Introduction to Civil Information Systems

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Overview

Part 4

Cyber-Physical Systems

New Computing Infrastructure $\rightarrow$ New System Abstractions

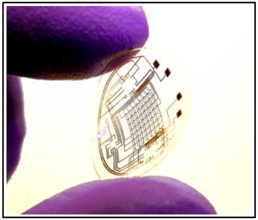
Cyber-Physical Systems

General Idea

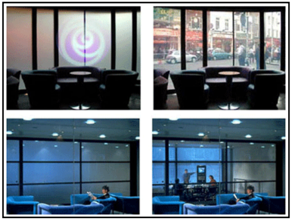
Embedded computers and networks monitor and control the physical processes, usually with feedback loops where computation affects physical processes, and vice versa.

Two Examples

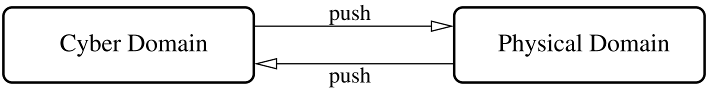
Programmable Contact Lens



Programmable Windows



Cyber-Physical Systems Overview



C–P Structure

Cyber capability in every physical component
Executable code
Networks of computation
Heterogeneous implementations

Spatial and network abstractions

–– physical spaces
–– networks of networks

Sensors and actuators.

C–P Behavior

Dominated by logic
Control, communications
Stringent requirements on timing
Needs to be fault tolerant

Physics from multiple domains.
Combined logic and differential equations.
Not entirely predictable.
Multiple spatial– and temporal– resolutions.

Cyber-Physical Systems

Physical System Concerns

- Design success corresponds to notions of enhanced performance, resilience and reliability.
- Behavior is constrained by conservation laws (e.g., conservation of mass, conservation of momentum, conservation of energy, etc..).
- Behavior often described by families of differential equations.
- Behavior tends to be continuous – usually there will be warning of imminent failure.
- Behavior may not be deterministic – this aspect of physical systems leads to the need for reliability analysis.
- For design purposes, uncertainties in behavior are often handled through the use of safety factors.

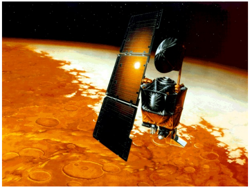
Cyber-Physical Systems

Software System Concerns

- Design success corresponds to notions of correctness of functionality and timeliness of computation.
- Computational systems are discrete and inherently logical. Notions of energy conservation ...etc... and differential equations do not apply.
- Does not make sense to apply a safety factor. If a computational strategy is logically incorrect, then "saying it louder" will not fix anything.
- The main benefit of software is that functionality can be programmed and then re-programmed at a later date.
- A small logical error can result in a system-wide failure.

Cyber-Physical Systems (Notable Failures)

Example 1. NASA's Mars Climate Orbiter, September 1999.



NASA's systems engineering process did not specify the system of measurement. One of the development teams used Imperial measurement; the other metric.

When parameters from one module were passed to another during orbit navigation correct, no conversion was performed, resulting in $125m loss.

Cyber-Physical Systems (Notable Failures)

Example 2. Denver Airport Baggage Handling System

1995. Baggage handling system is 26 miles of conveyors; 300 computers. Fixing the incredibly buggy system requires additional 50 percent of the original budget - nearly $200m.

2005. System still does not work. Airport managers revert to baggage carts with human drivers.

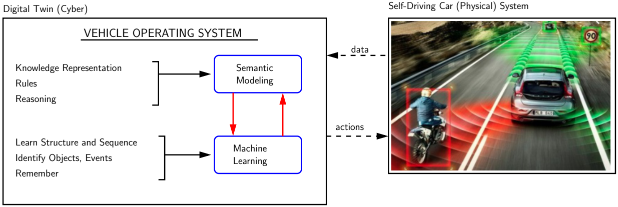
Source: Jackson, Scientific American, June 2006.

Digital Twin Systems

New Computing Infrastructure $\rightarrow$ New System Abstractions

Digital Twins (2000-today)

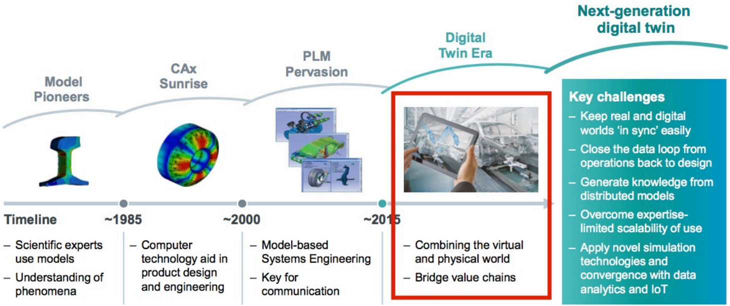
Definition. Virtual representation of a physical object or system that operates across the system lifecycle (not just the front end).



Required Functionality

- Mirror implementation of physical world through real-time monitoring and synchronization of data with events.
- Provide algorithms and software for observation, reasoning, and physical systems control.

Digital Twins (Business Case + Applications)



Many Applications

- NASA Spacecraft
- Manufacturing processes
- Building operations
- Personalized medicine
- Smart Cities
- ... etc.

