oCPS

Platform-aware Model-driven Optimization of Cyber-Physical Systems

Designing image-based control systems considering workload variations*

Sajid Mohamed, Dip Goswami, Twan Basten

*In CDC 2019.

S. Mohamed, et al., “Optimising QoC of multiprocessor IBC systems considering workload variations,” In DSD 2018.

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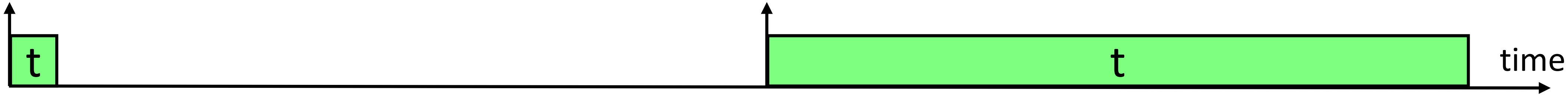
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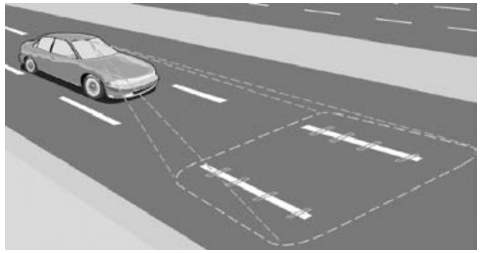
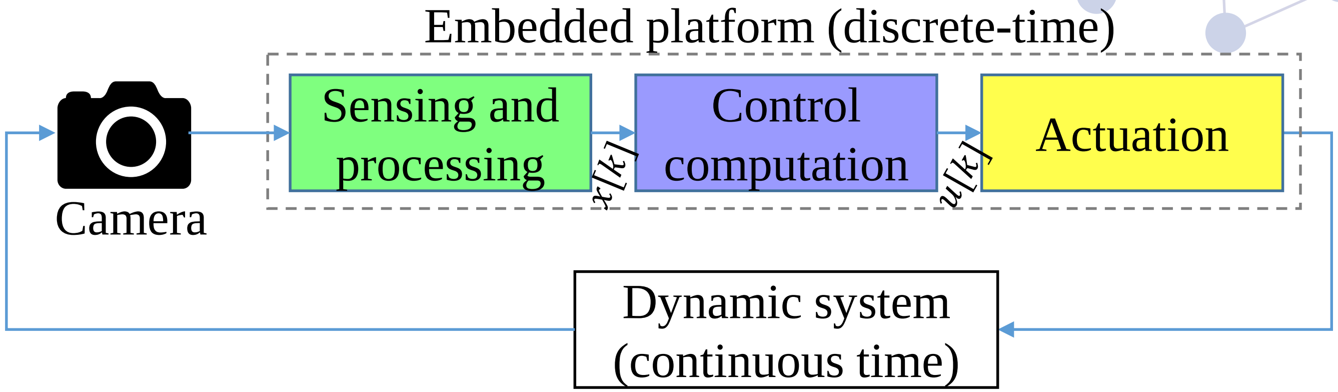
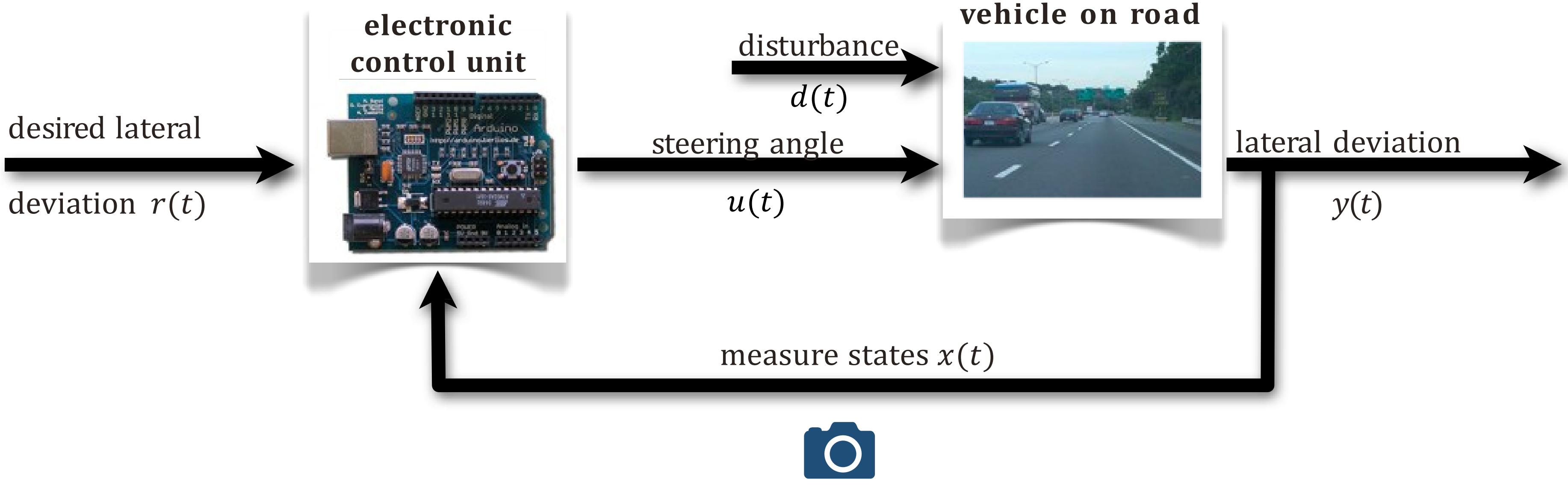
Image-based Control (IBC) System – an example



Vision-based lateral control of a vehicle





state-space model

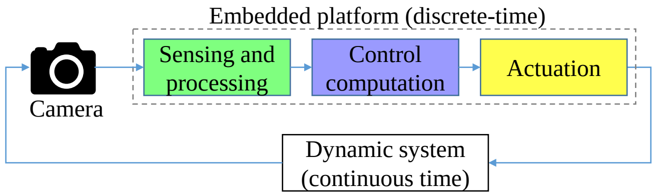
$$\dot{x}(t) = Ax(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t)$$

control law

$$u(t) = Kx(t) + Fr(t)$$

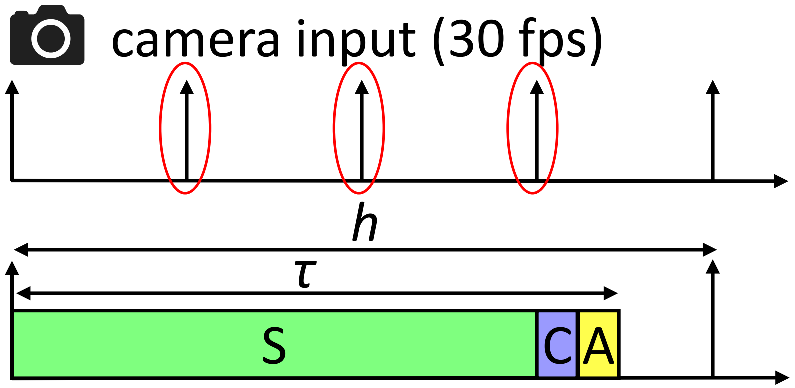
How to control the inputs $u(t)$ automatically to make the output $y(t)$ *track* the given reference $r(t)$?

