LET’S CONTROL EVERYTHING!

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LET US CONTROL EVERYTHING
CENTRAL THEMES OF THIS TALK...

• **CONTROL** is pervasive

• **CONTROL** is not just for systems

  (if you are a hammer, everything looks like a nail…)

• **CONTROL** doesn’t have to always be “sophisticated”

• **Principles** of **CONTROL THEORY** (FEEDBACK, DYNAMICS, etc)
  matter more than specific methodologies

• “When our classifications start breaking down, we know we are learning something exciting…”
A somewhat personal account of how the “control mindset” can lead to solutions of intriguing, unconventional problems, which in turn stimulate new theoretical developments.

- 1980’s
  - Manufacturing systems, kanban control
  - The roots of Discrete Event Systems

- 1990’s
  - Learning from sample paths of complex systems
  - Controlling elevators, Australian mines, air traffic, communication networks, command-control systems

- Future
  - Hybrid systems, complexity, computation...
CONTROL IN MANUFACTURING SYSTEMS

WORKCENTER

MACHINE

BUFFER

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A model for a manufacturing workcenter capturing part-by-part behavior:

\[ x(t) = 0, 1, 2, \ldots \]

Part Arrivals \( \{a_1, a_2, \ldots \} \)

\( x(t) \)

Processing Times \( \{p_1, p_2, \ldots \} \)

Part Departures \( \{d_1, d_2, \ldots \} \)

\( K \)
A continuous flow model for a manufacturing workcenter:

\[
\dot{x}(t) = \begin{cases} 
0 & \text{if } [x(t) = 0 \text{ and } \lambda(t) \leq \mu(t)] \\
0 & \text{if } [x(t) = K \text{ and } \lambda(t) \geq \mu(t)] \\
\lambda(t) - \mu(t) & \text{otherwise}
\end{cases}
\]
Limitations of the continuous flow model:

- Can only analyze averages

- Cannot deal with part-by-part control issues such as:
  - Is $n$th part guaranteed to be served within $T$ time units?
  - If a part is within $T$ time units from its due-date, serve it next
  - Prioritize RED parts over YELLOW parts
Manufacturing system with $N$ sequential operations:

- **Throughput** increases (GOOD)
- Average delay increases (BAD)

Increasing $\lambda(t)$ results in:

- Throughput increases (GOOD)
- Average delay increases (BAD)
TWO PROBLEMS

1. BUFFER ALLOCATION (FIAT, circa 1979)

\[ \max_{K_1,\ldots,K_N} J(K_1,\ldots,K_N) \quad \text{s.t.} \quad \sum_{i=1}^{N} K_i = C \]

PARAMETRIC OPTIMIZATION
2. FLOW CONTROL

**GO** if $x_i(t) < K_i$, **STOP** otherwise

No. of KANBAN (tickets) allocated to stage $i$
TWO PROBLEMS

\[ \max_{u_1,\ldots,u_N} J(u_1,\ldots,u_N) \quad \text{s.t.} \begin{cases} D(u_1,\ldots,u_N) \leq C \\ \text{system dynamics} \end{cases} \]
SUPERVISORY CONTROL PROBLEM

Supervise the proper execution of simple kanban-based control

1. MACH1 can only start when BUFFER is empty.
2. MACH2 can only start when BUFFER is full.
3. MACH1 cannot start when MACH2 is down.
4. If both MACH1 and MACH2 are down, then MACH2 is repaired first.
New modeling frameworks paralleling $\dot{x}(t) = f(x,u,t)$

- **Supervisory Control theory:** enable/disable controllable events
  - Ramadge, Wonham, Krogh, Lin, Rudie, Lafortune, etc.

- **Perturbation Analysis theory:** learning from state trajectories
  - Ho, Cassandras, Cao, Glasserman, Gong, etc.
**TIME-DRIVEN vs EVENT-DRIVEN SYSTEMS**

**TIME-DRIVEN SYSTEM**

**STATES**

STATE SPACE: \( X = \mathbb{R} \)

DYNAMICS: \( \dot{x} = f(x, t) \)

**EVENT-DRIVEN SYSTEM**

**STATES**

STATE SPACE: \( X = \{s_1, s_2, s_3, s_4\} \)

DYNAMICS: \( x' = f(x, t) \)

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AUTOMATON: \((E, X, \Gamma, f, x_0)\)

- \(E\): Event Set
- \(X\): State Space

\(\Gamma(x)\): Set of feasible or enabled events at state \(x\)

