Multi-Objective Co-Optimization of FlexRay-based Distributed Control Systems

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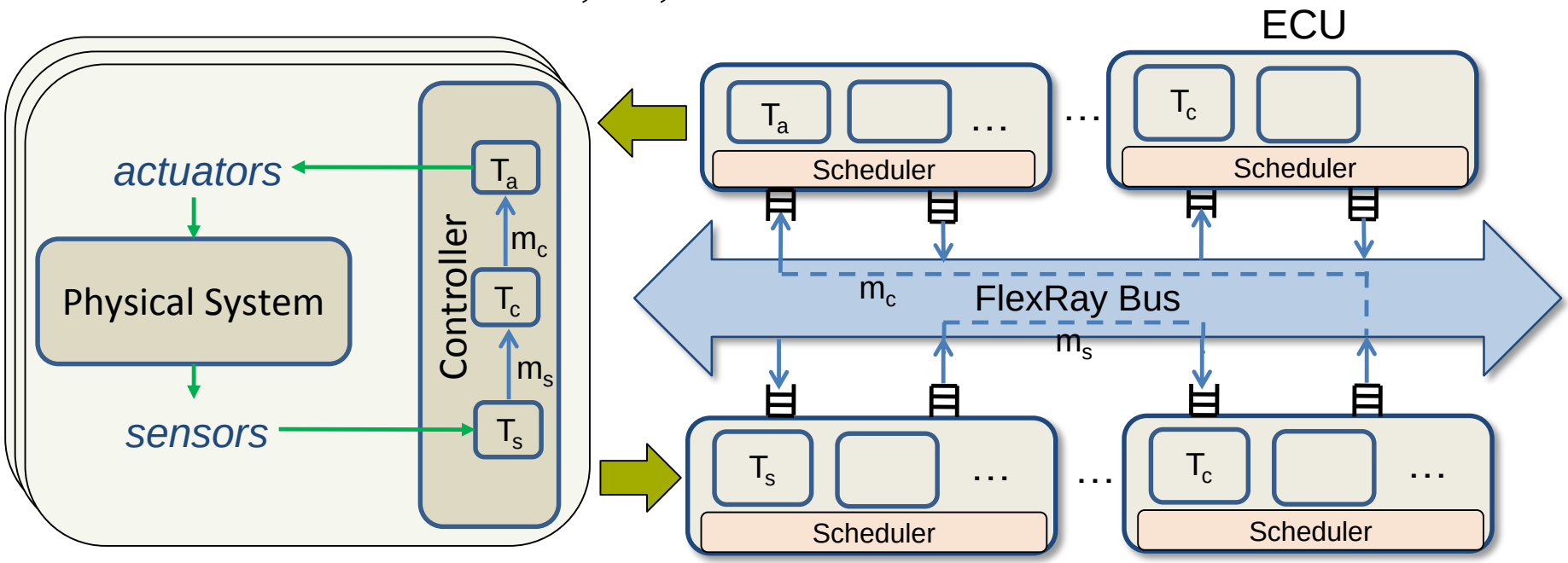
Overview

- FlexRay-based distributed control systems
- Co-synthesis of
  - Control parameters
  - Platform parameters
- Co-optimization of
  - Overall system performance
  - Communication cost, i.e., bus utilization



Introduction

Motivation:

- Separation between controller design and implementation is not sustainable

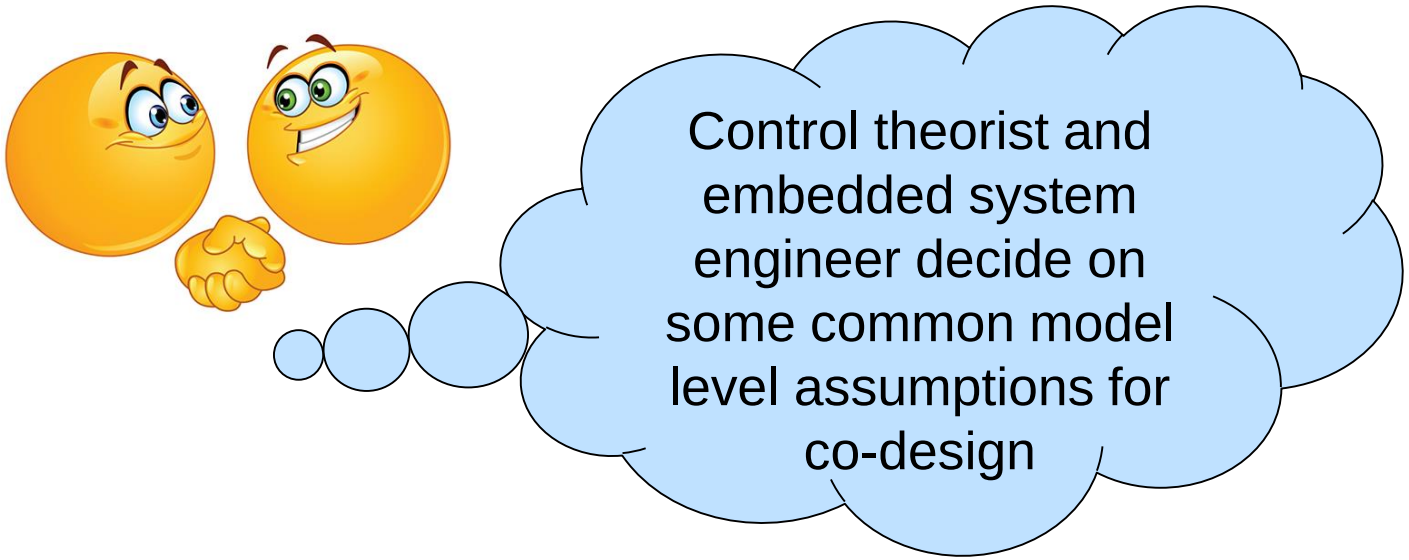
Control theorist says these are implementation details.
Not my problem!

Embedded system engineer says model level assumptions are not satisfied by implementation

Introduction

Motivation:

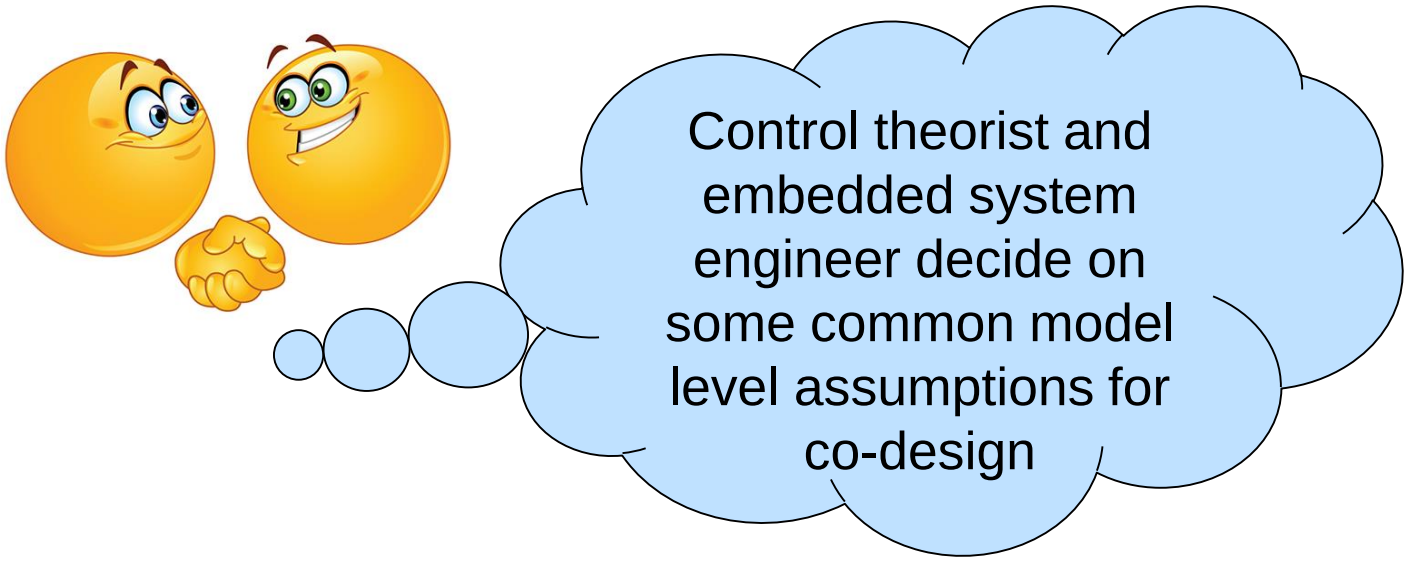
- Separation between controller design and implementation is not sustainable
- Need for co-design of control and platform parameters



Introduction

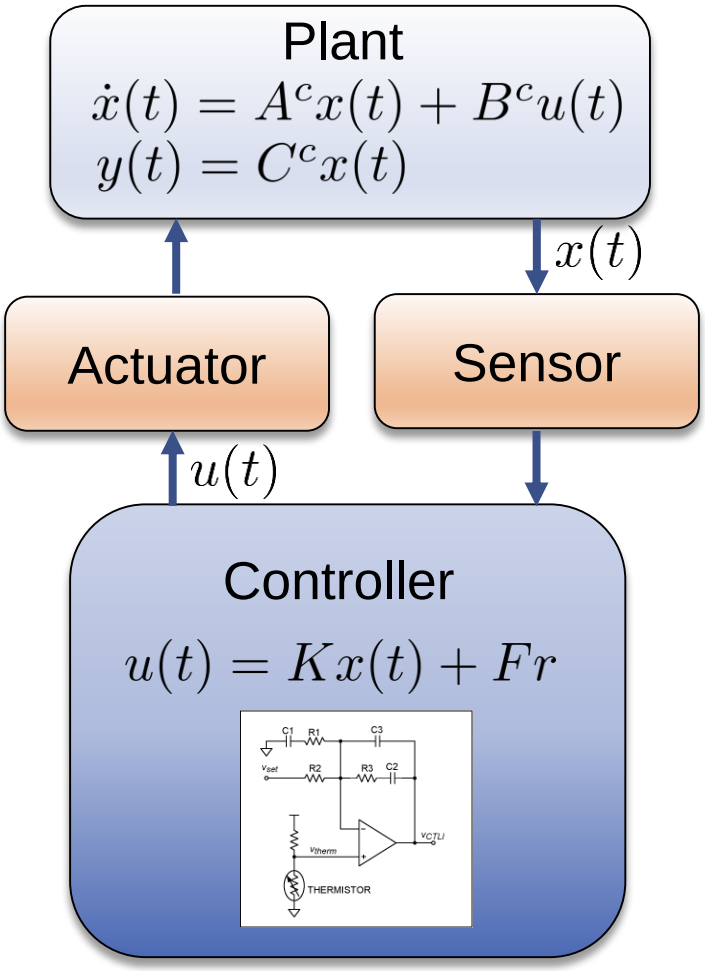
Challenge:

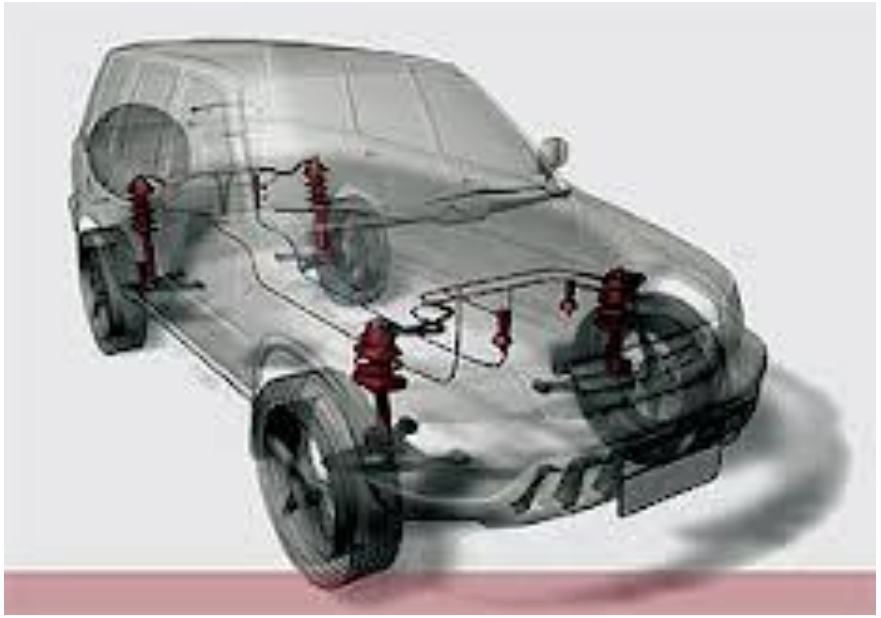
- Large design space including control and platform parameters
  - No standard closed-form optimal control design framework
  - Platform requires configuration of huge number of parameters