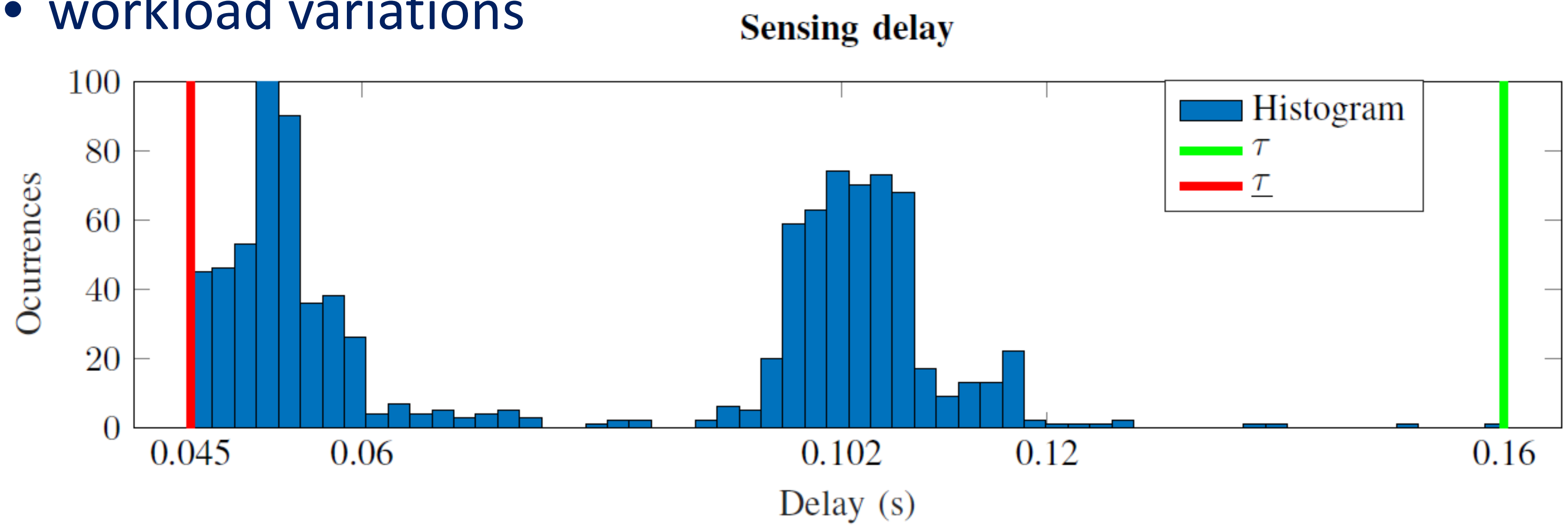
Control performance

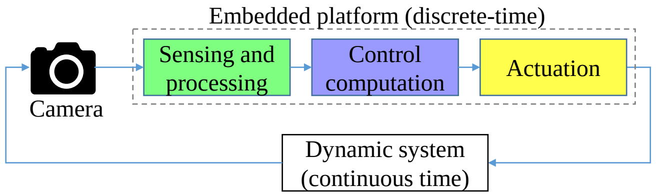


IBC system: characteristics

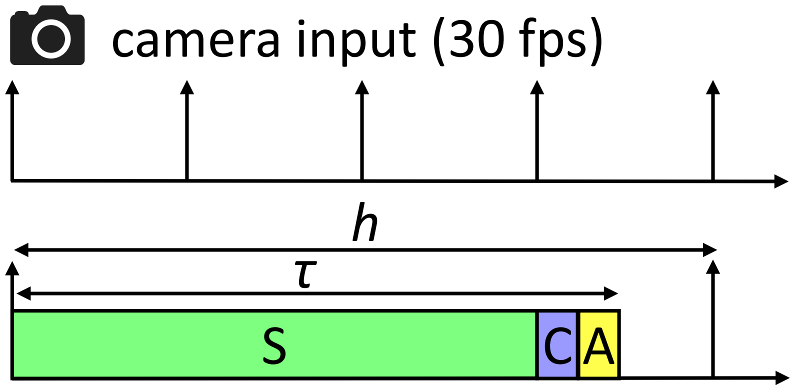
- Sensing delay is relatively long
  - applicable for 30 or 1000 frames per second (fps)
- Sensing delay more than frame rate
  - dropped camera frames
- Sensing delay is variable
  - workload variations



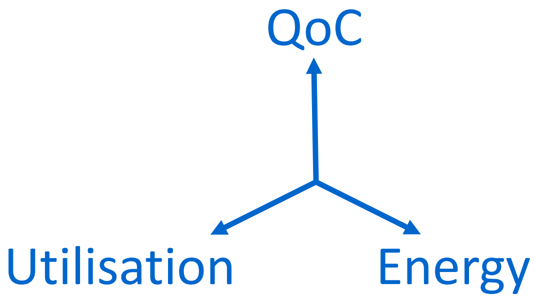




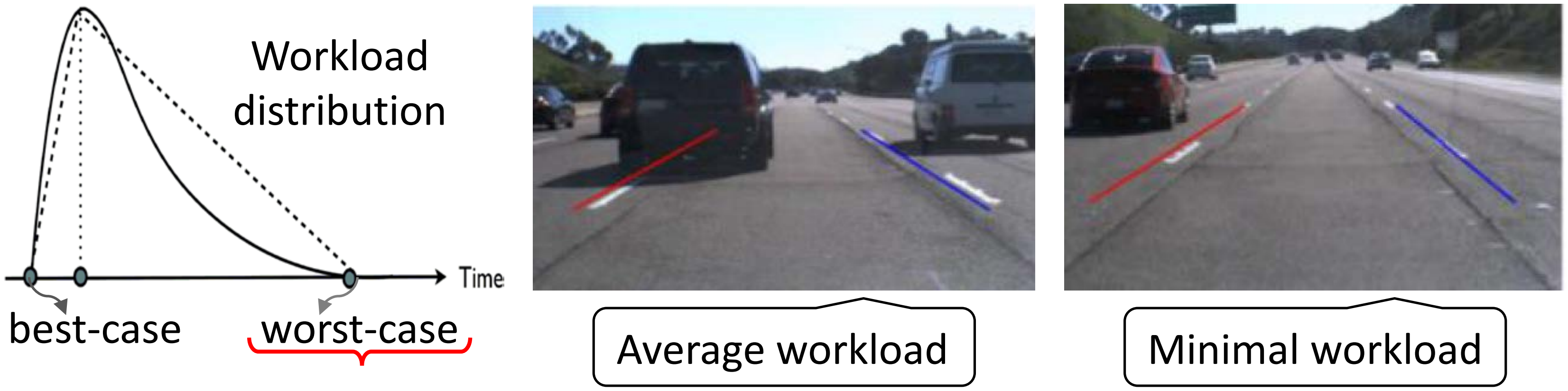
IBC system: characteristics

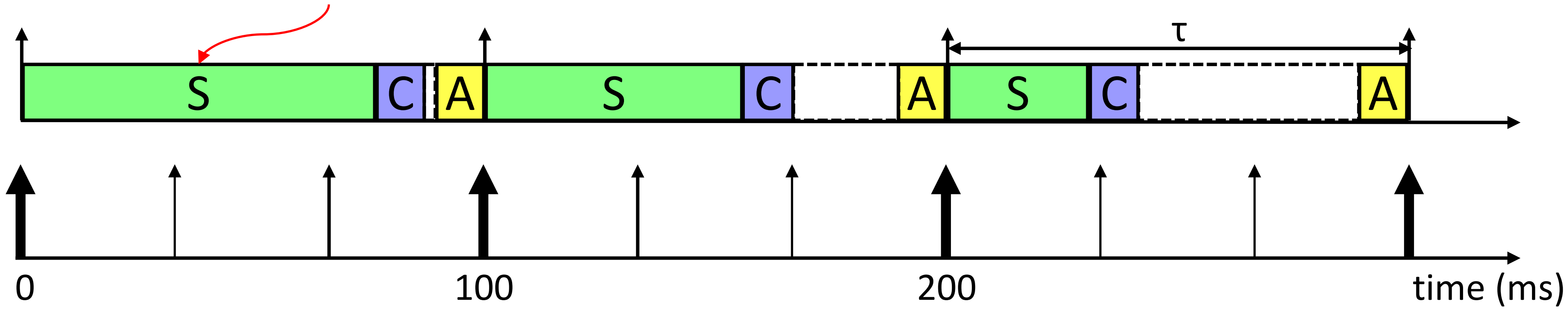


How to cope with this long, variable sensing delay
to improve system performance?



Workload Variations

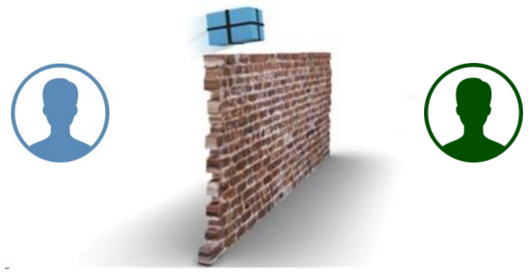




- Execution time of 'S' depends on workload variation
- A constant sensor-to-actuator delay τ and sampling period *h*
  → to guarantee system stability

Design vs Implementation

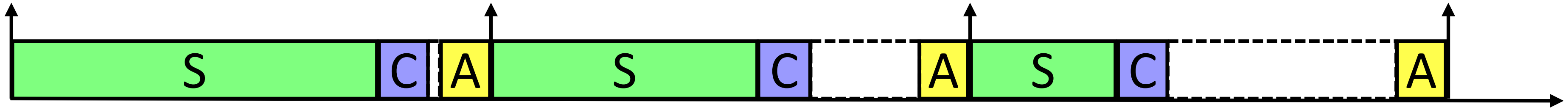
Control Design Engineer



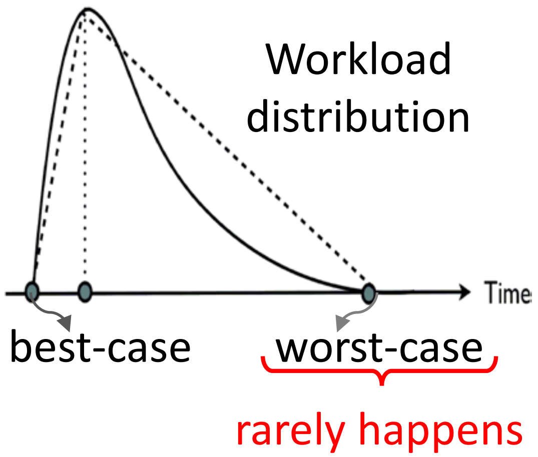
Embedded Systems Engineer

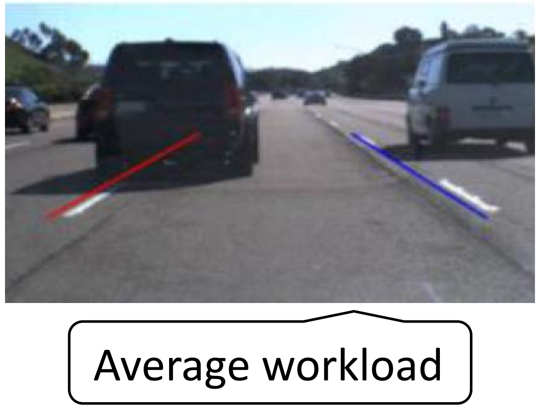
Worst-case workload is considered for design
Sensing task: black box

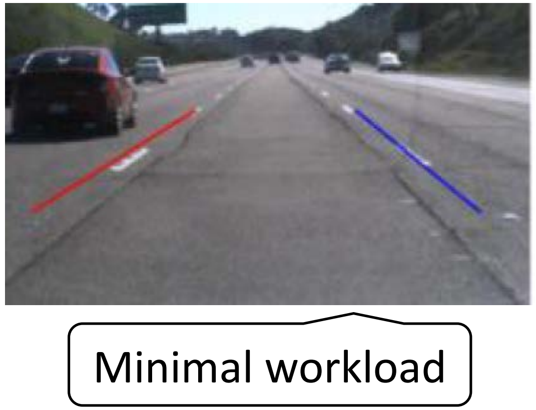
Allocates resources for the worst-case workload
Control design: black box

