Could an autonomous car be its own workshop?

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Problem

- Robots are complex engineering systems made of many mechanical, electronic and software components.
- Engineers use *mathematics* to model, design, analyze, and perform computer simulations.
- Robots also can use these models during operation to find the cause of anomalies and faults.
- Our goal: **To design a fault detection and isolation system for an autonomous robot.**

Model elements	Number
Unknown variables	50
Known variables	21
Fault variables	25
Equations	53

Overview

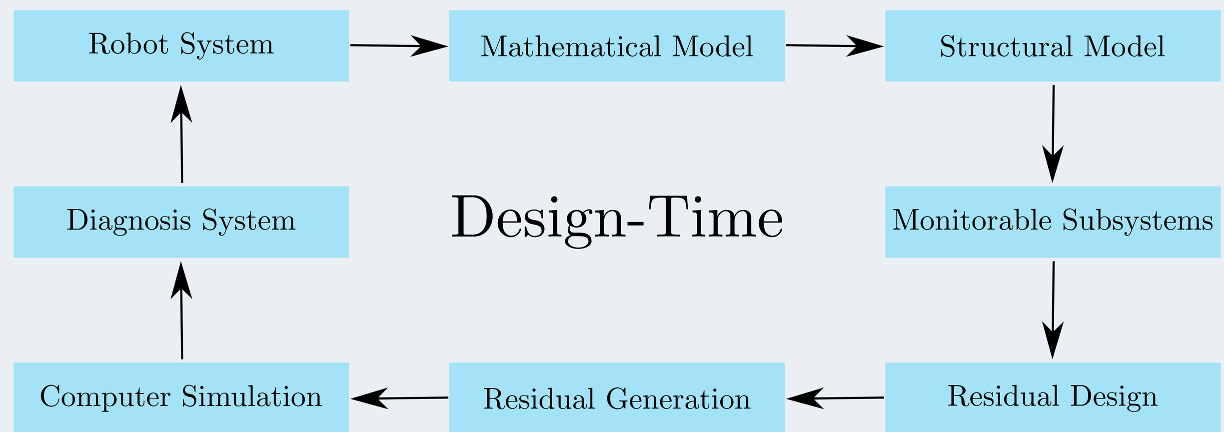


Figure: Structural Analysis [1]