Digital Twins (Technical Implementation)

Technical Implementation (2023, Google, Siemens, IBM)

- AI and ML will be deeply embedded in new software and algorithms.

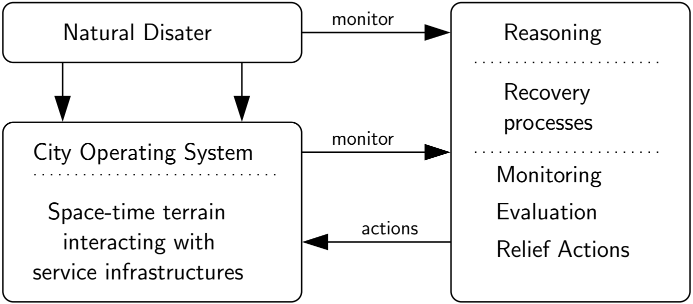
Artificial Intelligence:

- Knowledge representation and reasoning with ontologies and rules. Semantic graphs. Executable event-based processing.

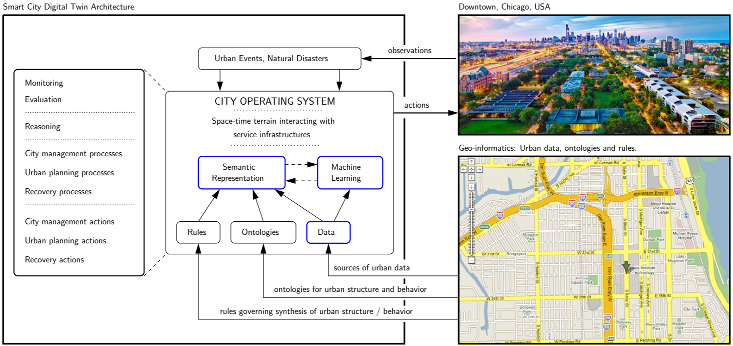
Machine Learning:

- Modern neural networks. Input-to-output prediction.
- Data mining.
- Identify objects, events, and anomalies.
- Learn structure and sequence. Remember stuff.

Digital Twin: City Operating Systems

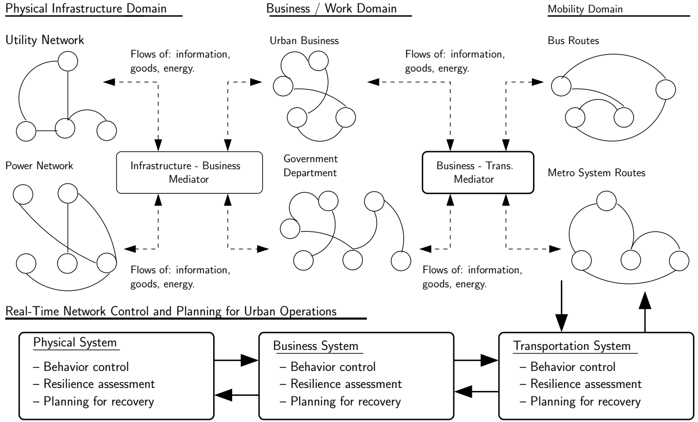


Smart City Digital Twins (2018-2019)



Required Capability. Monitoring and control of urban processes.
Complications. Potentially, a very large number of digital twins. Distributed decision making.

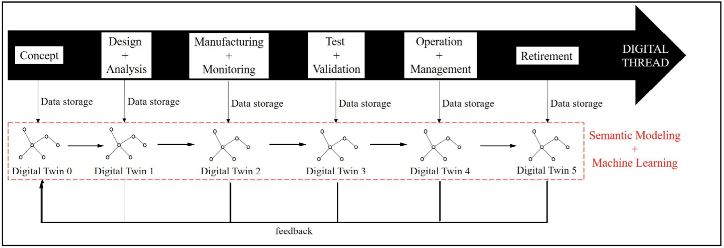
Smart City Digital Twins (2018-2019)



Requirements. Support for digital twin individuals and digital twin communities.

Digital Thread Systems

Digital Threads: (Cradle-to-Grave Lifecycle Support) ...

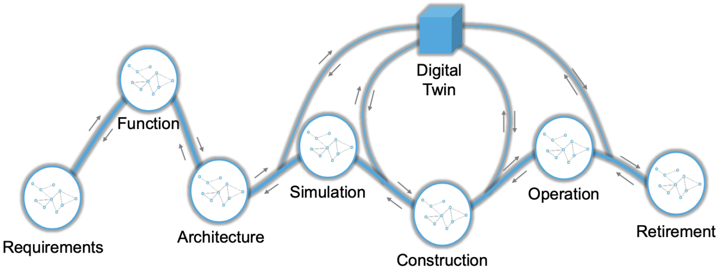


Graph-based Approach

A lot of model-centric engineering boils down to representation of systems as graphs and sequences of graph transformations punctuated by decision making and work/actions.

Digital Thread Systems

Digital Thread System at INL: (Conceptual Model) ...



Def'n: A digital thread is an interconnected software data exchange used to enable digital engineering and digital twinning systems ...

Source: Coelho and Browning, INL, 2022.

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