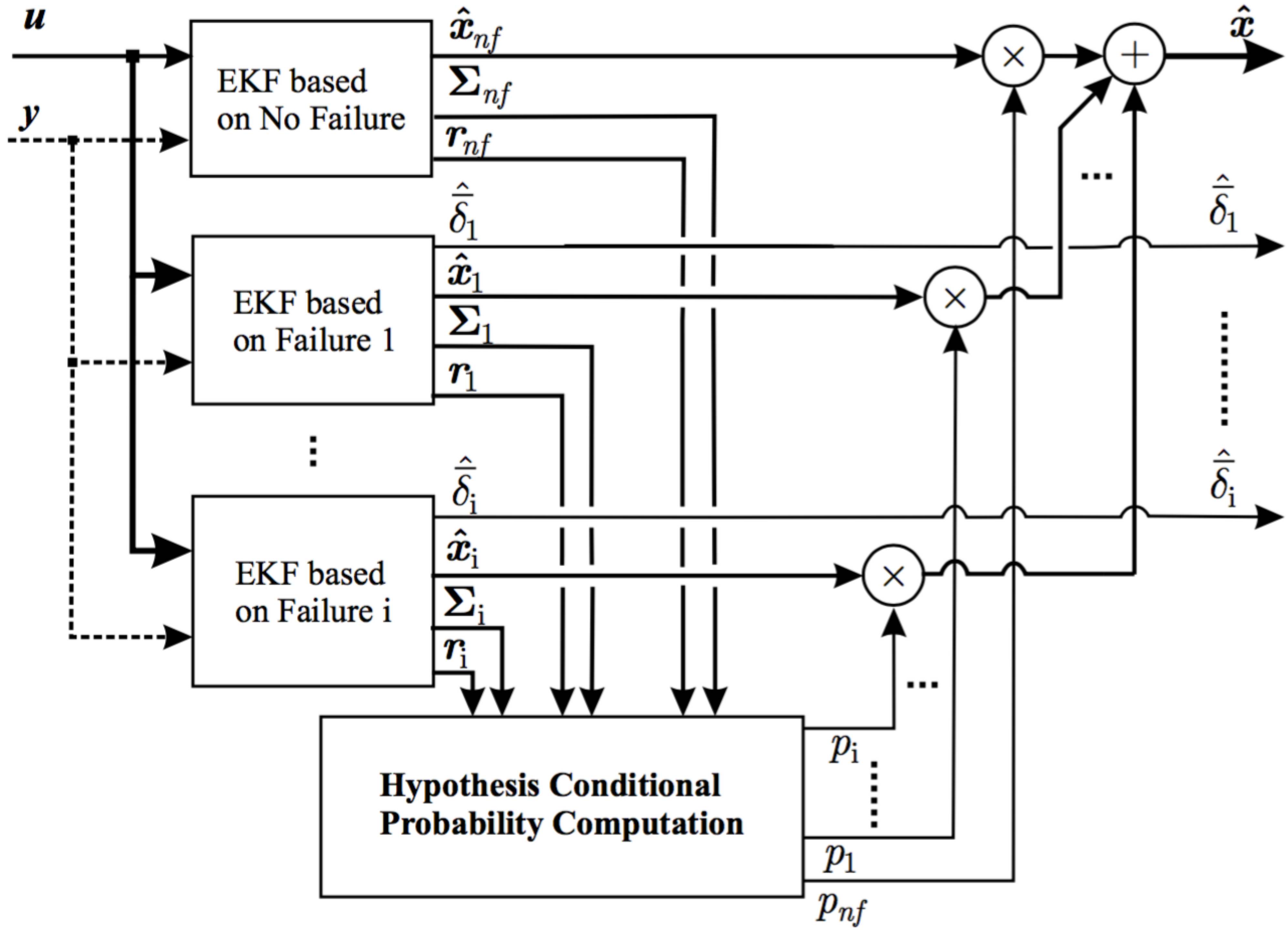
- Able to distinguish faults from disturbances (process noise) and measurement noise -> Robust to disturbances
- Sensitive enough to sense the faults