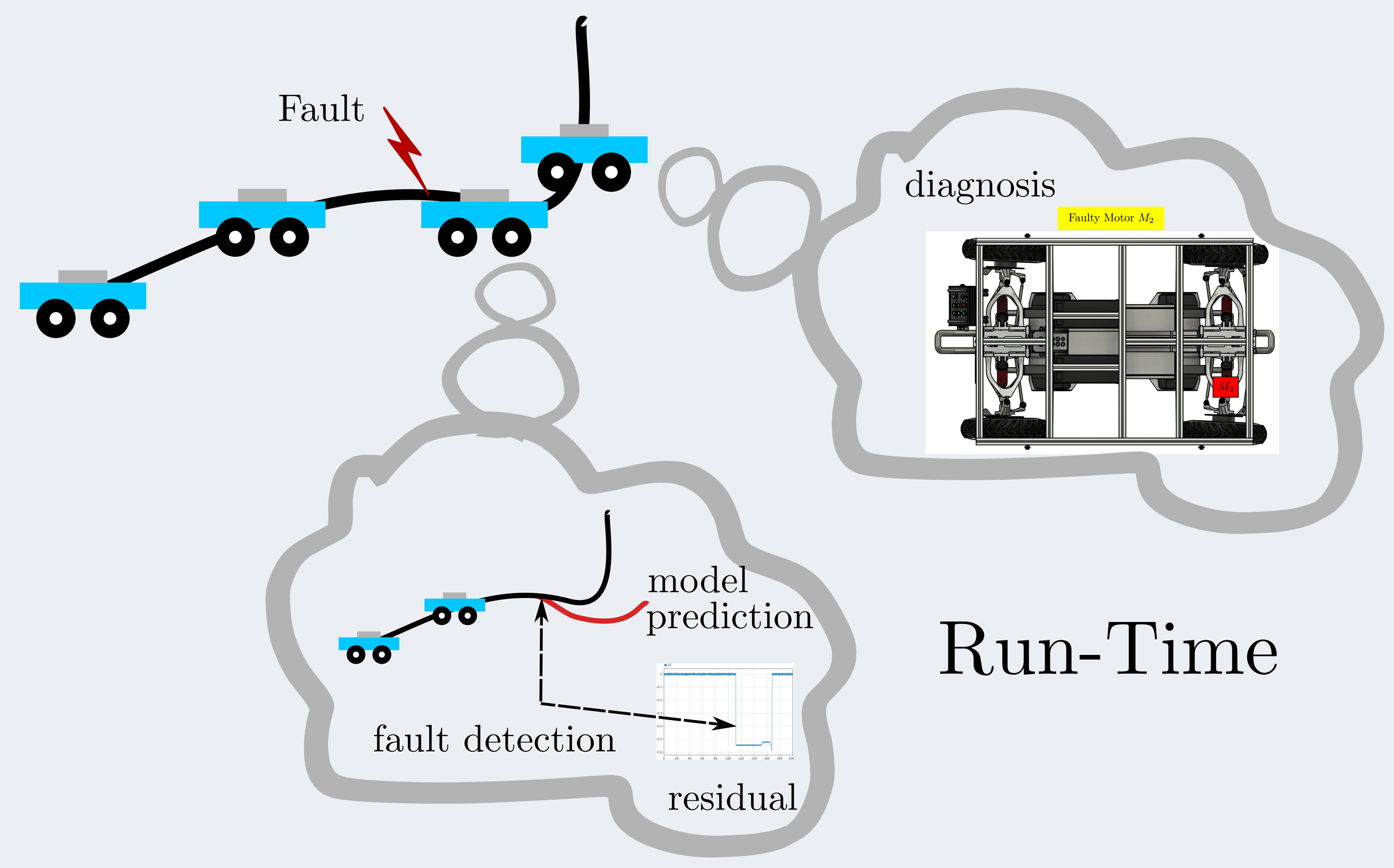


Figure: Model-Based Fault Detection and Identification based on Residuals.

Mercator Model Variables

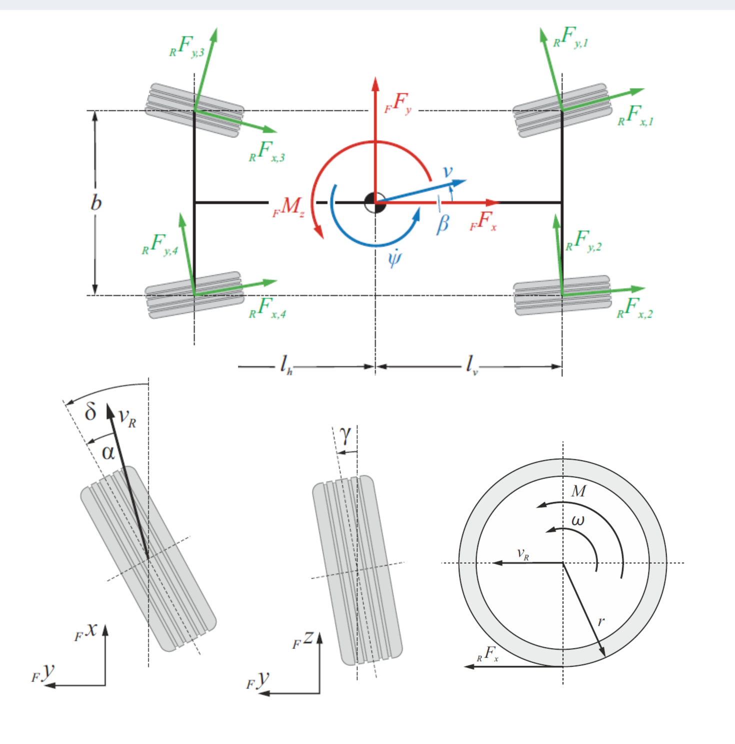


Figure: Based on Reinold's [2].