Feedback Control Systems

- Continuous-time model:

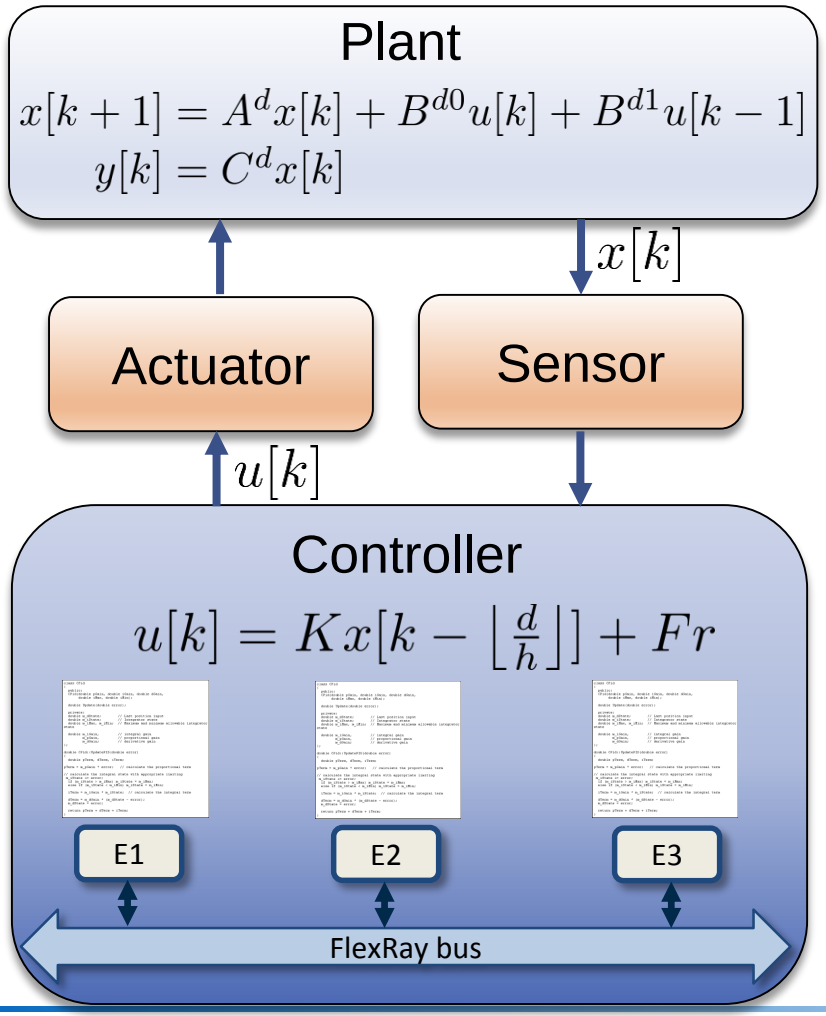




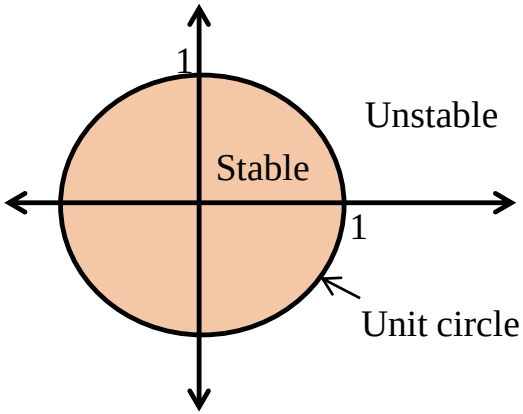
Car suspension system

Feedback Control Systems

- Discrete-time model:
  - Delay (d) and sampling period (h)



- $[A^d, B^{d0}, B^{d1}, C^d]$ can be calculated from $[A^c, B^c, C^c]$ and $[h, d]$
- Closed-loop system poles determine the system stability



Stability and Pole-Placement

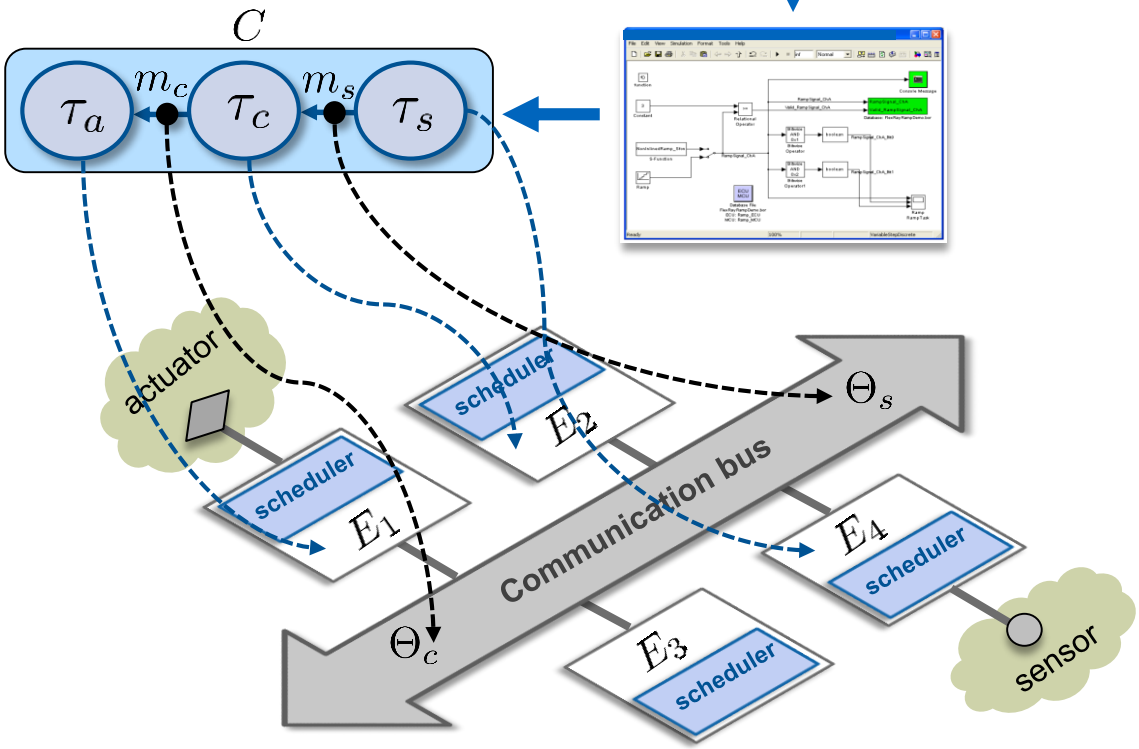
Distributed Time-Triggered Control System

Car Suspension

Distributed Time-Triggered Control System

Car Suspension

$$x[k+1] = A^d x[k] + B^d u[k]$$
$$u[k] = Kx[k-1] + Fr$$



Multiple processing units (PUs) connected via a bus

Distributed Time-Triggered Control System

Car Suspension

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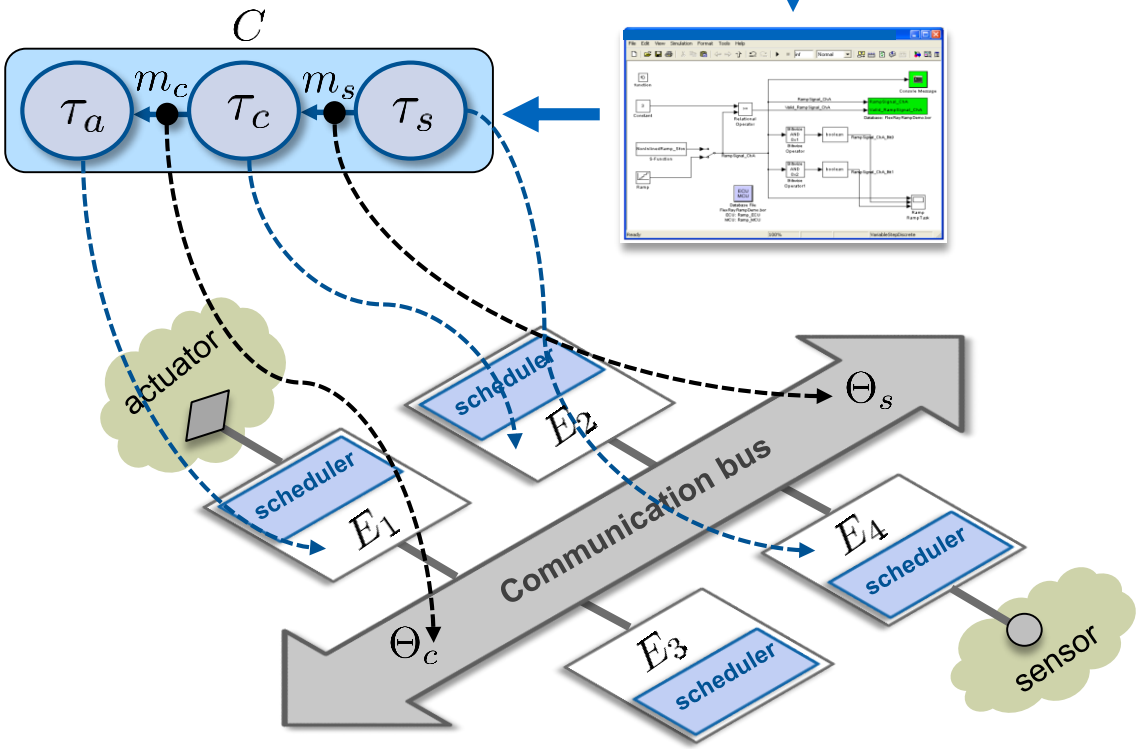


Multiple ECUs connected via a bus

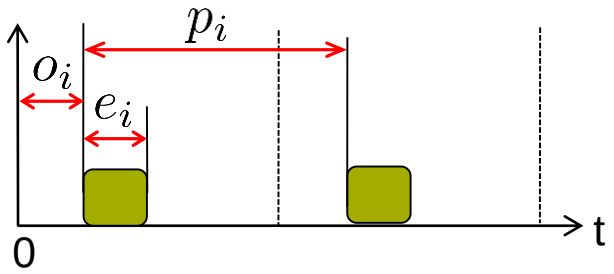
Task model:

- $\tau_x = \{o_x, p_x, e_x\}$
  - Offset o_x
  - Period p_x
  - WCET e_x
- k[th] execution start time

$$t(\tau_i, k) = o_i + (k-1)p_i$$

- k[th] execution finish time

$$\tilde{t}(\tau_i, k) = o_i + (k-1)p_i + e_i$$



FlexRay Communication

- FlexRay time is organized as an infinite repetition of series of 64 consecutive cycles (0 ... 63)

