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Building theoretical foundations for distributed control

A centralized paradigm dominates theory and curriculum today

We need methodology for
- Decentralized specifications
- Decentralized design
- Validation of global behavior

Approximating the Centralized Controller

Bellman’s equation $|x|^2 = \min_u (|Ax + Bu|^2 + |x|^2 + |u|^2)$ gives $u = -Lx$ where

$$L = \begin{bmatrix} 0.3420 & 0.0737 & 0.0046 & 0.0002 \\ 0.1839 & 0.3448 & 0.0736 & 0.0047 \\ 0.0103 & 0.1840 & 0.3447 & 0.0726 \\ 0.0008 & 0.0104 & 0.1808 & 0.3296 \end{bmatrix}$$

Diagonal dominance of $L$ suggests natural approximations:

$$L_0 = \begin{bmatrix} 0.34 & 0 & 0 & 0 \\ 0 & 0.34 & 0 & 0 \\ 0 & 0 & 0.34 & 0 \\ 0 & 0 & 0 & 0.33 \end{bmatrix}, \quad L_1 = \begin{bmatrix} 0.34 & 0.07 & 0 & 0 \\ 0.18 & 0.34 & 0.07 & 0 \\ 0 & 0.18 & 0.34 & 0.07 \\ 0 & 0 & 0.18 & 0.33 \end{bmatrix}$$

Today’s challenges: Distributed controller validation
Distributed control synthesis

Outline

- Introduction
- Game theory and dual decomposition
  - Dynamic dual decomposition
  - Distributed validation for wind farm example
  - Distributed synthesis

Needs for distributed control theory

Three major challenges:
- Rapidly increasing complexity
- Dynamic interaction
- Information is decentralized

A “Wind Farm” Case Study

$$x_1(t + 1) = \begin{bmatrix} 0.6 & 0.1 & 0 \\ 0.3 & \ddots & \ddots \\ \vdots & \ddots & 0.1 & \ddots \\ 0 & 0.3 & 0.6 & \ddots \end{bmatrix} x_n(t + 1) + \begin{bmatrix} u_1(t) + w_1(t) \\ u_2(t) + w_2(t) \\ \vdots \\ u_n(t) + w_n(t) \end{bmatrix}$$

Minimize $V = E \sum_{i=1}^n (|x|^2 + |u|^2)$

Inspiration from other fields

- Congestion control in networks
- Collective motion in biology
- Oscillator synchronization in physics
- Parallelization in optimization theory
- Saddle points and equilibria in economics
- Cooperative and non-cooperative game theory

Much focus on convergence to equilibria, less on dynamic performance.

50 years old idea: Dual decomposition

$$\min_{x,y,z,w} [V_1(x,y) + V_2(x,z) + V_3(x,w)]$$

$$= \max_{p,q} \min_{r,s} [V_1(x_1,y) + V_2(x_2,z) + V_3(x, w) + p(x_1 - x_2) + q(x_2 - x_3)]$$

The optimum is a Nash equilibrium of the following game:

The three computers try to minimize their respective costs

Computer 1: $\min_{x_1} [V_1(x_1, y) + px_1]$  
Computer 2: $\min_{x_2} [V_2(x_2, z) - px_2 + qx_3]$  
Computer 3: $\min_{x_3} [V_3(x_3, w) - qx_3]$  

while the “market makers” try to maximize their payoffs

Between computer 1 and 2: $\max_p [p(x_1 - x_2)]$  
Between computer 2 and 3: $\max_q [q(x_2 - x_3)]$
Potential game

The three computers try to minimize the potential function
\[ V_1(x_1,y) + V_2(x_2,z) + V_3(x_3,u) + p(x_1-x_2) + q(x_2-x_3) \]
while the market makers try to maximize it.
Finding a Nash equilibrium (where no player has an incentive to change strategy) is greatly simplified by existence of a potential function.

Decentralized Bounds on Suboptimality

Given any \( p,q,\hat{x},\hat{y},\hat{z},\hat{w} \), the distributed test
\[
\begin{align*}
V_1(\hat{x},\hat{y}) + p\hat{x} & \leq \min_{x,y} [V_1(x_1,y) + px_1] \\
V_2(\hat{x},\hat{z}) - p\hat{x} + q\hat{z} & \leq \min_{x,z} [V_2(x_2,z) - px_2 + qz_2] \\
V_3(\hat{\bar{x}},\hat{\bar{w}}) - q\hat{\bar{z}} & \leq \min_{x,w} [V_3(x_3,w) - qx_3]
\end{align*}
\]
implies that the globally optimal cost \( J^* \) is bounded as
\[
V_1(\hat{x},\hat{y}) + V_2(\hat{x},\hat{z}) + V_3(\hat{\bar{x}},\hat{\bar{w}}) \leq \min_{x,y,z,w} [V_1(x,y) + V_2(x,z) + V_3(x,w)]
\]
Proof: Add both sides up!

