Full Life-cycle Deployment of Distributed Control in Large-scale Infrastructures

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Contents

▪ Background
▪ Distributed Control
▪ Distributed Control Deployment
Our world is more complex and growing faster than our control methods can handle

Complex Systems

• Highly interconnected

• Heterogeneous device-human participation

• Extreme data

• Pervasive intelligence

• Increasing autonomy
Global energy goals cannot be met without changes in how we control complex systems

Energy System
- Potential for substantial efficiencies in end-user systems with new controls
- More data and devices available
- New assets difficult to coordinate
- Existing controls antiquated

Cyber-physical System
- Growing “edge” computing resources
- Cloud computing becoming paradigm
- Existing security models challenged

Traditional centralized control approaches are generally unable to resolve those issues
From Big Data to Distributed Control

The move from Big Data to Distributed Control involves addressing:

• Large numbers of sensing and/or control end points
• High complexity
• Node heterogeneity
• Multiple scales of operation
• Pervasive computing/autonomous nodes
• Wide geographical scope

The solutions must be:
*Deployable, scalable, robust, resilient, and adaptable*
Distributed Control Hypothesis

Hypothesis

Distributed control approach is the fastest way to advance control theory to address the challenges posed by large-scale infrastructure systems.
Electric power system as an example

- Difficult to maintain balance
  - Non-dispatchable
  - Intermittency
- Need demand-side control
  - Residential loads
  - Commercial buildings
Building-to-Grid (B2G) Integration

- Two fundamental questions for B2G integration
  - Characterize the capacity flexibility of commercial buildings
  - Control the power consumption to follow dispatched signals

Key: Respect distinct preferences of building occupants
Demand Side Response

• Manage power grid by actively engaging both customer-owned and third-party distributed energy resources (DERs) into system operation through

  ▪ Direct control
    ✓ Utility companies remotely control operations of residential loads based on prior agreements
    ✓ Traditionally concerned with peak load reduction
    ✓ Recent efforts focus on modeling and control of different types of loads to provide various grid services

  ▪ Price control
    ✓ Price signals directly sent to individual loads to affect local demand
    ✓ Example: time-of-use (TOU) pricing, critical peak pricing (CPP), real-time pricing (RTP)

  ▪ Transactive control
    ✓ Automated loads engaged in market interaction
    ✓ Information exchange includes quantity and price
Transactive Control

- Key features
  - Open, flexible and interoperable

- Value proposition
  - Promote voluntary participation by value-based incentives
  - Respect local objectives and choice domains
  - Ensure stability and predictability of system response
  - Simplify coordination through decomposition and localization
  - Engage multiple stakeholders with different preferences

Market-based Coordination

Value-driven Control
Fundamental Concepts

• Agent types
  ▪ Coordinator (market)
  ▪ Supplier (seller)
  ▪ Customer (buyer)

• Power systems
  ▪ Distributed generator
  ▪ Photovoltaic system
  ▪ Energy storage
  ▪ Residential appliances
  ▪ Building loads (AHU, chiller, etc.)
  ▪ Residential building
  ▪ Commercial building
  ▪ Community
  ▪ Microgrid
  ▪ Distribution system
Transactive Building
(BTO Transactive Campus)

- One commercial building with responsive building loads
- Objective: reduce peak demand during real-time operations

- **Customer – RTU, VAV, Lighting**
  \[
  \max_{\text{power}_i} \left( \text{utility}_i(\text{power}_i) - \text{payment}_i \right) \\
  \text{s.t. } i\text{-th load dynamics}
  \]

- **Coordinator – BMS**
  \[
  \max_{\text{power}_i} \sum_{i=1}^{N} \text{utility}_i(\text{power}_i) - \text{cost}(\text{power}_g) \\
  \text{s.t. } \text{power}_g = \sum_{i=1}^{N} \text{power}_i + \text{power}_{uc} \leq \text{limit} \\
  \text{i-th load dynamics}
  \]
RTU System
Real-time Market w/ Transactive Control

- Occupant Inputs
- Load Dynamics
- Control Response
- Power Demand
- Price Generation
- Preferences
- Power
- Price

- External Supply
- RT Supply Bidding
- RT Demand Bidding
- RT Market
- RT Clearing Price
- Load Control
- RT Control

- Load 1
- \( \cdots \)
- Load \( i \)
- \( \cdots \)
- Load \( N \)
Transactive Control – VAV/RTU System

• Control response curve for RTU or VAV Systems (Cooling for illustration)

Local Input = $T_{\text{set}}$

Parameter = \{ $T_{\text{min}}$, $T_{\text{max}}$, $T_{\text{desired}}$, \lambda_{\text{avg}}$, $\sigma$, $k$ \}

comfort saving

Occupant’s preference
• Coupling control response curve with load dynamics leads to demand curve

Load Dynamics
Hierarchical Market Clearing inside Building

- Market coordinator clears the market in one time through demand bidding

Without demand violation:

\[ \lambda (\$/kW) \]
\[ \lambda_{\text{cap}} \]
\[ \lambda_{\text{base}} \]
\[ P_{uc} \quad D \quad P \ (kW) \]

With demand violation:

\[ \lambda (\$/kW) \]
\[ \lambda_{\text{cap}} \]
\[ \lambda_{\text{base}} \]
\[ P_{uc} \quad D \quad P \ (kW) \]

\( \lambda_{\text{base}} \) Base energy price
\( \lambda_{\text{cap}} \) Price cap
A typical Distributed Control System - transactive control for commercial buildings

Campus or City Level Market

Demand Curves

Price

Meter

AHU+Chiller

VAV Control

AHU+Chiller

VAV Control

Light Control

Set Point

Building 1

Building P
A typical Distributed Control System - Requirement for large-scale deployment