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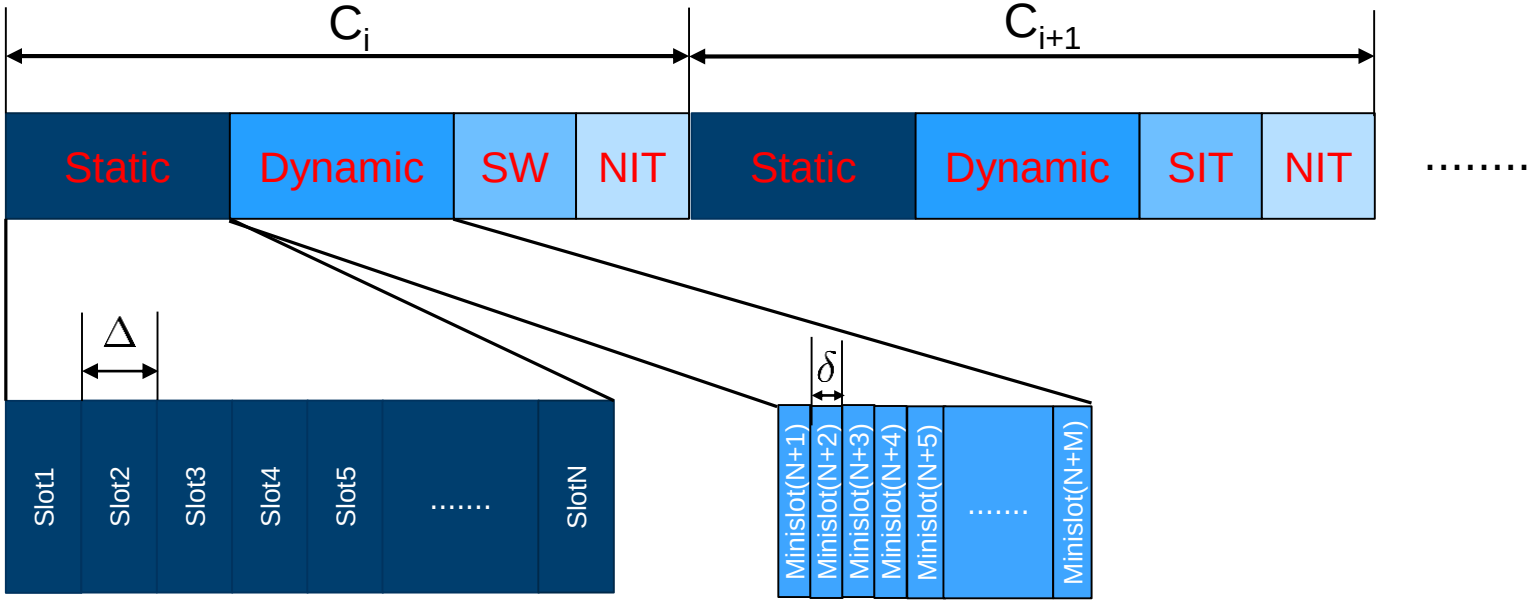


- Each cycle is of fixed length T_{bus} and consists of:
  - Static segment
  - Dynamic segment
  - Symbol Window
  - Network Idle Time

FlexRay Communication

FlexRay frame model

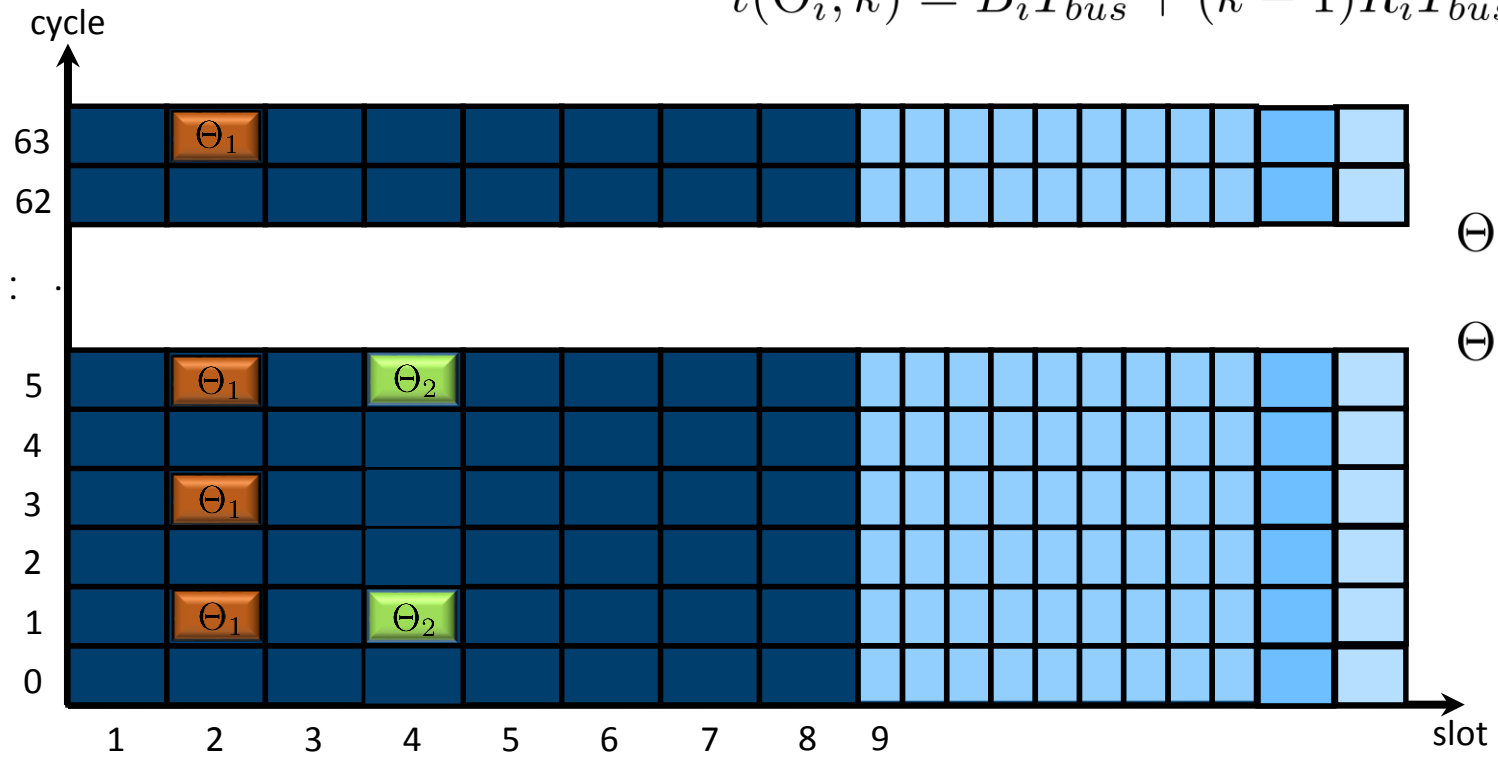
- $\Theta_x = \{S_x, B_x, R_x\}$
  - Slot identifier S_x
  - Base cycle B_x
  - Repetition rate R_x

- k[th] transmission start time

$$t(\Theta_i, k) = B_i T_{bus} + (k-1) R_i T_{bus} + (S_i - 1)\Delta$$

- k[th] transmission finish time

$$\tilde{t}(\Theta_i, k) = B_i T_{bus} + (k-1) R_i T_{bus} + S_i \Delta$$



$$\Theta_1 = \{2, 1, 2\}$$

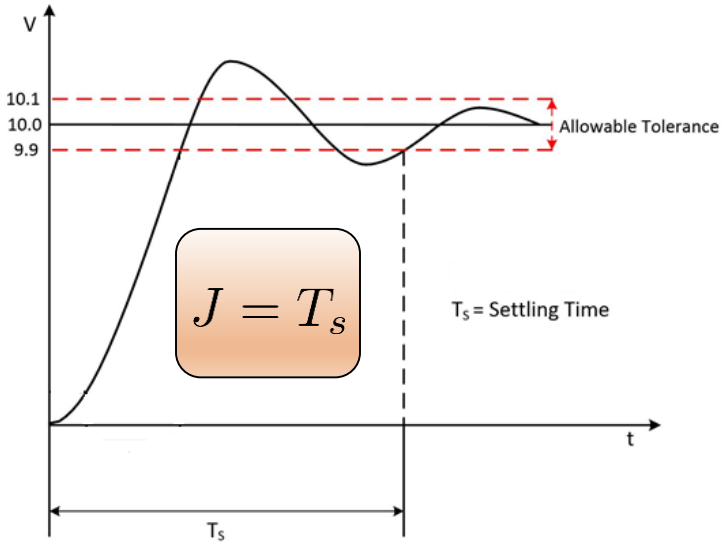
$$\Theta_2 = \{4, 1, 4\}$$

Objective Formulation

Overall system performance J_o

- Performance metrics like settling time, cost function, etc.
- Control performance must satisfy the performance criterion J^r
- Normalized control performance $J^n = \frac{J}{J^r} \times 100\%$

- $J_o = \sum_{C_i \in C} w_i J_i^n$ where $\sum_{C_i \in C} w_i = 1$



$$J = CF = \sum_{k=0}^{n} \left[\lambda u[k]^2 + (1-\lambda)(r - y[k])^2\right] h$$

Objective Formulation

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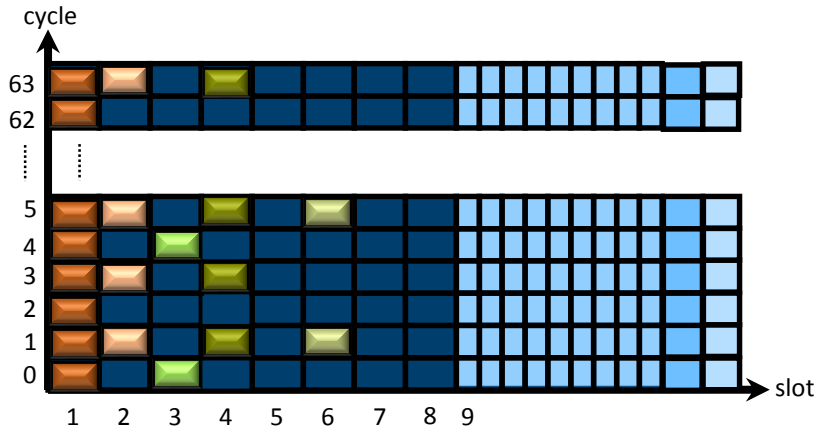
Bus utilization U

- Number of slots used in 64 consecutive cycles
- Slots used by a frame Θ_i is $\frac{64}{R_i}$
- $U = \sum_{\Theta_i \in \Gamma} \frac{64}{R_i}$
- Fraction of static bandwidth used

$$U_{\%} = \frac{U}{64N} \times 100\%$$



$$U = 64 + 32 + 16 + 32 + 16 = 160$$

$$U_{\%} = \frac{160}{512} \times 100\% = 31.25\%$$

Problem Description

Control Side

Given Parmeters:

- Plant Model (A_i^c, B_i^c, C_i^c)
- Performance metric $(T_s \text{ or } CF)$
- Required performance J_i^r

Platform Side

Given Parmeters:

- Bus configuration (T_{bus}, N, Δ)
- WCETs $(e_{s,i}, e_{c,i}, e_{a,i})$
- Task mappings

Problem Description

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- Plant Model (A_i^c, B_i^c, C_i^c)
- Performance metric $(T_s$ or $CF)$
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Variables:

- Sampling period h_i
- Feedback control gain K_i
- Feedforward control gain F_i

Platform Side

Given Parmeters:

- Bus configuration (T_{bus}, N, Δ)
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- Task mappings

Variables:

- Sensor task $\{o_{s,i}, p_{s,i}, e_{s,i}\}$
- Sensor message $\{S_{s,i}, B_{s,i}, R_{s,i}\}$
- Control task $\{o_{c,i}, p_{c,i}, e_{c,i}\}$
- Control message $\{S_{c,i}, B_{c,i}, R_{c,i}\}$
- Actuator task $\{o_{a,i}, p_{a,i}, e_{a,i}\}$

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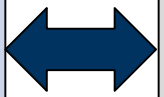
Objective:
- Bus utilization U

Control and Platform Interdependence

- Sampling period h_i
- Sensor-to-actuator delay d_i



- Task schedules $[\tau_s, \tau_c, \tau_a]_i$
- Message schedules $[\Theta_s, \Theta_c]_i$

Control and Platform Interdependence

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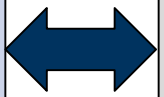

- Task schedules $[\tau_s, \tau_c, \tau_a]_i$
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Periodicity constraint

- Sampling period h_i of a control application C_i must coincide with the periods of the component tasks and message frames.
- $$\underset{\substack{C_i \in \mathcal{C} \\ x \in \{s,c,a\} \\ y \in \{s,c\}}}{\forall} (p_{x,i} = R_{y,i} T_{bus} = h_i)$$
- $$\underset{\substack{C_i \in \mathcal{C} \\ y \in \{s,c\}}}{\forall} (R_{y,i} \in \{1, 2, 4, 8, 16, 32, 64\})$$
- $h_i \in \{2^k T_{bus} | 0 \leq k \leq 6\}$