U	v	velocity	K,M	y_v	velocity
U	β	slip angle	K,M	y_β	slip angle
U	$\dot{\psi}$	yaw rate	K,M	$y_{\dot{\psi}}$	yaw rate
U	$_W F_i$	tire forces	K,M	y_a	acceleration
U,I	δ_i	steering angles	K,M	y_{δ_i}	steering angle
U	ω_i	angular velocities	K,M	y_{ω_i}	angular velocities
U	λ_i	longitudinal slip	F	$f_{r;x}$	reference quantity x
U	r_i	wheel radius	F	$f_{s;x}$	system quantity x
U,I	M_i	motor torques	F	$f_{m;x}$	measured quantity x

Table: Model variables. U: unknown, K : known, F: fault, I: input, M: measurement.

$$\dot{v} = \frac{1}{m_V} \cdot \left(\sum_{i=1}^{4} {_W F_{x,i}} \cdot cos(\delta_i - \beta) - \sum_{i=1}^{4} {_W F_{y,i}} \cdot sin(\delta_i - \beta) \right)$$
$$\dot{\beta} = \frac{1}{m_V \cdot v} \cdot \left(\sum_{i=1}^{4} {_W F_{x,i}} \cdot sin(\delta_i - \beta) + \sum_{i=1}^{4} {_W F_{y,i}} \cdot cos(\delta_i - \beta) \right) - \dot{\psi}$$

Table: Sample of some state variable equations.

Mercator Structural Analysis and design of residuals

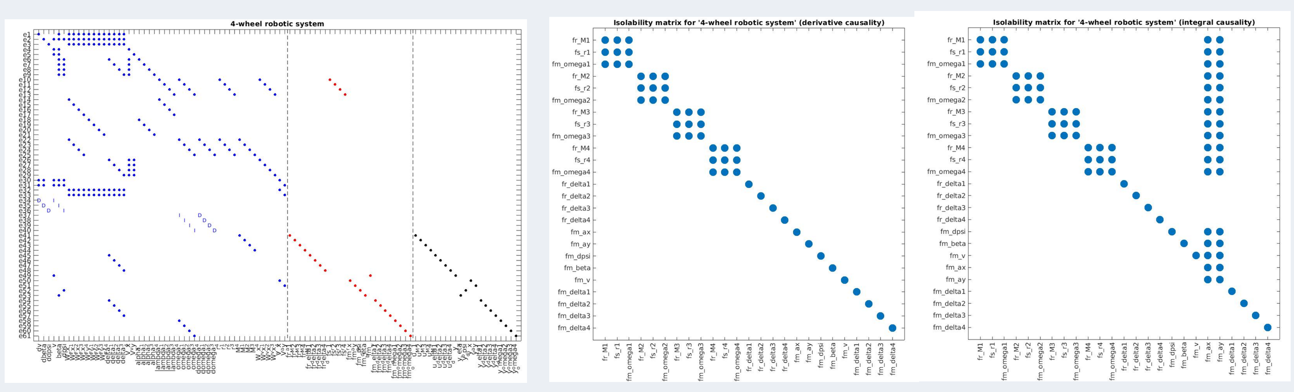
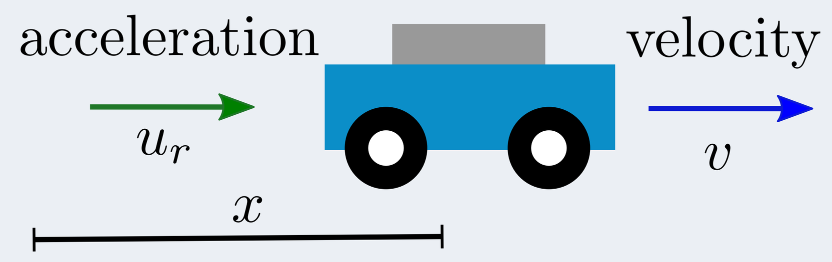


Figure: Model Structure (left). Derivative (center) and Integral (right) isolability.