A scalable deployment of the transactive control should be

- **Automated in terms of the control setup process**
  - Standardizing the control process

- **Extensible and adaptable to different applications with the minimized modifications**
  - Modular programming for realized different functionalities

- **Capable to handle large-scale communication at various time-resolutions with different protocols**
  - Data management auxiliary functions combined with databases
  - Generic communication interfaces
Deployment of transactive control
- Standardizing the control process

Diagram:
- Meter
  - AHU+Chiller
  - RTU Control
  - VAV Control
  - VAV Control

- Aggregator BP
  - Aggregator1
    - Control 1
    - Control n
    - Control n+1
Deployment of transactive control - Standardizing the control structure description

```
{ "Aggregator 1":
  {"type": "aggregator",
   "config": "/aggregaor1",
   "elements":
     {"Control 1":
      {"name": "vav1",
       "config": "/aggregaor1/vav1"},
      ...
     },
     ...
  },
  "Control n+1":
  { "name": "light1",
   "config": "/light1",
    ....
  }
}
```
Deployment of transactive control
- Separating functionality

- Quantity estimation
- Price response control
- Interface for control actuation
- Interface for market activities

- Interface for market activities: reservation, bidding, and clearing
- Price conversion
- Commodity conversion
Deployment of transactive control
- Separating functionality

- Quantity estimation
- Price response control
- Interface for control actuation
- Interface for market activities

Control

- Interface for market activities
- Price conversion
- Commodity conversion

Aggregator

Device Class

Control Class
Actuator Class
Market Service Class
Middleman Class
Deployment of transactive control
- Separating functionality

- Control Class
  - Actuator Class
  - Market Service Class
  - Middleman Class

- Device Class
  - Inherit
  - Aggregator Class

- Control Class
  - Inherit
  - VAV Control Agent

- Aggregator Class
  - Inherit
  - Control Agent
  - AGU Control Agent

- Instantiate
  - First order VAV model
  - Fan model
  - AHU Control Agent
Deployment of transactive control
- First order VAV model

First-order zone model

\[ C_i \frac{T_i^{k+1} - T_i^k}{\Delta t} = \frac{T_a^k - T_i^k}{R_i} + Q_{i,hvac}^k + Q_{i,dis}^k \]

Assuming \( Q_{dis}^k \) is constant:

\[ Q_{i,hvac}^k = C_i \frac{\Delta t}{T_i} T_i^{k+1} + \frac{\Delta t - C_i R_i}{R_i \Delta t} T_i^k - \frac{1}{R_i} T_a^k - Q_{i,dis}^k \]

Assuming \( T_i^{k+1} = T_{set,i}^{k+1} \):

\[ Q_{i,hvac}^k = C_i \frac{\Delta t}{T_{set,i}} T_{set,i}^{k+1} + \frac{\Delta t - C_i R_i}{R_i \Delta t} T_i^k - \frac{1}{R_i} T_a^k - Q_{i,dis}^k \]

Short-term prediction

\[ Q_{i,hvac}^k = a_i^0 T_{set,i}^{k+1} + a_i^1 T_i^k + a_i^2 T_a^k + a_i^3 \]

Long-term prediction

\[ Q_{i,hvac}^k = a_i^0 T_{set,i}^{k+1} + a_i^1 T_{set,i}^k + a_i^2 T_a^k + a_i^3 \]

\( T \): Temperature
\( C \): Thermal capacitance
\( R \): Thermal resistance
\( c \): Specific heat for air
\( Q \): Heat flux
\( m \): Mass flow rate
\( \Delta t \): Discrete time interval
\( a \): Regression coefficient

\( k \): Discrete time index
\( d \): Discharge
\( i \): Zone index
\( dis \): Disturbance
\( a \): Ambient
Deployment of transactive control  
- AHU model

AHU Fan power

$$P_m^k = b_m^1 (m_m^k) + b_m^2 (m_m^k)^2 + b_m^3 (m_m^k)^3$$

Chiller Power:

$$P_m^k = \begin{cases} 
0 & \text{if unoccupied or } T_a^k \leq T_{m,\text{dis}}^k \\
\frac{m_m^k C_{\text{air}} (T_{m,\text{mix}}^k - T_{m,\text{dis}}^k)}{\xi COP} & \text{else} 
\end{cases}$$

where

$$T_{m,\text{mix}}^k = \begin{cases} 
T_a^k & \text{if } T_a^k \leq T_{\text{eco}}^k \\
\varphi T_a^k + (1 - \varphi) T_{m,\text{ret}} & \text{else} 
\end{cases}$$

for VAV, $$T_{m,\text{dis}}^k = T_{m,\text{dis}}$$
Deployment of transactive control - Communication support from VOLTTRON

- Data management auxiliary functions
- BACnet/Modbus based communication
Deployment of transactive control - VOLTTRON-based Implementation

Aggregator BP

Aggregator 1

Control 1

Control n

Control n+1

Docker

VOLTTRON Environment

Agents

Model files

Configuration
Deployment of transactive control - VOLTTRON-based Implementation

VOLTTRON
Multiple-platform communication
Deployment of transactive control
- Vision for future integration

GridLAB-D → GridPACK
HELICS Docker

Docker Compose
Docker 1
... 
Docker P+1

BOPTEST
Docker 1
... 
BOPTEST*
Docker n

simulation tests

real building tests

Conclusions

- Distributed control is promising for operating large scale infrastructures

- Distributed control may pose new challenges in the real world deployment

- VOLTTRON can be used to facilitate the deployment of distributed control such as transactive control for building systems
Thank you