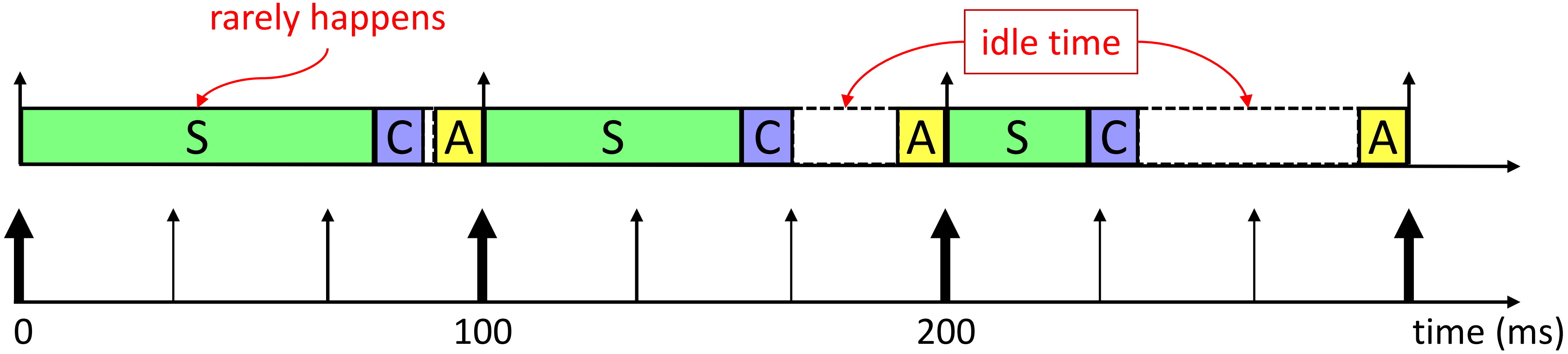


The Design-Implementation Gap



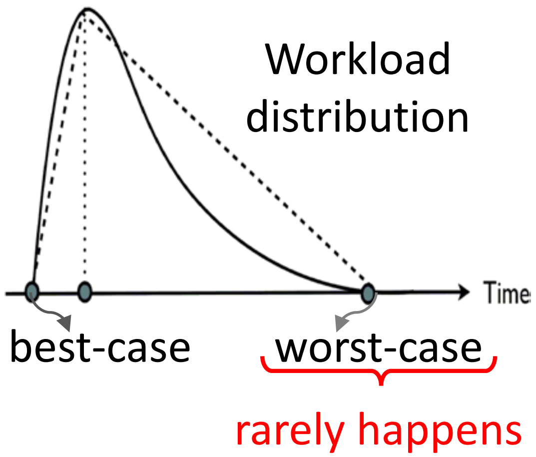


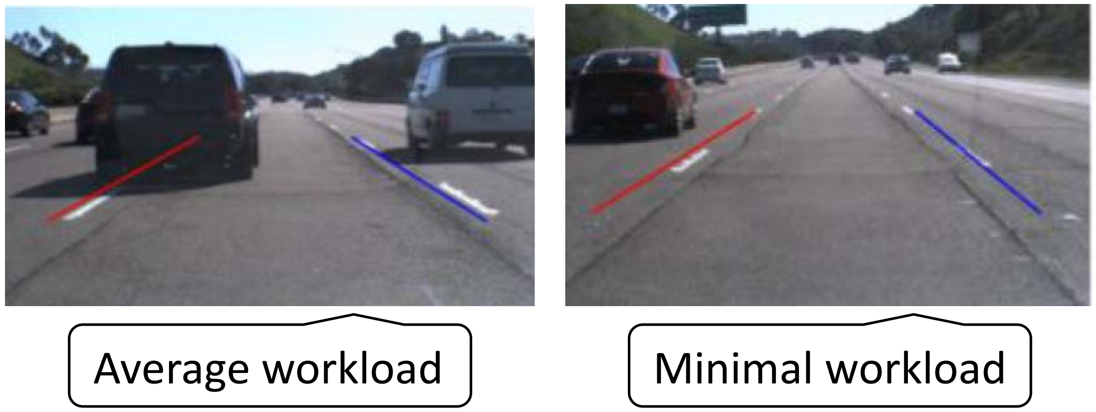


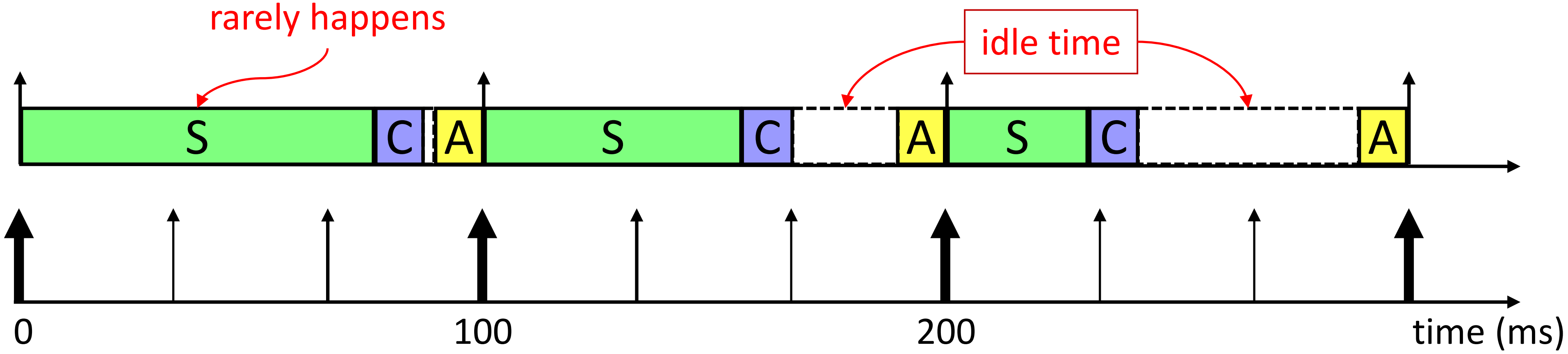


- Controllers designed for worst-case workload → rarely happens
- Idle resources for less workload → inefficient resource utilisation

Bridging the Gap

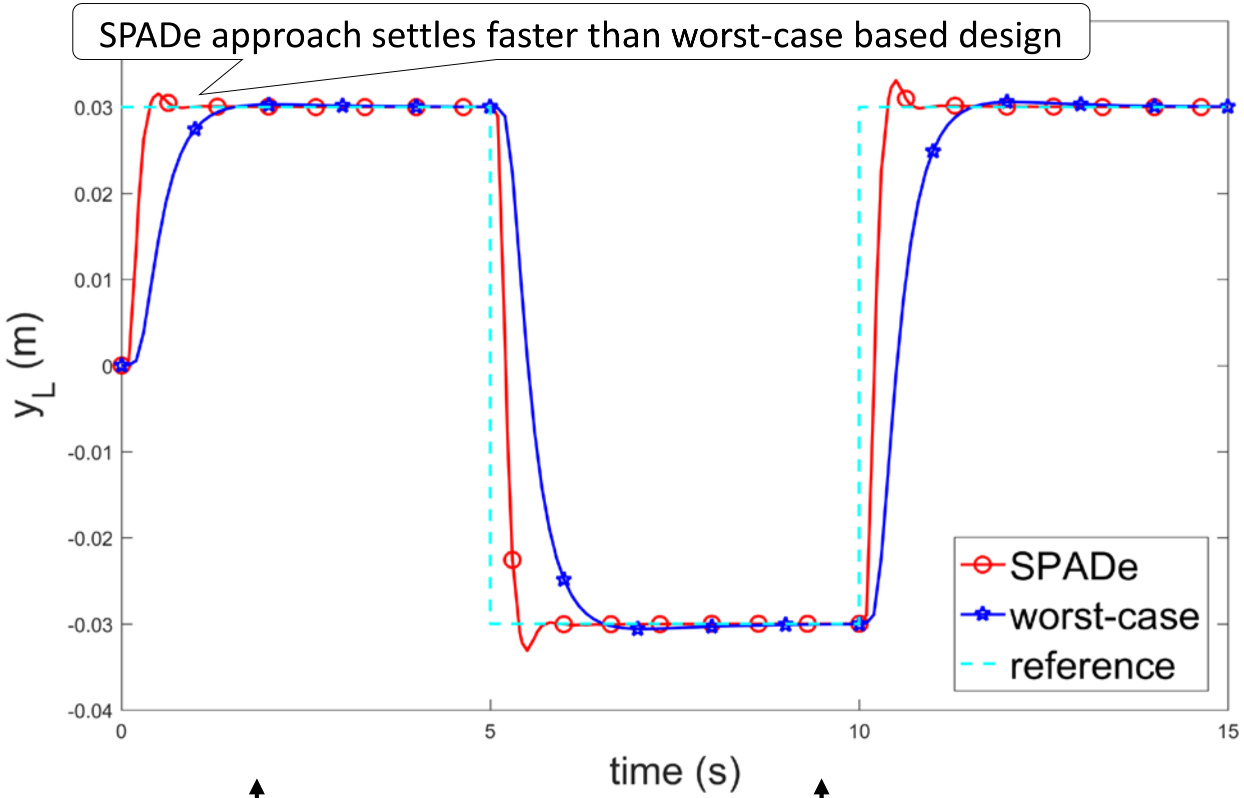


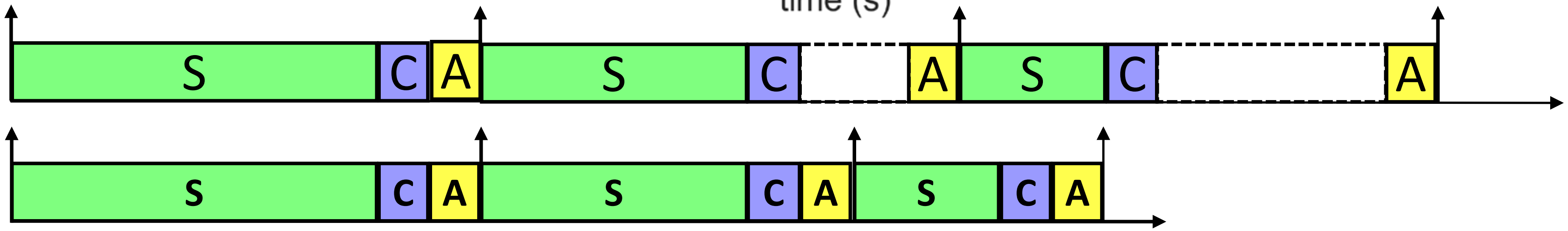




Can we optimise Quality-of-Control using multiprocessor technology?

