Simplified Testing Methods for Hybrid Powertrains

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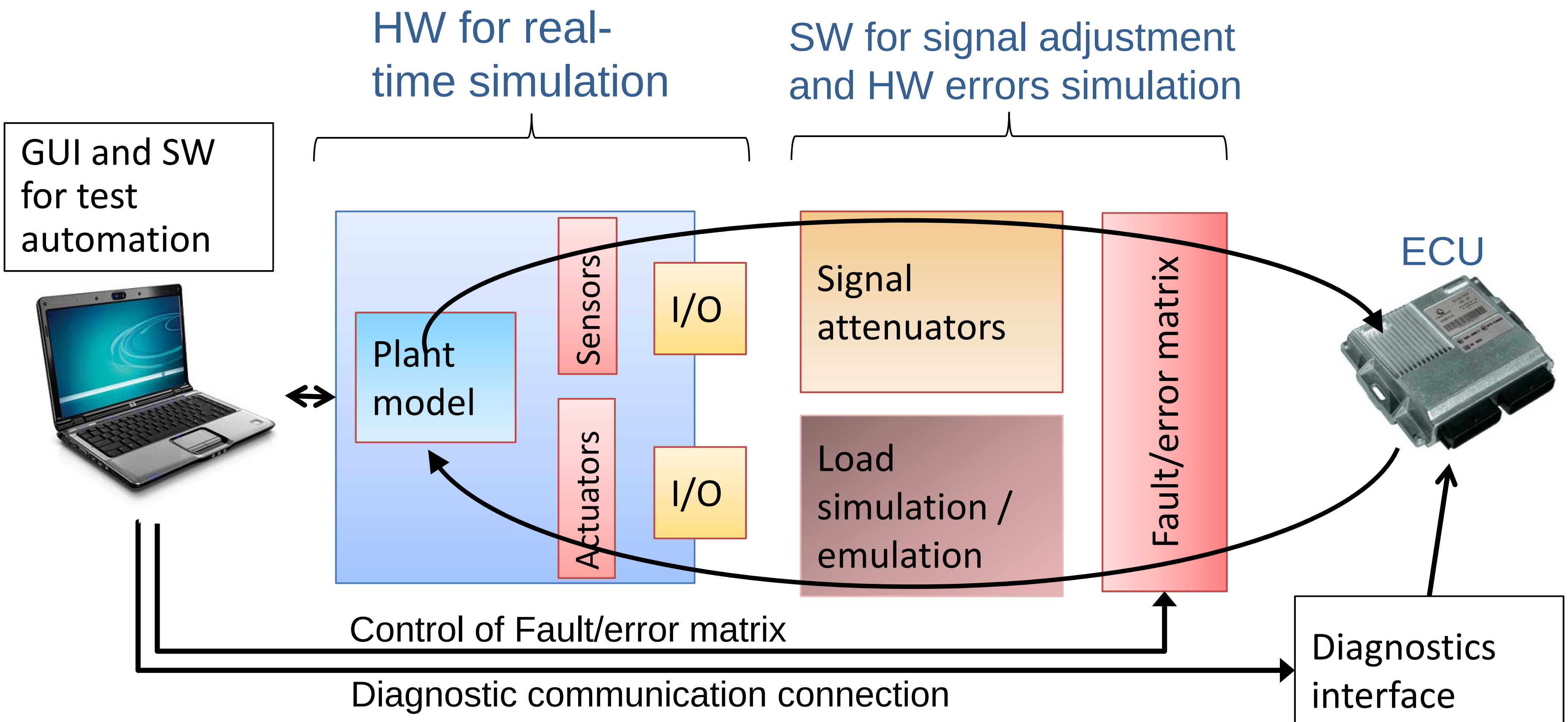
How can the method be simplified?

- By using standard (well-known) tools
  - Usually already qualified!
- By reducing the need for safety functions
- By the automatization of processes
  - Repeating the same test for several times
  - Changing only some inputs into tested HW/SW
- By performing tests on ground

How can the cost of testing be reduced?

- By reusing existing HW/SW
  - Tools need to be qualified!
- By replacing full devices with active loads
  - Using HiL systems
  - Applying emulation approaches
  - Separating unit from the vehicle and testing is possible, all other systems are emulated
- By performing tests on ground

