Situation Readiness and Resilience

Core competence: Sensor fusion and sensor systems

Fredrik Gustafsson

SEDIT
Sensor informatics and Decision-making for the Digital Transformation

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Sensor fusion and sensor systems

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Statistical signal processing, adaptive filtering and change detection, with applications to communication, vehicular, airborne, audio, and wildlife applications.

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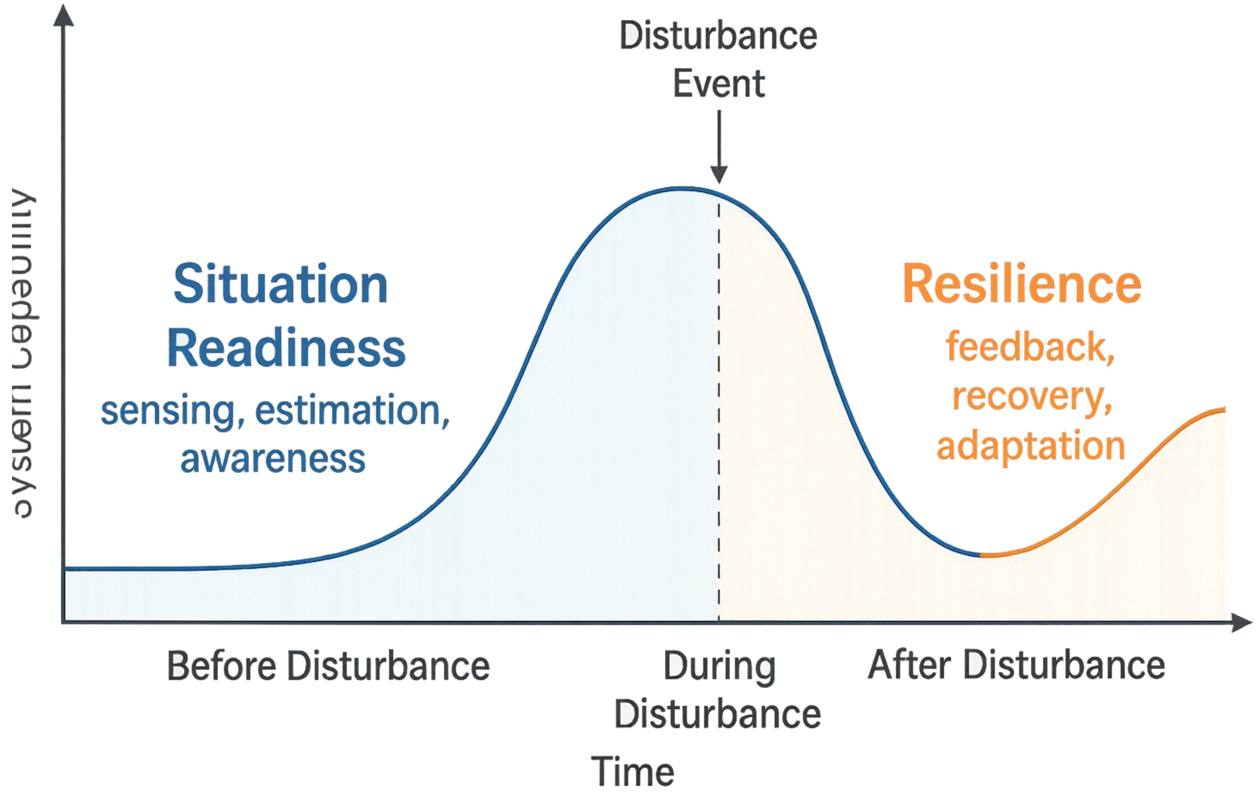
Situation Readiness and Resilience in Sensor-Driven Systems

Bridging Sensor Fusion and Automatic Control Perspectives

Concept Overview

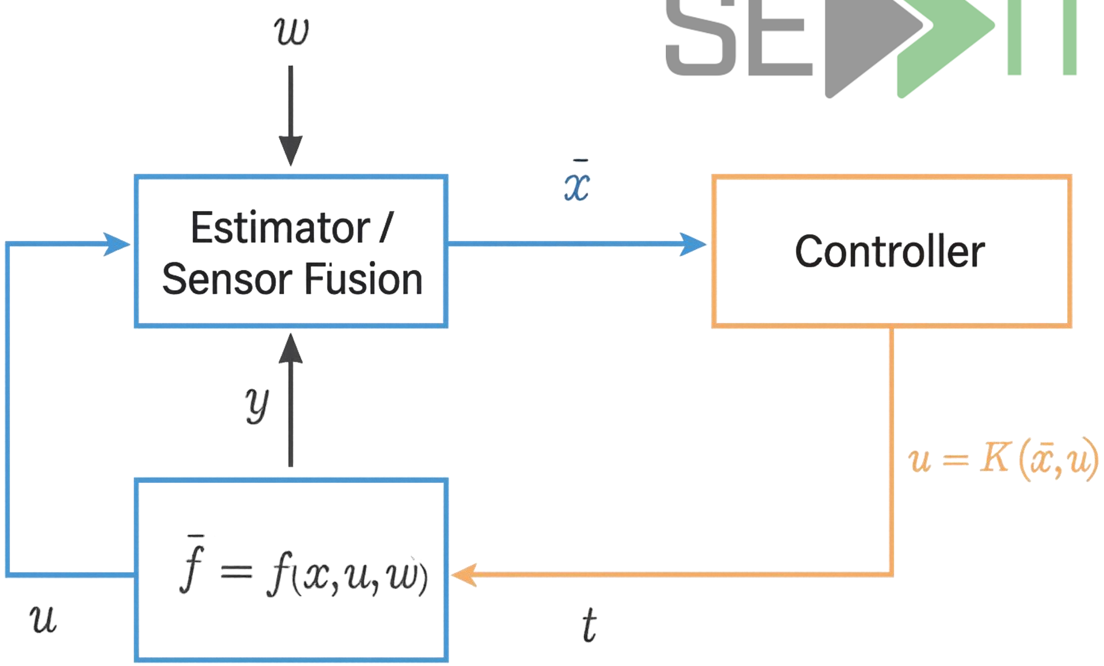
- Situation Readiness: system’s ability to rapidly perceive, interpret, and act on environmental changes.
- Resilience: system’s ability to maintain or restore function after disturbances.
- Combined: readiness ensures fast awareness, resilience ensures stable recovery.



SEDDIT Framing

System model: $\dot{x} = f(x, u, w)$

- x: state vector (e.g., position, velocity)
- u: control input
- w: external disturbance



Goal:

- Sensor fusion estimates both $\hat{x}$ and $\hat{w}$ from noisy data.
- Control uses these estimates to mitigate the effect of disturbances and stabilize behavior.