- \(f\): State Transition Function \(f: X \times E \to X\)
  - (undefined for events \(e \notin \Gamma(x)\))

- \(x_0\): Initial State, \(x_0 \in X\)
Add a **Clock Structure** \( V \) to the automaton: \((E, X, \Gamma, f, x_0, V)\)
where:

\[
V = \{ v_i : i \in E \}
\]

and \( v_i \) is a **Clock or Lifetime sequence**: \( v_i = \{v_{i1}, v_{i2}, \ldots\} \)

one for each event \( i \)

Need an *internal mechanism* to determine \( NEXT EVENT \ e' \) and hence \( NEXT STATE \ x' = f(x, e') \)

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HOW THE TIMED AUTOMATON WORKS...

- CURRENT STATE
  \[ x \in X \text{ with feasible event set } \Gamma(x) \]

- CURRENT EVENT
  \[ e \text{ that caused transition into } x \]

- CURRENT EVENT TIME
  \[ t \text{ associated with } e \]

Associate a

\textit{CLOCK VALUE/RESIDUAL LIFETIME} \( y_i \)

with each feasible event \( i \in \Gamma(x) \)
HOW THE TIMED AUTOMATON WORKS...  CONTINUED

- **NEXT/TRIGGERING EVENT** $e'$:
  
  $$e' = \arg\min_{i \in \Gamma(x)} \{y_i\}$$

- **NEXT EVENT TIME** $t'$:
  
  $$t' = t + y^*$$
  
  where:  
  
  $$y^* = \min_{i \in \Gamma(x)} \{y_i\}$$

- **NEXT STATE** $x'$:
  
  $$x' = f(x, e')$$
HOW THE TIMED AUTOMATON WORKS... CONTINUED

Determine new \textit{CLOCK VALUES} $y'_i$ for every event $i \in \Gamma(x)$

\[
\begin{align*}
    y'_i &= \begin{cases} 
        y_i - y^* & i \in \Gamma(x'), i \in \Gamma(x), i \neq e' \\
        v_{ij} & i \in \Gamma(x') - \{\Gamma(x) - e'\} \\
        0 & \text{otherwise}
    \end{cases}
\end{align*}
\]

where: $v_{ij}$ = new lifetime for event $i$

\[
x' = f(x, e'), \quad e' = \arg\min_{i \in \Gamma(x)} \{y_i\} \quad \{x_1, x_2, \ldots\}
\]

\[
y' = g(y, x, V)
\]

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TIMED AUTOMATON - AN EXAMPLE

**BUFFER**

**MACHINE**

Part Arrivals → Part Departures

\[ E = \{a, d\} \]

\[ X = \{0, 1, 2, \ldots\} \]

\[ f(x, e') = \begin{cases} 
  x + 1 & e' = a \\
  x - 1 & e' = d, \ x > 0 
\end{cases} \]

\[ \Gamma(x) = \{a, d\}, \text{ for all } x > 0 \]

\[ \Gamma(0) = \{a\} \]

Given input: \[ \nu_a = \{\nu_{a1}, \nu_{a2}, \ldots\}, \ \nu_d = \{\nu_{d1}, \nu_{d2}, \ldots\} \]
TIMED AUTOMATON - A TYPICAL SAMPLE PATH

\[ x_0 = 0 \quad x_0 = 1 \quad x_0 = 2 \quad x_0 = 3 \quad x_0 = 2 \]

\[ t_0 \quad t_1 \quad t_2 \quad t_3 \quad t_4 \]

\[ e_1 = a \quad e_2 = a \quad e_3 = a \quad e_4 = d \]

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STOCHASTIC TIMED AUTOMATON

- Same idea with the Clock Structure consisting of Stochastic Processes.

- Associate with each event \( i \) a Lifetime Distribution based on which \( v_i \) is generated.