Vision-based Lateral Control – Results



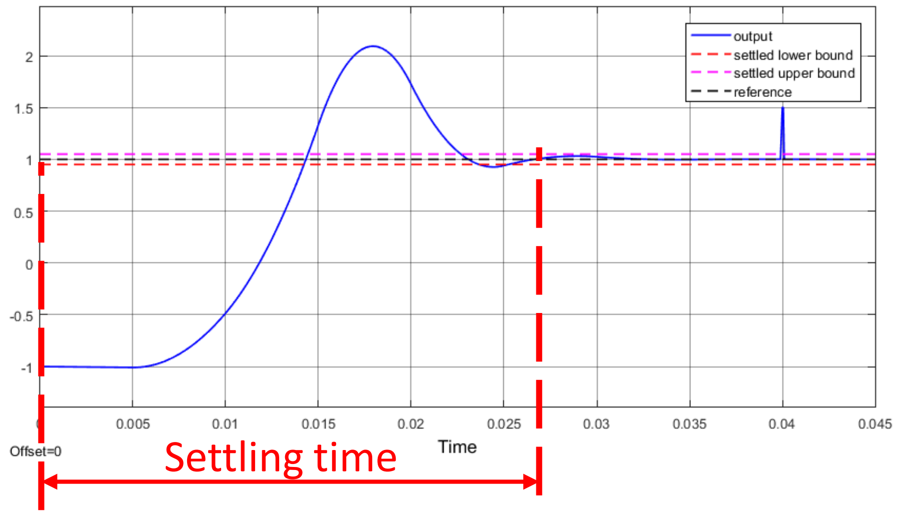


Can we optimise Quality-of-Control using multiprocessor technology?

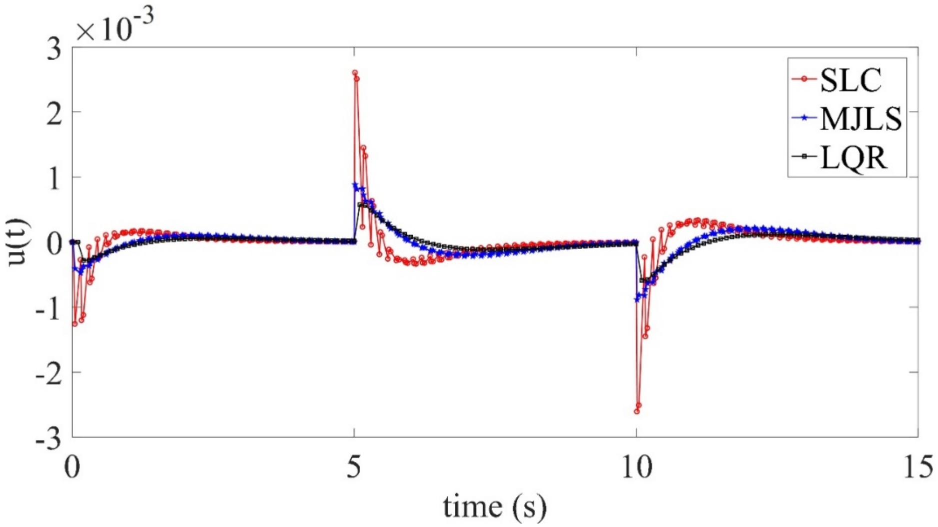
Yes, Scenario- and Platform-Aware Design (SPADe) approach.

Quality-of-Control (QoC) metrics

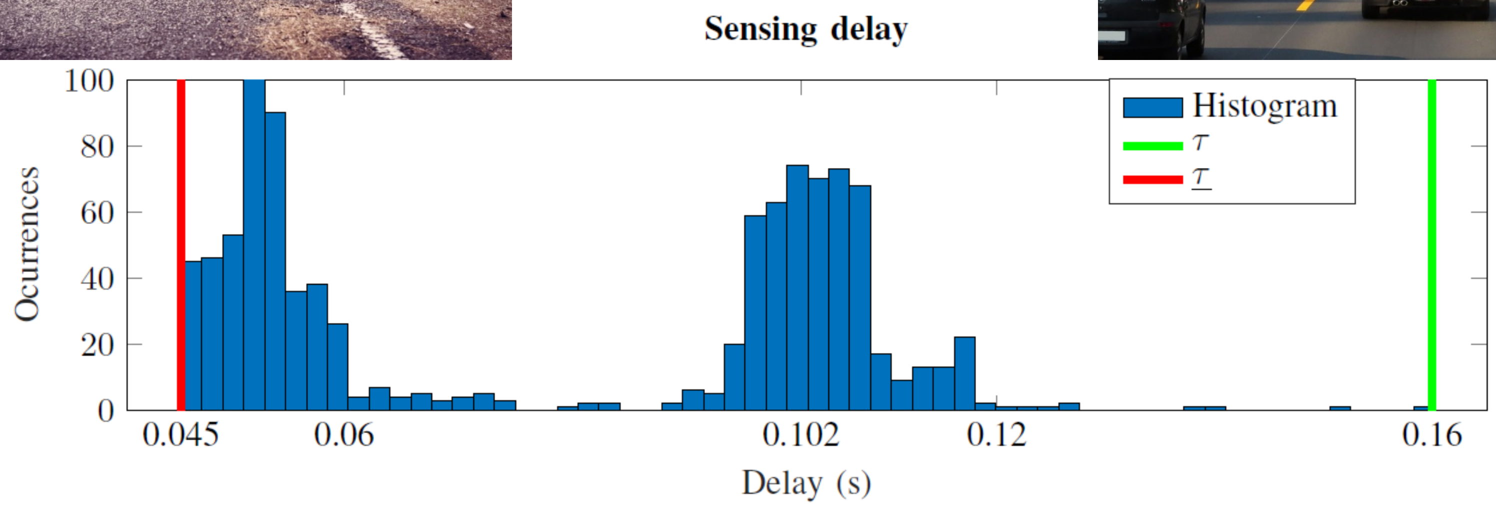
- Control performance
  - Settling time (ST)
    - vision-guided braking
  - Mean-square error (MSE)
    - $e = \frac{1}{n}\sum_{k=1}^{n}(x[k] - r)^2$
  - …



- Control energy/effort
  - Power spectral density (PSD)
  - Maximum control effort (MCE)
  - …



Scenarios based on workload



How to identify, model and characterise workload variations for IBC design?

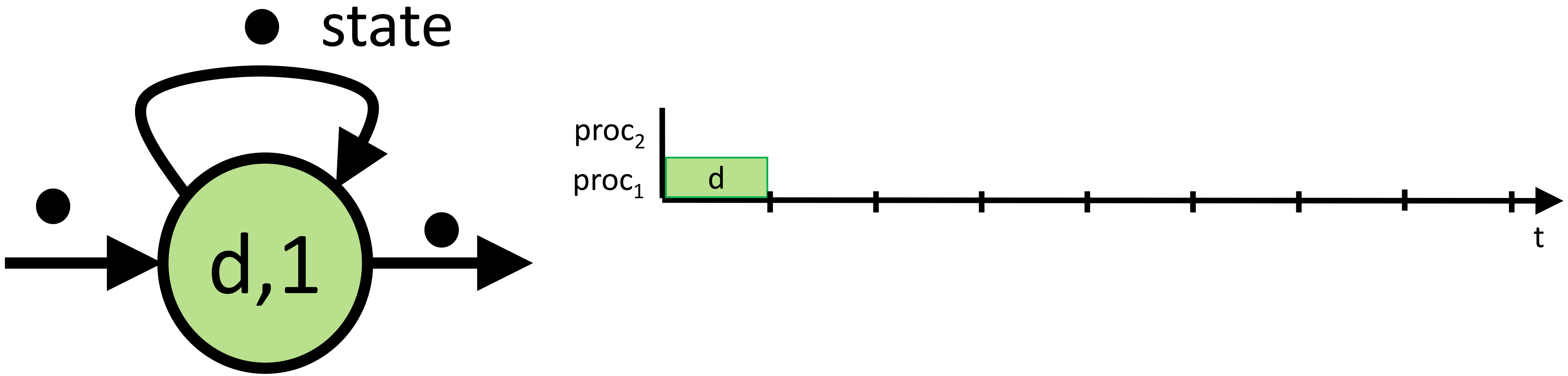
PERT distribution, Discrete-time Markov chain

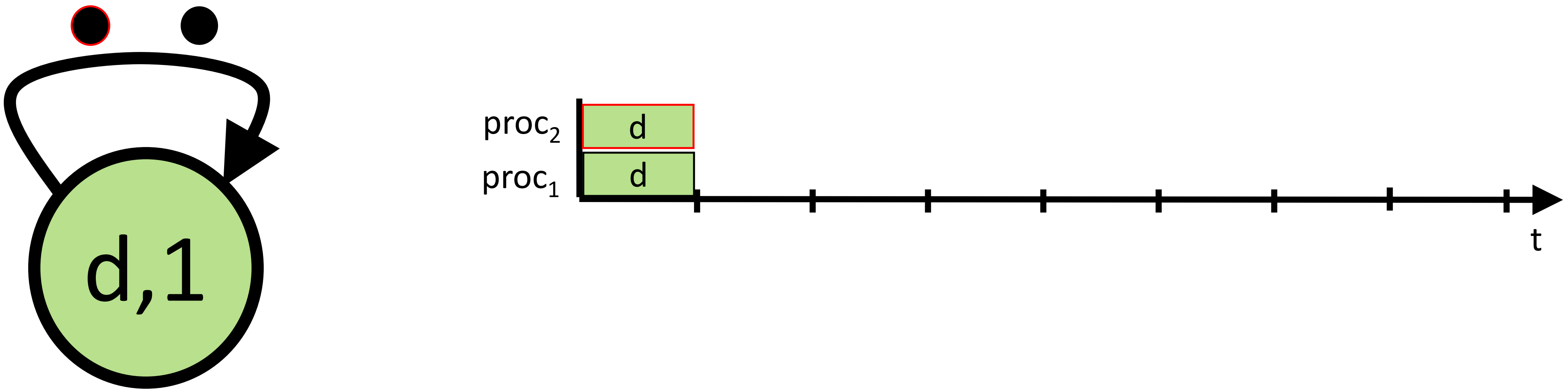
Why platform-aware?