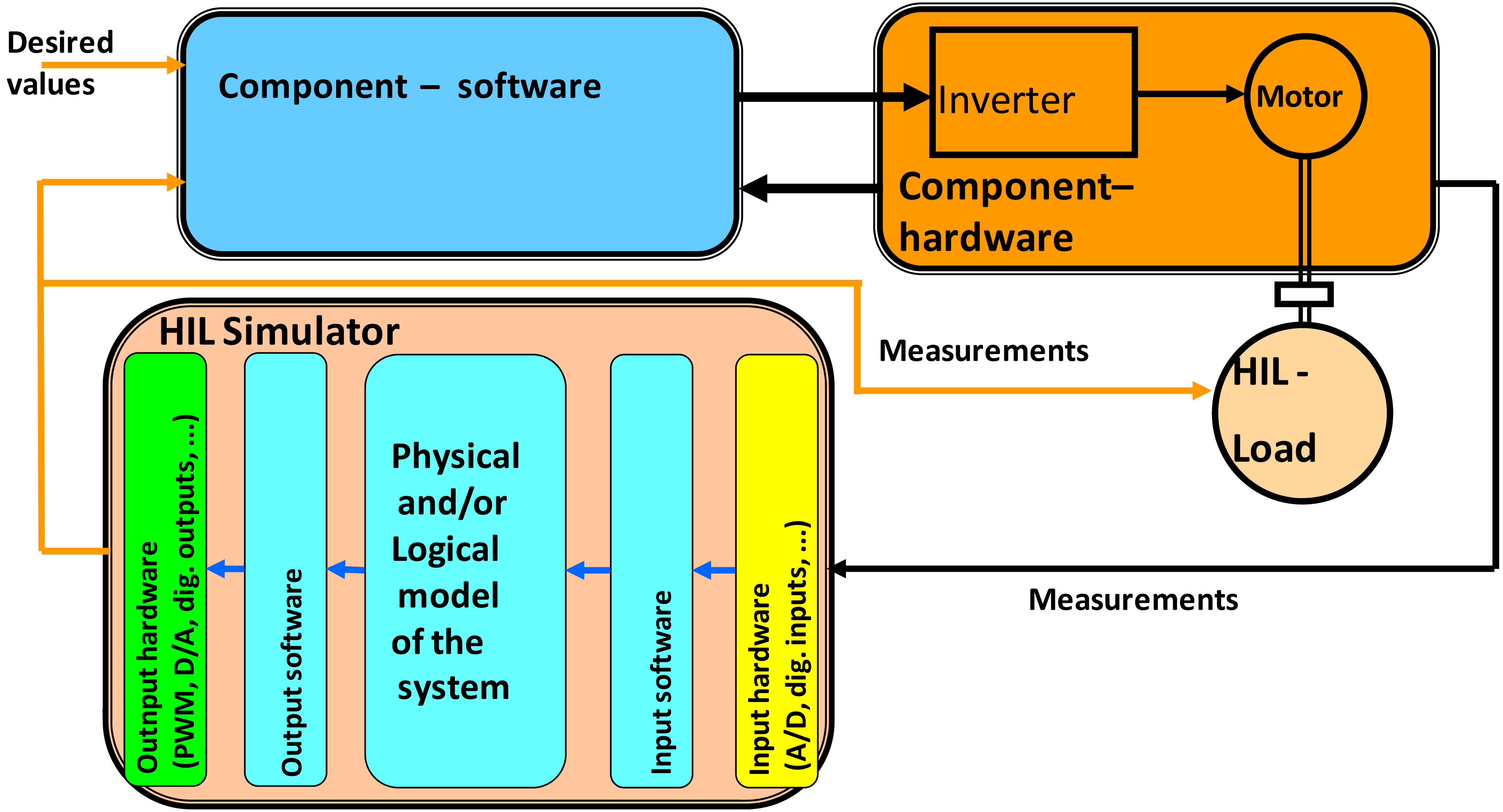
HiL (Hardware-in-the-Loop) system



Emulation of loads

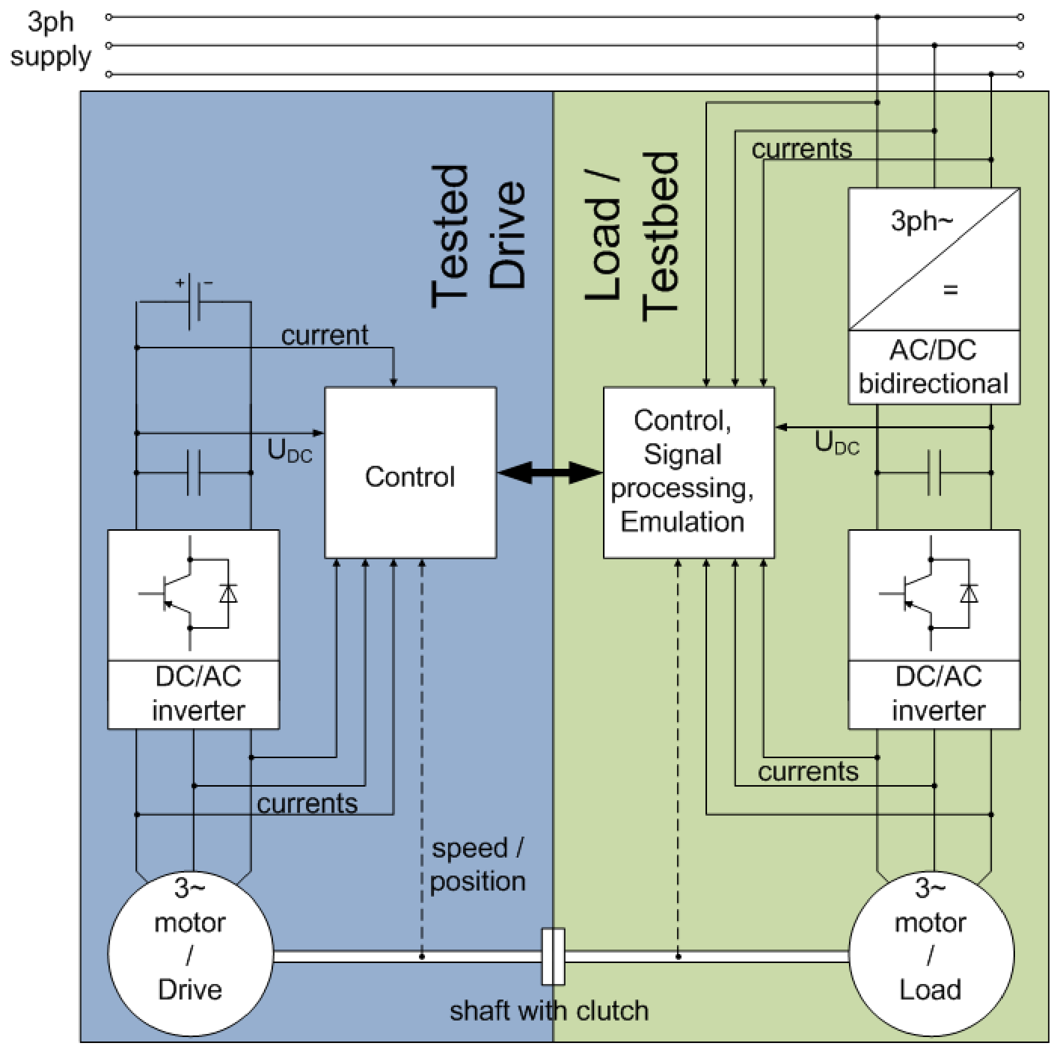
- Types of loads (also sources):
  - Mechanical loads
  - Electrical loads
  - Mixed loads
- Approaches:
  - Static emulation
  - Dynamic emulation
- Requirements-based testing
  - Black box!

HIL system in load emulation

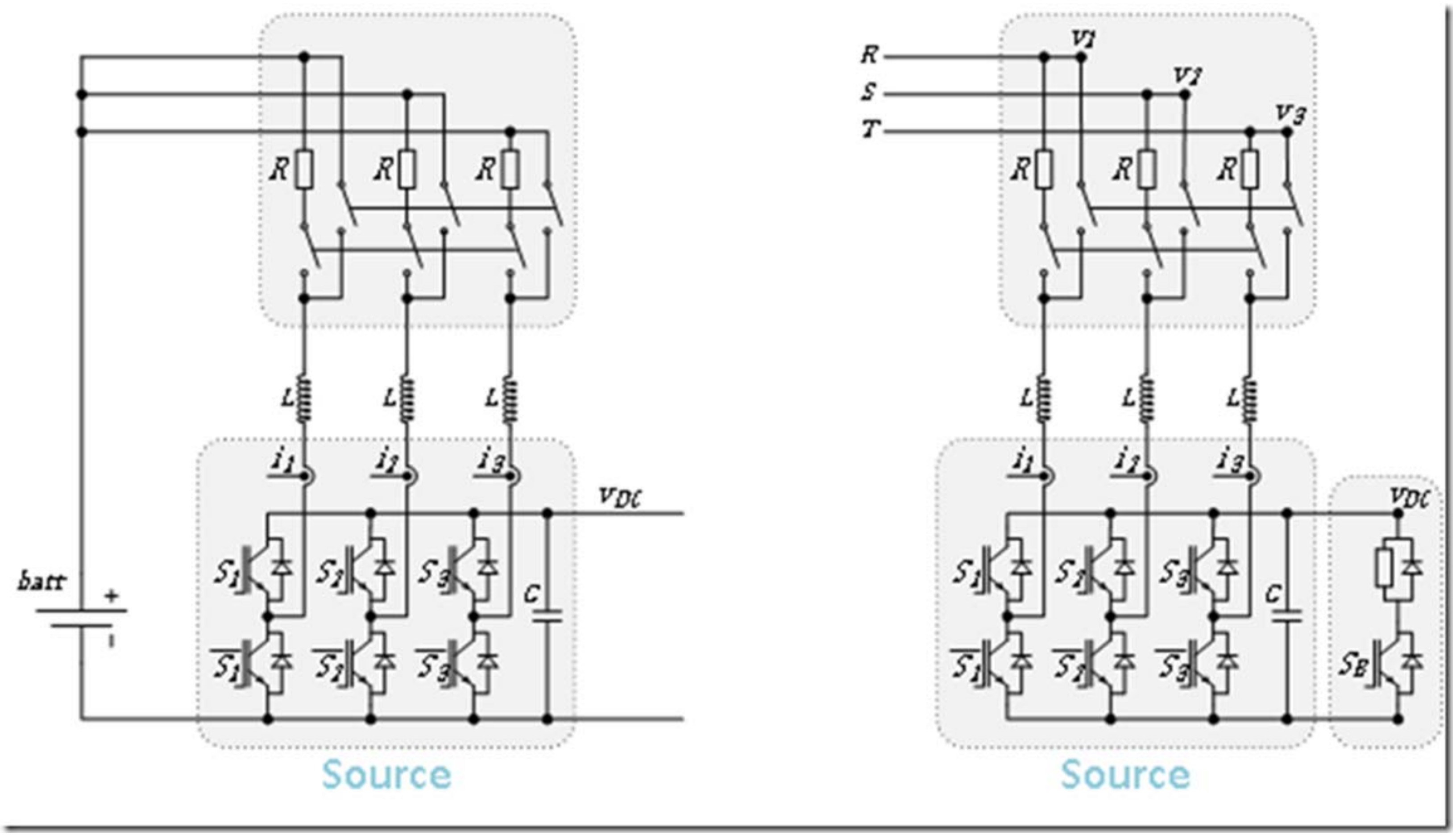


Setup – electrical – drives & batteries

- Two motors
  - Drive
  - Load / Testbed
- Load is connected to 3ph supply
  - Grid used instead of power dissipation
- Drive is powered by battery