Generalized Semi-Markov Process (GSMP)

In a simulator, \( v_i \) is generated through a pseudorandom number generator.
BACK TO THE **BUFFER ALLOCATION** PROBLEM

\[ \lambda(t) \]

\[ \cdots \]

\[ K_1 \]

\[ \cdots \]

\[ K_2 \]

\[ \cdots \]

\[ K_N \]

\[ \text{THROUGHPUT} \]

\[ J(K_1, \ldots, K_N) \]

\[ \max_{K_1, \ldots, K_N} J(K_1, \ldots, K_N) \text{ s.t. } \sum_{i=1}^{N} K_i = C \]

**PARAMETRIC OPTIMIZATION**
LEARNING BY TRIAL AND ERROR

CONVENTIONAL TRIAL-AND-ERROR ANALYSIS (e.g., simulation)

- Repeatedly change parameters/operating policies
- Test different conditions
- Answer multiple WHAT IF questions

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WHAT IF...
• Parameter $p_1 = a$ were replaced by $p_1 = b$
• Parameter $p_2 = c$ were replaced by $p_2 = d$

Performance Measures under all WHAT IF Questions

AUTOMATICALLY PROVIDED

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PERTURBATION ANALYSIS

Observed sample path: $K = 2$

$\Delta x = 0 \quad \Rightarrow \quad \Delta x = -1 \quad \Rightarrow \quad \Delta x = 0$

Perturbed sample path: $K = 1$

$\Delta x = 0 \quad \Rightarrow \quad \Delta x = -1 \quad \Rightarrow \quad \Delta x = 0$
PERTURBATION ANALYSIS CONTINUED

PERTURBATION DYNAMICS OBTAINED FROM OBSERVED NOMINAL SAMPLE PATH ONLY!

\[ \Delta x(t+\delta; \theta, \Delta \theta) = f[\Delta x(t; \theta, \Delta \theta), x(t; \theta); \theta, \Delta \theta] \]

Why does this work?
Because structural knowledge of \textit{nominal system dynamics} is also used

- **Constructability Theory:** Conditions under which this is possible and methods for constructing perturbed sample paths
- **Performance Analysis:** \[ \Delta J(t+\delta; \theta, \Delta \theta) = f[\Delta J(t; \theta, \Delta \theta), x(t; \theta); \theta, \Delta \theta] \]
- **Perturbation Analysis:** Obtaining unbiased, consistent estimators for \( \frac{dJ}{d\theta} \)
BACK TO THE **BUFFER ALLOCATION PROBLEM**

**ALLOCATION VECTOR:** \( \mathbf{A} = [K_1, \ldots, K_N] \)

\[ \omega \]

\[ \mathbf{A}_1 \] \rightarrow \mathbf{SYSTEM} \rightarrow \mathbf{J}(\mathbf{A}_1)

\[ \mathbf{A}_2 \] \rightarrow \mathbf{SYSTEM} \rightarrow \mathbf{J}(\mathbf{A}_2)

\[ \mathbf{A}_N \] \rightarrow \mathbf{SYSTEM} \rightarrow \mathbf{J}(\mathbf{A}_N)

\[ \vdots \]
“LET’S CONTROL EVERYTHING” IN THE 1980’s…

Anonymous referee comments for 1983 papers on Supervisory Control:  

(courtesy W.M. Wonham)

- **Automatica** (reject)  
  “Automata have no place in control engineering”

- **Math. Systems Theory** (reject)  
  “FSM and regular languages are nothing new at best and trivial at worst”

- **SIAM J. Control and Optimization** (accept)  
  “If it’s optimal control we’ll take it”

**W.M. Wonham’s conclusion:**  
“Crossing cultural divides can be a chilly business”
ELEVATOR DISPATCHING CONTROL

PASSENGER QUEUES

COMPLEXITY:
Huge state space, Movement constraints, incomplete state info., etc.

~10^{50}

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PROBLEM (OTIS Elevator, circa 1987)

- How should an elevator respond to calls?
- At each floor: **STOP, GO, or SWITCH DIRECTION?**
- **Goal:** Reduce waiting times and preserve fairness over all floor response times

Can you outperform existing patented elevator dispatch control?

Challenge posed to...

- A Computer Scientist
- A Control Engineer
ELEVATOR DISPATCHING CONTROL

How would you proceed?

**Computer Scientist**
- Build a database...
- ...collect data...
- ...design a user interface...

**Control Engineer**
- Build a model...
- ...formulate control/optimization problem...
  - Does a solution exist?
  - ...and, if so, is it unique?
2 weeks later, they are ready to propose...

**Computer Scientist**

$0.5M, 6-month project

Will deliver a database-driven Expert System focusing on AI methods and a java-based full-colored GUI running on a LAN with agent-based HLA-compatible interoperability.

**Control Engineer**

$50K, 1-year project

Let me investigate what insight I can gain from the system dynamics, and seek a solution to this complex, dynamic optimization problem...
6 months later: Can you outperform existing technology?

**Computer Scientist**

Success!... Expert system finds solutions... not always good, but that’s because we need a faster CPU for the neural net training... Need $200K more to upgrade.