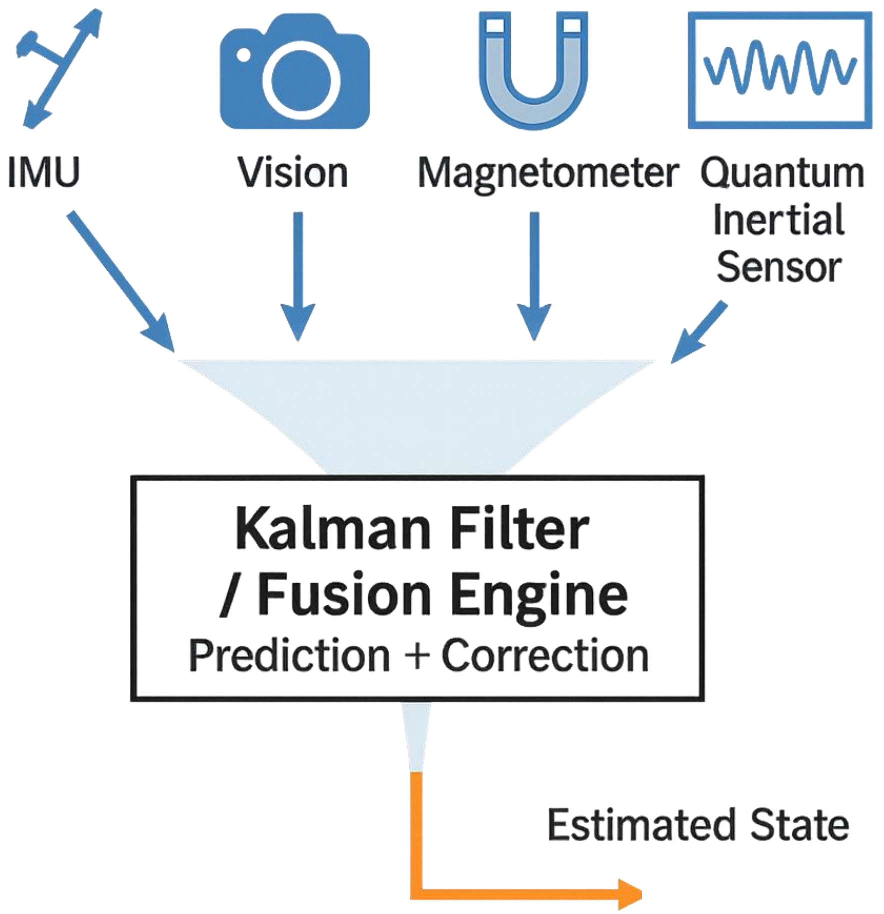
Used in many areas

- **Psychology / Behavioral Science**
  - Readiness = The cognitive, emotional, and physiological preparedness a person has for stressful or uncertain events.
  - Resilience = coping skills, recovery, stress-adaptation, and mental flexibility.
- **Organizational Behavior / Management**
  - Readiness = How prepared an organization is for change, crises, or transformation
  - Resilience =how willing and capable employees are to adopt changes
- **Emergency Management / Disaster Science**
  - Readiness = preparedness for natural disasters, pandemics, attacks
  - Resilience = the ability of a community or infrastructure to withstand and recover
- **Cybersecurity**
  - Readiness = systems designed so they can operate under expected and unexpected loads
  - Resilience = ability to maintain critical functions under attack, failure, or overload
- **Military & Defense Studies**
  - Readiness = operational preparedness of forces, equipment, logistics
  - Resilience = ability to recover from attacks, maintain command & control, and fight through disruption
- **Education / Youth Development**
  - Readiness = preparedness to navigate life transitions (school readiness, college readiness)
  - Resilience = ability to handle adversity, setbacks, or unstable environments

Example: GNSS-free navigation

Sensor Fusion for Situation Readiness

- Multi-sensor data fusion builds a coherent estimate of the system state and environment.
- Combines heterogeneous inputs (IMU, vision, field sensors, quantum data).
- Enhances readiness by providing timely, accurate situational awareness.
- Example algorithms: Kalman filtering, particle filters, neural estimators.



Related to: COLLABORATIVE LOCALIZATION IN GNSS DENIED ENVIRONMENTS and ESTIMATION AND INFORMATION HANDLING IN A HETEROGENOUS SOS and ROBUST LARGE-SCALE ESTIMATION and COLLABORATIVE EXPLORATIVE AGENTS IN UNKNOWN ENVIRONMENTS

Visionary Example: Quantum-Sensor-Based Autonomous Vehicle

Demonstrate readiness (accurate estimation) and resilience (adaptive control) under denial conditions.

- Goal: operate independently of GNSS or external infrastructure.
- Quantum-enhanced sensors (e.g., atom interferometers, NV magnetometers) provide precise inertial and magnetic data.
- Sensor fusion layer integrates quantum and classical sensors to estimate $\hat{x}$, $\hat{w}$ without GPS.
- Control layer adapts to disturbances (wind, road grade, magnetic anomalies) and maintains stable trajectory.

Example: real-time road monitoring

Trafikverkets generaldirektör Roberto Maiorana och infrastrukturminister Andreas Carlson (KD).

DAGENS NYHETER. Nyheter Sverige Världen Ekonomi Kultur Sport Klimatet Ledare

SVERIGE

Din bil ska ge Trafikverket info om var det är halt

Publicerad i går 13:59

Trafikverket kommer att köpa fordonsdata för sju miljoner kronor av flera fordonstillverkare för att förbättra vinterväghållningen.
Foto: Adam Ihse/TT

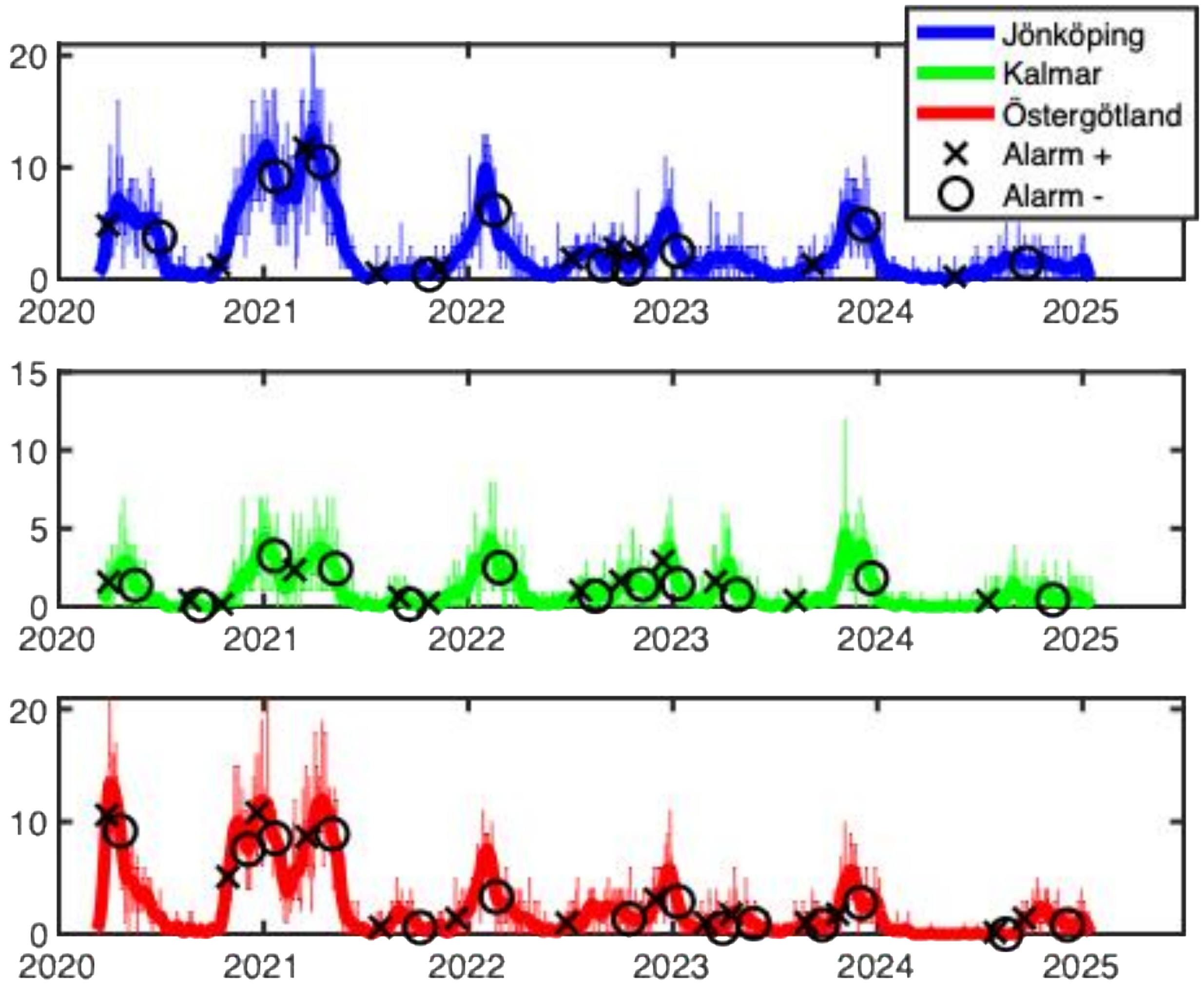
Trafikverket ska i ett unikt projekt köpa data från flera olika fordonstillverkare. Datan visar om det är halt eller inte – och den ska användas för att förbättra

Från 3000 till 300 miljoner mätningar av vinterväglaget

Tekniken har hög täckningsgrad på de högtrafikerade vägarna och även det mindre vägnätet får ofta några mätningar per dygn. Historiskt har ca 3 000 mätningar av väglaget registreras per säsong men med denna teknik utökas det till över 300 miljoner mätningar under en vinter.

