Class #1: Introduction to Dynamical Infrastructure Systems

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CEE572 – Dynamical Infrastructure Systems
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Systems in Civil Engineering
Character of Infrastructure Systems

- **Large physical systems of extreme economic importance:**
  - Massive systems spanning over large geographical areas
  - Critical to public safety and quality of life

- **Often dynamic with a time basis to their behavior:**
  - Extreme loads inducing mechanical response
  - Injection of contamination in system (e.g., potable drinking water)

- **Have complex interactions:**
  - Infrastructure-to-infrastructure interaction
  - Human-infrastructure interaction
  - Built environment-nature interactions
  - Cyber-physical interactions
Change in Perspectives

Historical Approach to Civil Engineering Education: Component-based Design

Today’s Approach to Civil Engineering Education: System-based Design
Emergence of Systemic Failure

There is an urgent need to study the interconnectedness of civilian infrastructure to prevent systemic failure of key societal systems.
Mega-scale Disasters

Failure of levees during Hurricane Katrina (2005)

Tsunami induced failure of chilled water cooling system in Fukushima reactors (2011)
Technology Trends Driving “Systems”

Moore’s Law for Processors and Memory
(Source: Intel)

Edholm’s Law for Wireless Communications
(Source: Chema et al. 2010)

Microelectromechanical Systems (MEMS)
(Source: Analog Devices)

Internet
(Source: Wikipedia)
Cyber-Physical Systems

- **Cyber-physical systems (CPS):**
  - Coordinated combination of sensing, computing and actuation
  - Integration of embedded computing, wireless communication and low-cost sensing allows the world to be densely sensed and controlled
  - Availability of wireless Internet gives field-based sensors/actuators increasing access to computing resources

![Early Earthquake Warning Systems](Source: NIPPONIA)

![Intelligent Transportation Systems](Source: University of Michigan)
Systems Education in CEE

• **Emergence of systems in UM’s civil engineering curriculum:**
  
  – CEE571: Linear System Theory:
    • Cross-listed College wide
    • Foundational course teaching well established linear system theory. Can be viewed as an “applied” linear algebra course given the heavy concentration on vector and matrix mathematical tools.
  
  – CEE572: Dynamical Infrastructure Systems:
    • Introductory course providing a core set of tools and techniques required for students studying the dynamics of infrastructure systems
    • Not specific to any one domain – rather, examples drawn from many application areas (structures, hydraulics, transportation, etc.)
    • Survey course of many system modeling concepts
    • *Intended to make up for potential deficiencies in UG preparations*
    • *After the course completion, students are better positioned to take advanced system courses across the College of Engineering*
What is a System?

A system is anything that is characterized by inputs and outputs:

\[ u \rightarrow \text{SYSTEM} \rightarrow y \]

\( u \) (input quantity)

\( y \) (output quantity)

Most often, relationships between inputs & outputs is dynamic:

\[ u(t) \rightarrow y(t) \]

Most systems have memory: Present outputs depend on previous inputs:

\[ u(t) \rightarrow y(t) \]
Some simple systems are characterized by a single input-single output (SISO):

\[
\begin{align*}
&u \quad \text{(input quantity)} \\
&\quad \text{system} \\
&\quad \quad y \quad \text{(output quantity)}
\end{align*}
\]

Most systems are characterized by multiple inputs-multiple outputs (MIMO):

\[
\begin{align*}
&u_1 \quad \text{system} \\
&u_2 \\
&\quad \quad y_1 \\
&\quad \quad y_2 \\
&\quad \quad y_3
\end{align*}
\]
Example: Building (Structure)

\[ y_1 = 1\text{st story disp} \]
\[ y_2 = 2\text{nd story disp} \]
\[ y_3 = 3\text{rd story disp} \]
Example: Bridges (Structure)

Bridge/sensor system

traffic loads, wind, earthquakes

sensor outputs

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Example: Wave Energy (Power)

Wave energy buoy array

\[ u_1 \rightarrow \text{wave heights} \rightarrow \text{buoy displacements} \rightarrow y_1 \]

\[ u_n \rightarrow \text{generator currents} \rightarrow \text{generator voltages} \rightarrow y_p \]

Power output
Example: Electrical Grid (Power)

- Power consumed by the 37 substations
- Velocities of the 10 generators
Example: Water Distribution (Hydro)

Water distribution network

$u_1$ \rightarrow \text{water dist. network} \rightarrow y_1$

$pump stations$

$u_n$ \rightarrow \text{pressures at network junctions}$

flow
Cascading Systems

- **Composite system of simpler systems:**
  - “System of systems” is a common phrase for composite systems
  - Strong relationships between subsystems that define the properties and behavior of the composite system
  - Can we observe and control each subsystem? If not, how does that effect our analysis, modeling and control of the composite system?
Feedback Systems

- Feedback is a common method of connecting subsystems:
  - Can be exploited to “control” the composite system
  - Even if all subsystems are stable, composite system may be unstable
  - Feedback requires all subsystems to be considered at once:
    - We cannot analyze or design each subsystem in isolation because they all interact with each other
New Carquinez Bridge

- New Carquinez Bridge (Vallejo, CA):
  - Located in the San Francisco Bay Area – seismically active area
  - Total bridge length is 1056 m (main span of 728 m)
  - Main deck consists of steel orthotropic box girders
  - Hollow concrete tower legs and pre-stressed link beam
System Monitoring

Known: Models for bridge, sensor subsystems, sensor voltages \( v_1 \ldots v_q \)

Find: Values of \( z_1 \ldots z_p \) which are as close as possible to \( y_1 \ldots y_p \)

... This is called system monitoring
Known: sensor outputs $v_1 \ldots v_q$
load data

Find: Approximate model for bridge system

... This is called system identification
Health Monitoring

Known: Models for bridge, sensor subsystems, sensor voltages $v_1 \ldots v_q$

Find: Likelihood & location of structural damage

... This is called damage detection or health assessment
System Control

Known: Models for bridge, sensor subsystems, actuation subsystem

Find: Most effective control force to apply for reduction of undesired response

... This is called feedback control
Course Content of CEE572

• **Systems science which emphasizes mathematical analysis:**
  – Modeling of dynamic systems as continuous and discrete-time systems:
    • Linear and nonlinear models
    • Differential equations and state-space models
    • Stability and typical responses
  – Transformation methods from time to frequency domains:
    • Laplace transform (Fourier) and Z-transform (discrete Fourier)

• **Systems engineering which emphasizes design and control:**
  – System identification of operational dynamic systems
  – Feedback control of dynamic systems

• **Applications:**
  – Structural dynamics
  – Transportation networks
  – Hydraulic networks