Methods

Data Driven

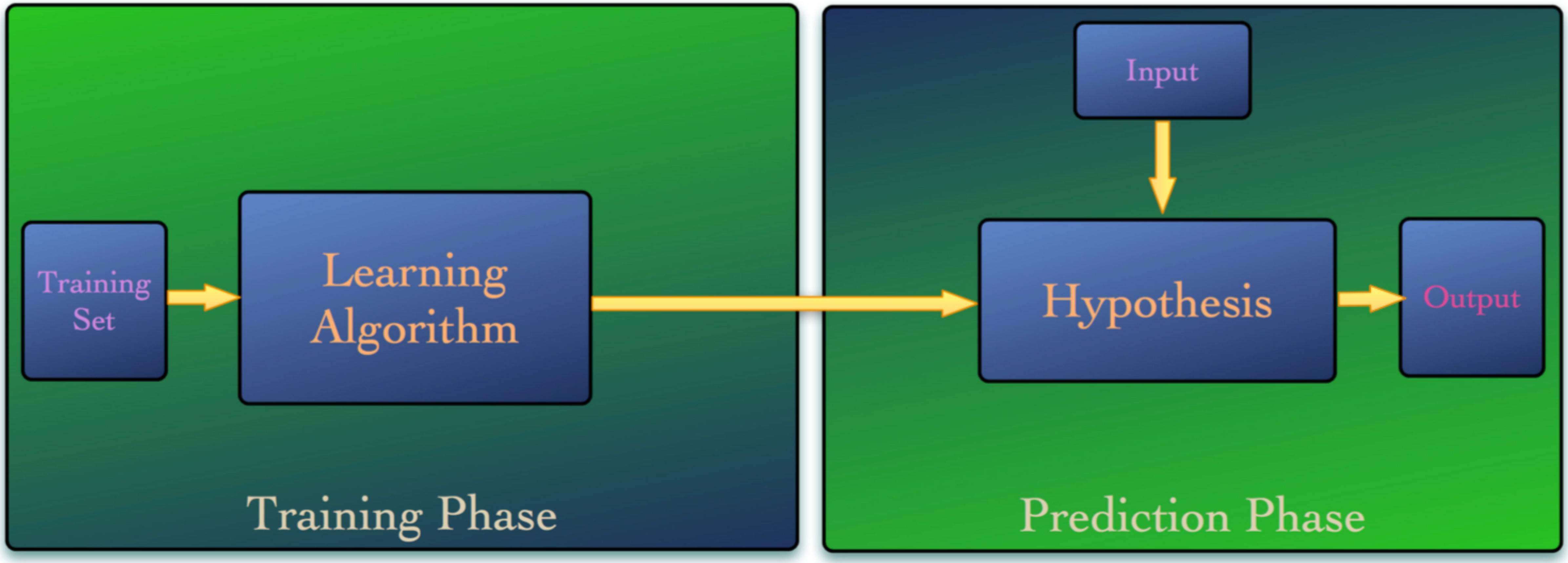
Model Based

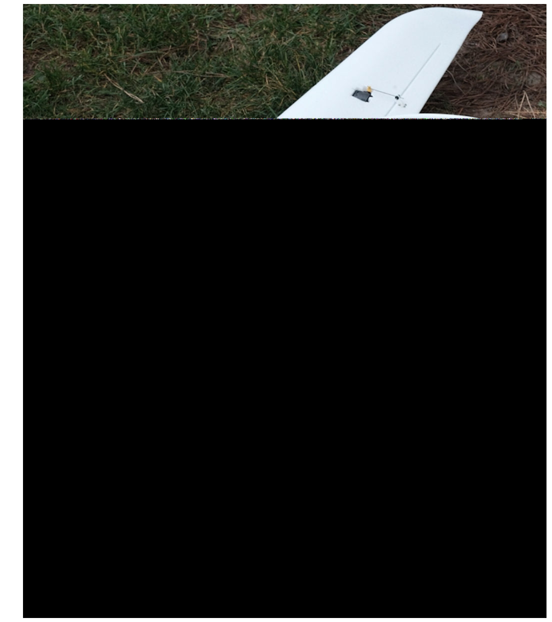
Model Based FDD



. Guillaume JJ Ducard. Fault-tolerant Flight control and guidance systems: Practical methods for small unmanned aerial vehicles. Springer Science & Business Media, 2009

Supervised Machine Learning





Nonlinear Aircraft Equations of Motion

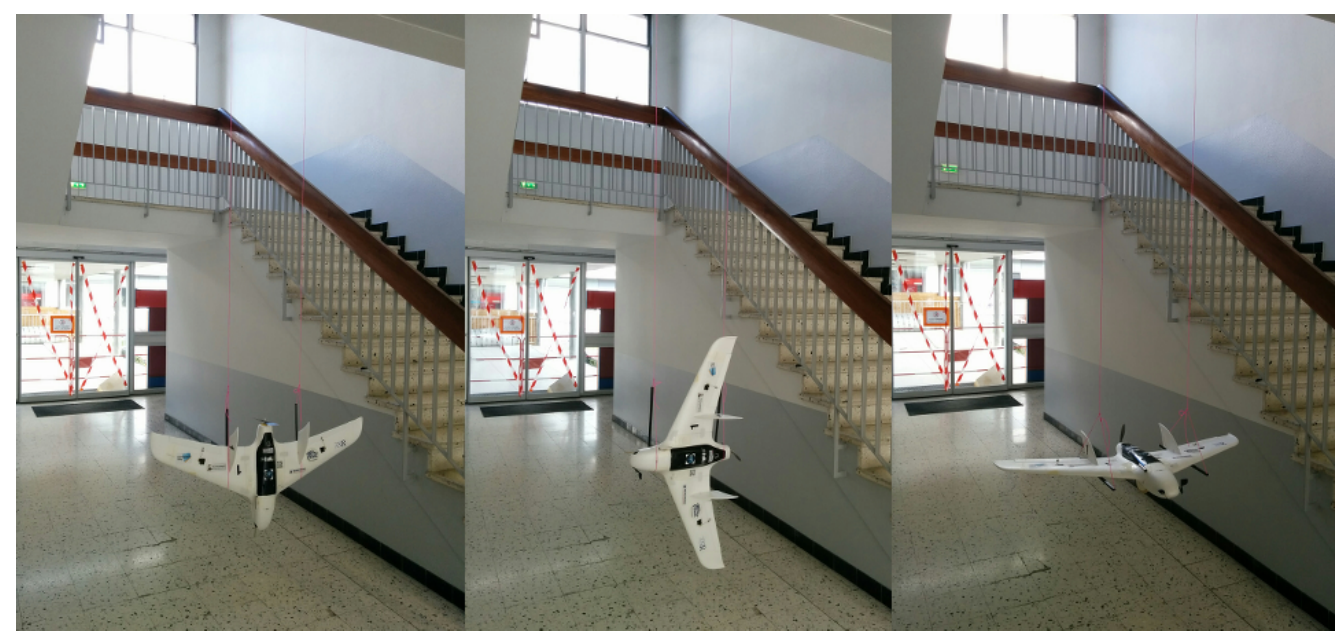
$$\begin{bmatrix} \dot{x}_N \\ \dot{x}_E \\ \dot{x}_D \end{bmatrix} = \boldsymbol{C}_b^n \begin{bmatrix} u \\ v \\ w \end{bmatrix},$$