A Simple Example

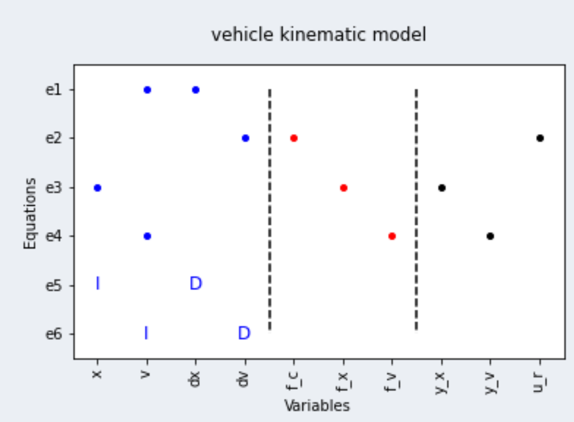


(1)

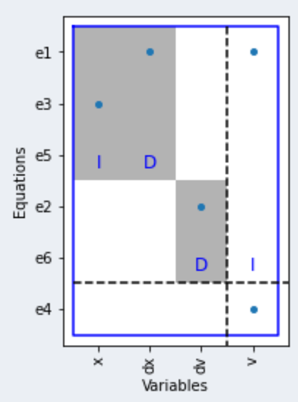
model		unknown	known	
$\dot{x} = v$	e_1	$y_x = x + f_x$		e_3
$\dot{v} = u_r + f_c$	e_2	$y_v = v + f_v$		e_4

faults

(2)



(3)



(4)

Minimally Structural Overdetermined (MSO)

$M_1 = \{e_2, e_4\}$ $M_2 = \{e_1, e_2, e_3\}$ $M_3 = \{e_1, e_3, e_4\}$

$$r_{1,1} = u_r - \dot{y}_v = u_r - \dot{v} - \dot{f}_v = -f_c - \dot{f}_v$$

derivative causality

fault sensitivity

$$r_{1,2} = y_v - \int u_r(\tau)d\tau = f_v + \int f_c(\tau)d\tau$$

integral causality

residuals

$$r_2 = y_v - \dot{y}_x = f_v - \dot{f}_x \qquad r_3 = \ddot{y}_x - u_r = \ddot{f}_x + f_c$$

	f_c	f_x	f_v
f_c	○		
f_x		○	
f_v			○

Fault isolability

	f_c	f_x	f_v
M_1	○		○
M_2		○	○
M_3	○	○	

Fault signature

Figure: Structural analysis for the kinematic model of a vehicle on a straight road.

Dependability of Autonomous Robots

- Fault detection and isolation is important for the *Dependability* of an autonomous robot.
- Model-based diagnosis in Mercator will allow it to respond intelligently to malfunction.
- Making Mercator Fault tolerant and able to reconfigure after faults is part of our future research.

Some References

[1] E. Frisk, M. Krysander, and D. Jung, "A toolbox for analysis and design of model based diagnosis systems for large scale models," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 3287–3293, 2017.

[2] P. Reinold, "Integrierte, selbstoptimierende fahrdynamikregelung mit einzelradaktorik," Ph.D. dissertation, Dissertation, Paderborn, Universität Paderborn, 2016, 2017.

At a Glance

- Problem: Diagnose faulty components in a robot.
- Idea: Use mathematical model and structural analysis.
- Results: Detection and isolation of faults is possible.