The saddle point algorithm

Update in gradient direction:
\[
\begin{align*}
\text{Computer 1:} & \quad \dot{x}_1 = -\partial V_1/\partial x - p \\
\text{Computer 1 and 2:} & \quad \dot{y} = -\partial V_1/\partial y \\
\text{Computer 2:} & \quad \dot{z} = -\partial V_2/\partial z \\
\text{Computer 2 and 3:} & \quad \dot{q} = x_2 - x_3 \\
\text{Computer 3:} & \quad \dot{w} = -\partial V_3/\partial w
\end{align*}
\]
Globally convergent if \( V_i \) convex! [Arrow, Hurwicz, Usawa 1958]
Lyapunov function: \( V = x_1^2 + x_2^2 + x_3^2 + y^2 + z^2 + w^2 + p^2 + q^2 \)

What do we achieve?

- Performance criteria for individual nodes
- Suboptimality bounds indicate where things went wrong
- Prices show the relative importance of different terms
- Sparsity structure useful for efficient computations

A General Optimal Control Problem

Minimize \( V(u) = E \sum_j \ell_i(x_i(t), u_i(t)) \)
subject to
\[
\begin{align*}
x_1(t+1) &= f_1(x_1,v_{1j},u_1,w_1) \\
&\vdots \\
x_n(t+1) &= f_n(x_n,v_{nj},u_n,w_n)
\end{align*}
\]
where
\[
v_{ij} = x_j
\]
holds for all \( i,j \).

Distributed Verification

\[
\begin{align*}
\max_p \sum_i \min_{u_i,v_{ij},p} E \left[ \ell_i(x_i(t), u_i(t)) - 2\sum_j (p_{ij})^T v_{ij} + 2(\sum_j p_{ij})^T x_i \right]
\end{align*}
\]
Each agent \( i \) makes the comparison
\[
EJ_i(\bar{x_i},\bar{u}_i,\bar{s}_i,\bar{p}) \leq \min_{u_i,v_{ij},p} EJ_i(x_i, u_i, v_{ij}, p)
\]
Actual cost in node \( i \) \( \text{Optimal cost in node } i \)
where minimization is subject to the local dynamics
\[
x_i(t+1) = f_i(x_i, v_{ij}, u_i, w_i)
\]
If no actual cost exceeds the expected cost by more than 10%, then the global cost is within 10% from optimal.

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Decomposing the Cost Function

\[
\begin{align*}
&\max_p \min_u \sum_i E \left[ \ell_i(x_i(t), u_i(t)) + 2\sum_j (p_{ij})^T v_{ij} + 2(\sum_j p_{ij})^T x_i \right] \\
&\quad = \max_p \min_u \sum_i \max_{p_{ij}} E \left[ \ell_i(x_i(t), u_i(t)) - 2\sum_j (p_{ij})^T v_{ij} + 2(\sum_j p_{ij})^T x_i \right]
\end{align*}
\]
so agent \( i \) should minimize the stationary value of what he expects others to pay him
\[
E(\ell_i(x_i(t), u_i(t)) - 2\sum_j (p_{ij})^T v_{ij} + 2(\sum_j p_{ij})^T x_i)
\]
his own cost
\[
-2\sum_j (p_{ij})^T v_{ij} + 2(\sum_j p_{ij})^T x_i
\]
what he pays others
Consider control laws $\dot{u}_i = \mu_i(x)$ and stationary solutions to
\[ \dot{x}_i(t+1) = f_i(x_i, \tilde{x}_i, \mu_i(x), \bar{w}_i) \]
where $\bar{w}_i(t)$ is stationary white noise. If $\alpha > 0$, then (I) implies (II):

(I) There exists $\vec{\rho} = \bar{\lambda}(\tilde{x})$ satisfying
\[ \mathbb{E}_t f_i(x_i, \tilde{x}_i, \bar{w}_i, \vec{\rho}) \leq \alpha \min_{x_i, \tilde{x}_i, \bar{w}_i} \mathbb{E}_t f_i(x_i, \tilde{x}_i, \bar{w}_i, \vec{\rho}) \]
when minimizing over stationary solutions to
\[ x_i(t+1) = f_i(x_i, \tilde{x}_i, \bar{w}_i, \vec{\rho}) \]

(II) $\sum_t \mathbb{E}_t f_i(x_i, \tilde{x}_i) \leq \alpha \min_{x_i, \tilde{x}_i, \bar{w}_i} \sum_t \mathbb{E}_t f_i(x_i, \tilde{x}_i)$ when minimizing over stationary solutions to
\[ x_i(t+1) = f_i(x_i, \tilde{x}_i, \bar{w}_i, \vec{\rho}) \]

If dynamics is linear, $\epsilon_i \geq 0$ convex and $\alpha = 1$, then (II) implies (I).