**Control Engineer**

Well, here is an algorithm that improves performance by 20%...
But I can prove convergence of my solution to the optimal only “in probability” -- not “with prob. 1”...
2 years later:

**Computer Scientist**
Still adding rules to the Expert System and training the neural net...
...but that User Interface is a real beauty!

**Control Engineer**
Algorithms developed now outperform existing solutions by 30%...
...Asking for $0.5M to add...
java-based full-colored GUI running on a LAN with agent-based HLA-compatible interoperability
A glimpse of the Control Engineer’s approach...
ELEVATOR DISPATCHING

CONTINUED

UPPEAK DISPATCHING CONTROL PROBLEM:

N identical elevators each with a capacity of C passengers

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3 elevators available at lobby...

Each person takes one and goes
Long waiting results...
A BETTER WAY TO CONTROL…

Force only 1 of the 3 elevators to be available
Can formally show (TCST, 1997) that a Markov Decision Problem formulation leads to a threshold-based optimal policy minimizing average waiting time.

Threshold parameters depend on

- passenger arrival rate
- car service rate

**CONTROLLER:**

- Load one car at a time
- Dispatch this car when
  \[ \text{number of passengers inside car} \geq \theta(\lambda, \mu) \]
Variation in $\lambda$ over 12 5-min. intervals for 1 hour uppeak traffic (courtesy B. Powell, OTIS Elevator)

PROBLEM:
- How to determine 12 thresholds, one for each 5 min. interval of fixed traffic rate?
- How to automatically adjust them on line?
CONCURRENT ESTIMATION APPROACH:

- Choose any set of 12 thresholds (one for each 5-min. interval)

- Observe system under given thresholds

- Apply Concurrent Estimation to “learn” effect of all other feasible thresholds (i.e., infer performance under hypothetical threshold values)

- Optimize thresholds
ELEVATOR DISPATCHING

CEDA: Concurrent Estimation Dispatching Algorithm

How fast did the CEDA learn optimal thresholds?

- Approximately 5 uppeak periods to converge (i.e., 5 real days)

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THE FUTURE

- COMPLEXITY
- HYBRID SYSTEMS
- COMPUTATIONAL CHALLENGES
- NEW OPTIMIZATION METHODS

OPPORTUNITIES...

- Mixed Initiative Control of Automa-teams (MICA)
THREE FUNDAMENTAL COMPLEXITY LIMITS

1/$T^{1/2}$ LIMIT

One order increase in estimation accuracy requires two orders increase in learning effort (e.g., simulation length $T$)

NP-HARD LIMIT

Tradeoff between GENERALITY and EFFICIENCY of an algorithm

[ Wolpert and Macready, 1997 ]

NO-FREE-LUNCH LIMIT

INFO. SPACE

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THREE FUNDAMENTAL COMPLEXITY LIMITS

1/\sqrt{T} LIMIT

NP-HARD LIMIT

NO-FREE-LUNCH LIMIT
HIERARCHICAL DECOMPOSITION OF COMPLEX SYSTEMS

TIME SCALE
- Weeks - Months
- Minutes - Weeks
- msec - Hours

MODEL
- Diff. Eq’s, LP
- Automata, Simulation, Queueing
- Diff. Eq’s, Detailed Simulation

DIFFERENTIAL EQUATIONS

DISCRETE-EVENT PROCESSES

PHYSICAL (TIME-DRIVEN) PROCESSES

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What exactly does that mean?
HYBRID SYSTEMS IN MANUFACTURING

Manufacturing system integration (ALCOA, 1997):

• How to integrate ‘process control’ with ‘operations control’?

• How to improve product quality within reasonable time?

PROCESS CONTROL
- Physicists
- Material Scientists
- Chemical Engineers
- ...

OPERATIONS CONTROL
- Industrial Engineers, OR
- Schedulers
- Inventory Control
- ...

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Thanks to several co-workers whose contributions are reflected in this talk...

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TO CONCLUDE...

...LET’S APPLY CONTROL PRINCIPLES LIKE FEEDBACK, etc. IN EVERYTHING...

...BUT...
LET'S NOT GET CARRIED AWAY EITHER...

WELL, YOU'VE BEEN A PRETTY GOOD HOSS, I GUESS. HARDWORKIN', NOT THE FASTEST CRITTER I EVER COME ACROSS, BUT...

NO, STUPID, NOT FEEDBACK. I SAID I WANTED A FEED BAG.