Uncertainty in Coupled Models of Cyber-Physical Systems

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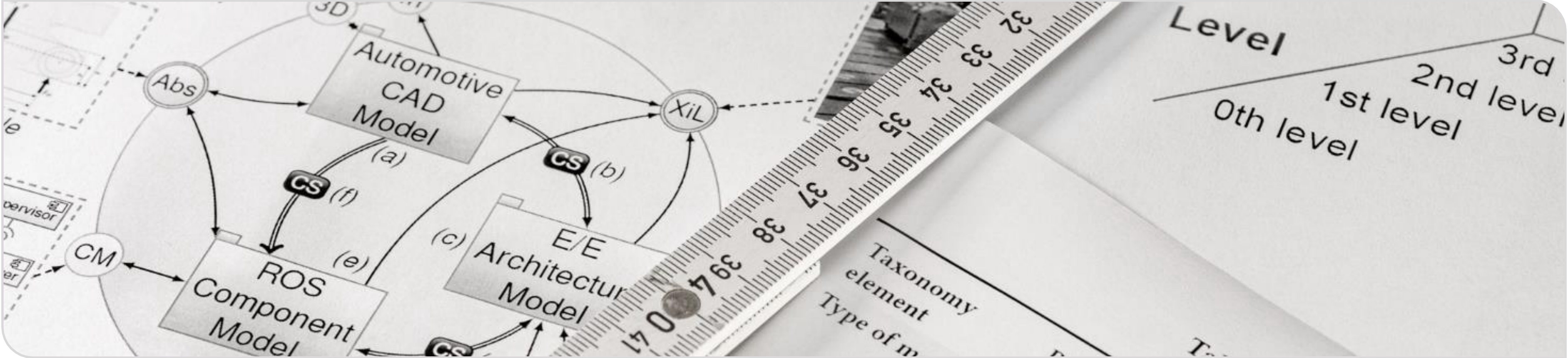
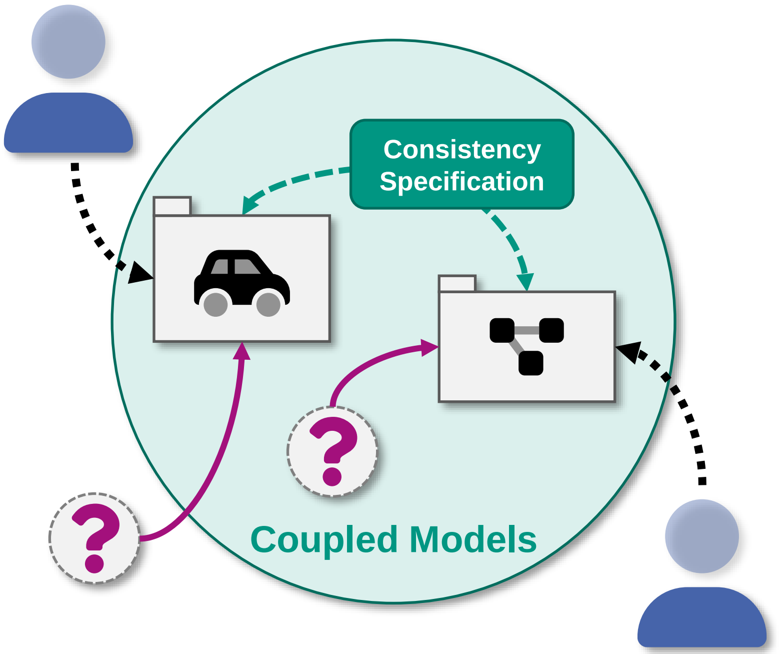


Motivation

- Engineering with coupled models for cyber-physical systems (CPS) is challenging
  - Collaborating experts from different disciplines
  - Consistency preservation between models
  - Not operated in isolation, i.e., **uncertainty**

- Gap: Understanding the types of uncertainty and their impact on coupled models of CPS