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} -g\sin\theta \\ g\sin\phi\cos\theta \\ g\cos\phi\cos\theta \end{bmatrix} + \frac{1}{m}\left[\begin{pmatrix} F_T \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} X^b \\ Y^b \\ Z^b \end{pmatrix}\right] - \begin{bmatrix} qw - rv \\ ru - pw \\ pv - qu \end{bmatrix}$$

Parameter	Value	Definition
Wing span	1.288	$[m]$
Wing surface area	0.27	$[m^2]$
Mean aero chord	0.21	$[m]$
Take-off mass	$0.7 - 2.0$	$[kg]$
Flight velocity	$10 - 25$	$[m/s]$
I_{xx}	0.02471284	$[kg \cdot m^2]$
I_{yy}	0.015835159	$[kg \cdot m^2]$
I_{zz}	0.037424499	$[kg \cdot m^2]$

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} -q_1 & -q_2 & -q_3 \\ q_0 & -q_3 & q_2 \\ q_3 & q_0 & -q_1 \\ -q_2 & q_1 & q_0 \end{bmatrix}\begin{bmatrix} p \\ q \\ r \end{bmatrix},$$

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \left(\boldsymbol{I}^b\right)^{-1}\left(\begin{bmatrix} L \\ M \\ N \end{bmatrix}^b - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \boldsymbol{I}^b \begin{bmatrix} p \\ q \\ r \end{bmatrix}\right),$$



. Guillaume JJ Ducard. Fault-tolerant Flight control and guidance systems: Practical methods for small unmanned aerial vehicles. Springer Science & Business Media, 2009