Related to: OPTIMIZING VEHICLE DATA TRANSMISSION FOR ACCURATE REGIONAL TEMPERATURE MAPPING

Example: detection of pandemics



$$\frac{dS}{dt} = -\lambda S I,$$
$$\frac{dI}{dt} = \lambda S I - \gamma I,$$
$$\frac{dR}{dt} = \gamma I.$$

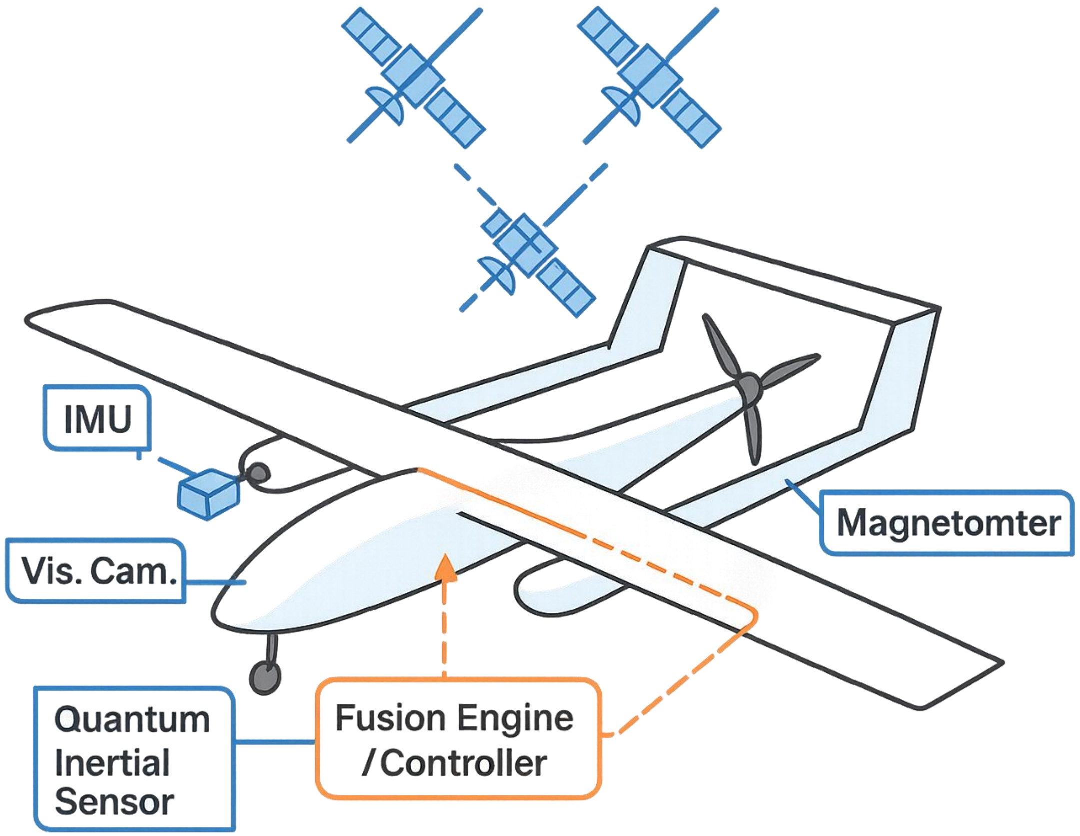
Hospitalizations

SIR model

Vision

Infrastructure-free autonomous vehicle enabled by sensor fusion.

- Readiness = estimation quality and timeliness.
- Resilience = recovery and adaptation through feedback.
- Sensor fusion and automatic control form a unified loop of situational intelligence.



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Situation Readiness and Resilience

Core competence: Data-driven modeling and diagnostics

Daniel Jung and Martin Enqvist

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Data-Driven Modeling and Diagnostics

Daniel Jung
Associate professor
Vehicular systems
Linköping University

Fault diagnosis for complex systems combining models and data, structural methods, fault isolation, and data-driven prognostics.

Martin Enqvist
Associate professor
Automatic control
Linköping University

System identification (data-driven modeling) with applications to aircraft, UAVs, marine vessels, electronic devices, neuroscience.

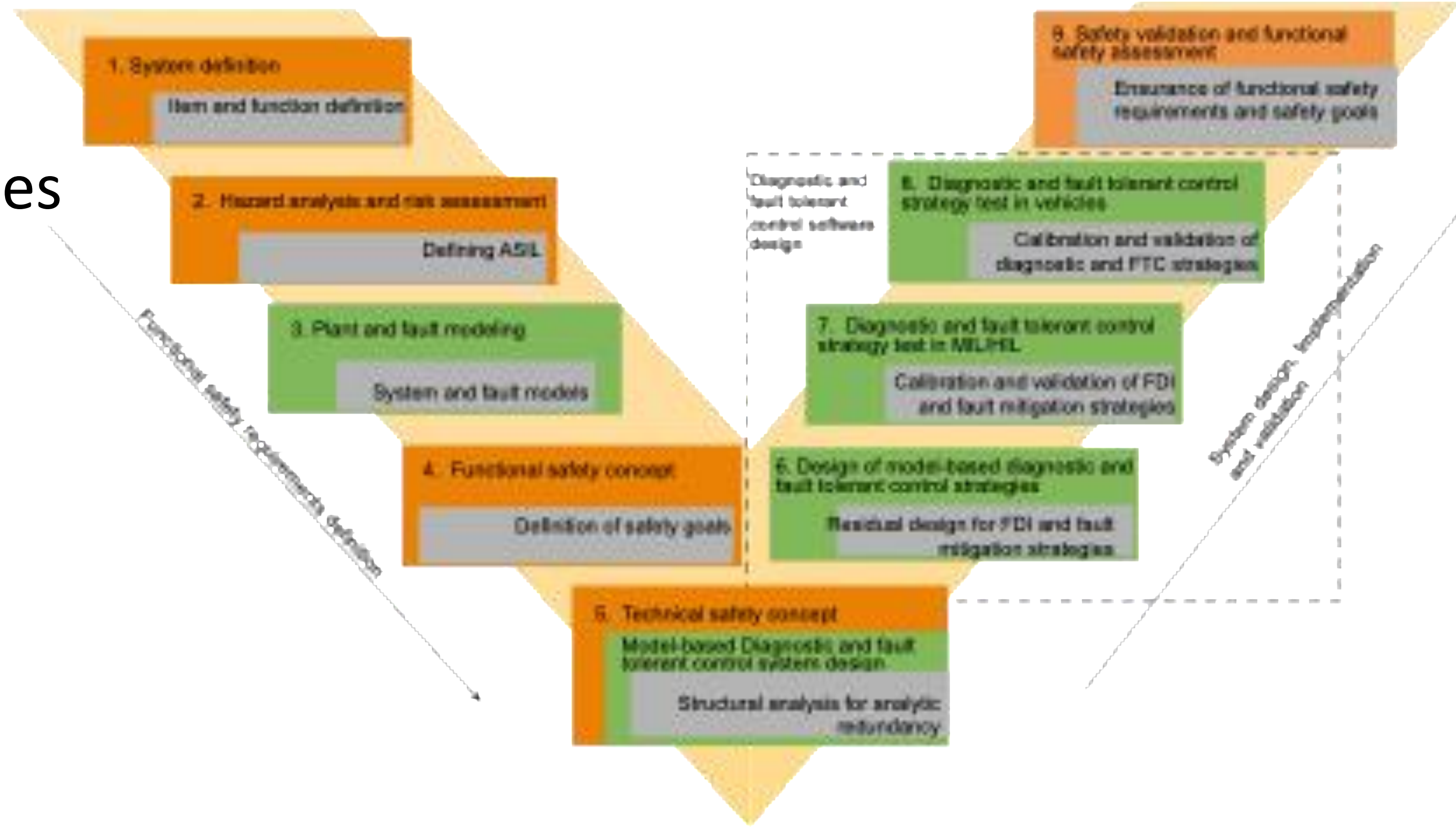
Fault Diagnosis and Prognostics

- Fault Diagnosis and Prognostics are central for design of resilient systems
  - ➢ Detecting abnormal system behavior and identify its cause
- Provide information for e.g. decision-making and fault tolerant control
  - ➢ Select more effective counter-measures when the fault is identified