Contributions

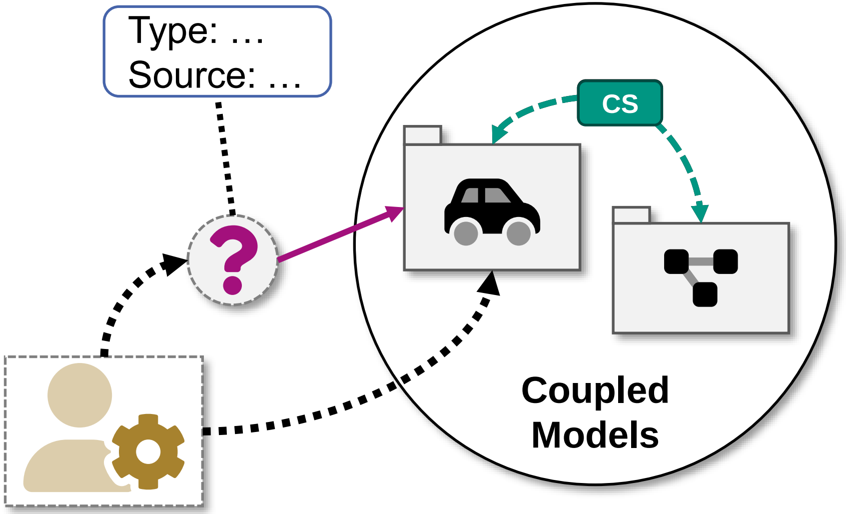
- A classification of uncertainty in CPS
- Propagation of uncertainty in coupled models

Foundations: Uncertainty

Uncertainty: “any departure from the unachievable ideal of complete determinism” **[1]**

Handling Uncertainty [2]

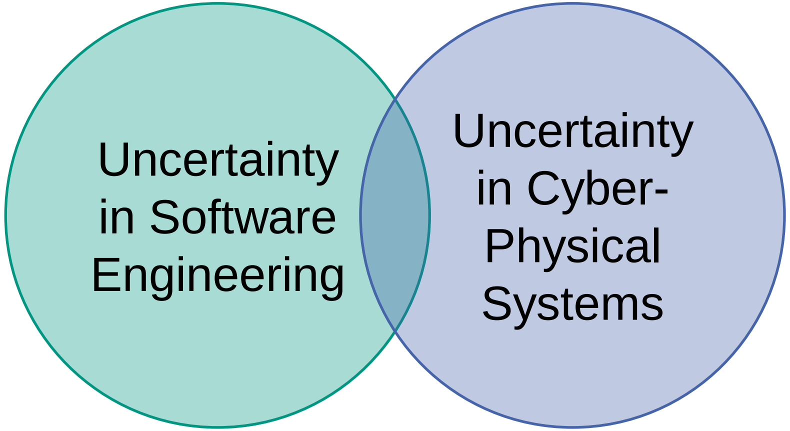
- Awareness: Recognize uncertainty, e.g., by asking experts, or using checklists
- Classification: Discover the type and source of the uncertainty, e.g., with a taxonomy
- Propagation: Understand the impact of the uncertainty in single or coupled models
- Mitigation: Apply appropriate strategies to support or resolve the uncertainty impact



[1] W. E. Walker et al., “Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support,” Integrated assessment, vol. 4, 2003.
[2] S. Mahdavi-Hezavehi et al., “Uncertainty in Self-Adaptive Systems: A Research Community Perspective,” ACM TAAS, 2021.