A “Wind Farm” Case Study

Minimize $V = \mathbb{E} \sum_{i=1}^4 (|x_i|^2 + |u_i|^2)$

\[
\begin{bmatrix}
  x_1(t+1) \\
  x_2(t+1) \\
  x_3(t+1) \\
  x_4(t+1)
\end{bmatrix} = \begin{bmatrix}
  0.6 & 0.1 & 0 & 0 \\
  0.3 & 0.6 & 0.1 & 0 \\
  0.3 & 0.3 & 0.6 & 0 \\
  0 & 0 & 0 & 0.33
\end{bmatrix}\begin{bmatrix}
  x_1(t) \\
  x_2(t) \\
  x_3(t) \\
  x_4(t)
\end{bmatrix} + \begin{bmatrix}
  w_1(t) + w_1(t) \\
  w_2(t) + w_2(t) \\
  w_3(t) + w_3(t) \\
  w_4(t) + w_4(t)
\end{bmatrix}
\]

Today’s challenges:
- Distributed controller validation
- Distributed control synthesis

\[
\begin{bmatrix}
  0.34 & 0 & 0 & 0 \\
  0 & 0.34 & 0 & 0 \\
  0 & 0 & 0.34 & 0 \\
  0 & 0 & 0 & 0.33
\end{bmatrix} \quad \begin{bmatrix}
  0.34 & 0.07 & 0 & 0 \\
  0 & 0.18 & 0.07 & 0 \\
  0 & 0 & 0.18 & 0.07 \\
  0 & 0 & 0 & 0.34
\end{bmatrix}
\]

Decomposing the turbine dynamics

Minimize $\mathbb{E} \sum_{i=1}^4 (|x_i|^2 + |u_i|^2)$

subject to

\[
\begin{bmatrix}
  v_{12} \\
  v_{21} \\
  v_{23} \\
  v_{24} \\
  v_{43}
\end{bmatrix} = \begin{bmatrix}
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3 \\
  x_4
\end{bmatrix}
\]

\[
\begin{bmatrix}
  v_{12} \\
  v_{21} \\
  v_{23} \\
  v_{24} \\
  v_{43}
\end{bmatrix} = \begin{bmatrix}
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0
\end{bmatrix}\begin{bmatrix}
  x_1 \\
  x_2 \\
  x_3 \\
  x_4
\end{bmatrix}
\]

Problem solved by the first turbine

Minimize $\mathbb{E}(|x_1|^2 + |u_1|^2 + 2p_{12}x_{12} - 2p_{21}x_1)$

when $x_1^* = 0.6x_1 + 0.1v_{12} + u_1 + w_1$

Test for suboptimality:

\[
\mathbb{E}(|x_1|^2 + |u_1|^2 + 2p_{12}x_{12} - 2p_{21}x_1) 
\leq \alpha \min_{x_1, x_1^*} \mathbb{E}(|x_1|^2 + |u_1|^2 + 2p_{12}x_{12} - 2p_{21}x_1)
\]

\[
\mathbb{E}(|x_1|^2 + |u_1|^2 + 2p_{12}x_{12} - 2p_{21}x_1)
\]

Validation Using Centralized Model

The variance $\mathbb{E} \sum_{i=1}^4 (|x_i|^2 + |u_i|^2)$ for the optimal centralized controller becomes

$V_c = 4.9904$

while the values for the decentralized approximations become

$V_0 = 5.2999 \quad V_1 = 4.9917$

These numbers were calculated using a global model.

We will next use dual decomposition to see that the control laws can be both validated and synthesized in a distributed way.

Problem solved by the first turbine

Minimize $\mathbb{E}(|x_1|^2 + |u_1|^2 + 2p_{12}v_{12} - 2p_{21}x_1)$

when $x_1^* = 0.6x_1 + 0.1v_{12} + u_1 + w_1$

using measurements of $x$ and knowledge of the joint spectral density of $x$, $w$, $u_{12}$ and $p_{21}$.