Fault detection and isolation	Fault estimation and reconstruction	Fault mitigation and fault tolerant control	Reconfiguration	Prognostics	Predictive maintenance

Functional Safety

- Ensure that a system operates correctly and reliably
- Maintain operability during faulty states

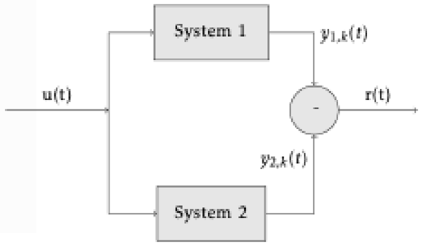


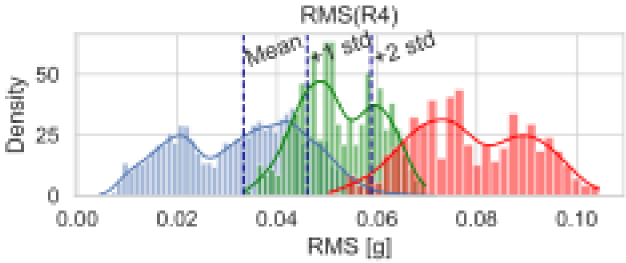
Zhang, J., Rizzoni, G., Cordoba-Arenas, A., Amodio, A., & Aksun-Guvenc, B. (2017). Model-based diagnosis and fault tolerant control for ensuring torque functional safety of pedal-by-wire systems. *Control Engineering Practice*, *61*, 255-269.

Redundancy

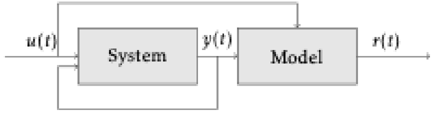
- Hardware Redundancy
  - ➢Triple-redundancy (e.g. aircraft)
  - ➢n-1 criterion (e.g. power grid)
- Analytical Redundancy
  - ➢Virtual sensors
- Reconfigurability and Safe Modes
  - ➢”Limp-home” mode

Hardware redundancy





Analytical redundancy



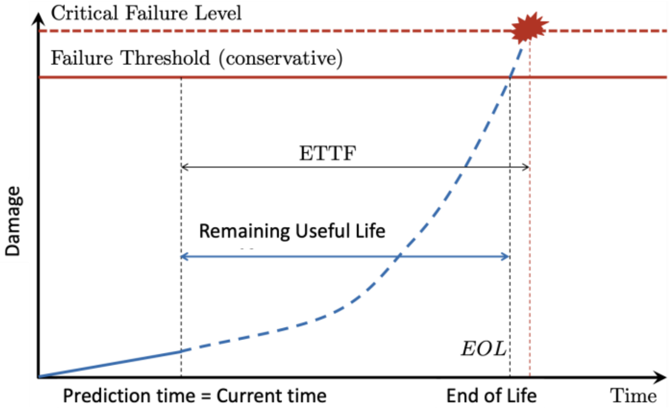
Idermark, M. & Erlandsson, V. (2024) Vibration Health Monitoring Using a Flight-State Aware Autoencoder on a Helicopter Main Rotor Masters thesis, LiTH-ISY-EX--24/5702—SE, Linköpings universitet

Andersson, M. (2013) Fault Diagnosis of a Fixed Wing UAV Using Hardware and Analytical Redundancy. Masters thesis, LiTH-ISY-EX--13/4661--SE, Linköpings universitet.

Jung, D., & Ahmed, Q. (2018). Active fault management in autonomous systems using sensitivity analysis. *IFAC-PapersOnLine*, *51*(24), 1099-1104.

Decision Support

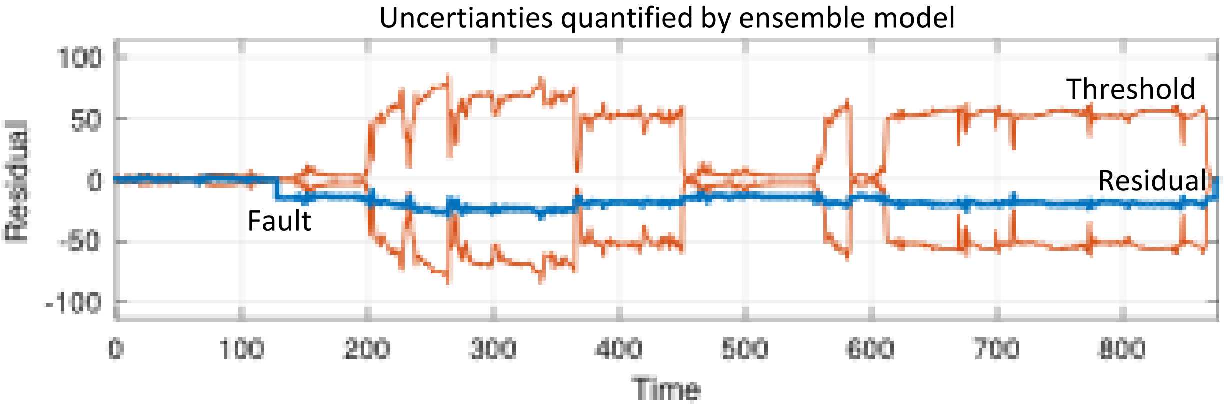
- Mission Planning
  - ➢Can the system fulfill its mission?
  - ➢Monitoring system degradation and Remaining Useful Life (e.g., Digital Twins*)
  - ➢Schedule maintenance when needed



*Glaessgen, E., & Stargel, D. (2012, April). The digital twin paradigm for future NASA and US Air Force vehicles. In *53rd AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics and materials conference 20th AIAA/ASME/AHS adaptive structures conference 14th AIAA* (p. 1818).

Data-Driven Modeling for Fault Diagnosis

- Quality of training data
  - How to handle scenarios not represented in training data?



- When can we trust the model?
  - Distinguish between model inaccuracies and changes in system behavior
  - ”When is a detected anomaly caused by a fault?”

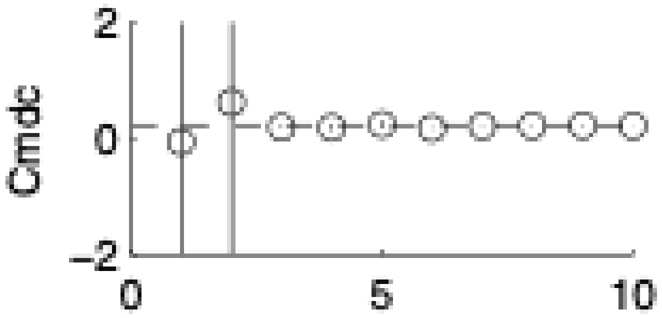
- Human-in-the-loop

Mohammadi, A., Krysander, M., & Jung, D. (2025). Consistency-based diagnosis using data-driven residuals and limited training data. *Control Engineering Practice.*

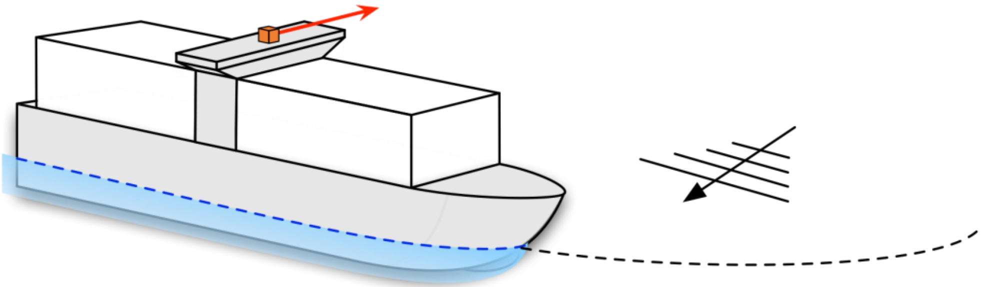
Jung, D., & Westny, T. (2026). Uncertainty-aware fault diagnosis of unknown faults using ensemble-based NODE residuals. *Mechanical Systems and Signal Processing*.