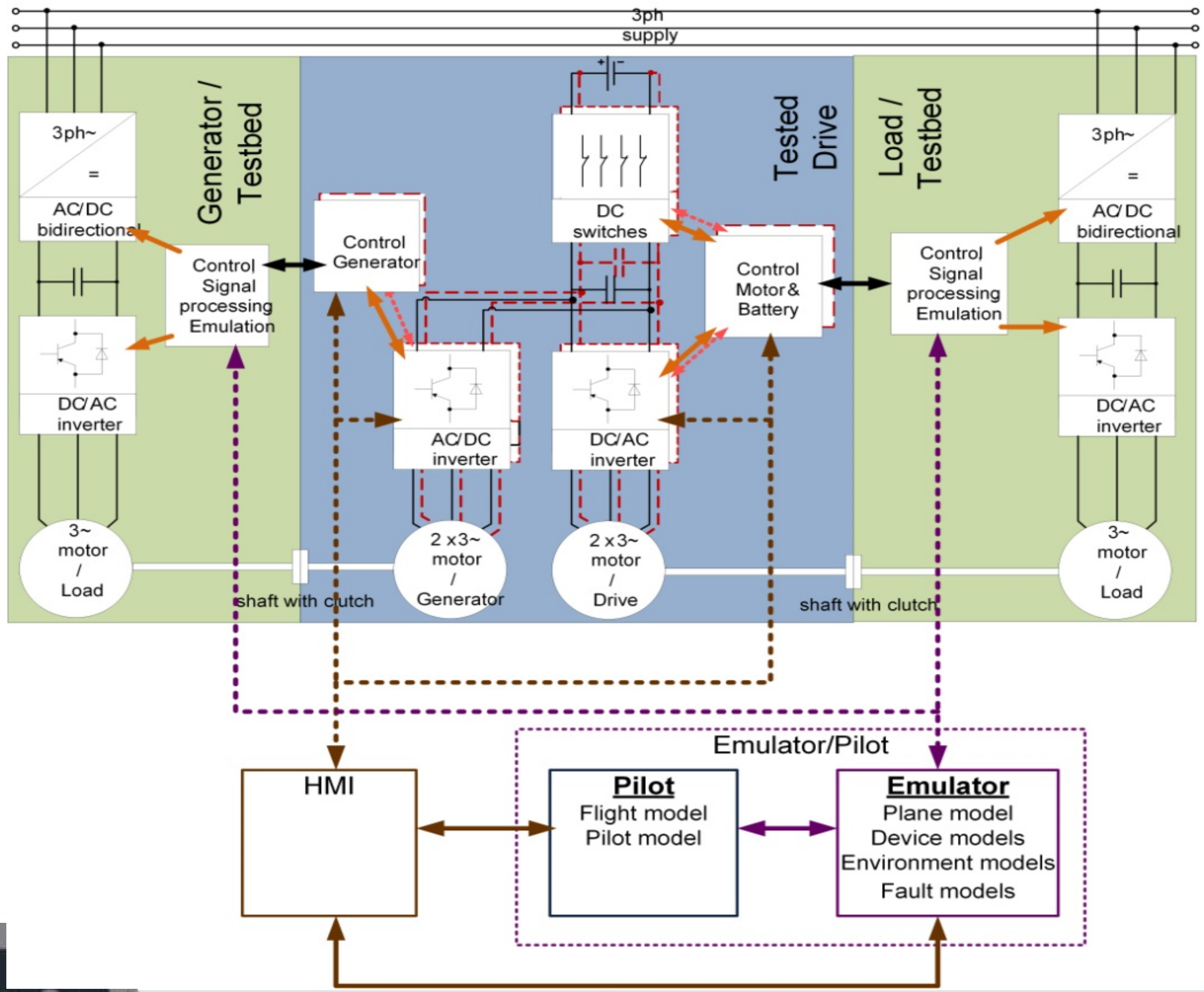


Setup – electrical – testing of batteries



Battery can be connected to same circuit as 3ph PFC!

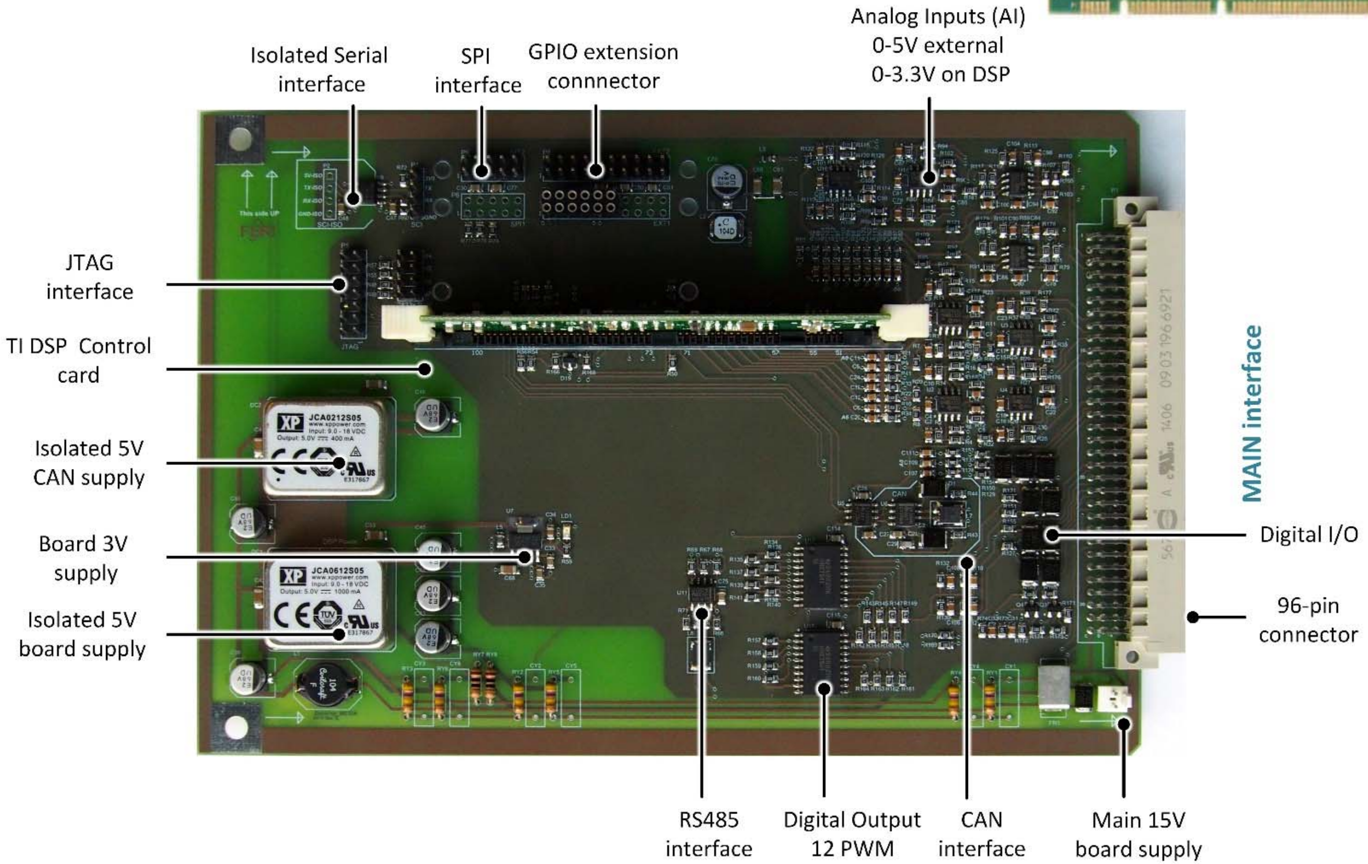
Setup – drivetrain (drive & generator & batteries, no ICE)