Control and Platform Interdependence

- Sampling period h_i
- Sensor-to-actuator delay d_i

$\Leftrightarrow$

- Task schedules $[\tau_s, \tau_c, \tau_a]_i$
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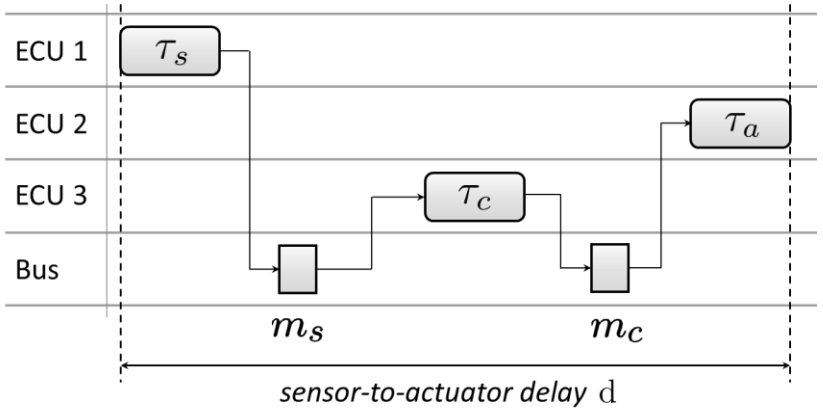
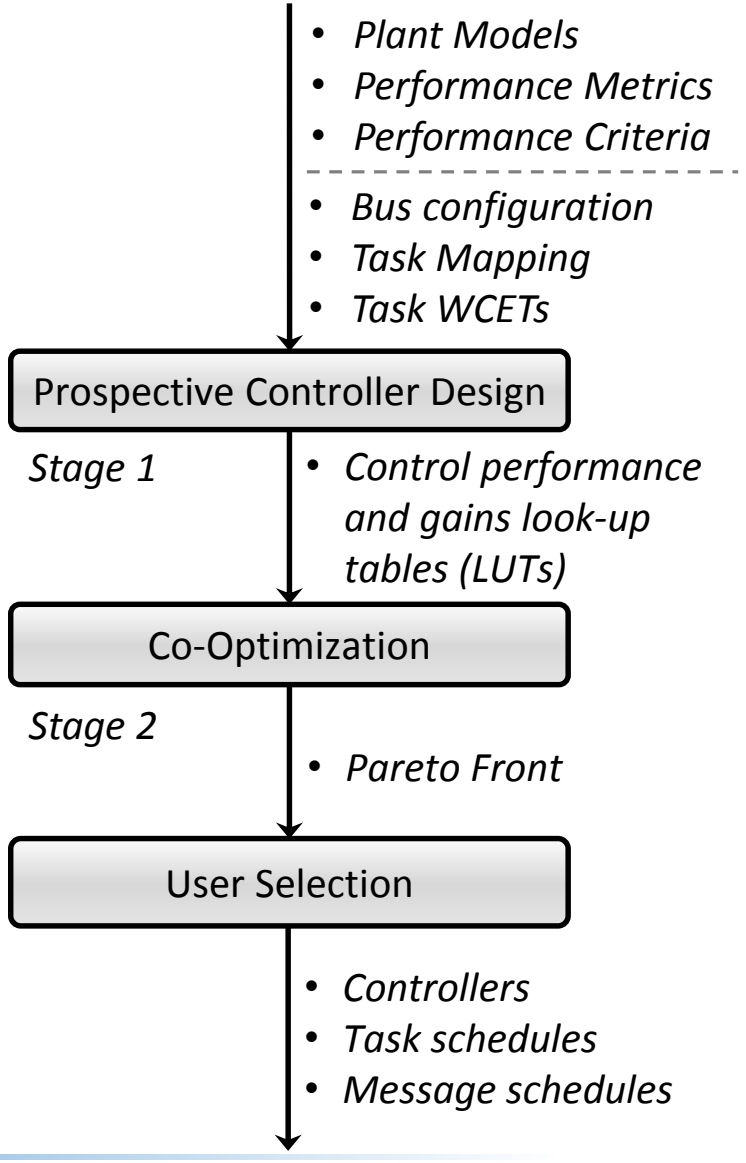
Delay constraint



- $\forall_{\substack{k \in \mathbb{Z}^* \\ C_i \in \mathcal{C}}} (\tilde{t}(\tau_{a,i}, k) - t(\tau_{s,i}, k) = d)$

The Proposed Approach



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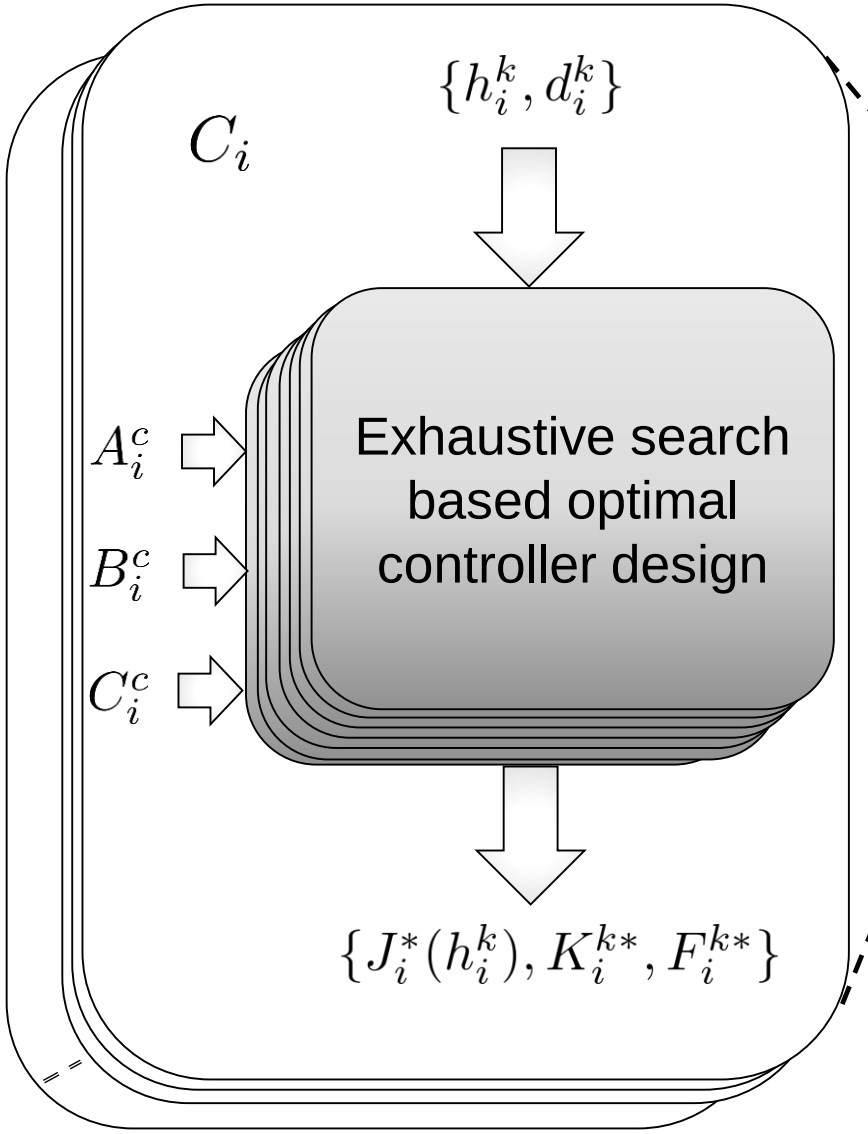