Data-Driven Modeling for Adaptivity

- Online/Sequential/Recursive data-driven modeling enables **adaptivity**, which relates both to **situation readiness** and **resilience**



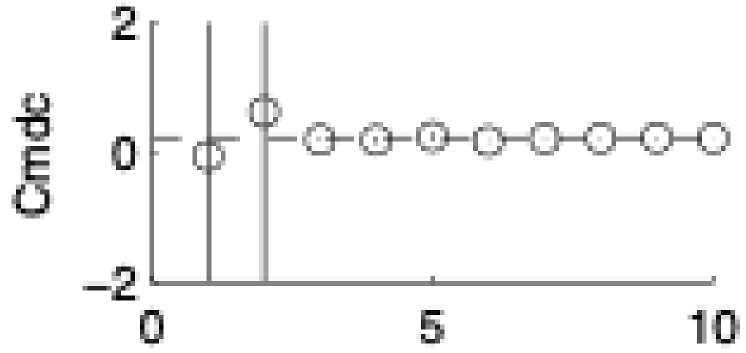
- Accurate and up-to-date models are useful for:
  - Controller tuning, model predictive control, updated safety limits, etc. (cf. indirect adaptive control)
  - Localization
  - Predicting future behaviors, path planning
  - Diagnosis (both automatic and manual)
- Methods need to be robust against varying environmental disturbances



Example: Aircraft Monitoring

Sequential estimation of aircraft properties

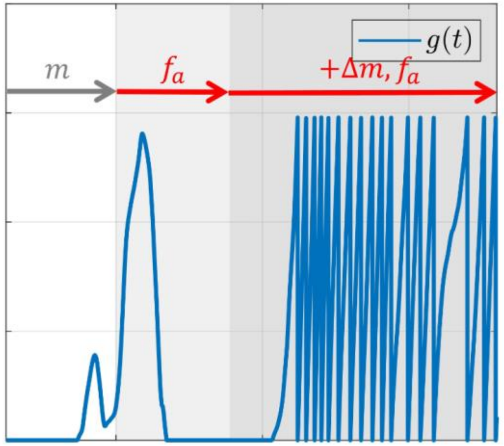
- Gives up-to-date information about physical parameters for manual or automatic analysis
- Developed for flight test conditions but can be used during normal operation
- **Situation readiness**, mainly with respect to **internal changes**, with **humans in the loop**



Example: Unmanned Aerial Vehicles (UAVs)

Robust closed-loop fault detection of UAVs

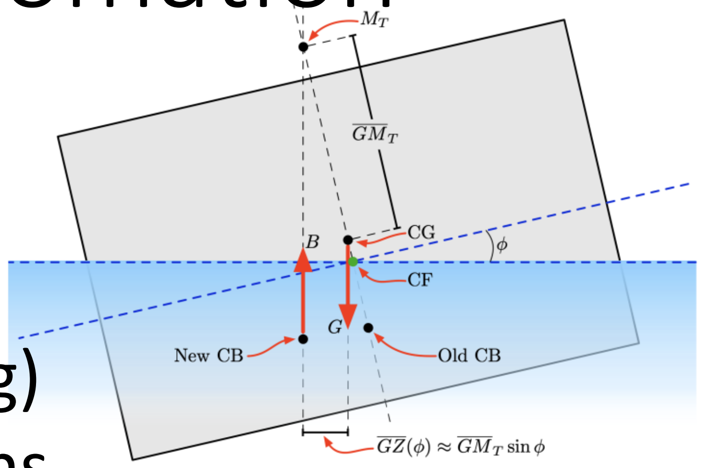
- Combination of additive faults (e.g., in sensors), additive disturbances (e.g., wind) and nonadditive faults (e.g., mass changes)
- Closed-loop operations provides additional challenges
- **Situation readiness** for **both internal and external faults** of different nature



Example: Marine Automation

Estimation of cargo-dependent parameters of ships

- Maintaining safe operations (control, predictions, planning) despite varying load conditions
- Detecting abnormal behaviors (free-surface effects from water on deck, etc.)
- **Situation readiness** and **resilience**



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Situation Readiness and Resilience

Core competence: Learning methods for control

Farnaz Adib

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Learning methods for control

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Modeling, identification, control, and diagnosis of industrial robots.

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Learning methods for control, Reinforcement Learning (RL), generative methods for control, Behaviorak.

Ayca Özcelikkale
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Uppsala university

Machine learning, neuromorphic computing, statistical signal processing, communications and optimization.

Uncertainty & Speed

We need a

Grandmaster

Situation readiness and resilience

Perception

Comprehension

Projection

Decision

Pillar focus

Managing Trust, Uncertainty, and Explainability

Trust:
- Accuracy
- Generalization
- Physical consistency
- Formal verification

Uncertainty:
- Model confidence
- Data noise
- Non-Markovian

Explainability:
- Feature attribution
- Sensitivity analysis
- Physics-informed explanations

Resilience-Beyond adaptivity

- Not surviving a known failure mode;

but

- generalized capacity to cope with *unexpected disruptions*.

Resilience gap- old school fails

Simplified models

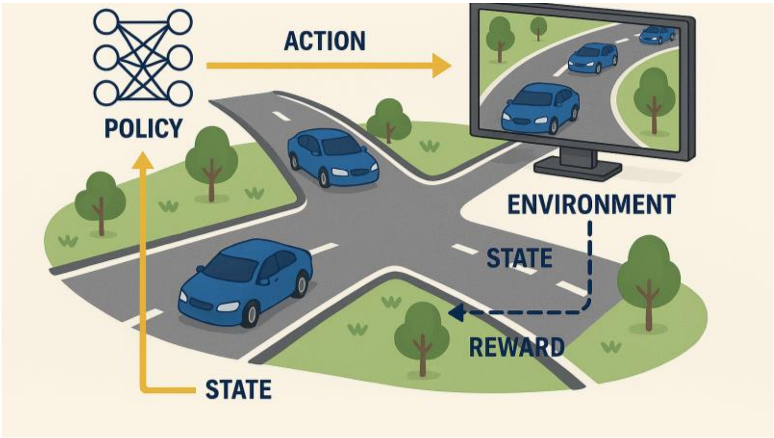
We

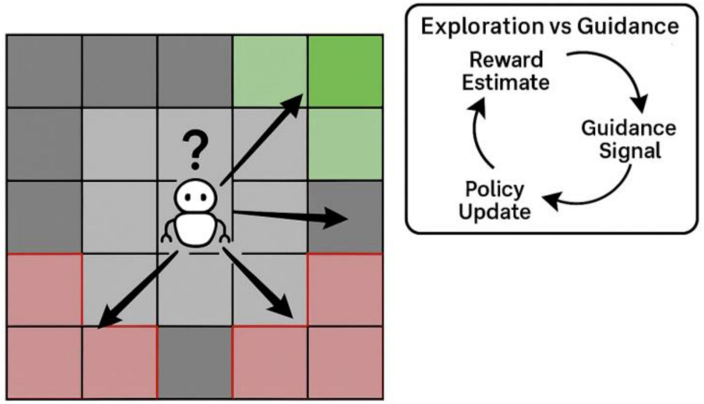
Linear Systems

Out Of Distribution (OOD)

Lacks generalizability

Resilience: Response and recover





Multi-Agent RL

- Life-long learning
- Rooted in experience
- Decentralized

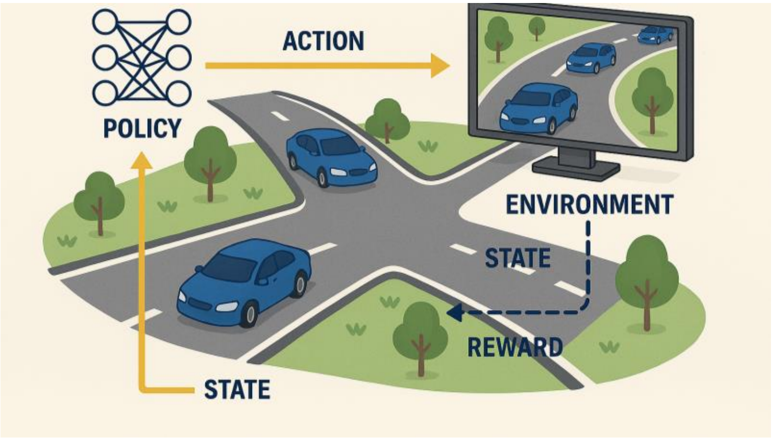
Behavioral Cloning

- Rapid expert recovery

Guided search

- Combination of RL and BC

Impact



Fleet of cars

- Safe coordination,
- mitigating the risk of human takeovers
- Massive economic benefits of efficiency and safety

Power grids

- predict transient stability
- preventing blackouts
- enabling reliable emergency control.