- Model-of-Computation: synchronous dataflow (SDF)

Synchronous dataflow (SDF)

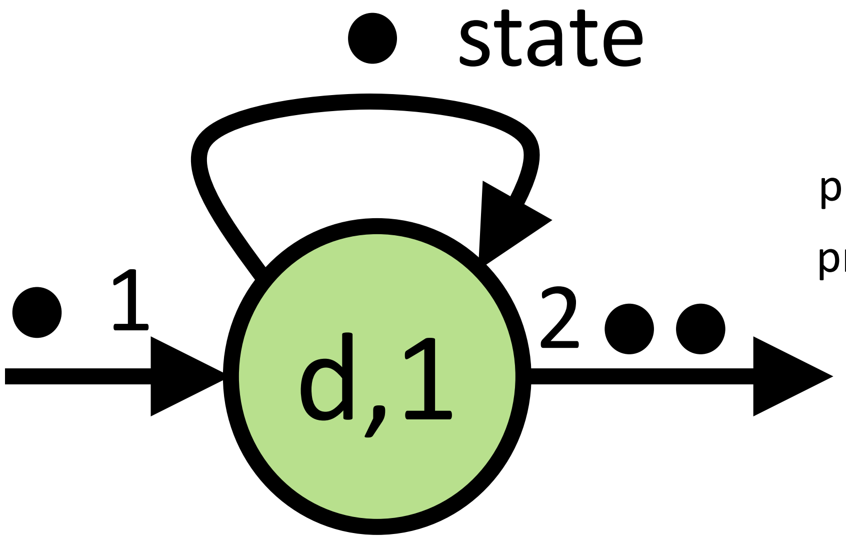
- Actor, channel, tokens, rates

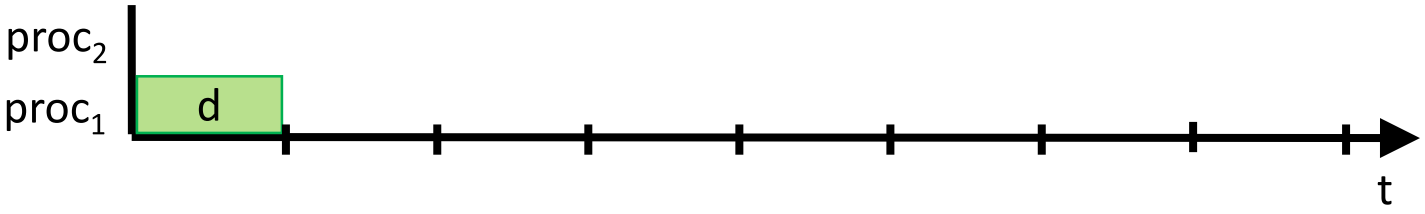


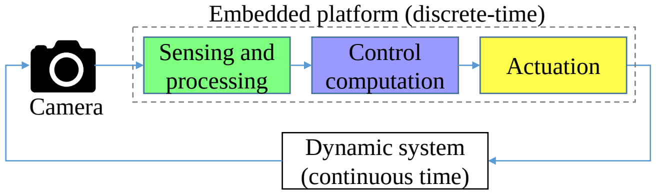


Synchronous dataflow (SDF)

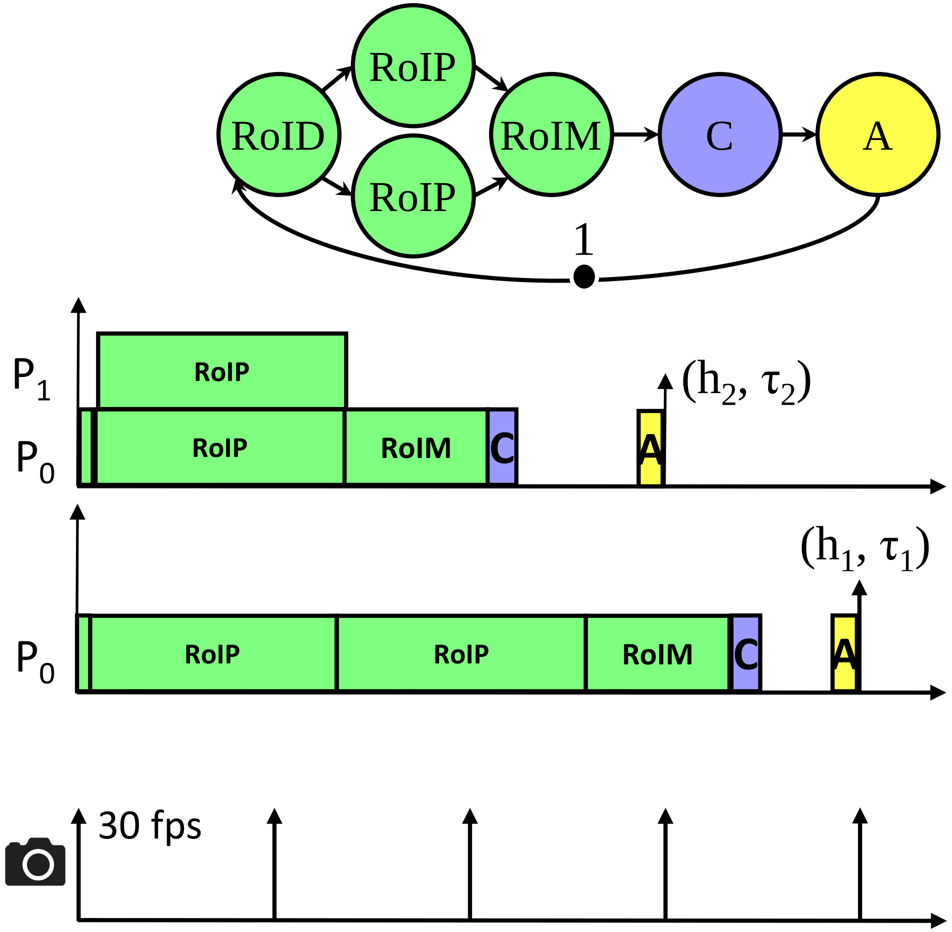
- Actor, channel, tokens, rates



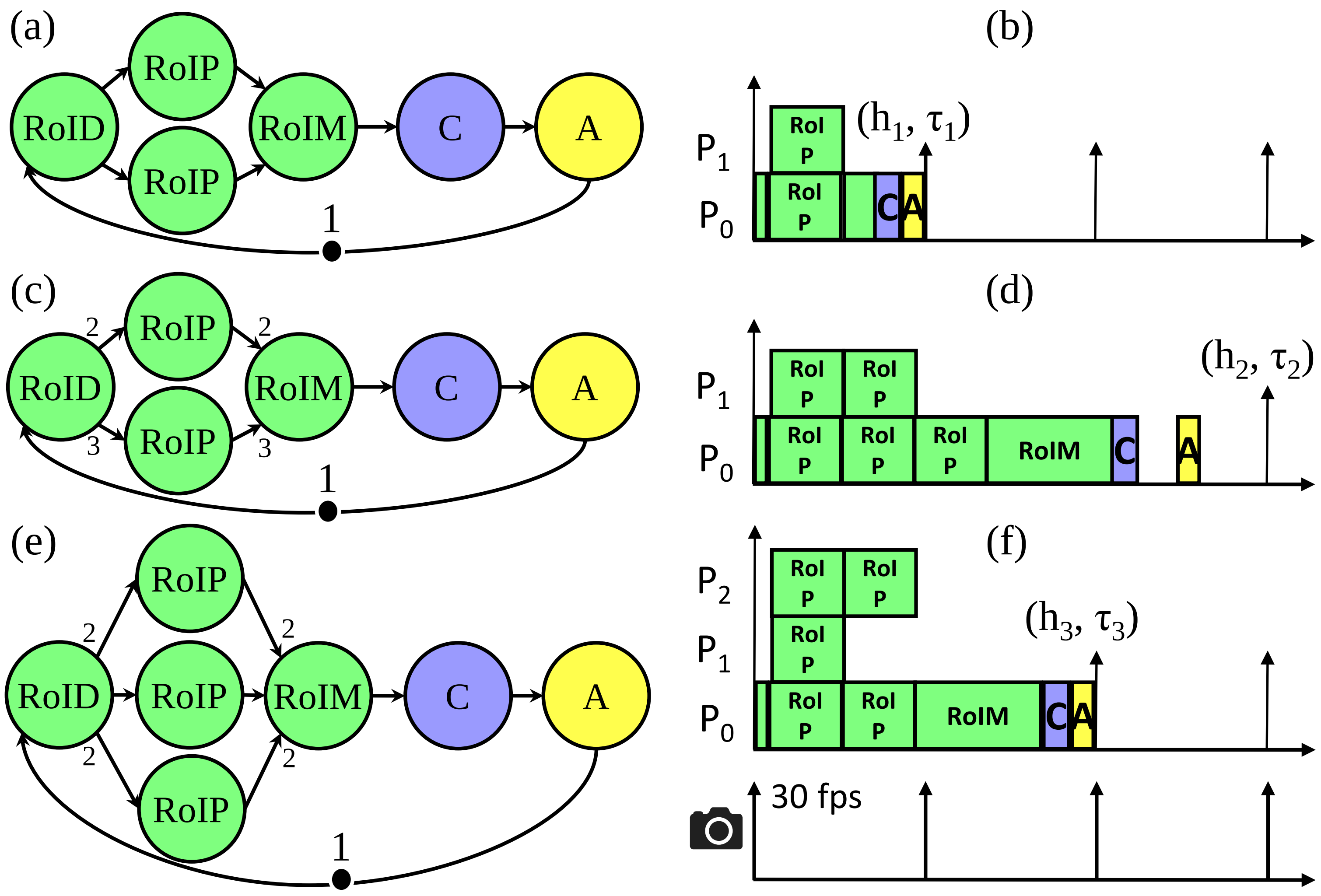




Why platform-aware?