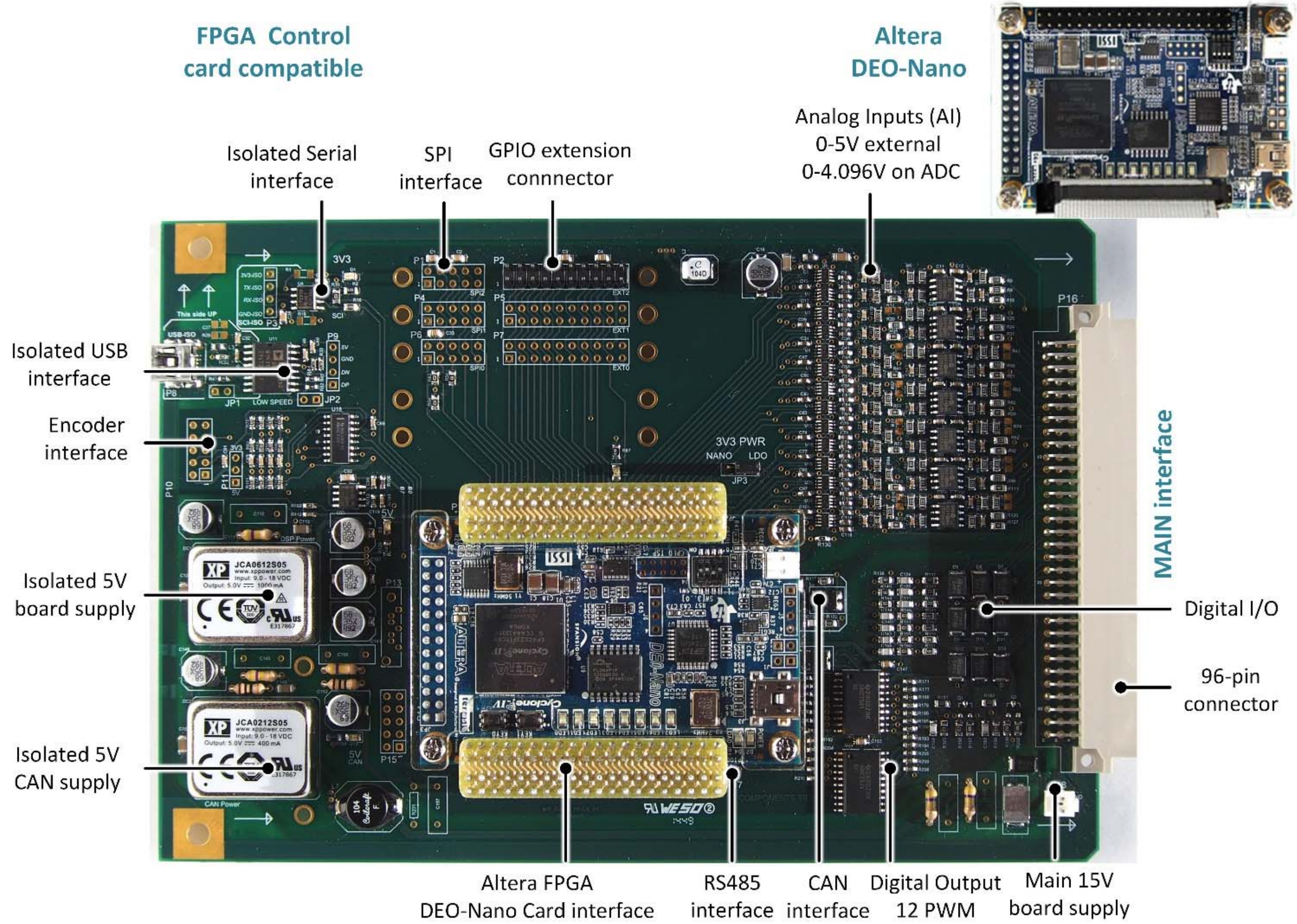
Microcontroller card

TI DSP Control card compatible

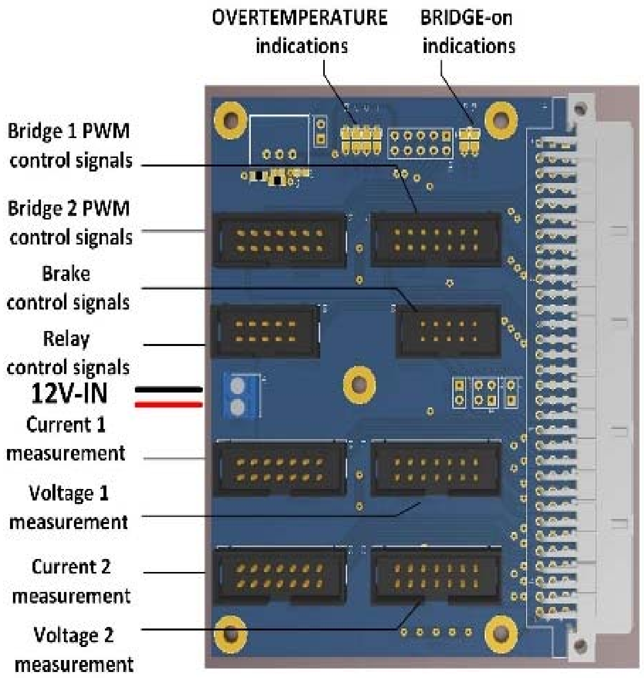
F2808, F28044, F28335 (Delfino), F2803x (Piccolo), F2806x (Piccolo), F28M35xx (Concerto)

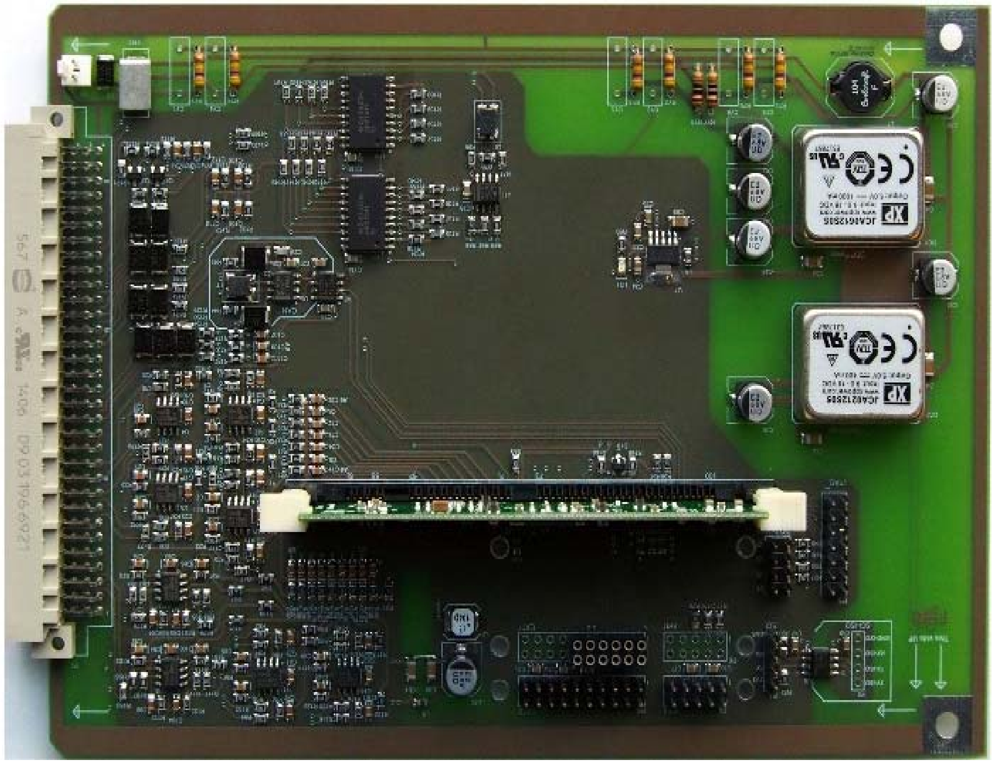


FPGA card

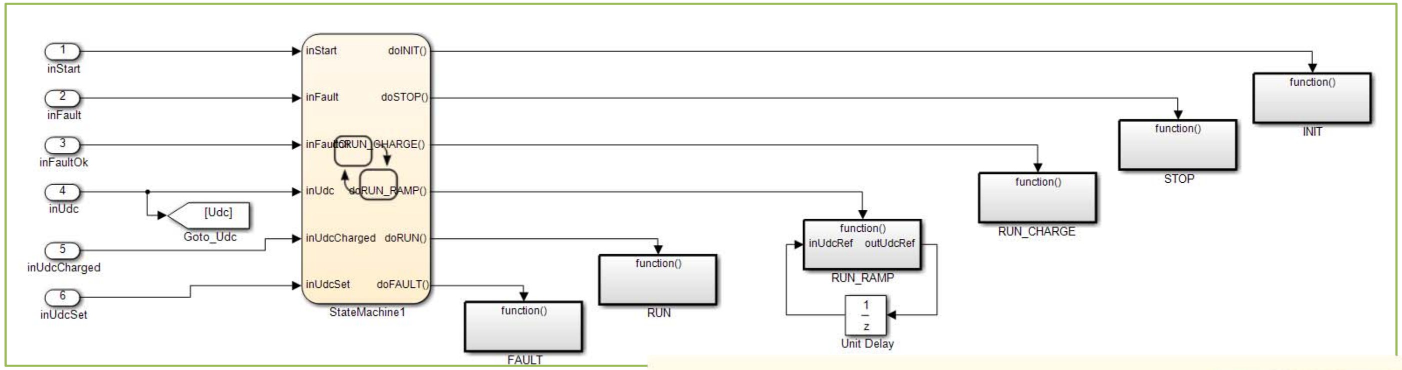

FPGA Control
card compatible
Altera
DEO-Nano
Isolated Serial
interface
SPI
interface
GPIO extension
connnector
Analog Inputs (AI)
0-5V external
0-4.096V on ADC
Isolated USB
interface
Encoder
interface
Isolated 5V
board supply
Isolated 5V
CAN supply
MAIN interface
Digital I/O
96-pin
connector
Altera FPGA
DEO-Nano Card interface
RS485
interface
CAN
interface
Digital Output
12 PWM
Main 15V
board supply