- *Plant Models*
- *Performance Metrics*
- *Performance Criteria*

- *Bus configuration*
- *Task Mapping*
- *Task WCETs*

Prospective Controller Design

Stage 1

- *Control performance and gains look-up tables (LUTs)*

Co-Optimization

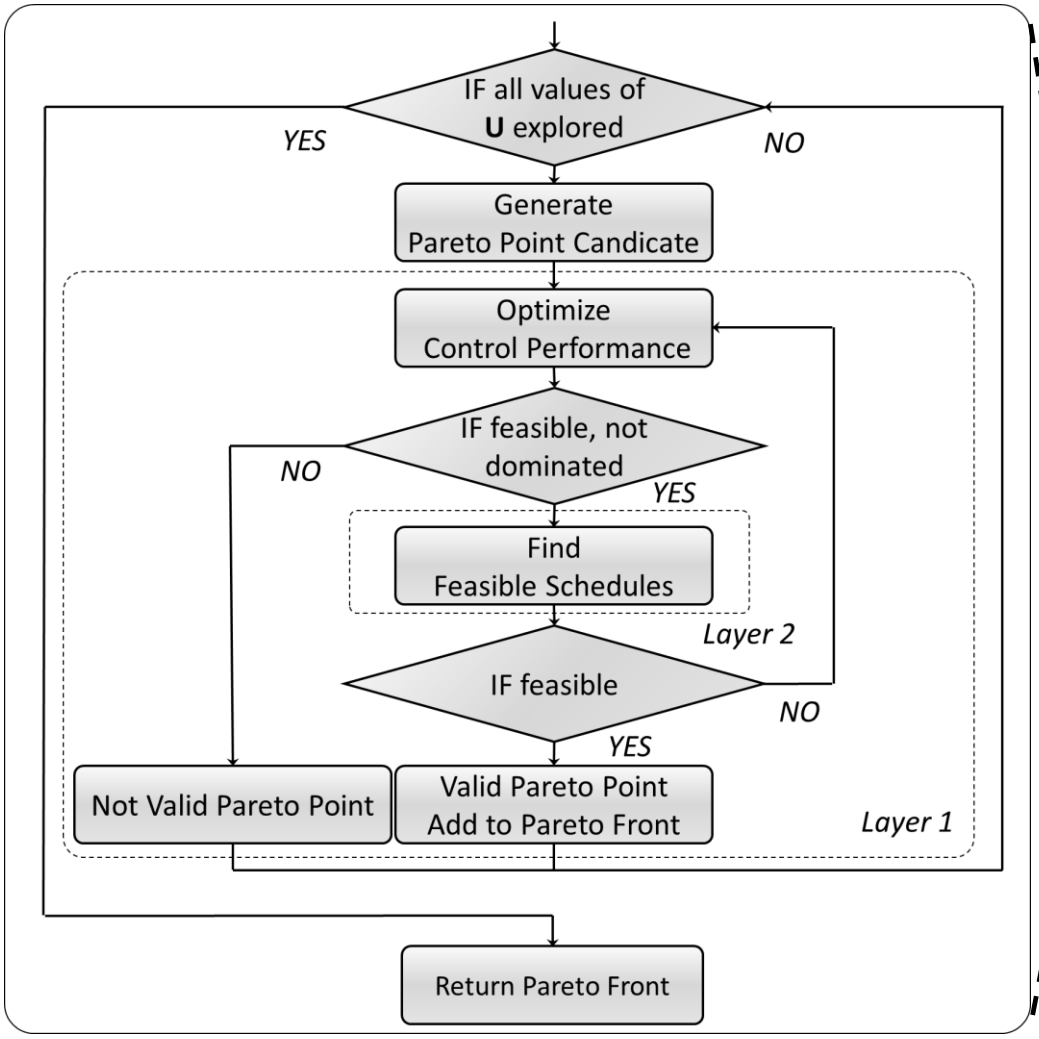
Stage 2

- *Pareto Front*

User Selection

- *Controllers*
- *Task schedules*
- *Message schedules*

The Proposed Approach



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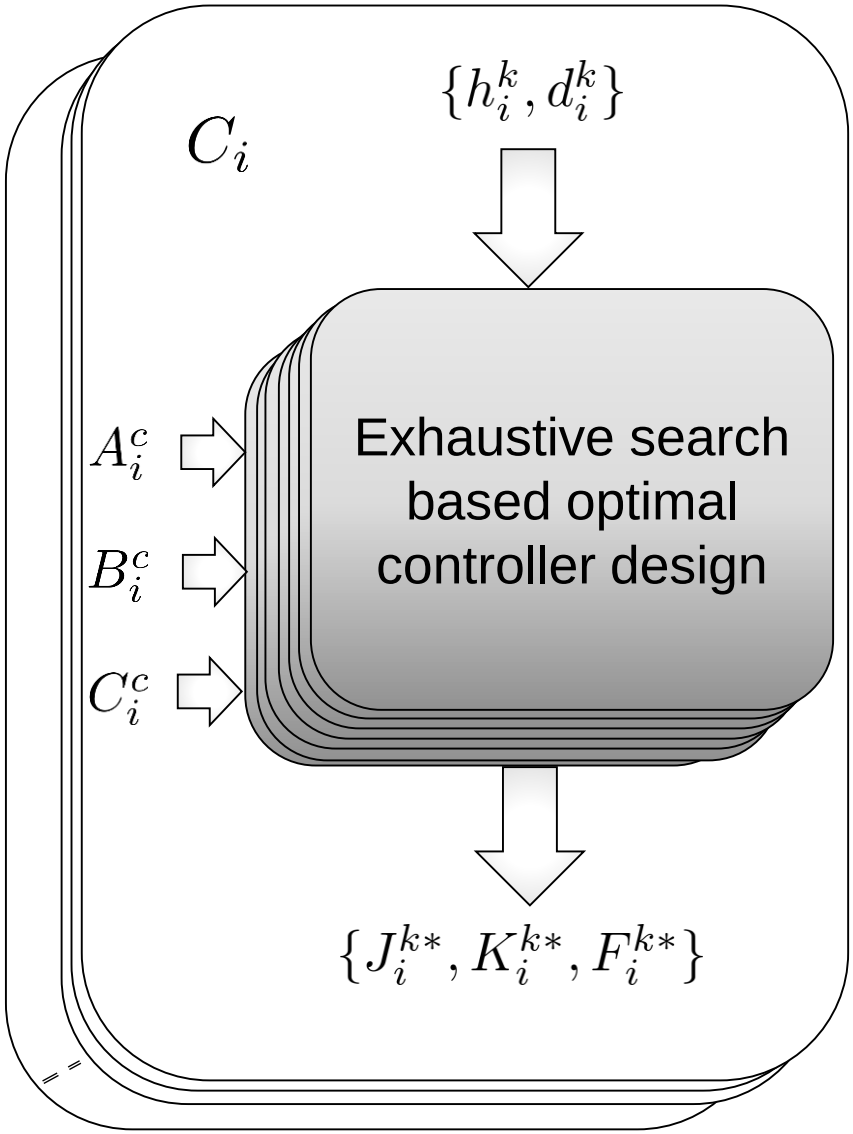
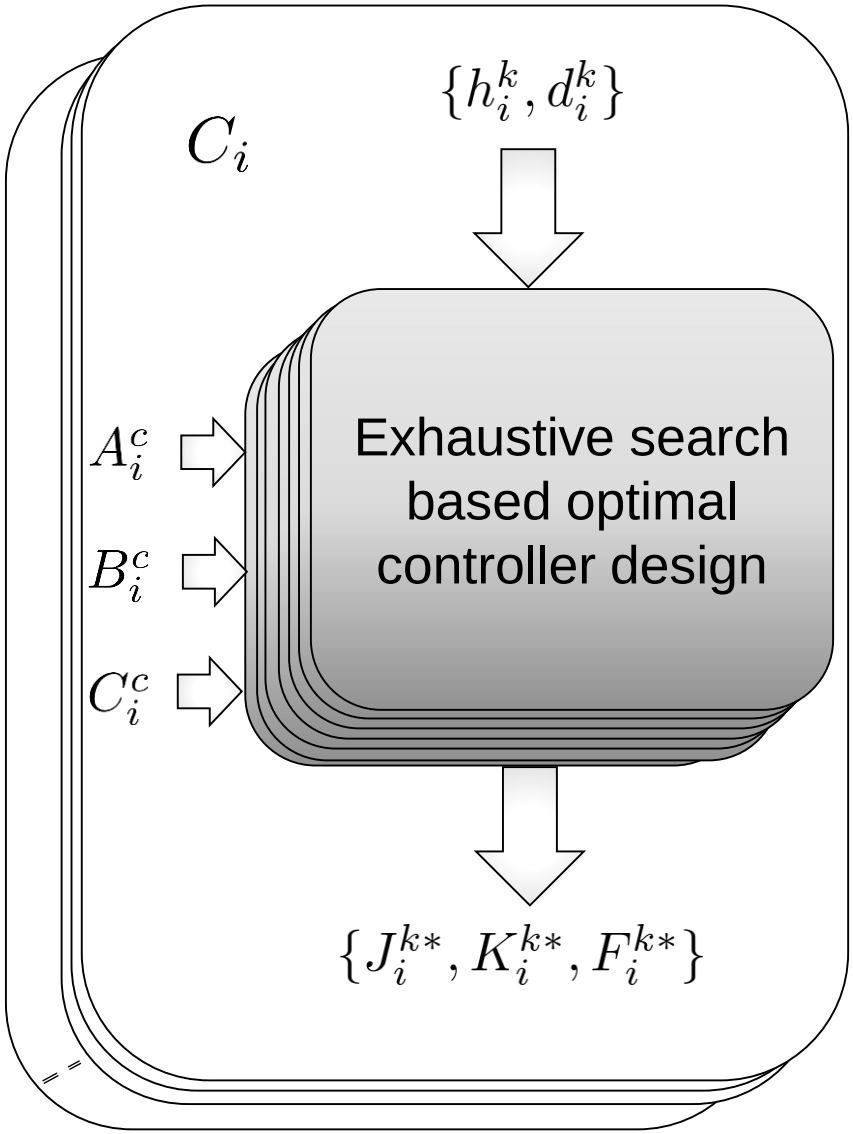
Stage 1: Prospective Controller Design

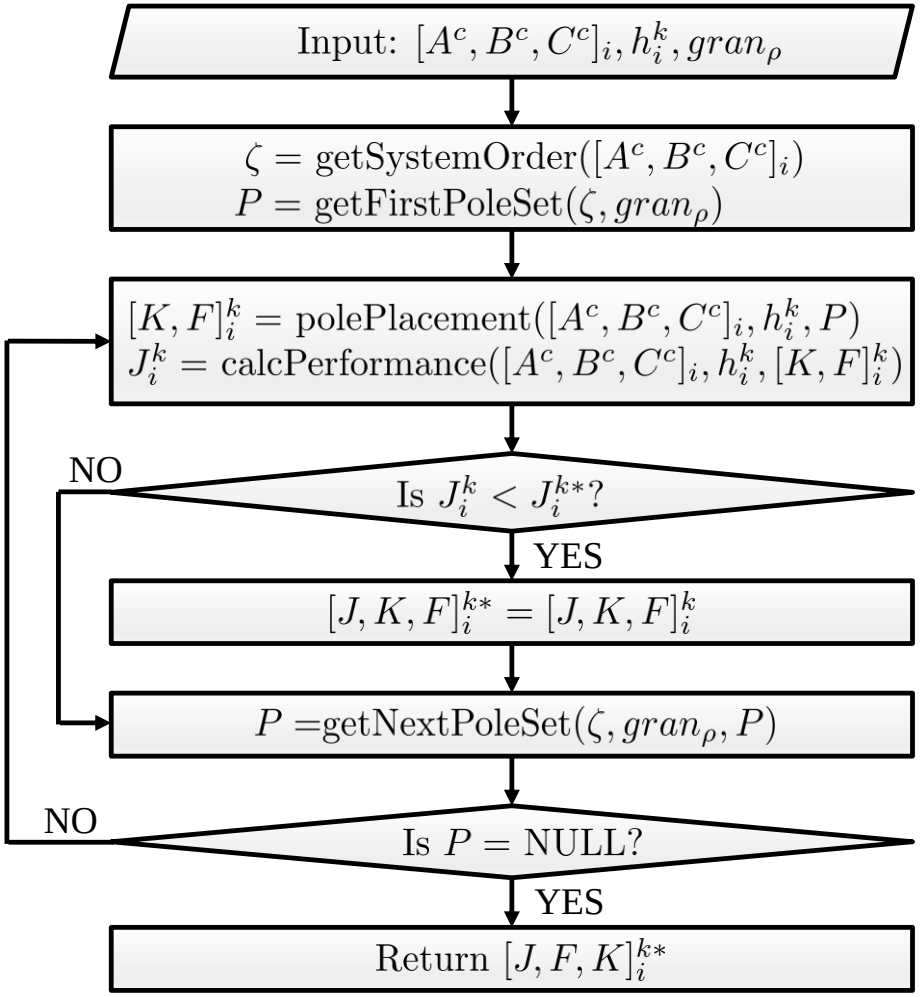


- $h_i \in \{2^k T_{bus} | 0 \leq k \leq 6\}$
- $d_i = h_i$
- Develop exhaustive search based optimal control design algorithm
  - Determine control gains K_i^{k*}, F_i^{k*} which optimizes the control performance to $J_i^*(h_i^k)$ at h_i^k, d_i^k

Stage 1: Prospective Controller Design



Optimal control design



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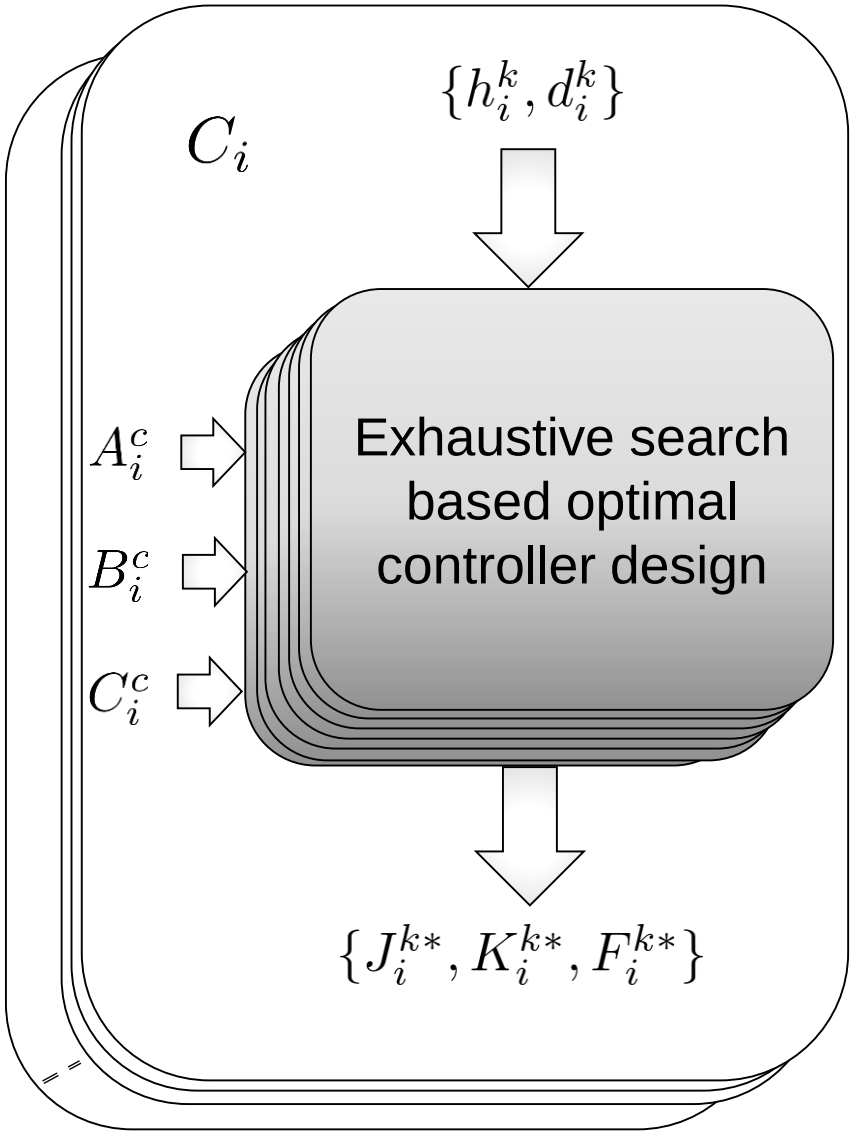
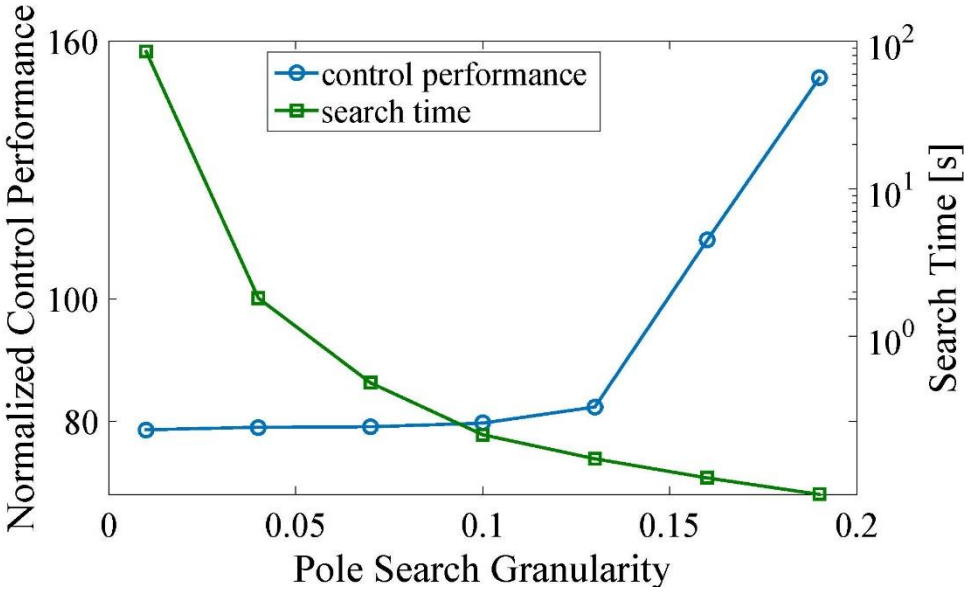