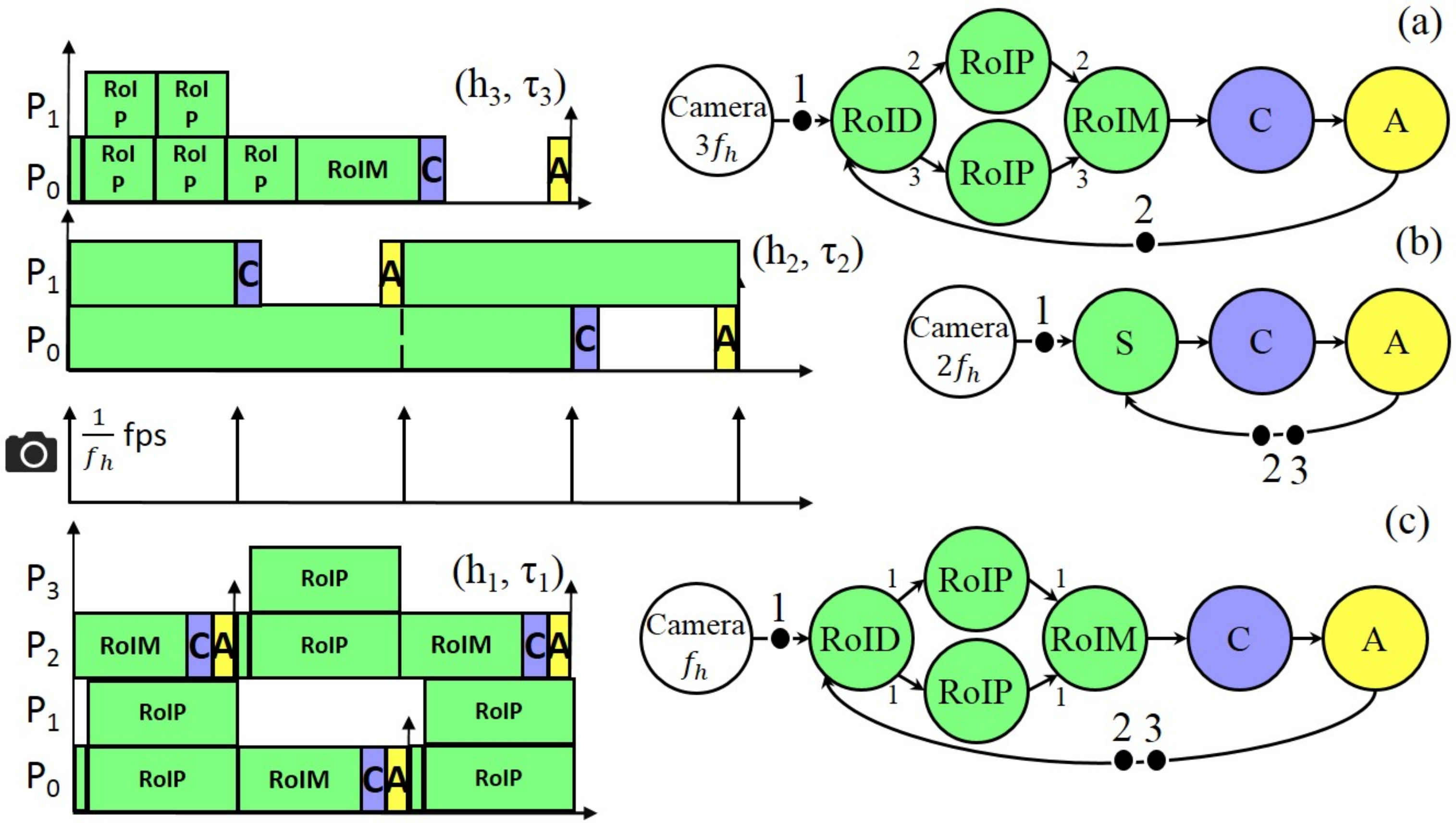


Workload scenarios

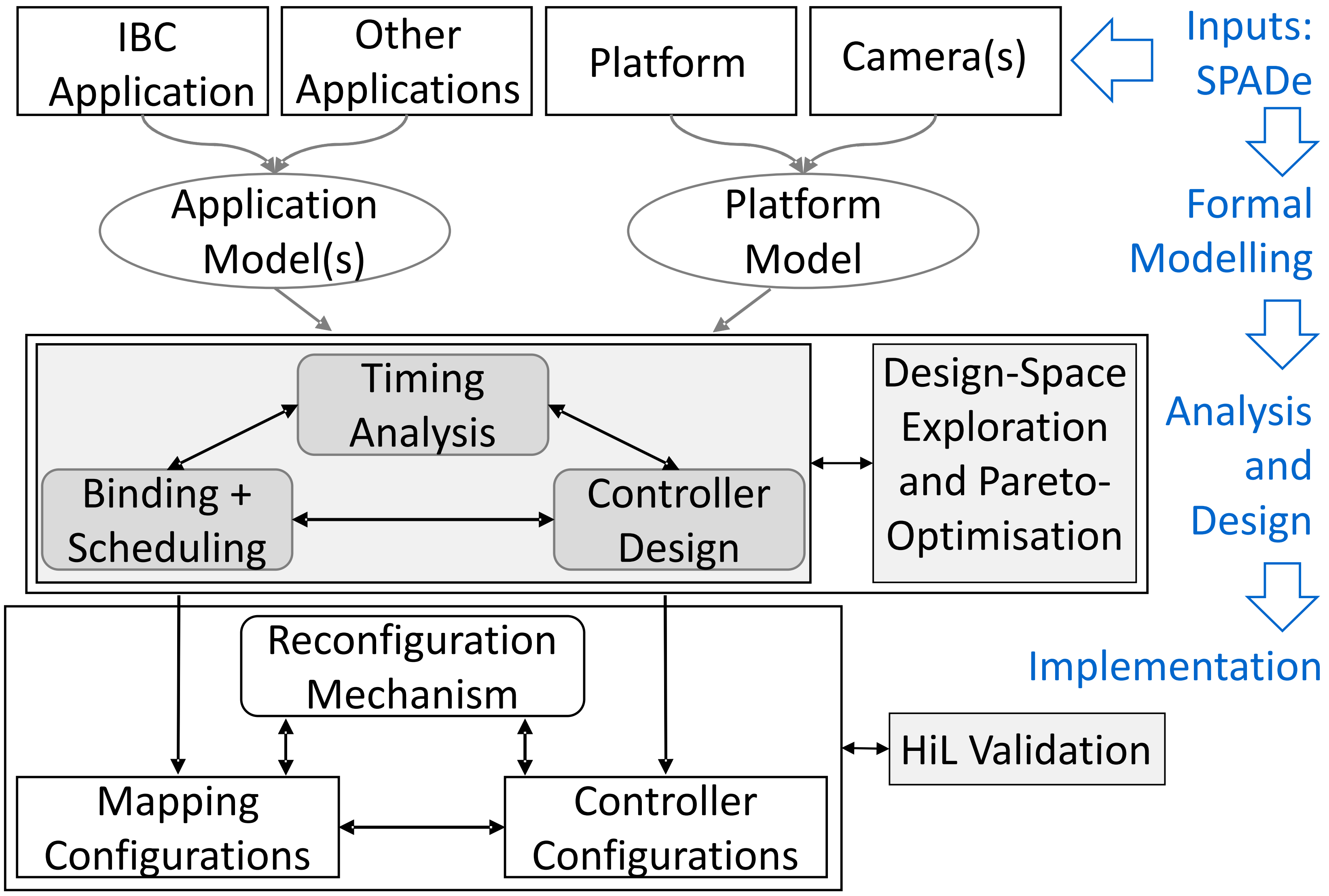


Pipelining and/or parallelization

- Throughput of the dataflow graph = sampling period
- Latency of the dataflow graph = sensor-to-actuator delay