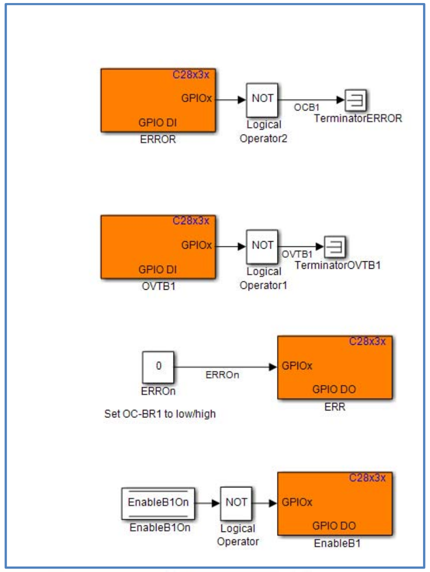
Board & module

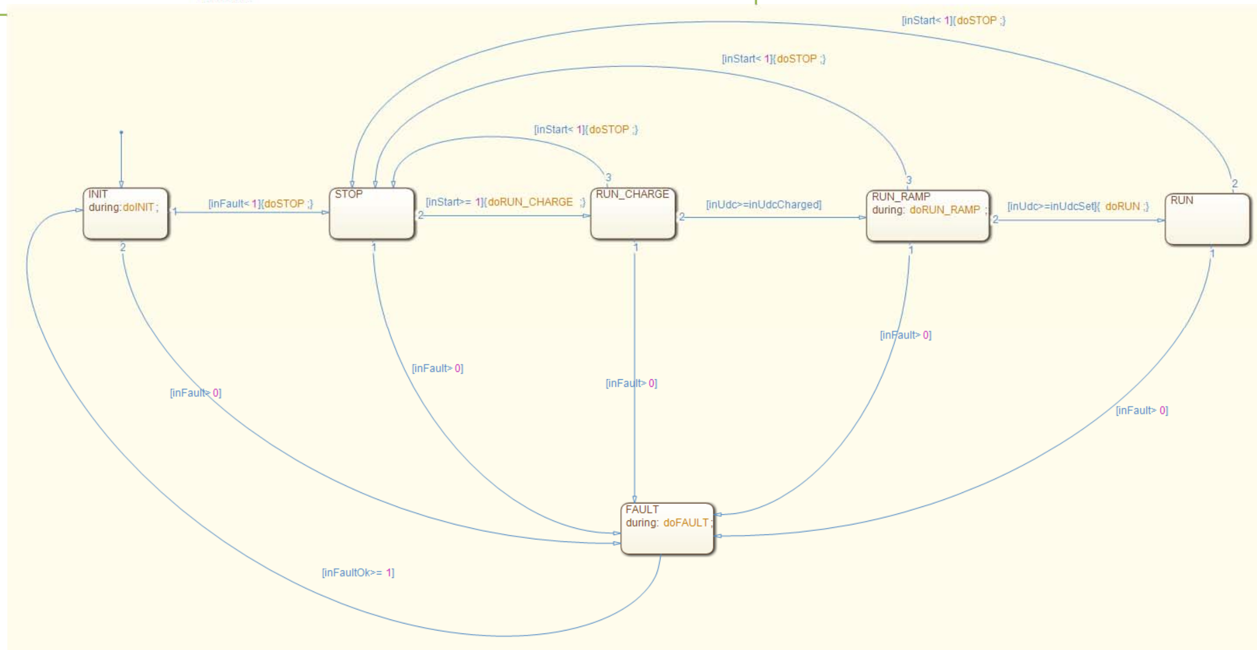




Use of states, I/O







Static emulation of mechanical loads

- Classical approach for the measurement of electric motors characteristics
- Control systems can be tested
- Testing is possible with constant or stationary loads
- “Open-loop” emulation

Static emulation – some loads

- Basic principle:

$$T_e - T_L = J_m \frac{d\omega}{dt} + B_m \omega$$

- Various load types:
  - Linear friction: $T_L = B_v \omega$
  - Static friction: $T_L = B_{st}\,\mathrm{sign}(\omega)$
  - Air resistance: $T_L = B_{air}\omega^2$

Static emulation - disadvantage

- The method is only practical for the testing of stationary operation.
- It fails in cases of:
  - – Nonlinear systems
  - – Systems with changing inertia

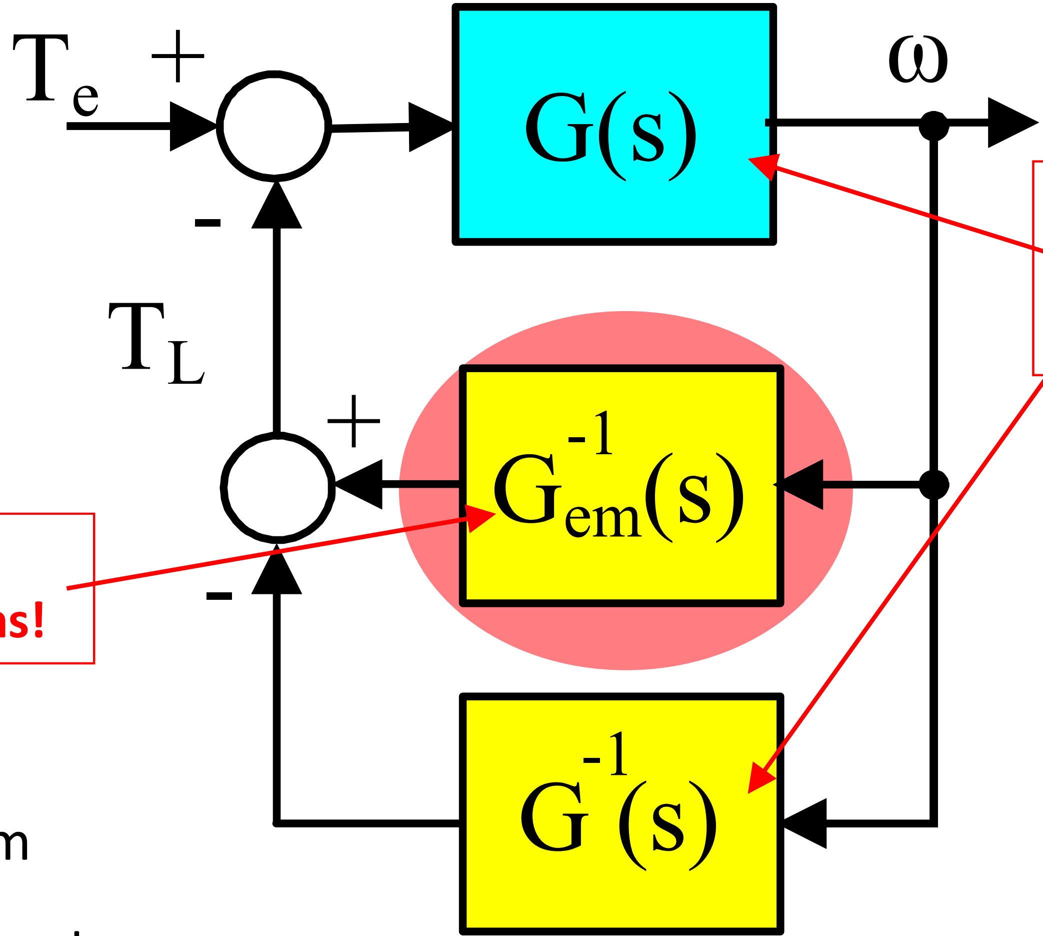
$$T_L = (J_{em} - J_m)\frac{d\omega}{dt} + (B_{em} - B_m)\omega$$

Numerical derivation would be required!