Effect of search granularity



Stage 2: Co-Optimization

Problem formulation

- Constraints
  - C1: Performance requirement
  - C2: Dataflow
  - C3: Non-overlapping tasks
  - C4: Non-overlapping messages

- Objectives
  - O1: Overall system performance
  - O2: Bus utilization

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(C1) Performance requirement

- For each control application C_i, control performance J_i, must satisfy the control performance requirement J_i^r.

$$\underset{C_i \in \mathcal{C}}{\forall} (J_i \leq J_i^r)$$

- If $h_i = 2^k T_{bus}$ then $J_i^{k*} \leq J_i^r$

Stage 2: Co-Optimization

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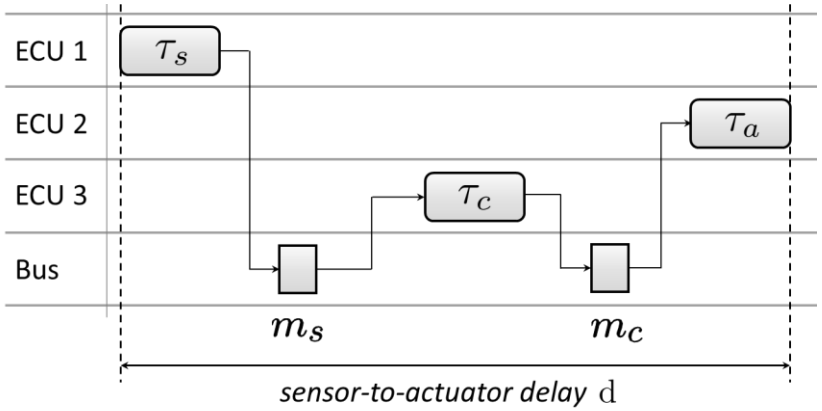
(C2) Dataflow



- $\underset{\substack{k\in\mathbb{Z}^* \\ C_i\in\mathcal{C}}}{\forall} (\tilde{t}(\tau_{s,i},k)+\epsilon < t(\Theta_{s,i},k))$
- $\underset{\substack{k\in\mathbb{Z}^* \\ C_i\in\mathcal{C}}}{\forall} (\tilde{t}(\Theta_{s,i},k) < t(\tau_{c,i},k)-\epsilon)$
- $\underset{\substack{k\in\mathbb{Z}^* \\ C_i\in\mathcal{C}}}{\forall} (\tilde{t}(\tau_{c,i},k)+\epsilon < t(\Theta_{c,i},k))$
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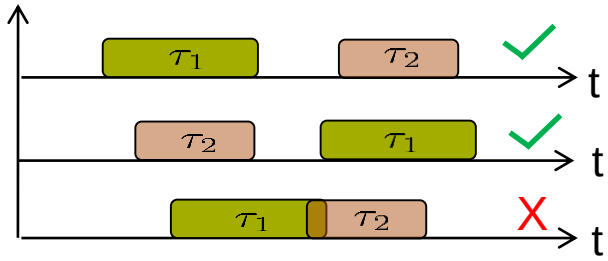
(C3) Non-overalapping tasks

- For two tasks mapped on the same ECU, none of their instances must overlap in time.



$$\forall_{\substack{C_i,C_j\in\mathcal{C}\\ x,y\in\{s,c,a\}\\ \tau_{x,i},\tau_{y,j}\in\mathcal{T}_{E_k}}} \Big[\big(\tilde{t}(\tau_{x,i},m)+\epsilon\cdot\mathbb{1}(x\in\{s,c\})< t(\tau_{y,j},n)-\epsilon\cdot\mathbb{1}(y\in\{c,a\})\big)$$

or

$$\big(\tilde{t}(\tau_{y,j},n)+\epsilon\cdot\mathbb{1}(y\in\{s,c\})< t(\tau_{x,i},m)-\epsilon\cdot\mathbb{1}(x\in\{c,a\})\big)\Big]$$

where,

$$\{m\in\mathbb{Z}^*|0\le m<lcm(p_{x,i},p_{y,j})/p_{x,i}\}$$

$$\{n\in\mathbb{Z}^*|0\le n<lcm(p_{x,i},p_{y,j})/p_{y,j}\}$$

Stage 2: Co-Optimization

Problem formulation

- Constraints
  - C1: Performance requirement
  - C2: Dataflow
  - C3: Non-overlapping tasks
  - C4: Non-overlapping messages
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  - O1: Overall system performance
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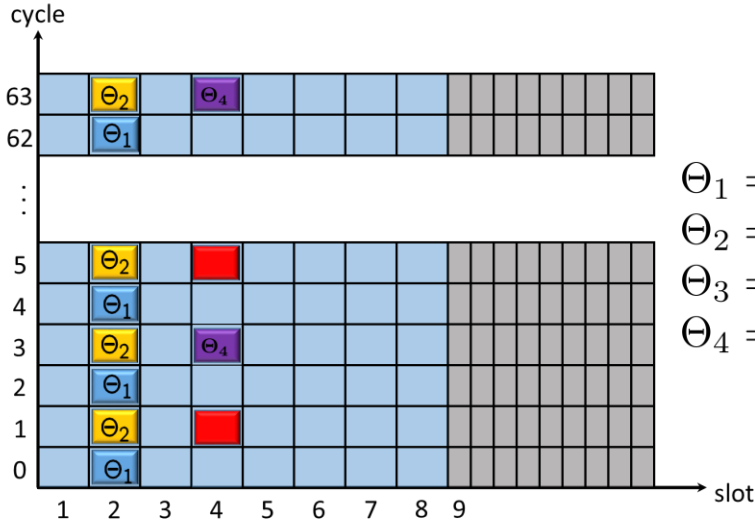
(C4) Non-overalapping messages

- No two messages must be transmitted in the same slot of the same cycle.



$$\forall_{\substack{C_i, C_j \in \mathcal{C} \\ x,y \in \{s,c\}}} \left(\text{if } S_{x,i} = S_{y,j} \text{ then } B_{x,i} + nR_{x,i} \neq B_{y,j} + mR_{y,j} \right)$$

where,

$$\{m \in \mathbb{Z}^* | 0 \leq m < lcm(p_{x,i}, p_{y,j})/p_{x,i}\}$$

$$\{n \in \mathbb{Z}^* | 0 \leq n < lcm(p_{x,i}, p_{y,j})/p_{y,j}\}$$

Stage 2: Co-Optimization

Problem formulation

- Constraints
  - C1: Performance requirement
  - C2: Dataflow
  - C3: Non-overlapping tasks
  - C4: Non-overlapping messages

- Objectives
  - O1: Overall system performance
  - O2: Bus utilization

(O1) Overall system performance

- $$J_o = \sum_{C_i \in \mathcal{C}} w_i J_i^n = 100 \sum_{C_i \in \mathcal{C}} \frac{w_i J_i}{J_i^r}$$

- $$J_o = 100 \sum_{C_i \in \mathcal{C}} w_i \sum_{k=0}^{6} \mu_{i,k} J_i^{k*}$$

$$h_i = \sum_{k=0}^{6} \mu_{i,k} h_i^k$$

where,

$$\mu_{i,k} \in \{0,1\}, \sum_{C_i \in \mathcal{C}} w_i = 1, \sum_{k=0}^{6} \mu_{i,k} = 1$$

Stage 2: Co-Optimization

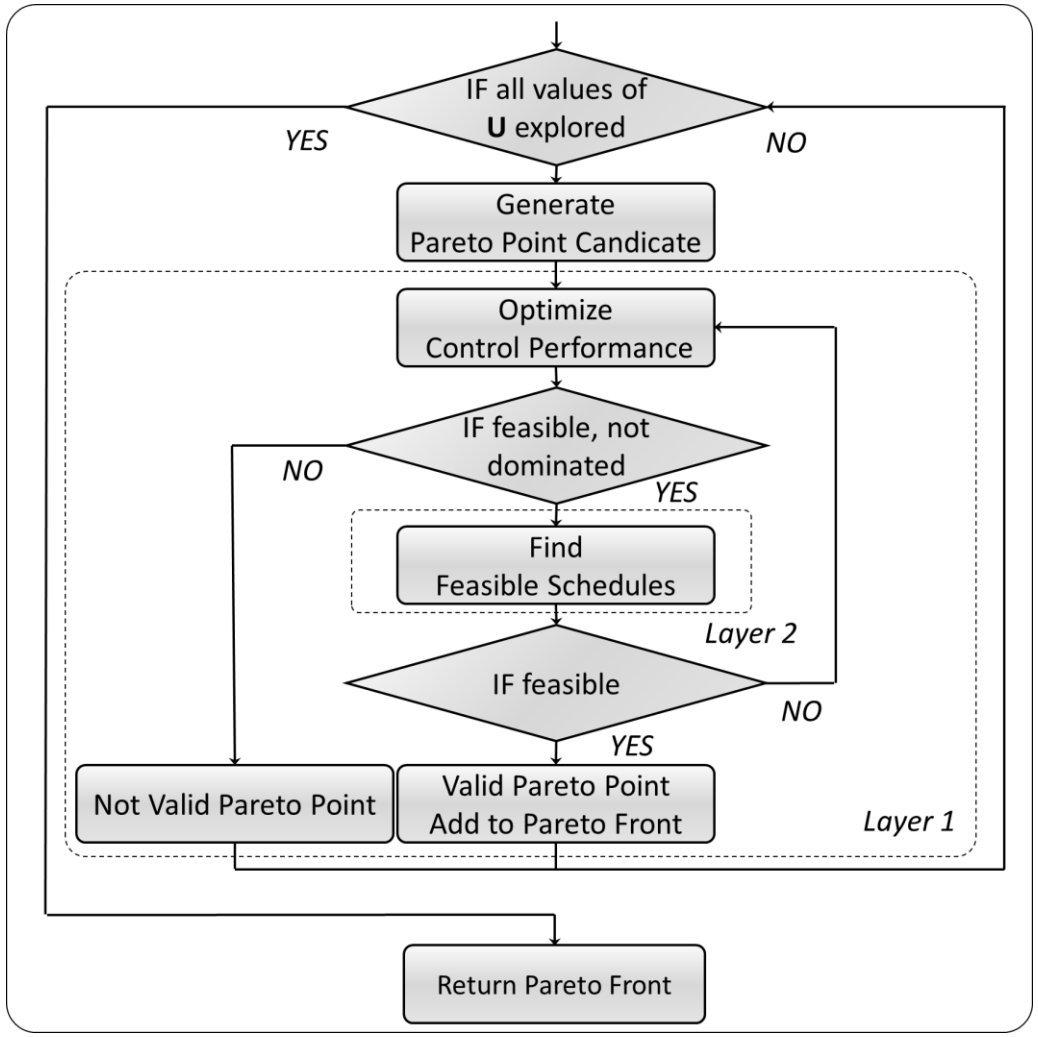
Problem formulation

- Constraints
  - C1: Performance requirement
  - C2: Dataflow
  - C3: Non-overlapping tasks
  - C4: Non-overlapping messages
- Objectives
  - O1: Overall system performance
  - O2: Bus utilization