Notice: Once the price sequences $p_{12}(t), p_{21}(t)$ are given, no other knowledge of the outside world is relevant. However, since future prices are usually not available, knowledge of other states can be useful for price prediction.

Performance degradation due to decentralization

\[
\begin{bmatrix}
  0.24 & 0 & 0 & 0 \\
  0 & 0.24 & 0 & 0 \\
  0 & 0 & 0.24 & 0 \\
  0 & 0 & 0 & 0.34
\end{bmatrix} \quad \begin{bmatrix}
  0.04 & 0.04 & 0.04 & 0.04 \\
  0.04 & 0.04 & 0.04 & 0.04 \\
  0.04 & 0.04 & 0.04 & 0.04 \\
  0.04 & 0.04 & 0.04 & 0.04
\end{bmatrix} \quad \begin{bmatrix}
  0 & 0.07 & 0 & 0.17 \\
  0 & 0.07 & 0 & 0.17 \\
  0 & 0.07 & 0 & 0.17 \\
  0 & 0.07 & 0 & 0.17
\end{bmatrix} \quad \begin{bmatrix}
  0.05 & 0.13 & 0.13 & 0.13 \\
  0.15 & 0.29 & 0.29 & 0.29 \\
  0.29 & 0.57 & 0.57 & 0.57 \\
  0.57 & 0.57 & 0.57 & 0.57
\end{bmatrix}
\]

Compare expected and actual costs for the two control laws:

$u = -L_{\delta x}$ and $\bar{\rho} = \bar{M} x$:

\[
\begin{align*}
1.5647 & \leq 1.5350 \alpha \\
0.9833 & \leq 0.8558 \alpha \\
0.9833 & \leq 0.8558 \alpha \\
1.5647 & \leq 1.5350 \alpha
\end{align*}
\]

\[
\begin{align*}
1.5741 & \leq 1.5740 \alpha \\
0.9132 & \leq 0.9217 \alpha \\
0.9132 & \leq 0.9217 \alpha \\
1.5741 & \leq 1.5740 \alpha
\end{align*}
\]

\[
\begin{align*}
1.062 & \leq \alpha = 1.27 \\
1.0003 & = \frac{V}{V_c} \leq \alpha = 1.0094
\end{align*}
\]
Optimal Prices by Dynamic Programming

Optimal control problem:

Minimize \( E(|x|^2 + |u|^2) \)

when \( x^* = Ax + Av + Bu + w \) and \( v = Sx \)

Dynamic programming gives control law as well as prices:

\[
|x|^2 = \max_p \min_{x,v} \left[ Ax + Av + Bu + |x|^2 + |u|^2 - 2pt(v - Sx) \right]
\]

\[
p(t) = \begin{bmatrix}
0.0342 & 0.2574 & 0.0010 & 0.0002 \\
0.5545 & 0.1013 & 0.0382 & 0.0038 \\
0.0024 & 0.0867 & 0.0755 & 0.0025 \\
0.0002 & 0.0010 & 0.0010 & 0.0002 \\
\end{bmatrix} \begin{bmatrix}
x_1(t) \\
x_2(t) \\
x_3(t) \\
x_4(t) \\
\end{bmatrix}
\]

\( M \)

The same \( P \) and \( u(t) = -Lx(t) \) as in classical solution.

**Distributed gradient iteration for control law**

By the maximum principle, optimal solutions to

Minimize \( E(|x|^2 + |u|^2 + 2p_{12}v_{12} - 2p_{21}x_1) \)

when \( x^* = 0.6x_1 + 0.1v_{12} + u_1 + u_2 \)

must minimize the Hamiltonian

\( E(|x|^2 + |u|^2 + 2p_{12}v_{12} - 2p_{21}x_1 - \lambda_1(0.6x_1 + 0.1v_{12} + u_1 + u_2)) \)

This allows us to modify the control law

\( u_1 = \begin{bmatrix} 11 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \)

in the gradient direction using correlation estimates from the time interval \( t = 1, \ldots, T. \)

**Gradient iteration for the wind park**

\[
\text{cost} = 5.3183
\]

\[
L = \begin{bmatrix}
0.0366 & 0.0411 & 0 & 0 & 0 \\
0.0386 & 0.0623 & 0.0546 & 0 & 0 \\
0 & 0.0555 & 0.0686 & 0.0544 & 0 \\
0 & 0 & 0.0554 & 0.0620 & 0.0405 \\
0 & 0 & 0 & 0.0385 & 0.0363 \\
\end{bmatrix}
\]