Dynamic emulation of mechanical loads

- Same hardware as for static emulation can be used.
- Only software needs to be upgraded.
- Control systems can be tested under dynamic conditions
- “Closed-loop” emulation

Dynamic emulation … - basic principle



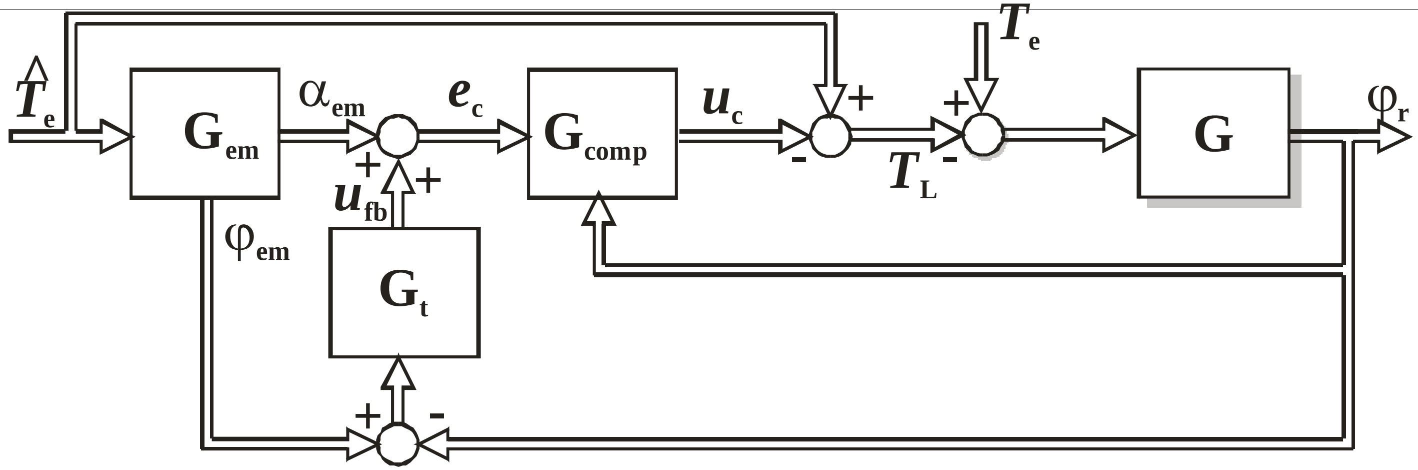
Usually
not known well enough,
G^{-1} is not precise

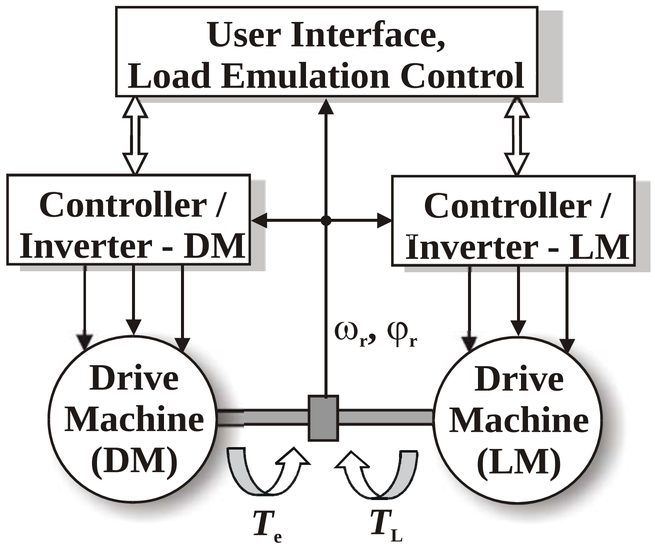
Hard to get for
Non-linear systems!

G(s) – actual system

$G_{em}(s)$ – emulated system

Dynamic emulation … – applied principle





$G(s)$ – actual system

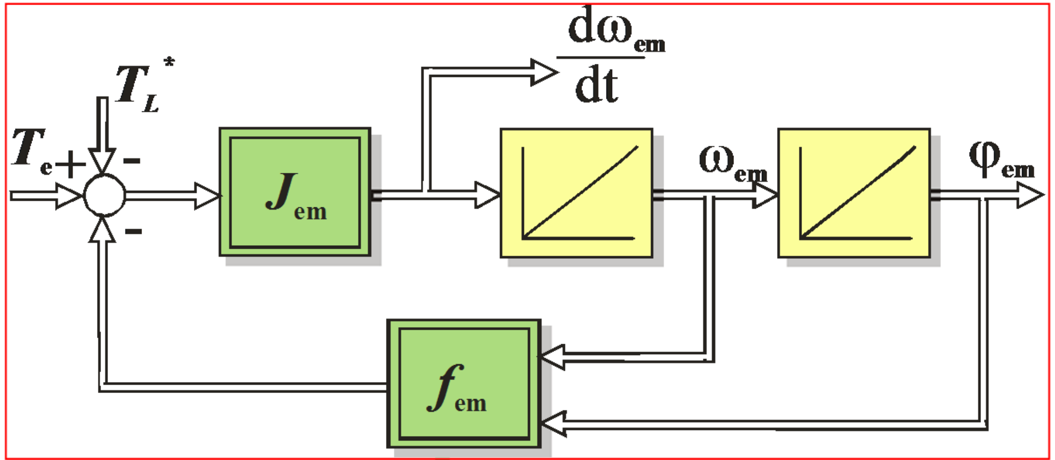
$G_{em}(s)$ – emulated system

$G_t(s)$ – torque controller

G_c (s) – compensation algorithm

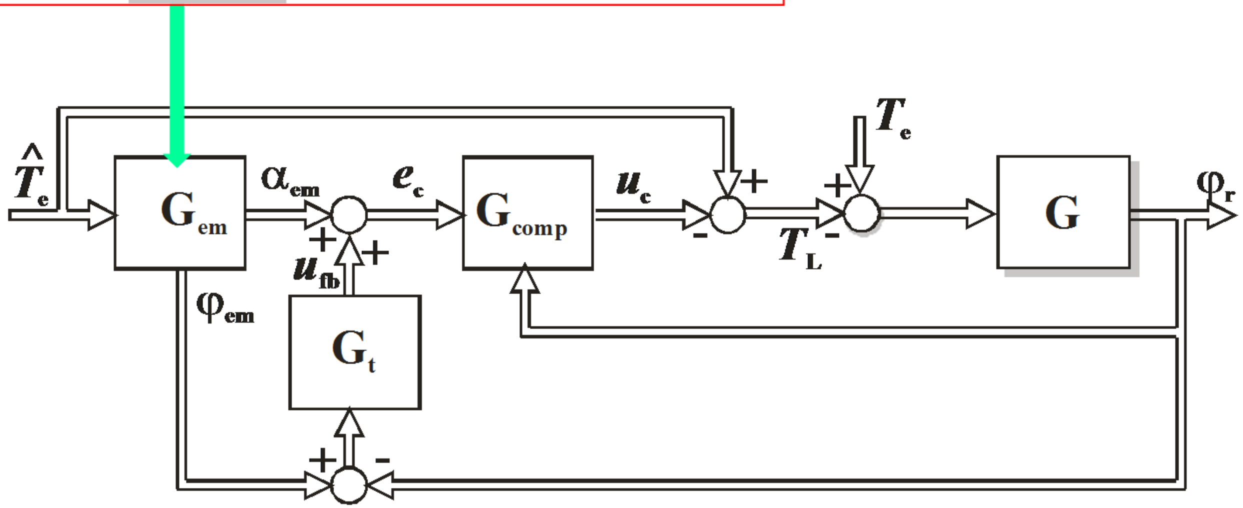
Additional feedback control is used ($G_t(s)$)