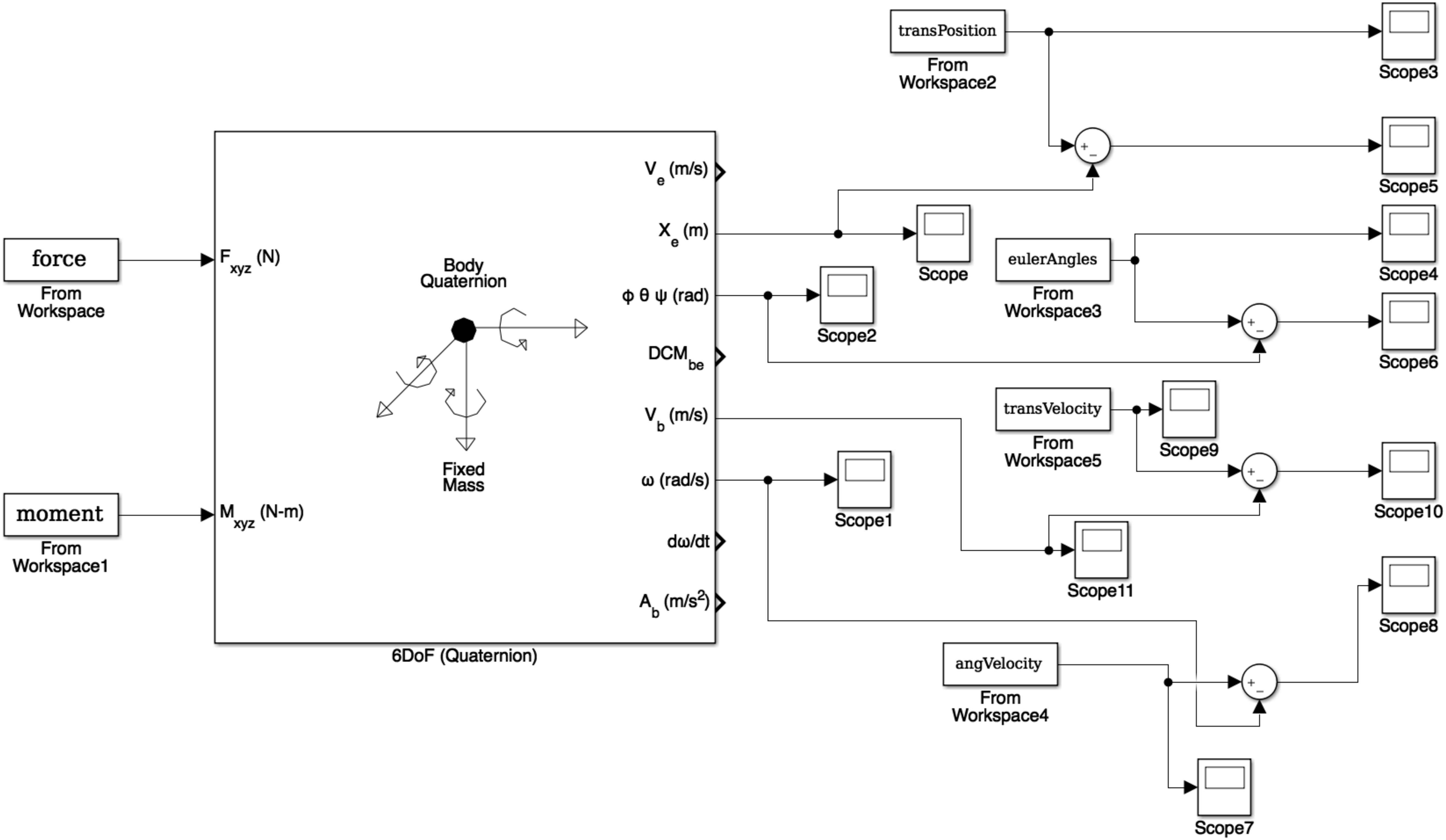
AVL

Parameter	Value	Definition
C_{L_a}	-0.1956×10^{-2}	roll derivative
$C_{L_{\tilde{p}}}$	-4.095×10^{-1}	roll derivative
$C_{L_{\tilde{r}}}$	6.203×10^{-2}	roll derivative
C_{L_β}	3.319×10^{-2}	roll derivative
C_{M_0}	0	pitch derivative
C_{M_e}	-0.076×10^{-1}	pitch derivative
$C_{M_{\tilde{q}}}$	-1.6834	pitch derivative
C_{M_α}	-32.34×10^{-2}	pitch derivative
C_{N_a}	-0.0126×10^{-2}	yaw derivative
$C_{N_{\tilde{p}}}$	-4.139×10^{-2}	yaw derivative
$C_{N_{\tilde{r}}}$	-0.1002×10^{-1}	yaw derivative
C_{N_β}	2.28×10^{-2}	yaw derivative

Parameter	Value	Definition
C_{Z_0}	-8.53×10^{-2}	lift derivative
C_{Z_α}	3.9444	lift derivative
C_{Z_q}	4.8198	lift derivative
C_{Z_e}	1.6558×10^{-2}	lift derivative
C_{X_0}	2.313×10^{-2}	drag derivative
C_{X_k}	1.897×10^{-1}	drag derivative
C_{Y_β}	-2.708×10^{-1}	side force derivative
$C_{Y_{\tilde{p}}}$	1.695×10^{-2}	side force derivative
$C_{Y_{\tilde{r}}}$	5.003×10^{-2}	side force derivative
C_{Y_a}	0.0254×10^{-2}	side force derivative

Parameter	Value	Definition
$C_{F_{T1}}$	1.342×10^{-1}	thrust derivative
$C_{F_{T2}}$	-1.975×10^{-1}	thrust derivative
$C_{F_{T_{rpm}}}$	7.048×10^{-6}	thrust derivative
D	$0.228\,m$	propeller diameter