State of the Art: Overview

- Uncertainty as first-class entity **[3]**
- Surveys and SLRs **[4, 5]**
- Classifications and taxonomies **[6, 7]**
- Design space exploration and fuzzy values **[8, 9]**



[3] D. Garlan, "Software engineering in an uncertain world", FoSER, 2010.
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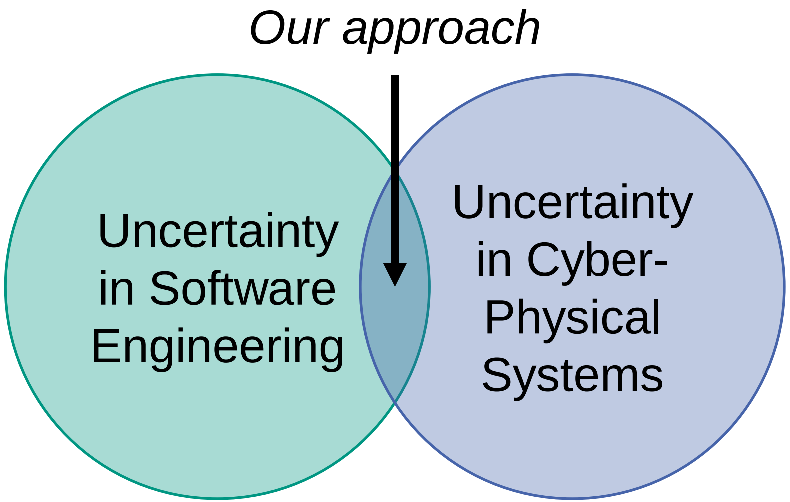

- Classifications and taxonomies **[10, 11, 12]**
- Representing uncertainty in CPS development **[13]**
- Uncertainty due to decision making **[14]**

[10] M. Zhang et al., "Understanding Uncertainty in Cyber-Physical Systems: A Conceptual Model", Springer LNCS, 2016.
[11] W. Chipman et al., "Coverage of Uncertainties in Cyber-Physical Systems", ZuE, 2015.
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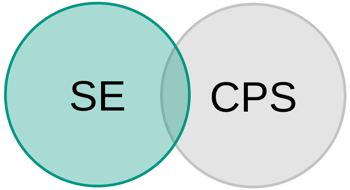
[13] T. Bandyszak et al., "Orthogonal Uncertainty Modeling in the Engineering of Cyber-Physical Systems", IEEE T-ASE, 2020.
[14] M. Famelis and M. Chechik, "Managing design-time uncertainty", Software & Systems Modeling, 2019.

Uncertainty in Self-Adaptive Systems



Uncertainty [6]

Location (of the Source)

- Context: Completeness, w.r.t. the real world
- Structural: Accurately representing a subset of the real world
- Input: Values of parameters in use

Level (Knowledge)

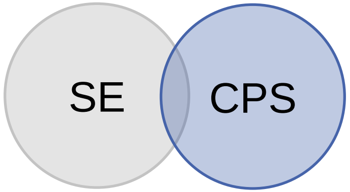
- 0: Lack of uncertainty
- 1: Lack of knowledge (i.e., *known unknowns*)
- 2: Lack of awareness
- 3: Lack of awareness and process

Nature (Reason)

- Epistemic: Lack of data, imperfection, lack of knowledge
- Aleatory: Inherent variability or random events

[6] D. Perez-Palacin and R. Mirandola, "Uncertainties in the modeling of self-adaptive systems: a taxonomy and an example of availability evaluation", In: ICPE, 2014.

Uncertainty in Technical Systems



Uncertainty [12]

Effect (Knowledge about Uncertainty)