(O2) Bus utilization

- $U = \sum_{\Theta_k \in \Gamma} \frac{64}{R_k}$
- $U = \sum_{C_i \in \mathcal{C}} \frac{64}{R_{s,i}} + \frac{64}{R_{c,i}}$
- $U = \sum_{C_i \in \mathcal{C}} \frac{128 T_{bus}}{h_i}$

Stage 2: Co-Optimization



Pareto front construction

- Pareto point is better than any other point in the design space in atleast one objective
- Discrete values of U
- Minimum value of U

$$\check{U} = \sum_{C_i \in \mathcal{C}} \frac{128 T_{bus}}{\hat{h}_i}, \text{ where}$$

$$\hat{h}_i = T_{bus} \cdot 2^{\max\{k | 0 \leq k \leq 6 \wedge J_i^{k*} \leq J_i^r\}}$$

- Maximum value of U

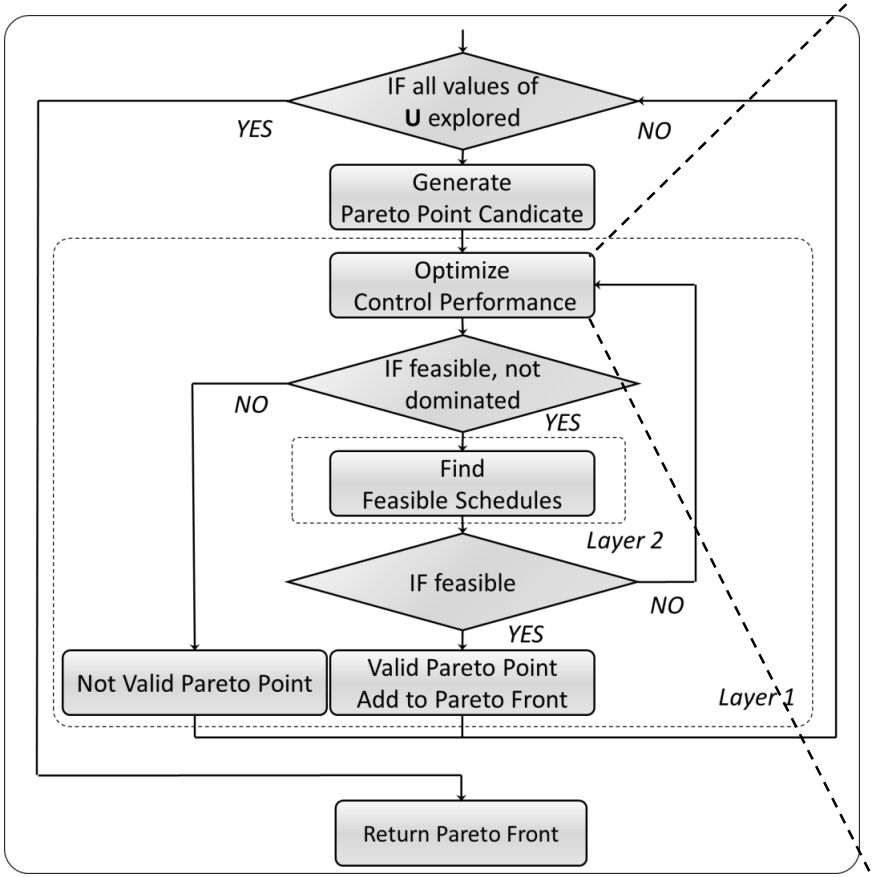
$$\hat{U} = \sum_{C_i \in \mathcal{C}} \frac{128 T_{bus}}{\check{h}_i}, \text{ where}$$

$$\check{h}_i = T_{bus} \cdot 2^{\min\{k | 0 \leq k \leq 6 \wedge J_i^{k*} \leq J_i^r\}}$$

- Minimum difference between two values of U

$$U^{\Delta} = \frac{128 T_{bus}}{\max\limits_{C_i \in \mathcal{C}} \hat{h}_i}$$

Stage 2: Co-Optimization



optCP

- U and J_o depends only on $\{h_i\}$
- Solves an ILP problem
- Variables: $\{h_i\}$
- Objective:

  O1: Overall system performane J_o

- Constraints:

  Objective bound: $\check{J}_{o,L} < J_{o,L} < \hat{J}_{o,L}$

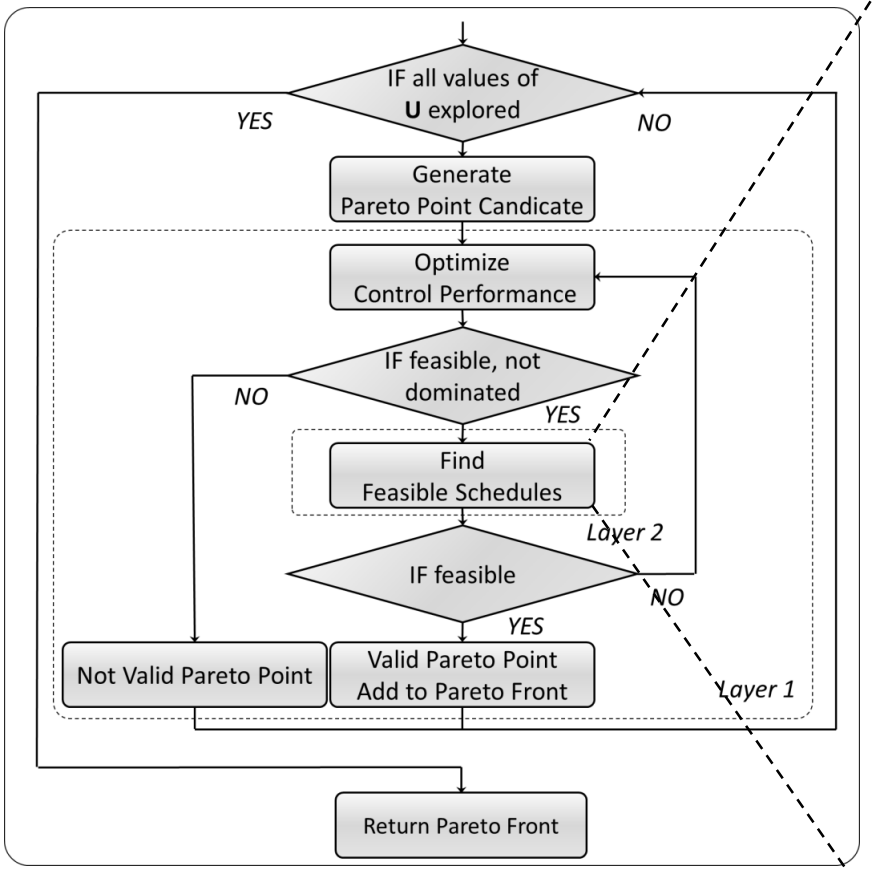
  C1: Performance requirement

$$\underset{C_i \in \mathcal{C}}{\forall} \left(J_i \leq J_i^r \right)$$

  O2: Equality constraint on U

$$U = \sum_{C_i \in \mathcal{C}} \frac{128 T_{bus}}{h_i} = U_L$$

Stage 2: Co-Optimization



findSchedules

- Solves a constraint satisfaction problem
- Variables:
  - Task schedules $[\tau_s, \tau_c, \tau_a]_i$
  - Message schedules $[\Theta_s, \Theta_c]_i$
- Constants:
  - Periods and repetition rates
  - Periodicity constraint

$$\underset{C_i \in \mathcal{C}}{\forall} (p_{x,i} = R_{y,i} T_{bus} = h_i)$$

- Constraints:

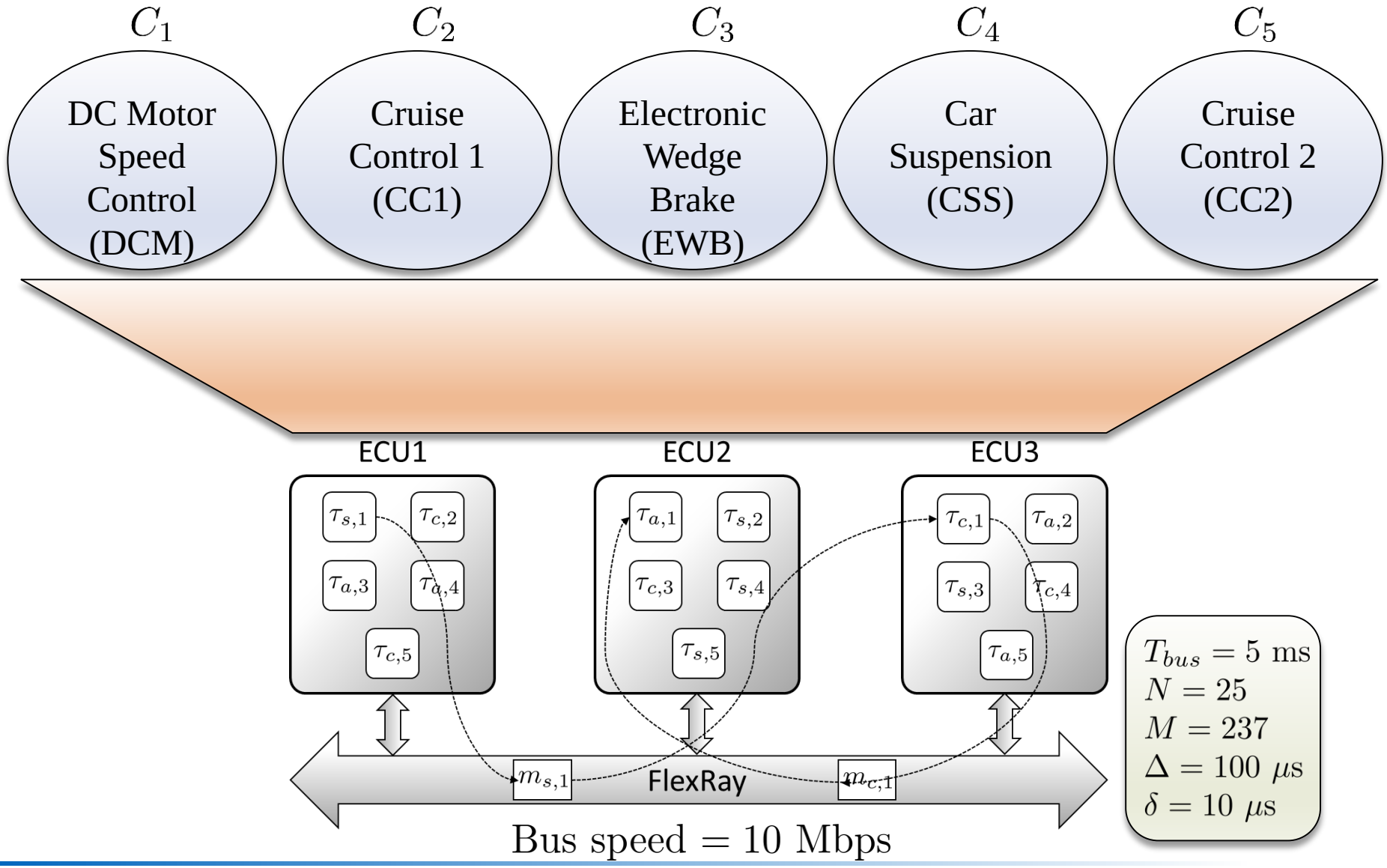
  Delay constraint

  C2: Dataflow

  C3: Non-overlapping tasks

  C4: Non-overlapping messages

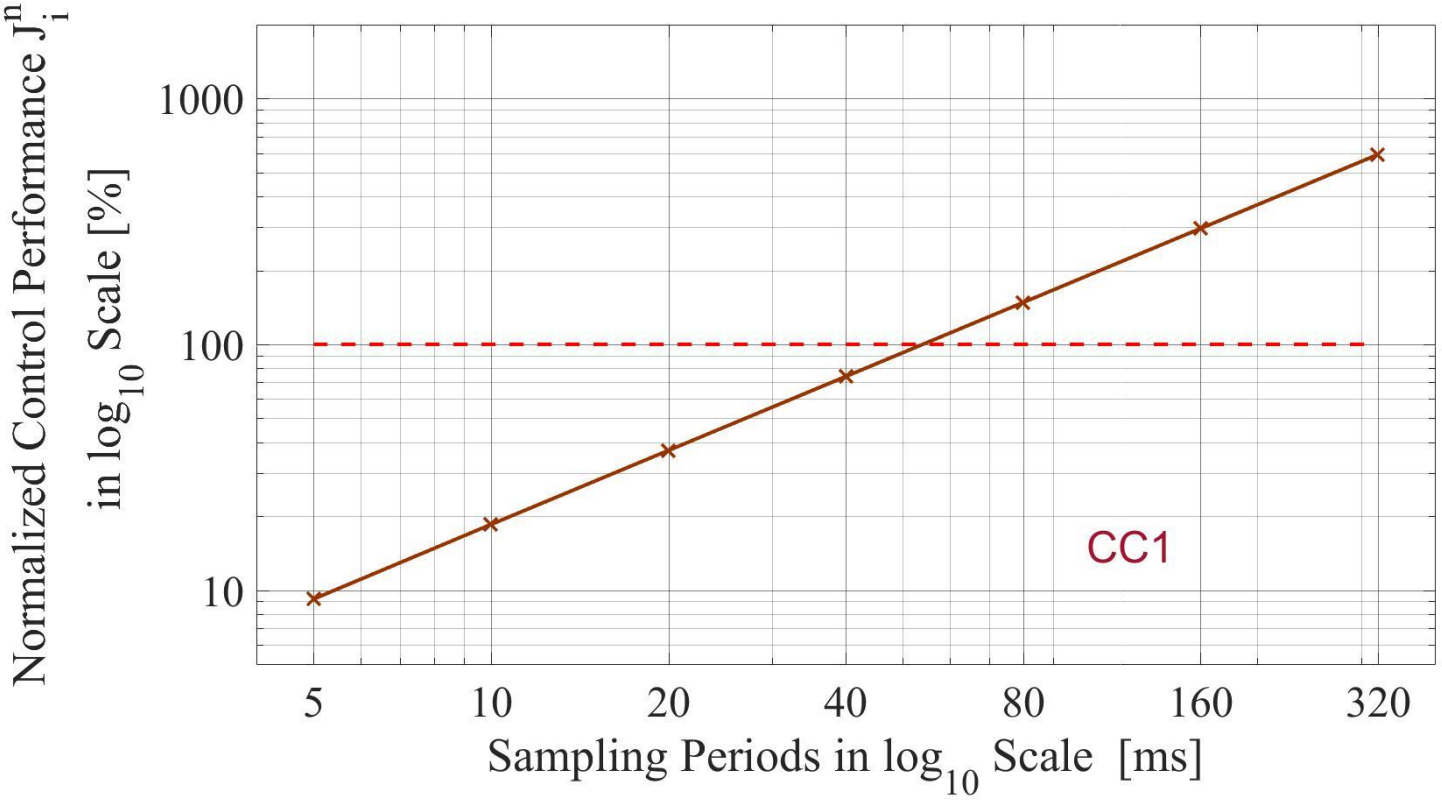
An Example Automotive System



An Example Automotive System

Stage 1: Prospective controller design

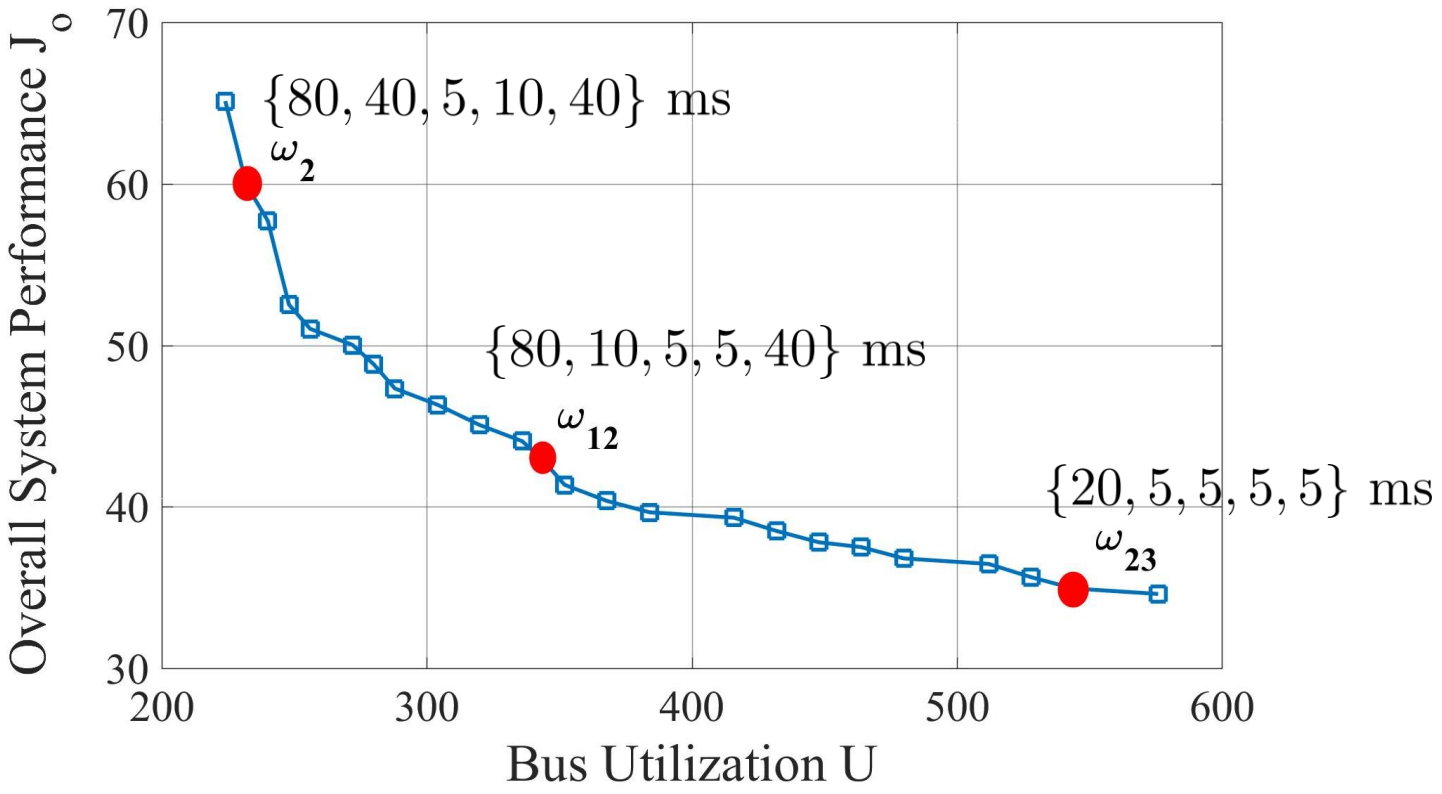
- For each control application
  - Determine optimal performances at seven possible sampling periods



An Example Automotive System

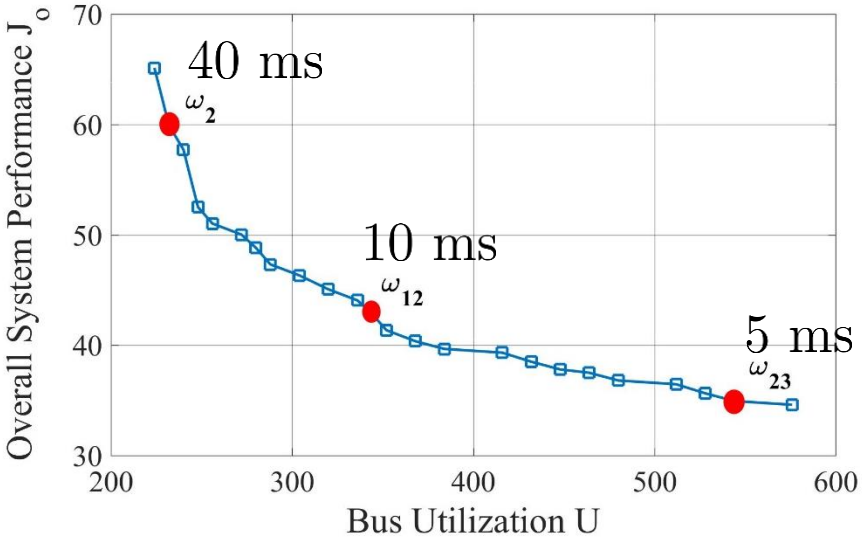
Stage 2: Co-optimization

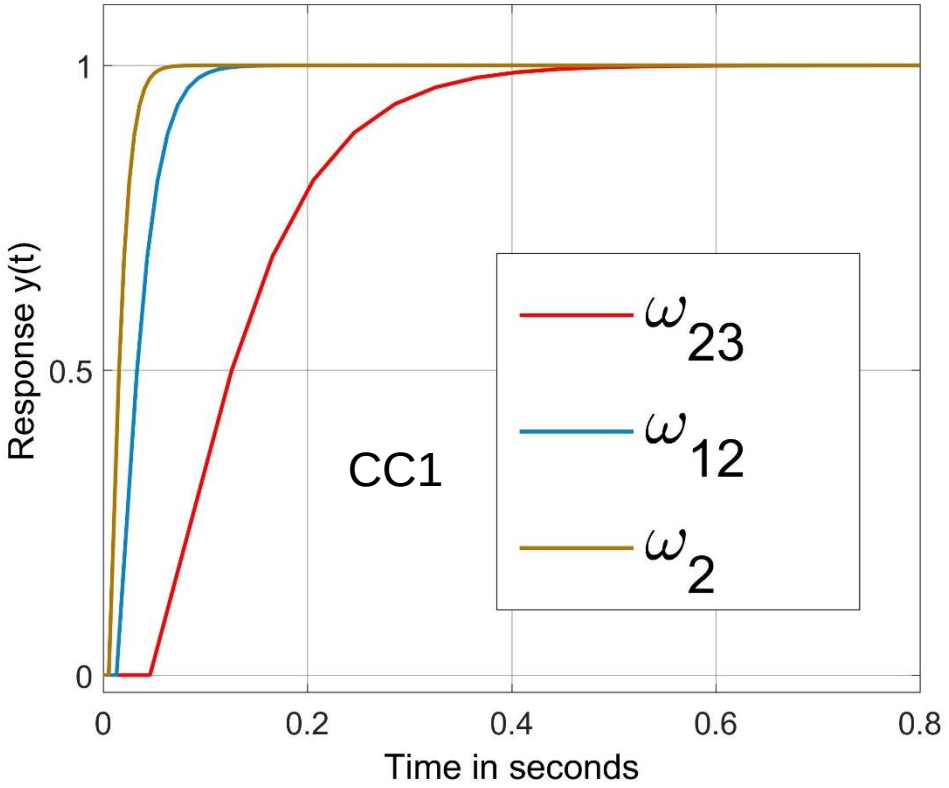
- Pareto front depicts the trade-off between objectives
- 24 reasonably well-distributed pareto points



An Example Automotive System

Simulation validation using SIMTOOLS + MATLAB/SIMULINK





Concluding Remarks

Approach

- Design of FlexRay-based distributed control systems
- Design objectives
  - Overall system performance
  - Bus utilization
- Two-stage approach
  - Exhaustive search based design of prospective optimal controllers
  - Nested two-layered technique to solve the co-optimization problem
- Pareto front depicting the trade-off between objectives is constructed

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Outlook

- Incorporate variable sensor-to-actuator delays
- Extension to heterogenous systems

Thank You

Q/A