Validation via Simulink



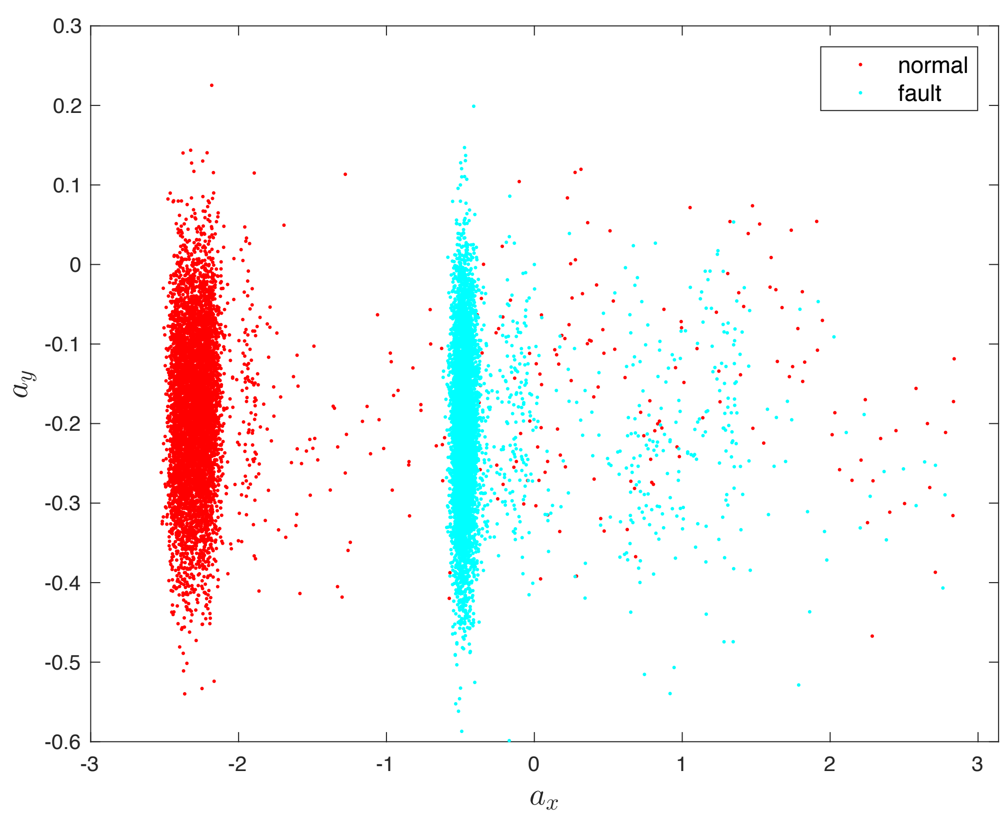
Sensor & Fault Simulation

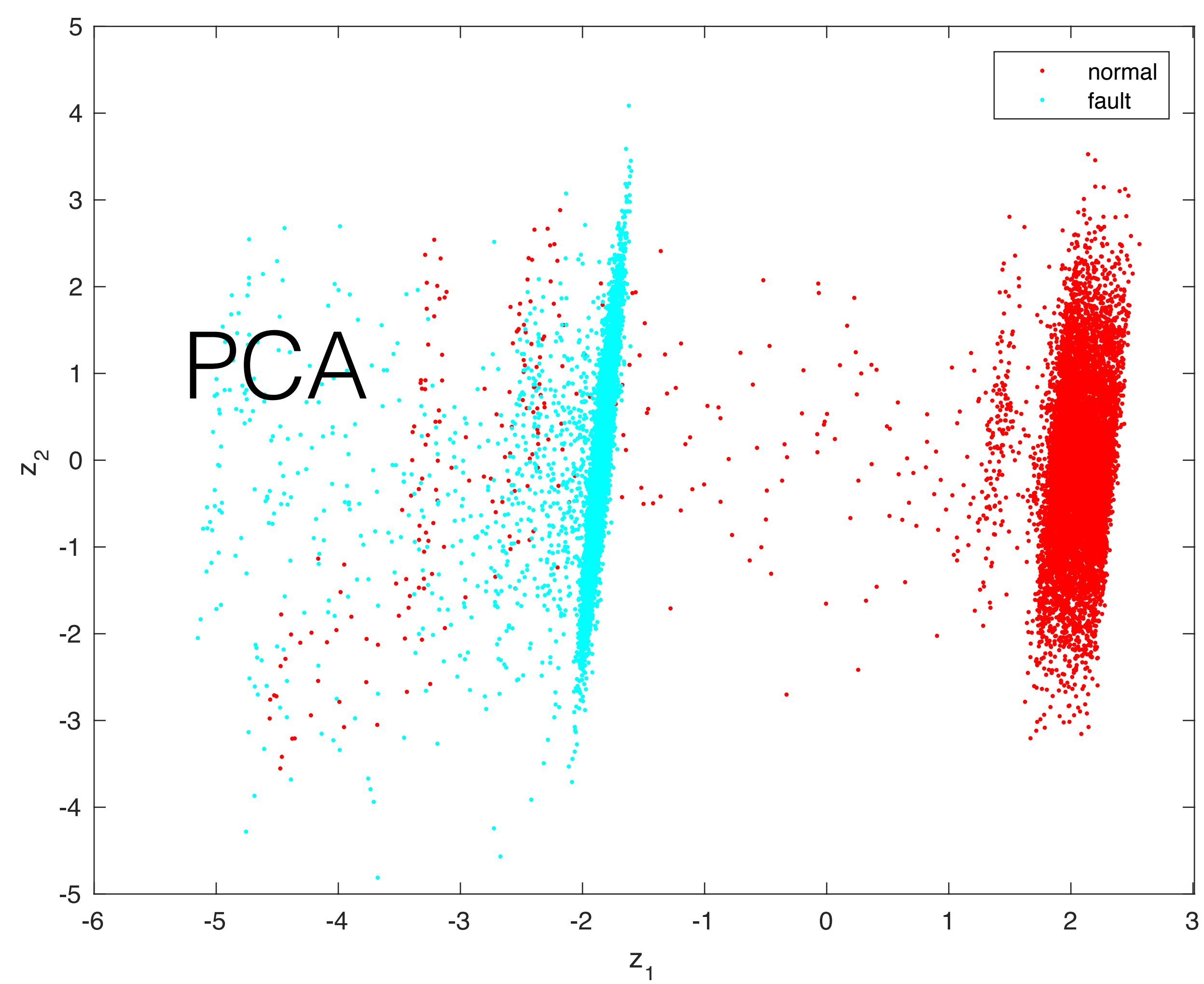
$$z_{gyro} = k_{gyro}\omega^b_{b/i} + \beta_{gyro} + \eta_{gyro}$$
$$z_{acc} = k_{acc}\omega^b_{b/i} + \beta_{acc} + \eta_{acc}$$