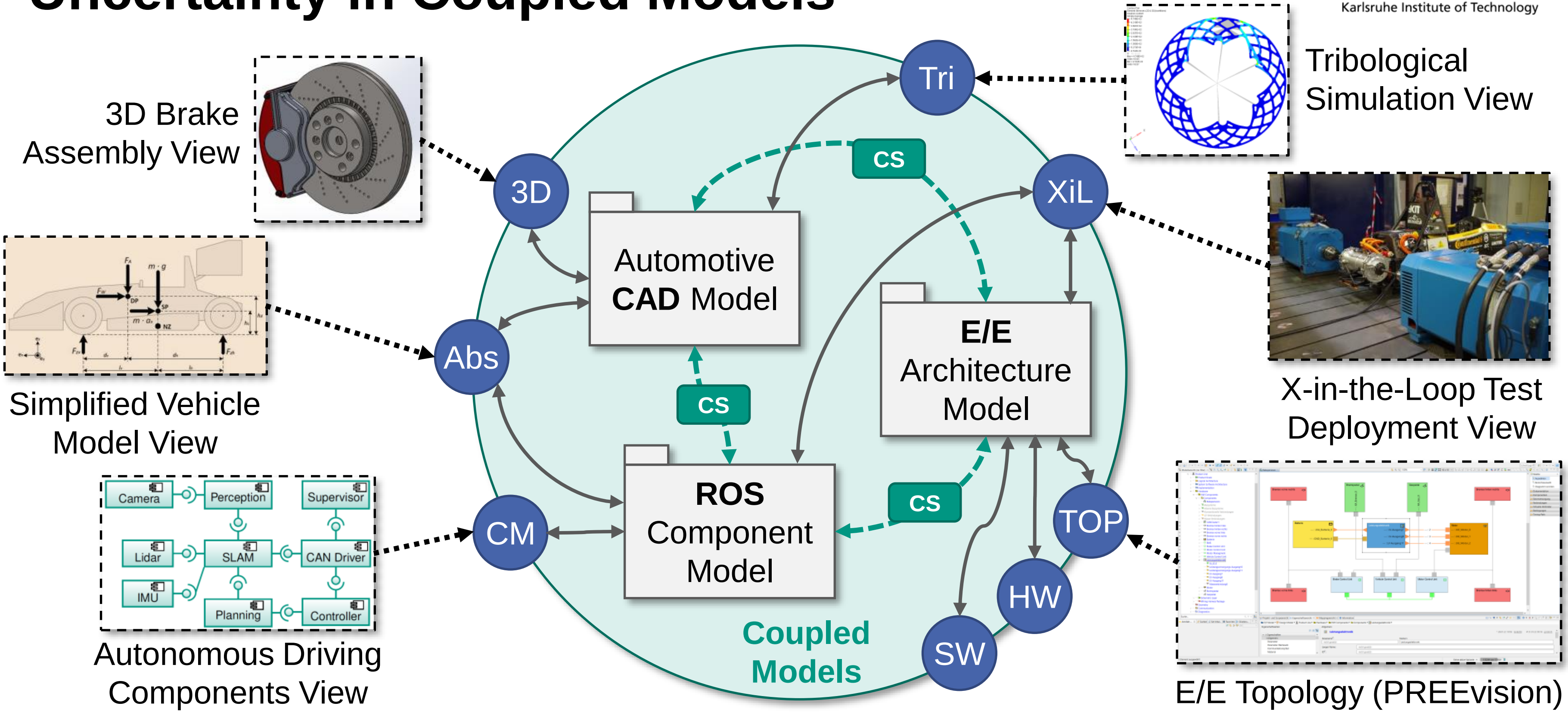
- Stochastic: Expressible as probability
- Incertitude: Only partially quantifiable
- Ignorance: Effect unknown (not modeled)

System Design (Type of Uncertainty)

- Data: Parameters or internal variables
- Model: Gap between model and reality
- Structure: Incompleteness of the model

[12] P. F. Pelz et al., “Types of Uncertainty”, Mastering Uncertainty in Mechanical Engineering , Springer, 2021.