Call for competences

Learning methods for control

Sensor fusion and sensor systems

Situation readiness and resilience

Control-oriented physics-based modeling

Data-driven modeling and diagnostics

Optimization and planning for control and autonomy

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Core competence: Control-oriented physics-based modeling

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Control-oriented physics-based modeling

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Modeling, identification, control, and optimiztion of vehicle propulsion systems.

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Vehicular Systems, LiU
Traton Group

Modeling, estimation, and control of vehicle propulsion systems.

What is a Model?

- A model is a predictor!
- Predict the result of future experiments.
- Example:
  - Dropping a ball.
  - $v = g\,t, \quad s = g\,\frac{t^2}{2}, \quad t = \sqrt{\frac{2\,s}{g}}$
  - A 2 m drop takes $t \approx \sqrt{\frac{4}{9.81}} \approx 0.6$ s
- High heights & velocities, air-drag plays a rol
- Simplification, useful for low heights.
- All models are simplifications.
- Physics helps us extrapolate sanely, force balance with Newton’s law.

-All Models are Wrong!
-But, Some are Useful!
G.P. Box

Relying on Physics in Engineering

- Resilience is not only about preventing failure—it is about maintaining function despite failures.
- Even if things go wrong the laws of physics still hold.
- Physics-based and model-based strategies are powerful because they give insight into what the system **can do**, **should do**, and **will do**, even in *adverse conditions*.
- Handling rare events can give a need for extrapolation.

Interplay Between Diagnosis and Control

Observers can detect:

- actuator faults,
- sensor drifts,
- structural damage,
- thermal anomalies,
- unwanted oscillations.

Once a fault is detected, model-based control can help:

- reconfigure control loops,
- redistribute loads,
- gracefully degrade performance,
- enter safe modes.

-Use all methods and tools available.
-SEDDIT competences contribute to performance and resilience.

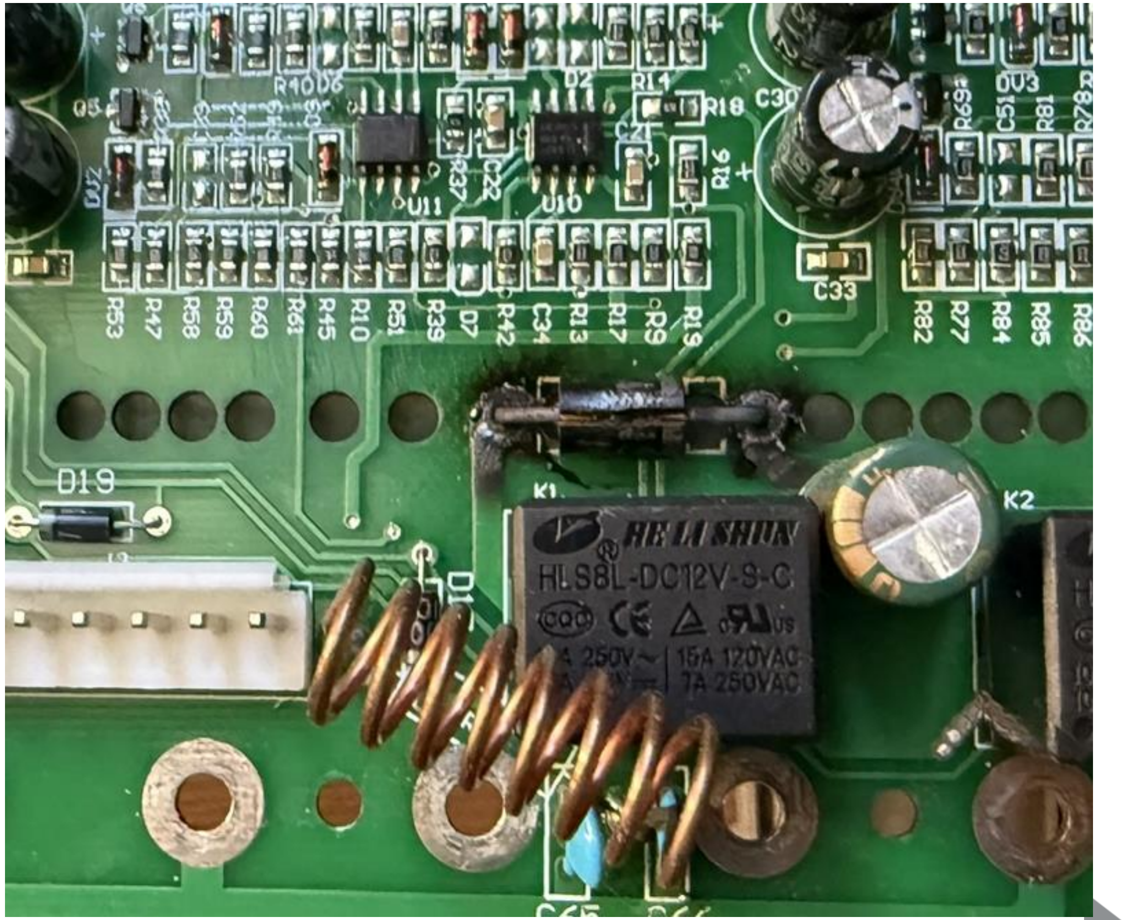
Benefits from support in extrapolation

Real systems can’t always be tested under:

- extreme loads,
- component failures,
- multi-fault conditions, or
- cascading disturbances.

Physical models can simulate dangerous scenarios safely and cheaply.

Example: Coolant system ageing & clogging, battery temperature rise, electric machine overheating, critical down-hill driving.



Resilience when Physics-Based and Model-Based Approaches Work Together

Resilience is strongest when:
- **physics-based models** provide insight, fidelity, and predictive capability,
- **model-based control** exploits that insight to optimize behavior in real time.

This integrated approach makes it possible to:
- anticipate failure,
- operate near physical limits safely,
- adapt to degradation,
- recover from faults.

Example applications:
- **Automotive:** Energy management + thermal + torque-vectoring controllers use battery/motor/tire models to stay within safe regions.
- **Wind turbines:** Models of aerodynamics and loads enable fault-tolerant pitch/torque control.
- **Power grids:** Physics-based power-flow models combined with MPC support fault ride-through and black-start strategies.

Physics-based and model-based control design towards resilience in systems engineering by enabling

a) Prediction

- Understanding how disturbances and failures propagate through the physical system.

b) Prevention

- Acting ahead of time to avoid unsafe states.

c) Adaptation

- Reoptimizing or reconfiguring control actions as the system degrades.

d) Robust Response

- Maintaining stability and performance under faults and uncertainties.

e) Recovery

- Using models to guide safe restoration of normal operation.

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Situation Readiness and Resilience

Core competence: Optimization and planning for control and autonomy

Johan Löfberg

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Optimization & planning for control and autonomy

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Fast optimization algorithms, real-time certification, MPC, optimal motion planning, high-performance computing, applications,...

Johan Löfberg
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Automatic Control
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Optimization modelling and software, robust optimization, control theory,...

Christos Verginis
Assistant Professor
Signals & Systems
Uppsala University

Coordination of multi-agent autonomous systems, entailing learning, planning, and control.