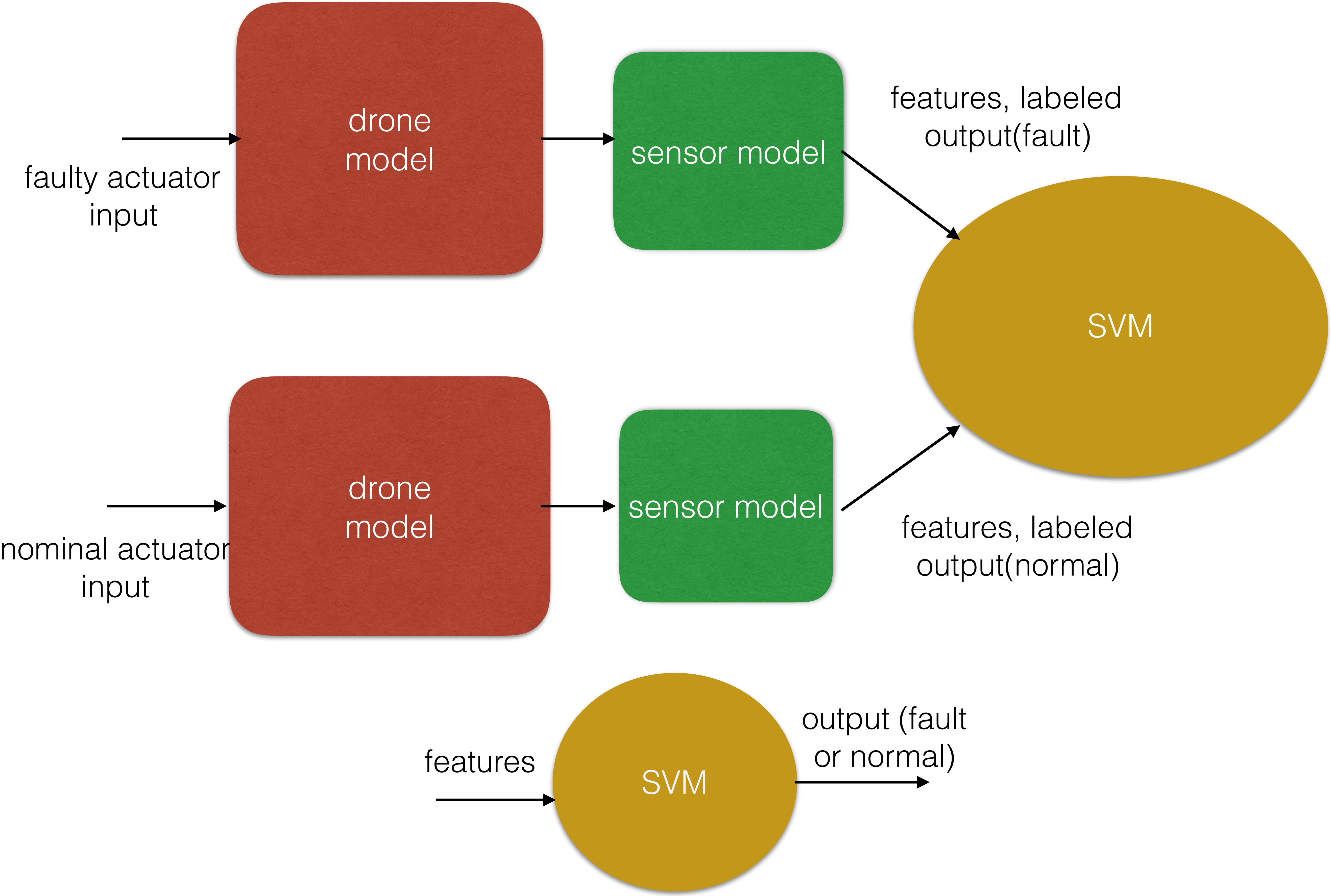
Measurement	β	σ
z_{accx}	0.142	0.0319
z_{accy}	-0.3	0.0985
z_{accz}	0.19	0.049
z_{gyro_x}	-1.55	0.0825
z_{gyro_y}	-1.13	0.1673
z_{gyro_z}	-1.7	0.2214