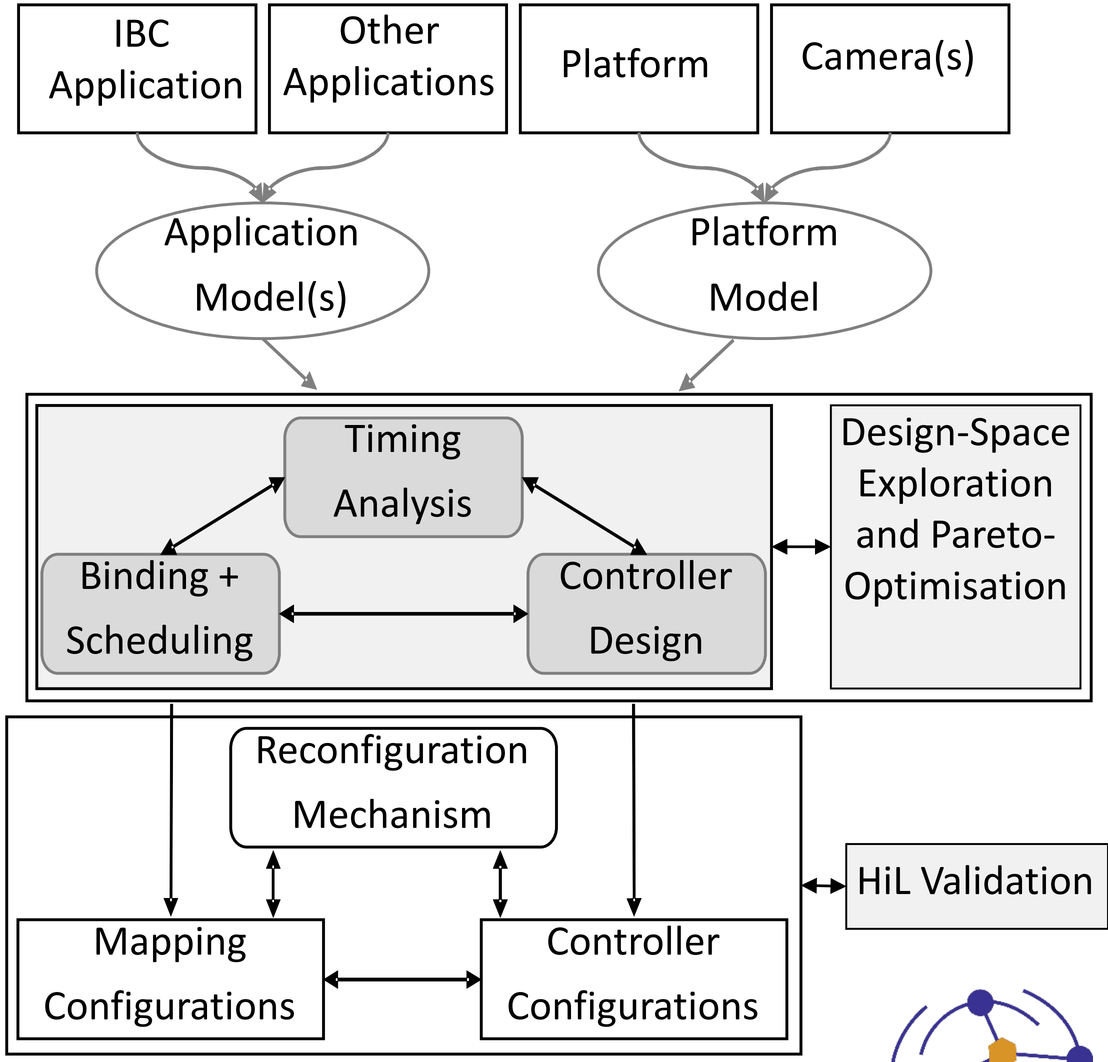


Scenario- and Platform-Aware Design flow



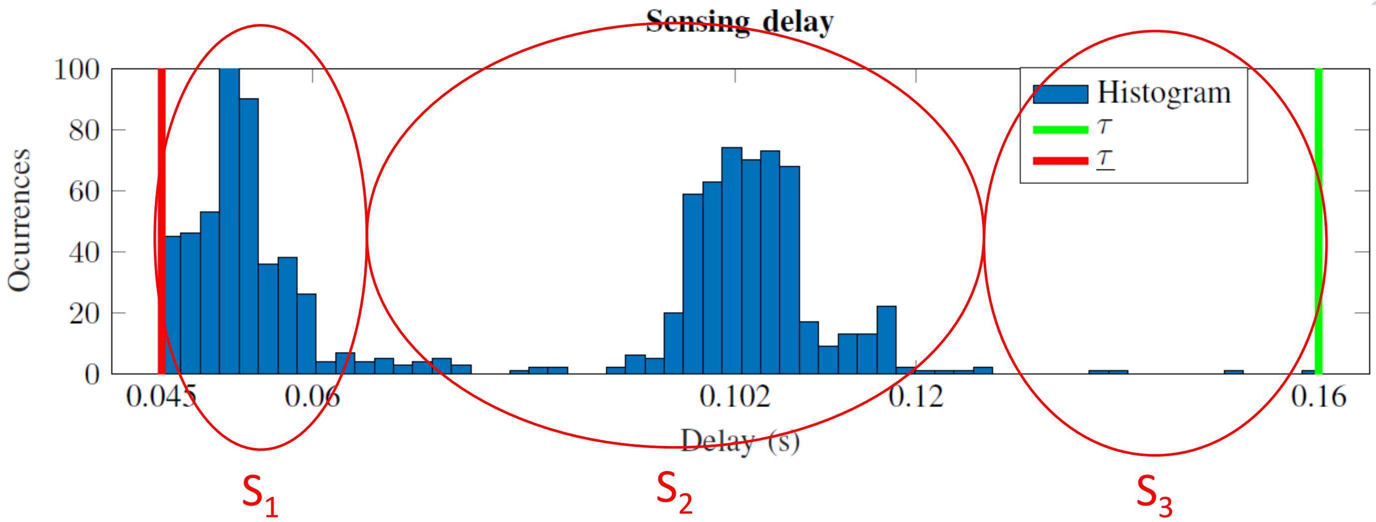
SPADe approach

1. Identify, model, and characterise workload (scenario) variations
   - PERT distribution
   - Discrete-time Markov chain
2. Find optimal mappings for a given platform allocation
   - SDF3 flow
3. Identify system scenarios
   - Implementation constraints
4. Design a controller
   - LQR with worst-case sampling period
   - Switched linear control (SLC) system
   - Markovian jump linear system (MJS)
   - Pipelined controller

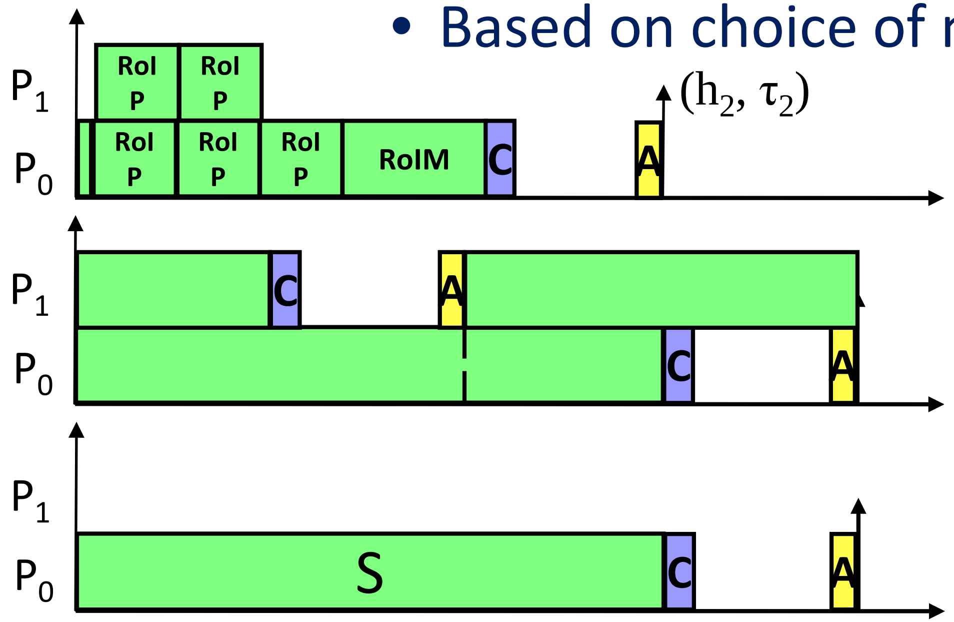


Scenario identification

- Based on workload



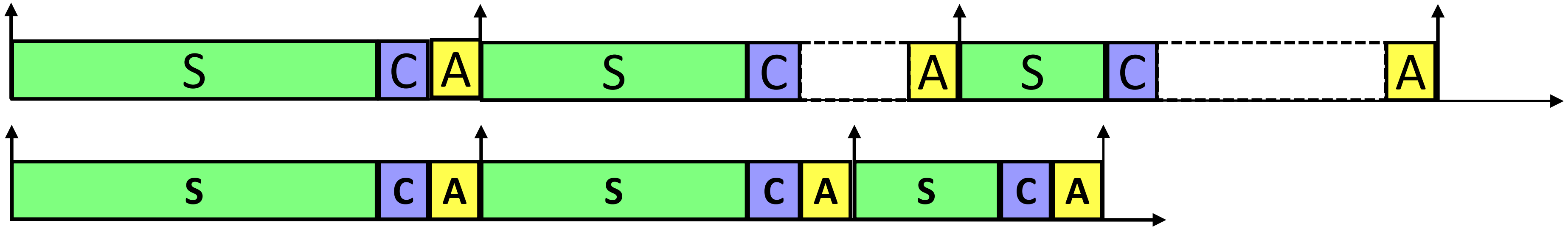
- Based on choice of mapping and choice of pipelining and/or parallelization



Control Design

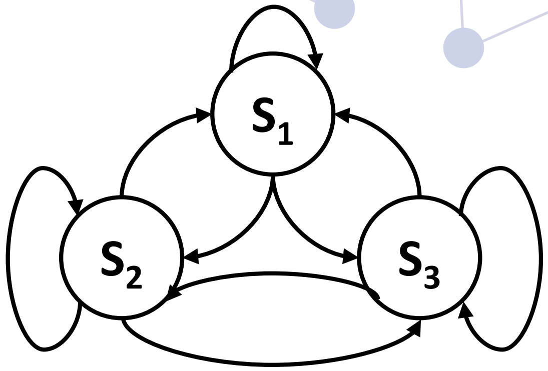
- LQR control
- Switched linear control (SLC)
  - Identify system scenarios (from e.g. PERT distribution)
  - Prove stability (common/switched quadratic Lyapunov function)

$$J(u) = \sum_{k=0}^{\infty} z[k]^T d_s C_{aug}^T C_{aug} z[k] + d_u^2 |u[k]|^2$$