Dynamic emulation … – applied principle – emulated load



$$G_{em}(s)=\frac{\varphi_{em}(s)}{\hat{T}_e(s)}:$$

$$=\begin{cases}\dfrac{d\omega_{em}}{dt}=\alpha_{em}=J_{em}^{-1}(\omega_{em},\varphi_{em})\left[T_e-T_L^{*}-f_{em}(\omega_{em},\varphi_{em})\right]\\[2mm] \dfrac{d\varphi_{em}}{dt}=\omega_{em}\end{cases}$$



Dynamic emulation … – some loads

- Linear load emulation

$$J_{em}\frac{d\omega_{em}}{dt}+B_{em}\omega_{em}=T_e-T_L^*$$

$$\frac{d\varphi_{em}}{dt}=\omega_{em}$$

- Nonlinear load emulation

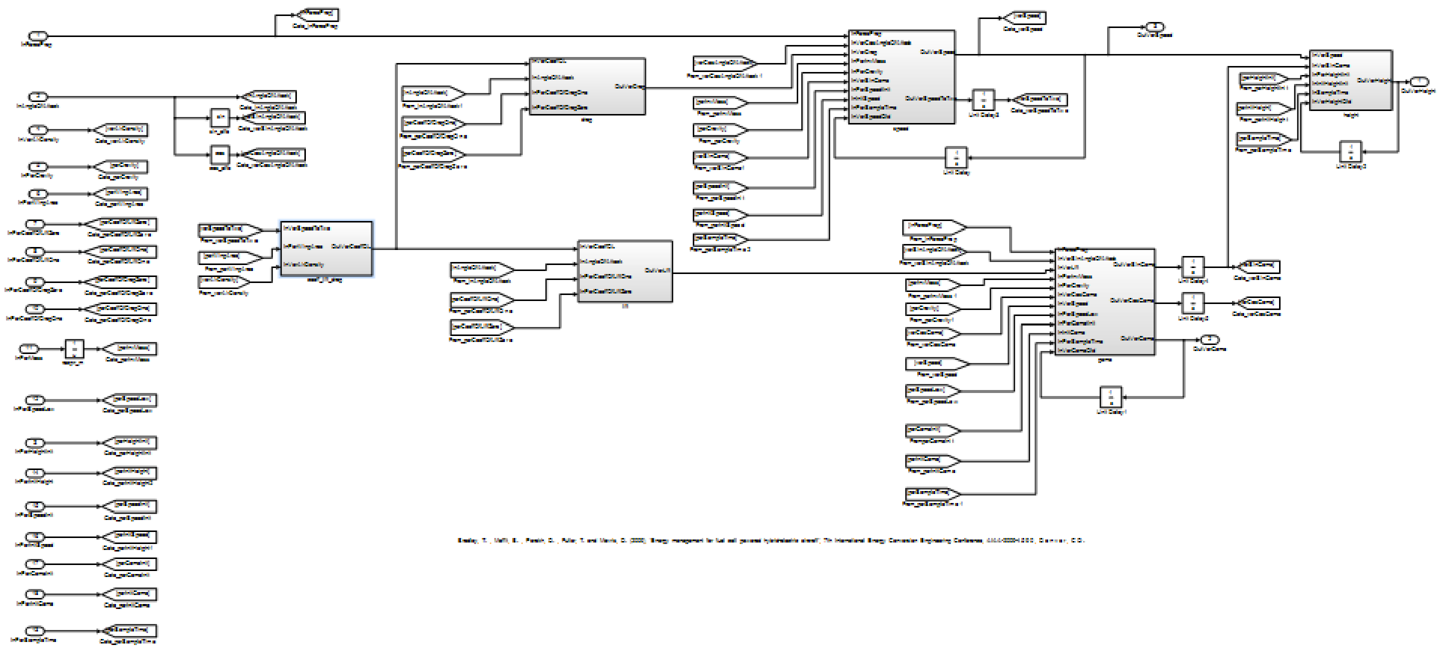
$$J_{em}\frac{d\omega_{em}}{dt}+B_{em}\omega_{em}+mgl\sin\left(R\varphi_{em}\right)=T_e-T_L^*,$$

$$\frac{d\varphi_{em}}{dt}=\omega_{em}$$

- Electric vehicle emulation

$$\frac{d\omega_{em}}{dt}=\frac{T_e-RT_b-Rr\left(C_aR^2r^2\omega_{em}^2+B\omega_{em}+mg\sin\alpha\right)}{J_e+R^2(J_w+mr^2)}$$

Airplane model



Aircraft altitude:

$$\frac{dh}{dt} = v \sin(\gamma)$$

Airspeed:

$$\frac{dv}{dt} = \frac{F_{prop} \cos(\alpha) - D}{m} - g \sin(\gamma)$$

Aircraft flight path angle:

$$\frac{d\gamma}{dt} = \frac{F_{prop} \sin(\alpha) + L}{mv} - \frac{g}{v} \cos(\gamma)$$

Lift and drag:

$$L = \frac{1}{2} \rho_a v^2 S_w \left(C_{L,\alpha} \alpha + C_{L,0} \right)$$

$$D = \frac{1}{2} \rho_a v^2 S_w \left(C_{\mathrm{D},\alpha} \alpha + C_{\mathrm{D},0} \right)$$

The drag force (thrust) and propeller torque:

$$F_{prop} = \rho_a \left(\frac{\omega}{2\pi} \right)^2 C_{\mathrm{T}} d^4$$

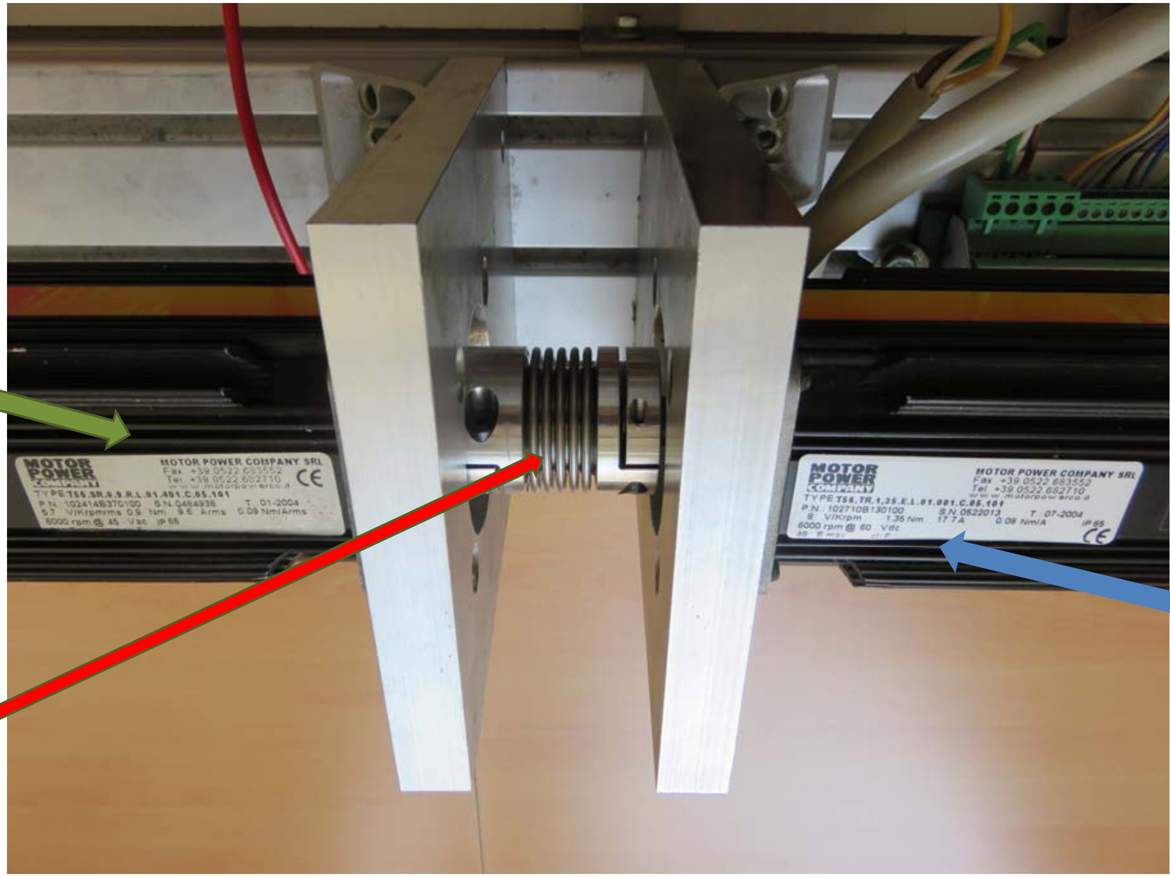
$$T_{prop} = \rho_a \left(\frac{\omega}{2\pi} \right)^2 C_{\mathrm{T}} d^5 .$$

Electric motor mechanism dynamics:

$$J_{drive} \frac{d\omega}{dt} = T_{drive} - T_{friction} - T_{prop}$$

HIL system – drive and load

drive



load

clutch

Not always practical for high powers (and in planes – propeller!)