Fault addition

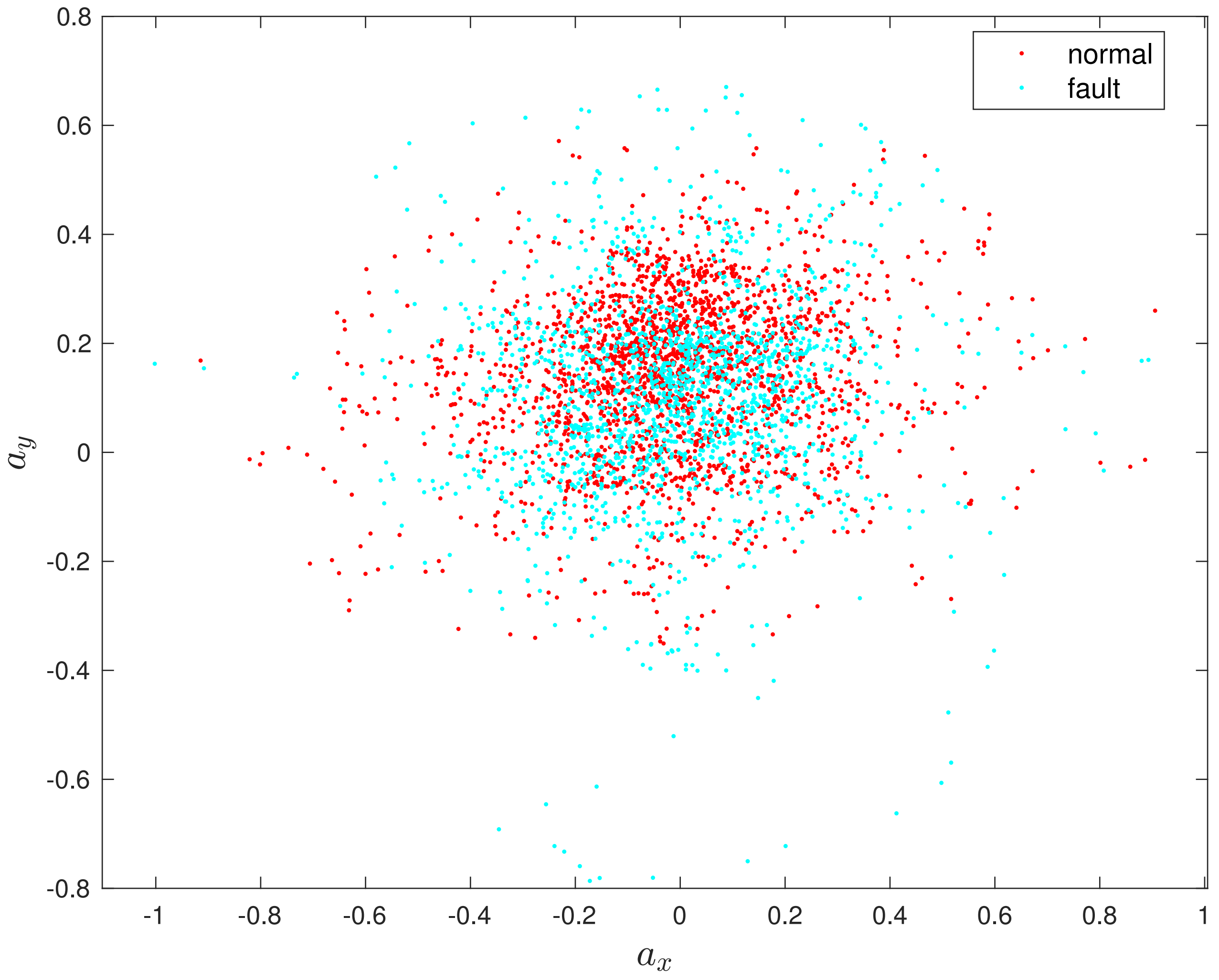
$$u(t) = Eu_c + u_f$$





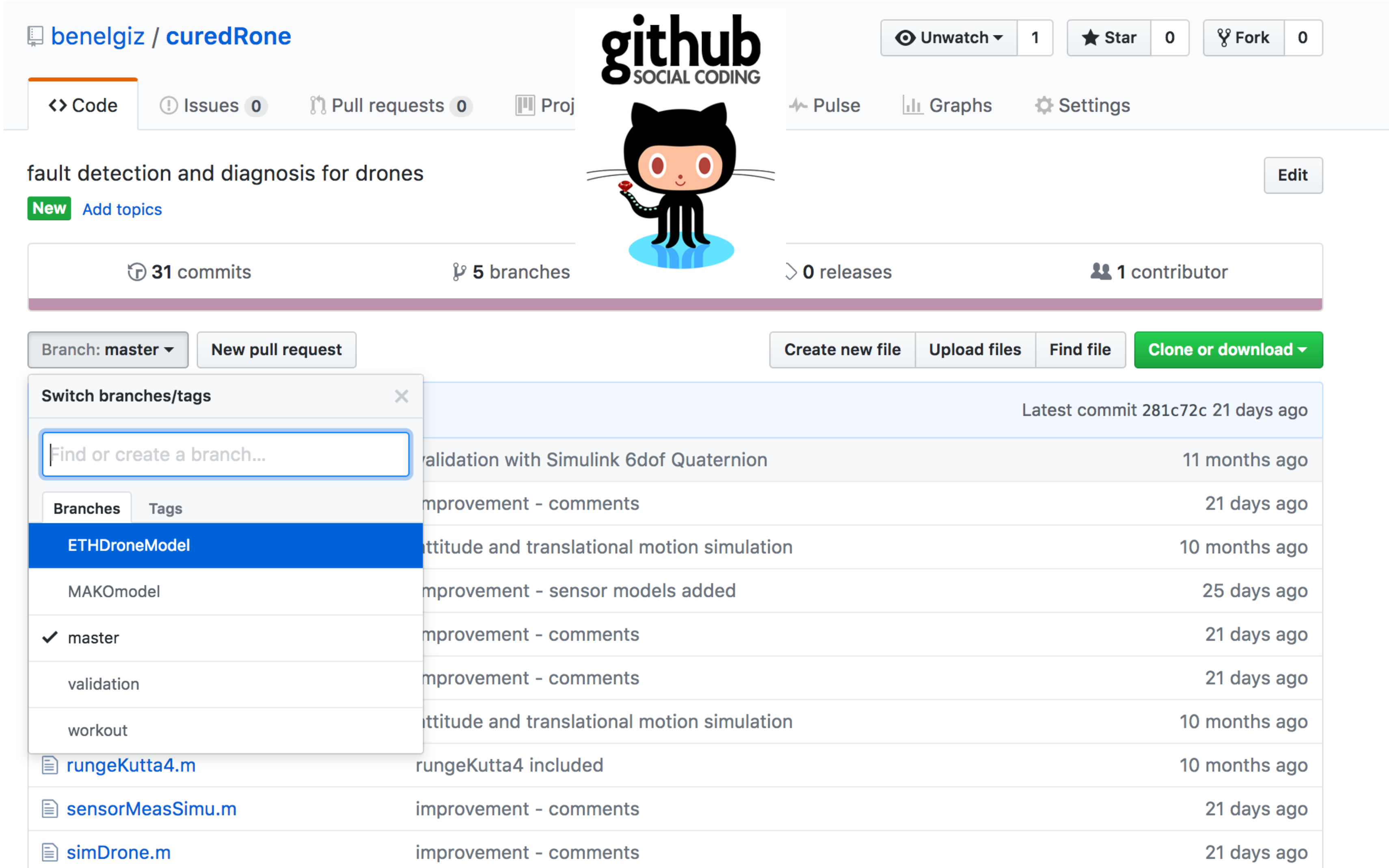

drone model
sensor model
features, labeled output(fault)
faulty actuator input
SVM
drone model
sensor model
nominal actuator input
features, labeled output(normal)
features
SVM
output (fault or normal)

next …



normal
fault
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
a_y
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