Uncertainty in Coupled Models

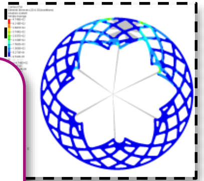


Karlsruhe Institute of Technology

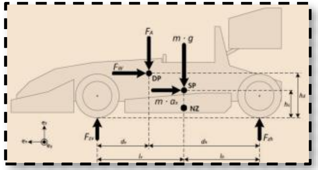
Uncertainty in Coupled Models

3D Brake Assembly View

Tribological Simulation View



? Uncertainty due to the system or environment?
➪ *Hard to propagate*

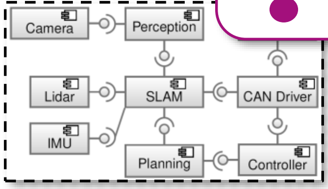


Simplified Vehicle Model View

? Runtime vs. design-time?
➪ *Taxonomy does not fit*

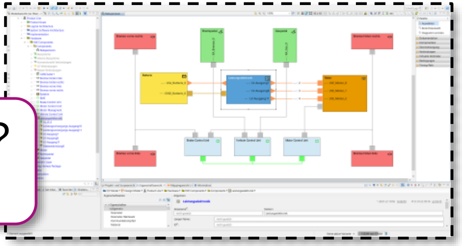
X-in-the-Loop Test Deployment View

? Impact of uncertainty in abstract properties on the system design?
➪ *Hard to propagate*



Autonomous Driving Components View

? Ranges vs. concrete values?
➪ *Taxonomy does not fit*



E/E Topology (PREEvision)

Classification of Uncertainty in Coupled Models

Dimension	Options	Comparison and Benefits
Modeling the effect of uncertainty *(representing uncertainty)*	▪ Probabilistic approaches ▪ Incertitude-based (e.g., fuzzy values, or intervals) ▪ Tagging uncertainty without further characterizing it	Merged both taxonomies **[6, 12]** ➪ No model type restrictions ➪ More precise representation ➪ Tagging known unknowns
Handling uncertainty *(timing)*	▪ Design-time ▪ Runtime	Merged both taxonomies **[6, 12]** ➪ Documenting when to handle
Locus of uncertainty *(in the model)*	▪ Parameters ▪ Model ▪ Analysis ▪ Decision making	New dimension of our taxonomy ➪ Location of uncertainty impact ➪ Closer to engineering activities
Source of uncertainty *(in the real world)*	▪ System ▪ Environment	Location **[6]** or not considered **[12]** ➪ Clearly defines the system boundaries

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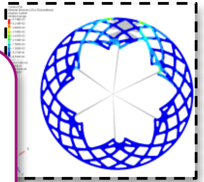
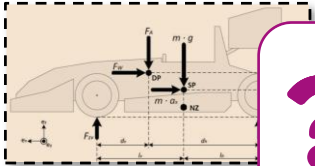
Classification of Uncertainty in CPS

3D Brake Assembly View

Effect: *any*
Handling: Design-time
Locus: Analysis
Source: Environment / System



Tribological Simulation View

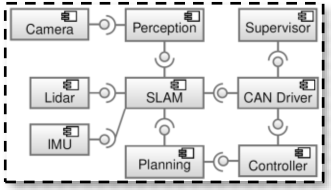


Simplified Vehicle Model View

Effect: Probabilistic / Incertitude
Handling: Design-time
Locus: Parameters
Source: System

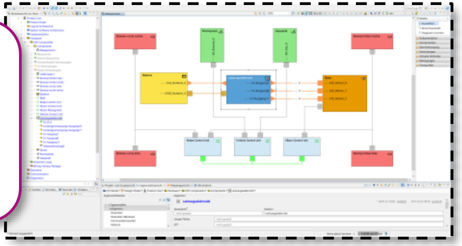
Effect: *any*
Handling: Runtime
Locus: Analysis
Source: System