Producing load torque with propeller

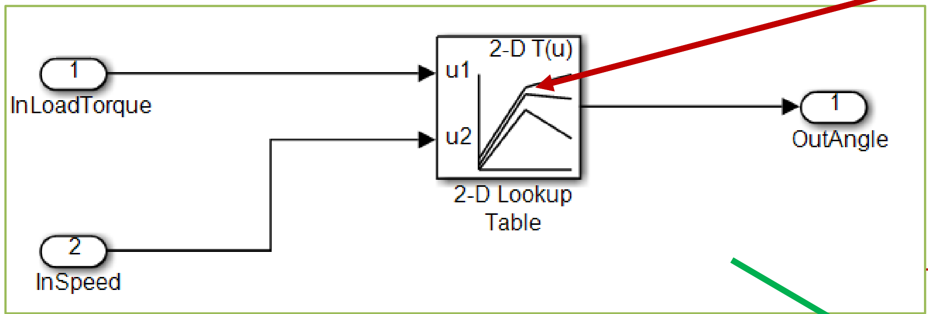
Propeller torque:

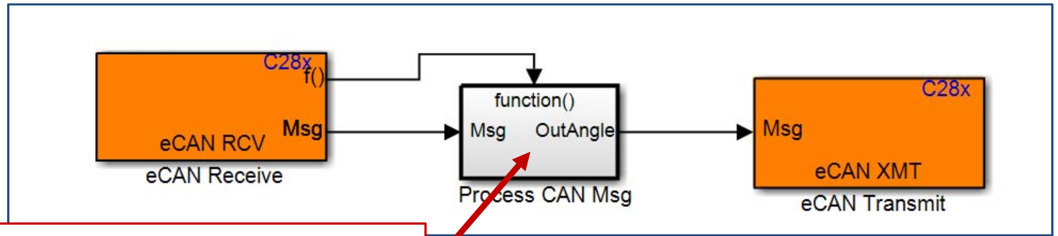
$$T_{prop} = \left(C_L \cos(\beta-\alpha) - C_D \sin(\beta-\alpha)\right)\frac{1}{2}\rho_a A_{prop} r \left(\frac{r\omega}{\cos(\beta-\alpha)}\right)^2$$

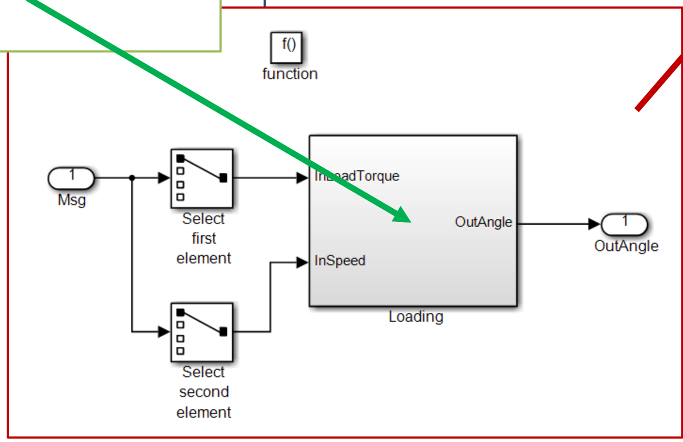
Can be rewritten as:

$$T_{prop} = f\left((\beta-\alpha),\omega\right)$$

Inverse function not that simple – Lookup-table (LUT) should be used



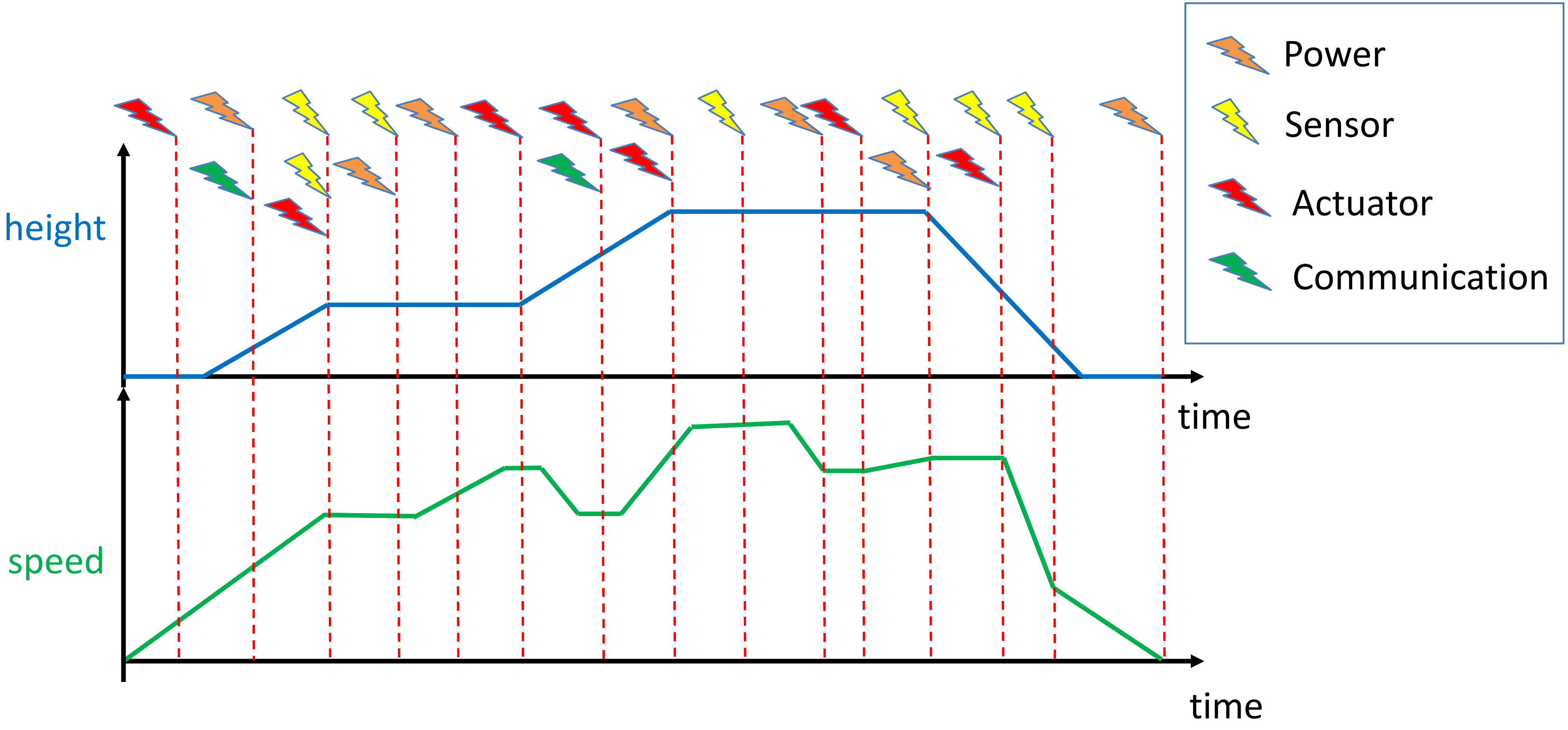




Better (also more cost effective) idea Equivalence to be demonstrated!

To be performed using CAN

Additional tests



Testing has better chance to be successful if multiple events occur simultaneously!

Conclusion

- Cost of testing can be significantly reduced
- HiL systems are a good solution
  - High cost, but can be reused
  - Low cost solutions are possible
  - Multiple events can be generated
  - Data can be logged

Discussion