Control Design

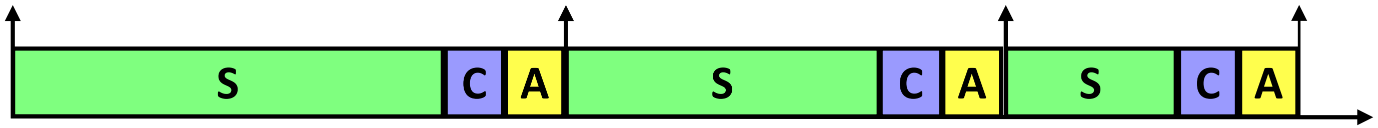
- Markovian jump linear system (MJS)
  - Model workload variations as discrete-time Markov chain



$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix}$$

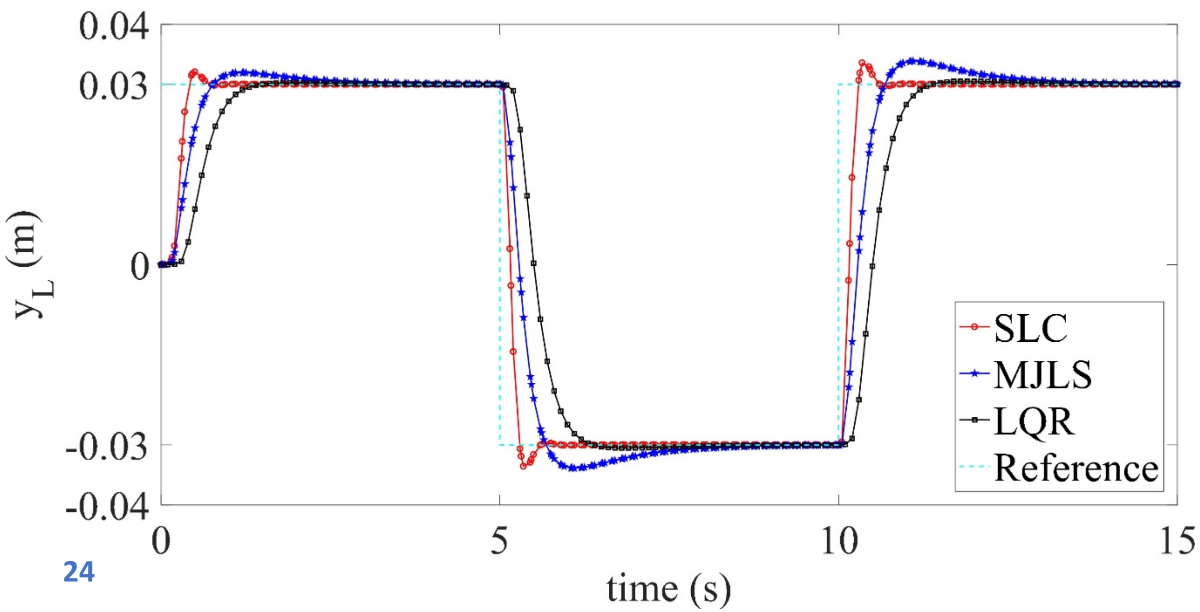
$$\begin{aligned} z[k+1] &= A_{aug,\theta[k]} z[k] + B_{aug,\theta[k]} u[k] \\ y_z[k] &= C_{aug} z[k] \end{aligned}$$

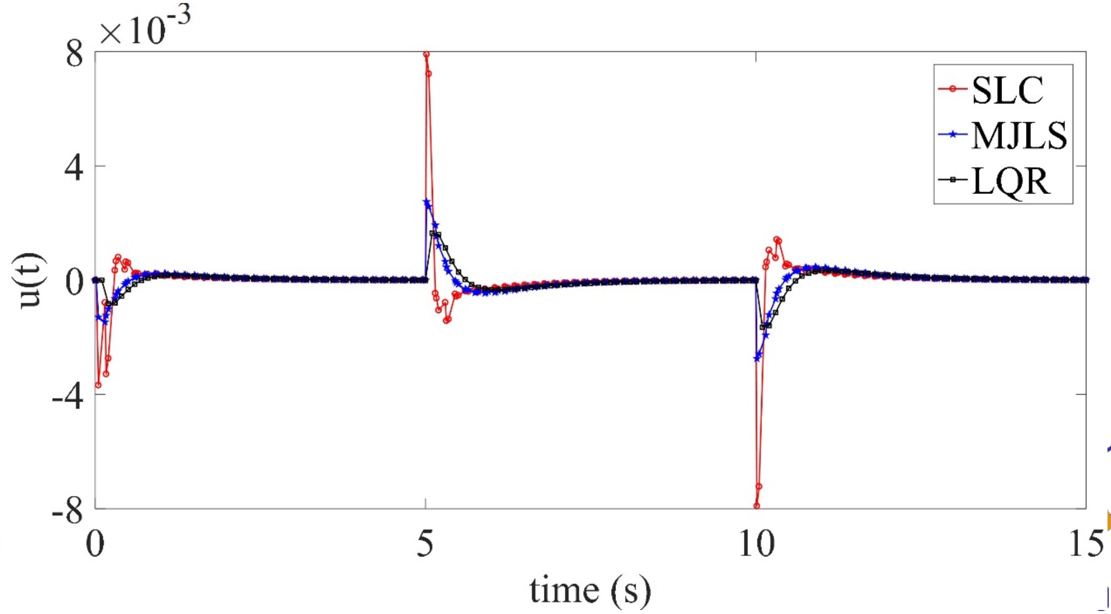
$$J(\theta[0], z[0], u[0]) = \sum_{k=0}^{\infty} \mathbb{E}[z[k]^T C_{aug}^T C_{aug} z[k] + d_u^2 |u[k]|^2]$$



Design guidelines

Available system knowledge	QoC metrics				
	Performance		Control energy		Performance and Energy
	MSE	ST	MCE	PSD	
Only worst-case workload information	LQR	LQR	LQR	LQR	LQR
Frequently occurring workloads as a PERT	SLC	SLC	LQR	LQR	SLC/ LQR
Frequently occurring workloads and their transition probabilities as a DTMC	SLC/ MJS	SLC/ MJS	MJS/ LQR	MJS/ LQR	MJS





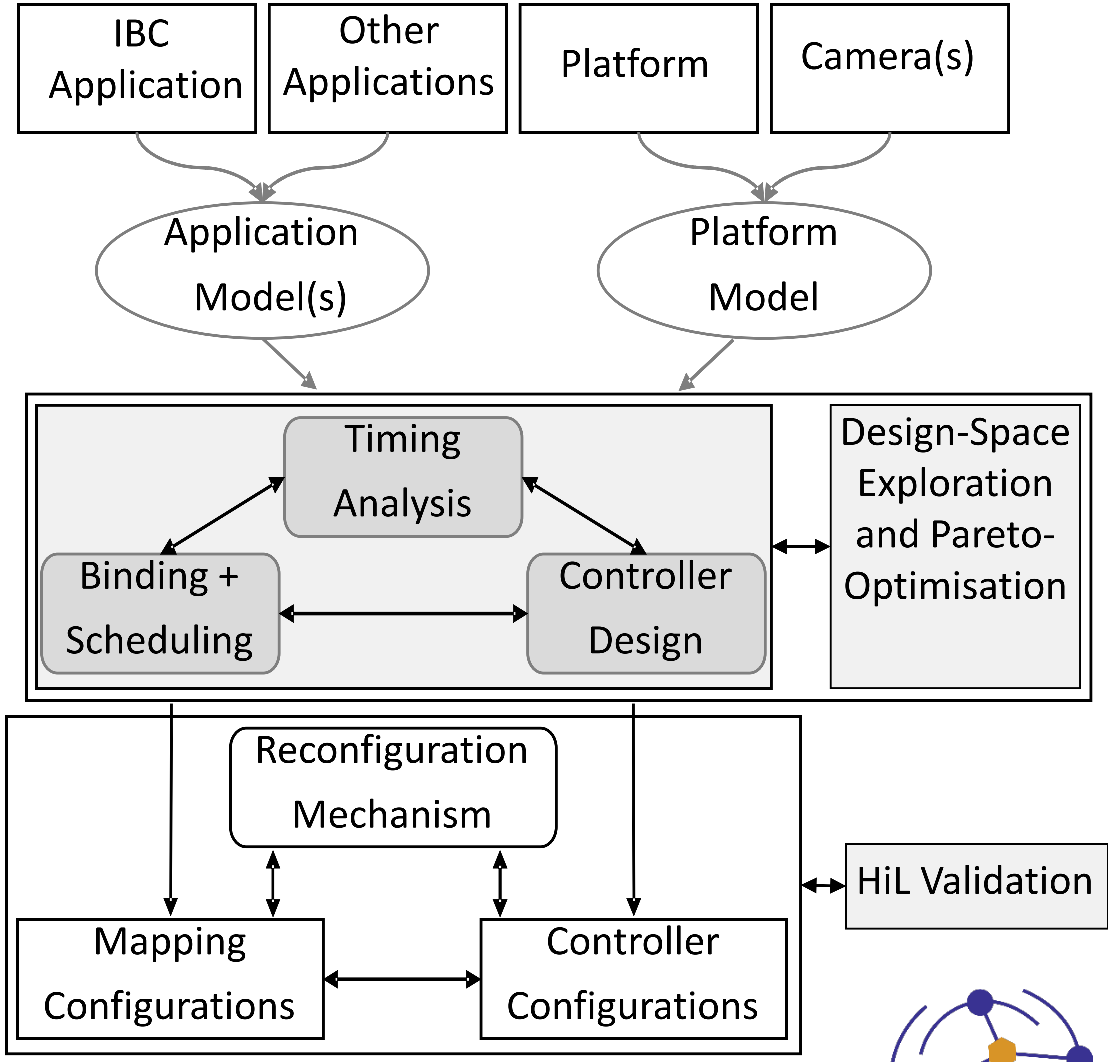
Conclusion

How to cope with long image sensing delay?

- SPADe approach
- Considering workload variations is beneficial
- Pipelining
- Parallelization

Future work:

- Develop I^{2}C tool based on SPADe approach
  - Inputs: application and platform model, requirements and constraints
  - Output: System configurations and controller code



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