X-in-the-Loop Test Deployment View



Autonomous Driving Components View

Effect: Tagging
Handling: Design-time
Locus: Decision making
Source: System



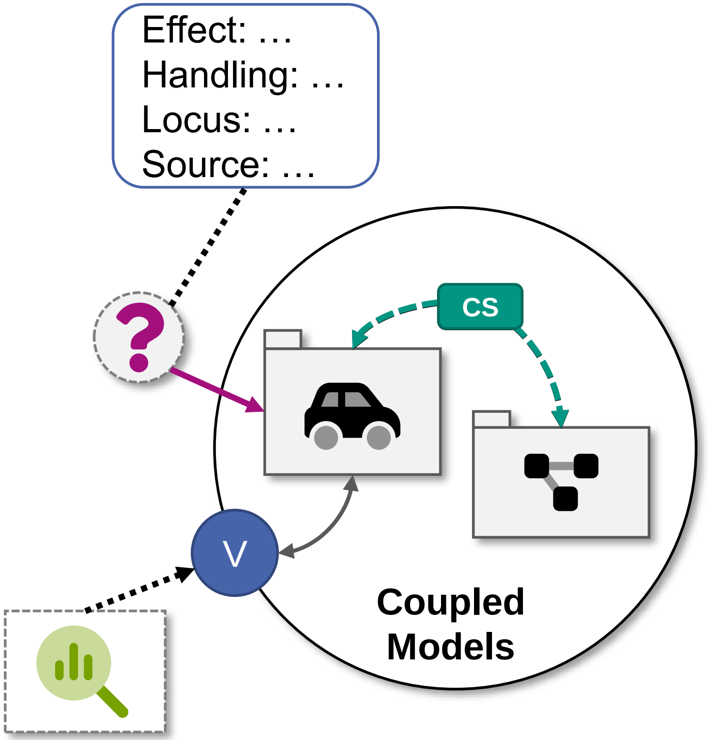
E/E Topology (PREEvision)

Propagation of Uncertainty in Coupled Models

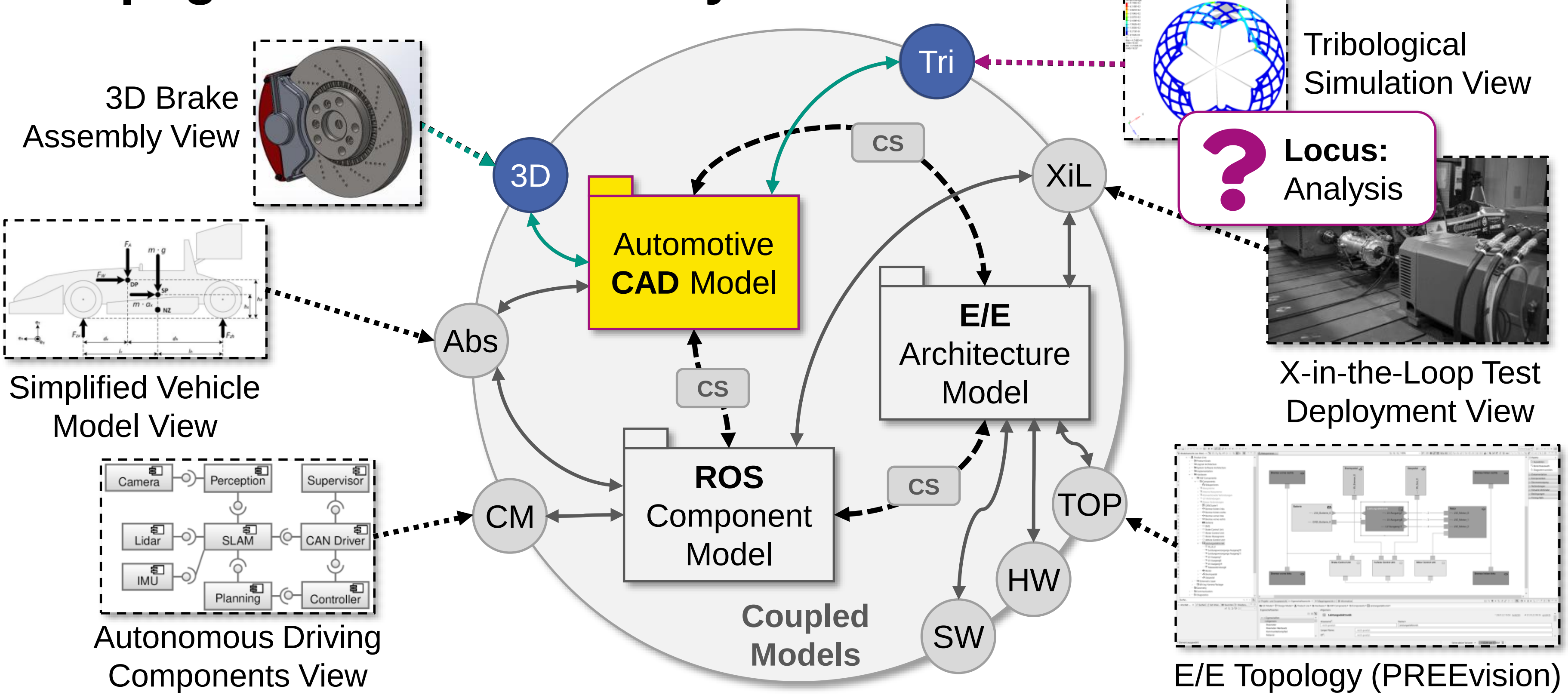
- Idea: Reuse existing consistency specifications, or new rules based on domain knowledge
- Approaches: Uncertainty-aware analysis or uncertainty-aware framework