Erik Frisk
Professor
Vehicular systems
Linköping University

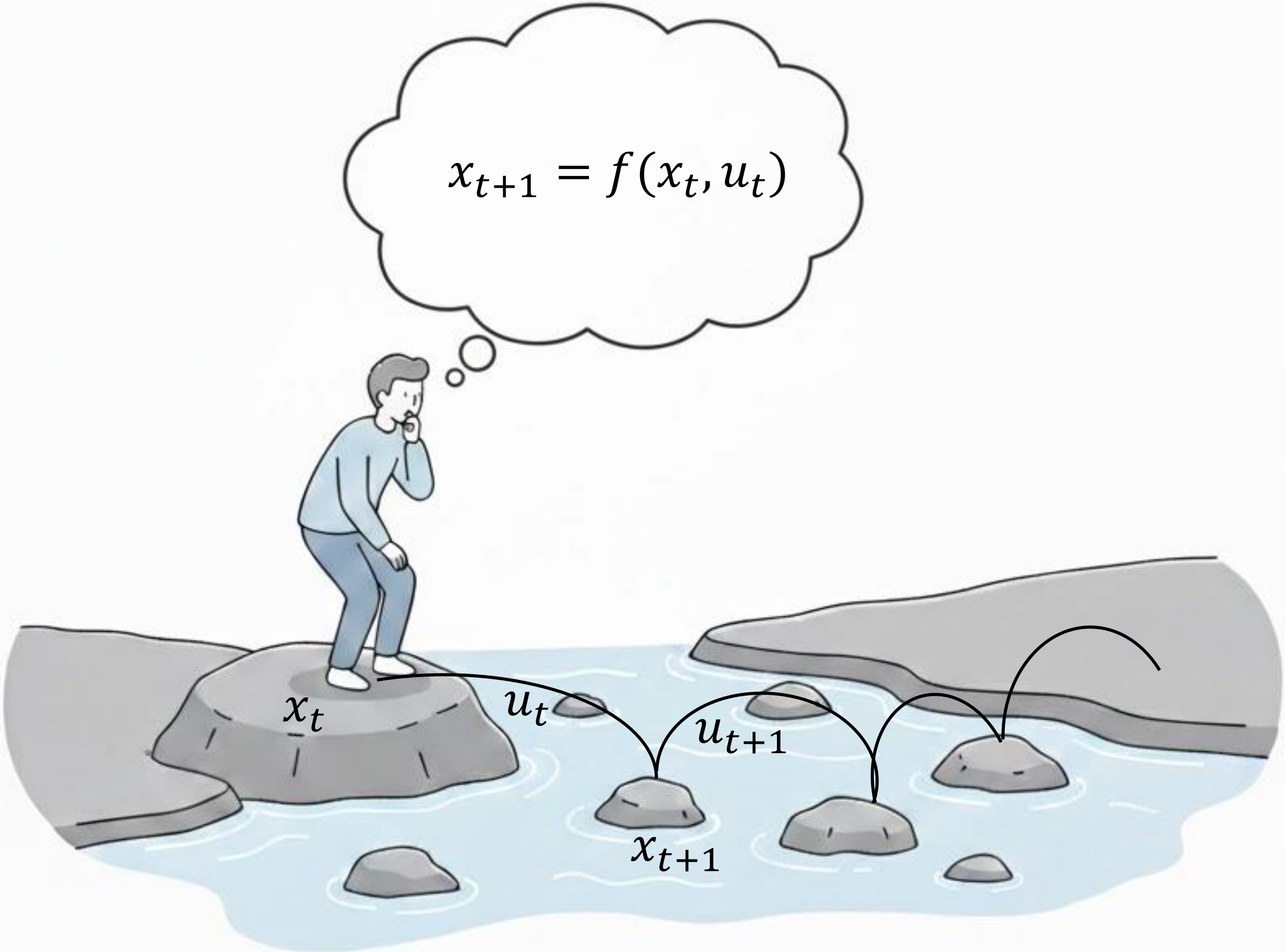
Planning and control under uncertainty, interacting multi-agent autonomous systems, learning systems, large-scale optimization in planning

Control & feedback → Resilience

The End. Questions?

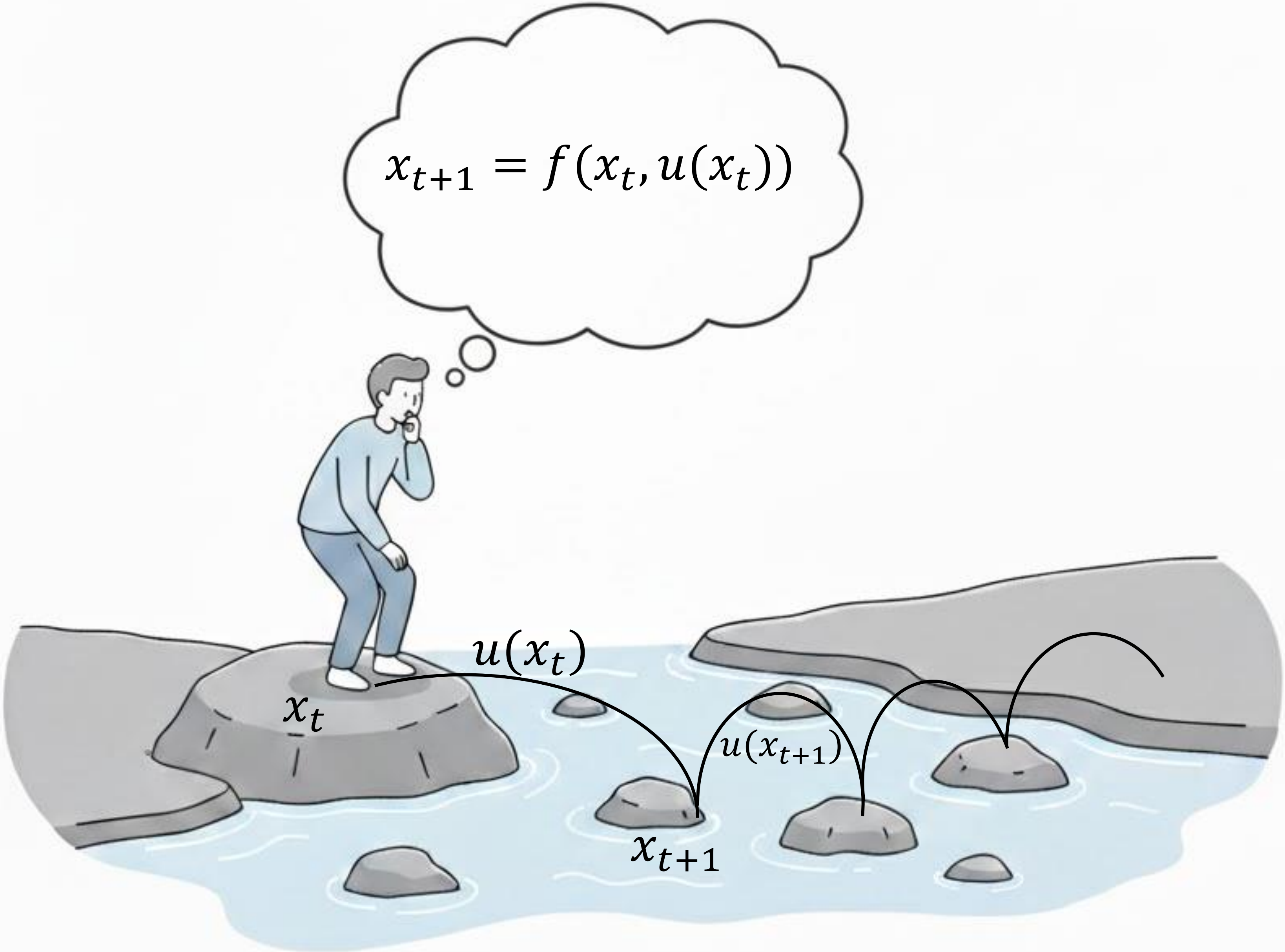
Level 2: Resilient control – Resilient resiliancy?

