A Control Perspective on Cyber-Physical Systems

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Outline

- Control systems: Privileged technology?
- When do control systems become cyber-physical systems?
- Opportunities for control in cyber-physical systems
  - Networked (wireless) control systems
  - Smart mobility
  - Resource-aware control
- Outlook

Control of Dynamical Systems

- Common simplifying assumption in standard control textbooks:
  - Data can be processed without any restrictions
Control systems

Privileged Technology??

Control System

Actuators Sensors

Dynamical System

Control System

• Same formalism for
  – Plant / dynamical system
  – Control system

\[
\begin{align*}
\dot{x}_p &= Ax_p + Bu \\
y &= Cx_p + Du
\end{align*}
\]

\[
\begin{align*}
\dot{x}_c &= Kx_c + L(y-r) \\
u &= Mx_c + Nu
\end{align*}
\]

Control of Dynamical Systems

Mono-disciplinary view ...

• Validity of this assumption is lost when
  • Systems are large
  • Systems are fast/accurate
  • Communication platform is unreliable
Cyber-physical systems

- Separation of concerns no longer works
- Cyber-physical systems: combining the physical world and the cyber world (control, computation and communication)

Growth of CPS: physical, biological and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.

Need for fundamental understanding of interaction control, computation, communication (cyber) and physical behavior

Opportunities

- Making computation / communication (cyber) infrastructure "perfect"
  - Impossible
  - Extremely costly from financial or design point of view
- Analyze effects of "imperfect" cyber structure on physical (control) performance, and deal with it on the cyber-physical level

Examples:
- Networked (wireless) control systems & Smart mobility
- Resource-aware control

Appealing advantages of WCSs
- Ease of installation and maintenance
- Large flexibility
- Deployment in harsh environments
- Lower costs
- Less wires = less wear, less weight, less disturbances
Application potential WCS

- High-tech and Automotive Systems
- Autonomous Vehicles
- Large-scale Systems

Current control solution

- Sensors, controllers, actuators connected through dedicated point-to-point connections

Networked Control Systems

- Communication through a shared (wireless) network

Software

Control

Algorithm

Actuators

Sensors

Dynamical System

Control System

Networked Control Systems

Large-scale networked control systems applications
Networked Control Systems

- Communication through a shared (wireless) network
- Dropouts: data can get lost
- Delays: data takes some time to arrive
- Sampling variations (jitter): data consists of discrete measurements
- Scheduling: not all data arrives simultaneously

How to analyse and design Networked Control Systems?

Hybrid systems

- Understanding CPS and NCS requires hybrid models:
  - Discrete models such as finite state machines/automata for describing e.g. scheduling protocol and packet loss behaviour
  - Continuous models such as differential equations for describing e.g. physics of plants and continuous control algorithms

Multidisciplinary tradeoffs

- Analyze effects of "imperfect" cyber structure on physical (control) performance, and deal with it on the cyber-physical level
- Quality-of-Service (Maximum Allowable Delay/Transmission Interval) vs. Quality-of-Control
- Multi-disciplinary tradeoffs
**Smart mobility**

- Integrated design approach for safety-critical real-time automotive systems.
- Project in rCPS program with NXP, TNO-Automotive, TU/e and UT.

**Grand Challenge**

- Abandoning linear control domain and moving to hybrid domain:
  - (More) difficult to assess stability & performance
  - Conservative

**Resource-aware control**

- Next generation wafer scanners:
  - More control loops
  - Higher sampling rates
  - E.g. Non-rigid body motion control of the wafer stage
  - Several crucial control applications will operate at significantly higher sampling rates than others
  - Current design practice: Single rate

- How to unite accurate linear control design methods and hybrid (CPS) tools?
Resource-aware control

- Next generation wafer scanners:
  - More control loops
  - Higher sampling rates
- E.g. Non-rigid body motion control of the wafer stage
- Several crucial control applications will operate at significantly higher sampling rates than others
- Current design practice: Single rate (linear time-invariant systems)
- Multi-rate high-performance control (linear time-varying systems)
- Project in rCPS program with ASML, TNO-ESI, TU/e

Example

\[
\begin{align*}
\dot{x}_p &= \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix} x_p + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \end{bmatrix} w \\
y &= \begin{bmatrix} 1 & 0 \end{bmatrix} x_p \\
\dot{x}_c &= \begin{bmatrix} -2 & 1 \\ -13 & -3 \end{bmatrix} x_c + \begin{bmatrix} -2 \\ -5 \end{bmatrix} y + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \hat{u} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \hat{w} \\
u &= \begin{bmatrix} 5 \\ 2 \end{bmatrix} x_c \\
0 & 5 & 10 & 15 & 20 & 25 & 30 \\
-2 & 10 & -1 & 10 & 0 & 10 & 1 \\
\end{align*}
\]
Example

\[
\begin{align*}
\dot{x}_P &= \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix} x_P + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u_P + \begin{bmatrix} 0 \\ 0 \end{bmatrix} w_P, \\
\dot{x}_C &= \begin{bmatrix} -2 & -13 & -3 \end{bmatrix} x_C + \begin{bmatrix} -2 & -5 \end{bmatrix} u_C + \begin{bmatrix} -2 \end{bmatrix} y_C
\end{align*}
\]

- Act when needed!
- Control loop becomes hybrid system - Grand Challenge!

Conclusions

- Need fundamental understanding of interaction control, computation, communication (cyber) & physical behavior (multi-disciplinary tradeoffs)
- Making computation / communication (cyber) infrastructure “perfect”
  - Impossible / extremely costly
- Analyze effects of “imperfect” cyber structure on physical (control) performance, and deal with it on the cyber-physical level

- rCPS program good vehicle to
  - address the “Challenges and Opportunities”
  - build CPS eco-system to sustain future developments