Build on the *locus* dimension

- Parameters: Direct impact propagation, Non-probabilistic functions, or no propagation
- Model: Propagation based on the structure, boundaries and interconnection of models
- Analysis: Propagation of the analysis output
- Decision making: a mix of the above



Propagation of Uncertainty in CPS



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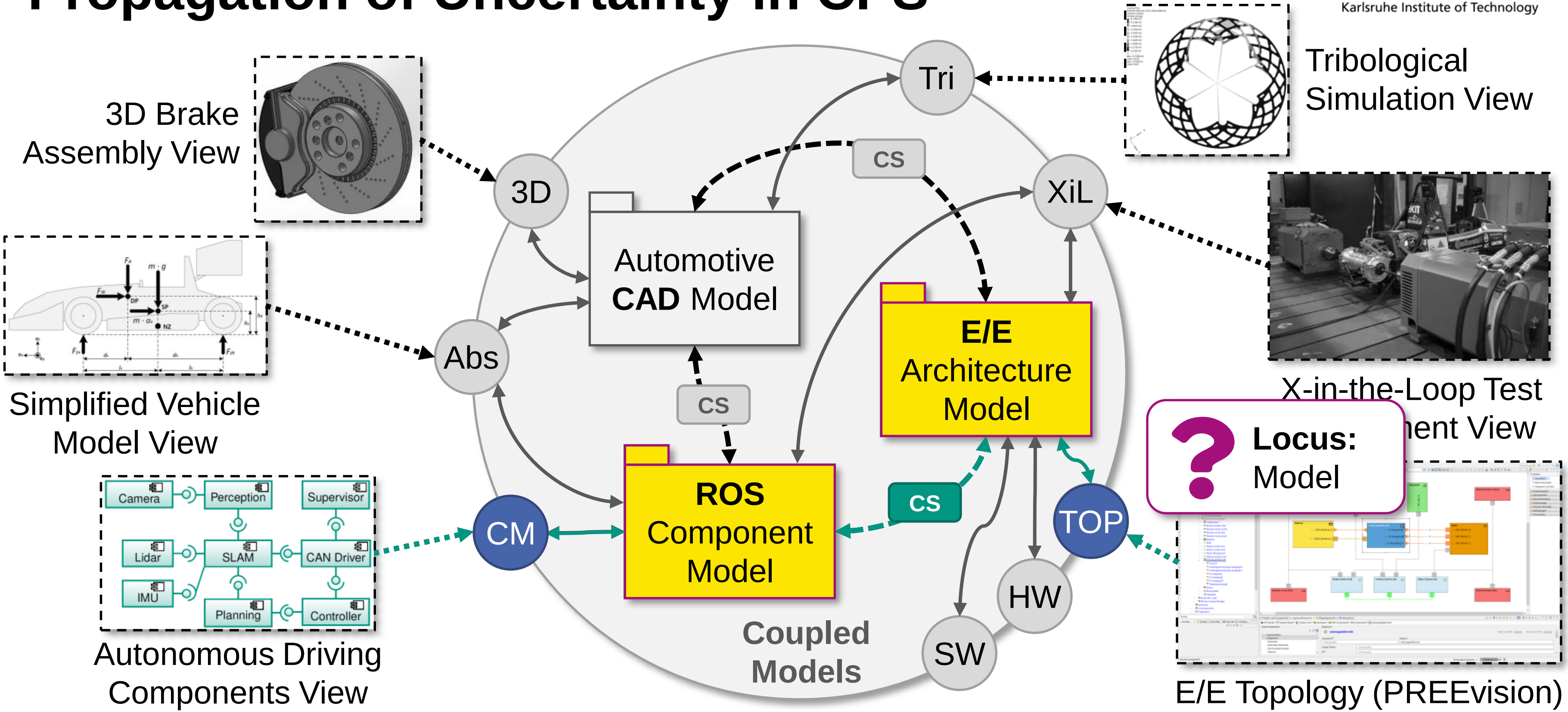