Robustness, Adaptivity, Recoverability

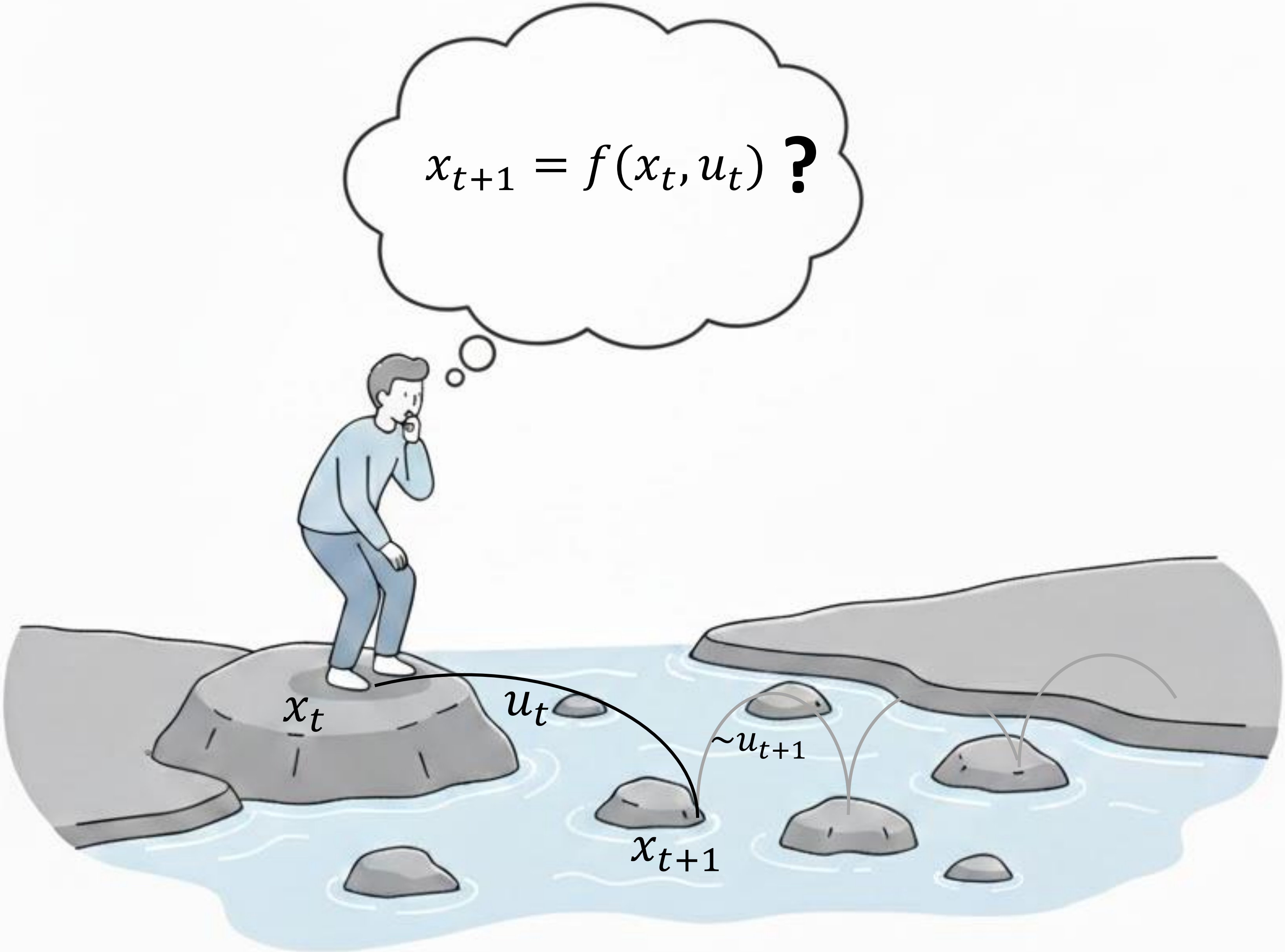


Planning

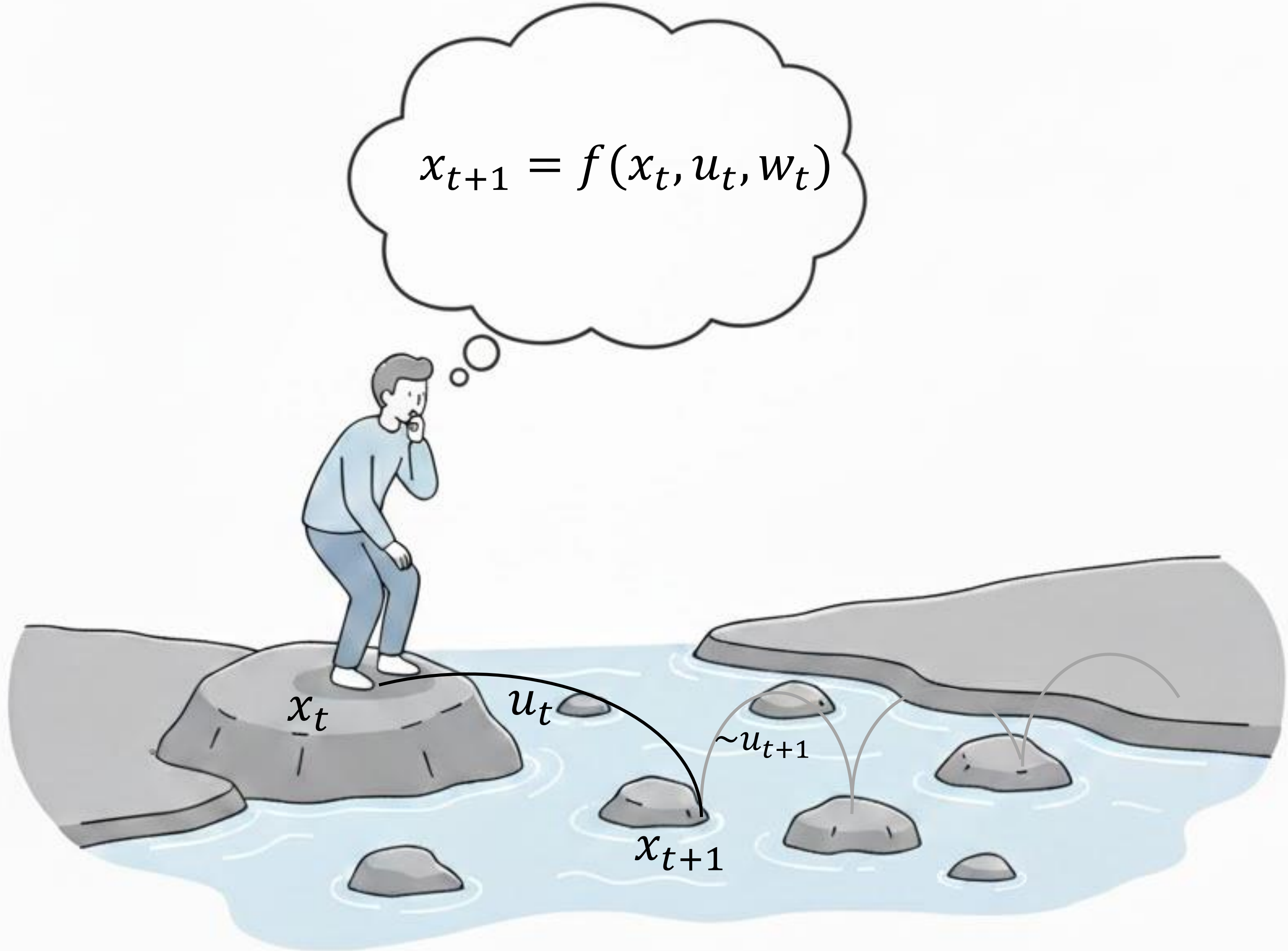

Everyone has a plan until they get punched in the face
Mike Tyson



Feedback control



MPC = update plan → feedback



Incorporate knowledge about unkowns


Deterministic
Unknown bounded
Worst-case
Stochastic
Distributions
Probabilities

Both can lead to conservative solutions

Knowledge about feedback necessary

Optimize approximate robust policies

Don’t fear the unknown, fear the unknown unknown

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