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- Distributed synthesis

"Wind Farm" Revisited

Minimize \( V = E \sum_{i=1}^n (|x|^2 + |u|^2) \)

\[
\begin{bmatrix}
x_1(t+1) \\
x_2(t+1) \\
\vdots \\
x_n(t+1) \\
\end{bmatrix} = \begin{bmatrix}
0.6 & 0.1 & 0 & \cdots & 0 \\
0.3 & \ddots & \ddots & \ddots & 0.1 \\
0 & \ddots & \ddots & \ddots & 0.3 \\
0 & 0 & 0.3 & \ddots & 0.3 \\
0 & 0 & 0 & 0.3 & \ddots \\
\end{bmatrix} \begin{bmatrix}
x_1(t+1) \\
x_2(t+1) \\
\vdots \\
x_n(t+1) \\
\end{bmatrix} + \begin{bmatrix}
u_1(t) + w_1(t) \\
u_2(t) + w_2(t) \\
\vdots \\
u_n(t) + w_n(t) \\
\end{bmatrix}
\]

We will optimize a tri-diagonal control structure

\[
L = \begin{bmatrix}
0 & 0 & \cdots & 0 \\
0 & \ddots & \ddots & \ddots \\
\ddots & \ddots & \ddots & \ddots \\
0 & 0 & \cdots & 0 \\
\end{bmatrix}
\]

Prices by distributed gradient iteration

Diagonal dominance suggests a tri-diagonal structure for \( M \)

\[
\begin{bmatrix}
p_{11}(t) \\
p_{12}(t) \\
p_{21}(t) \\
p_{22}(t) \\
p_{31}(t) \\
p_{32}(t) \\
p_{41}(t) \\
p_{42}(t) \\
\end{bmatrix} = \begin{bmatrix}
m_{11} & m_{12} & 0 & 0 \\
m_{21} & m_{22} & 0 & 0 \\
m_{31} & m_{32} & m_{33} & 0 \\
m_{41} & m_{42} & m_{43} & m_{44} \\
0 & 0 & m_{53} & m_{54} \\
0 & 0 & 0 & m_{64} \\
0 & 0 & 0 & 0 & m_{65} \\
\end{bmatrix} \begin{bmatrix}
x_1(t) \\
x_2(t) \\
x_3(t) \\
x_4(t) \\
x_5(t) \\
x_6(t) \\
x_7(t) \\
x_8(t) \\
\end{bmatrix}
\]

After running the system with fixed prices and control laws during a time interval \( t = 1, \ldots, T, \) the correlation between state measurements and constraint violations can be estimated as

\[
E \left[ x_1(t) v_{12} - x_2(t) \right] \approx \frac{1}{T} \sum_{t=1}^T \left[ x_1(t) v_{12} - x_2(t) \right]
\]

If the correlation is non-zero, the prices \( m_{11}, m_{12} \) are adjusted.

Gradient iteration for the wind park

\[
\text{cost} = 7.4944
\]

\[
L = \begin{bmatrix}
0.0138 & 0.0195 & 0 & 0 & 0 \\
0.0162 & 0.0283 & 0.0294 & 0 & 0 \\
0 & 0.0264 & 0.0333 & 0.0294 & 0 \\
0 & 0 & 0.0264 & 0.0283 & 0.0195 \\
0 & 0 & 0 & 0.0162 & 0.0138 \\
\end{bmatrix}
\]

Gradient iteration for the wind park

\[
\text{cost} = 4.4277
\]

\[
L = \begin{bmatrix}
0.0709 & 0.0629 & 0 & 0 & 0 \\
0.0666 & 0.1025 & 0.0749 & 0 & 0 \\
0 & 0.0853 & 0.1070 & 0.0744 & 0 \\
0 & 0 & 0.0851 & 0.1016 & 0.0611 \\
0 & 0 & 0 & 0.0662 & 0.0697 \\
\end{bmatrix}
\]
### Convergence rate versus state dimension

![Convergence rate versus state dimension](image)

For a fixed number of iterations and fixed sparsity structure of $L$, $M$, the computational cost grows linearly with $n$!

---

### Conclusions

We have seen dynamic dual decomposition used for:

- Distributed validation
- Distributed synthesis

Benefits to be obtained:

- Reduced complexity
- Control structure reflects plant structure
- Flexibility and robustness

We have the tools to deal with dynamics!

---

### Welcome to join the efforts!

Much (most) remains to be done and much is happening already at this conference!

See [Rantzer CDC07]

[Rantzer ACC09] covers much of this lecture. Working paper on www.control.lth.se/user/anders.rantzer

Lund University funds postdocs and will also hire new faculty members to complement the competence of our current staff.
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