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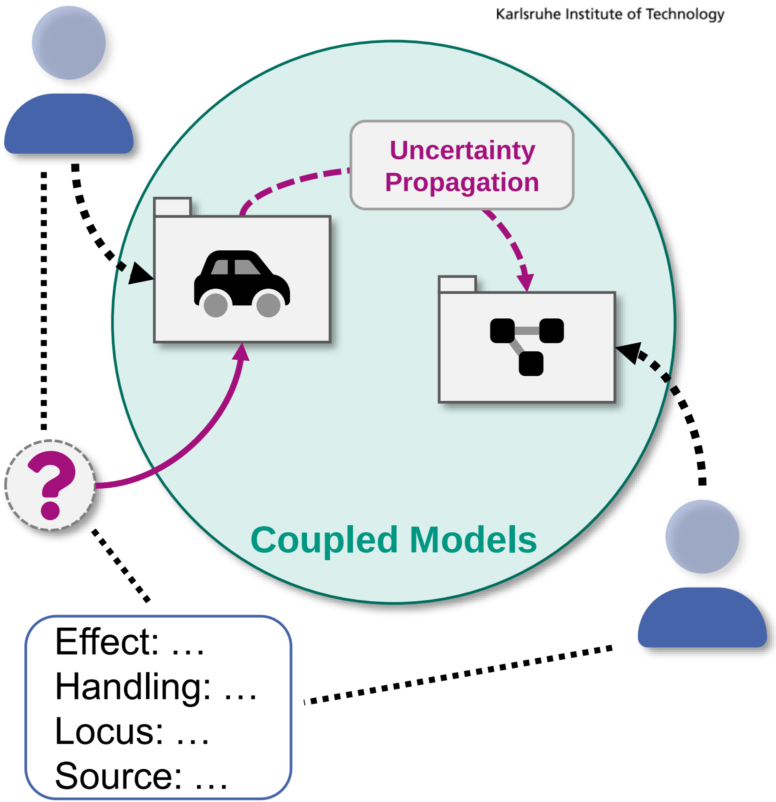
Conclusion and Future Work

- Problem: Understanding uncertainty and its impact on coupled models
- Contribution: A classification that helps describing and propagating uncertainty in cyber-physical systems
- Benefit: More precise and more comprehensive statements about type and impact of uncertainty



Future Work

- Extend existing consistency management approaches, e.g., the VITRUVIUS approach
- Validation with experts from other domains

References

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