a_x

Branches

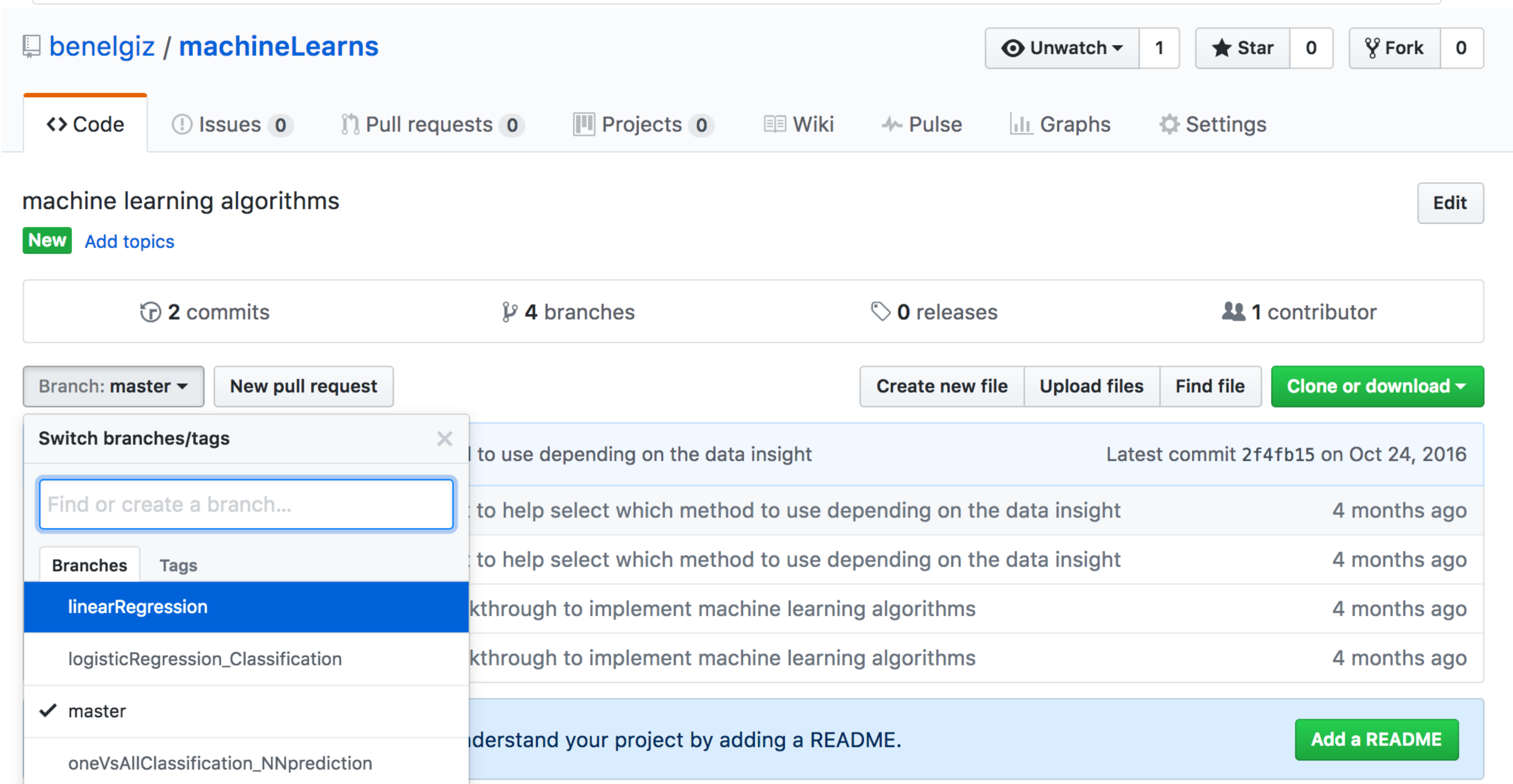


Simulation of a larger drone(drone from ETH Zurich) — ETHDrone Model

Simulation of MAKo — MAKomodel

SVM(Support vector machines) for FD — master

validate simulator with MATLAB/Simulink 6DOF — validation



Regression — linearRegression

1 class Classification — logisticRegression_Classification

Machine learning Walkthrough — master

Prediction with Neural Networks — oneVsAllClassification_NNprediction