United Technologies

Climate | Controls | Security

Control Design and Verification with Physics Based Models for HVAC/R Applications

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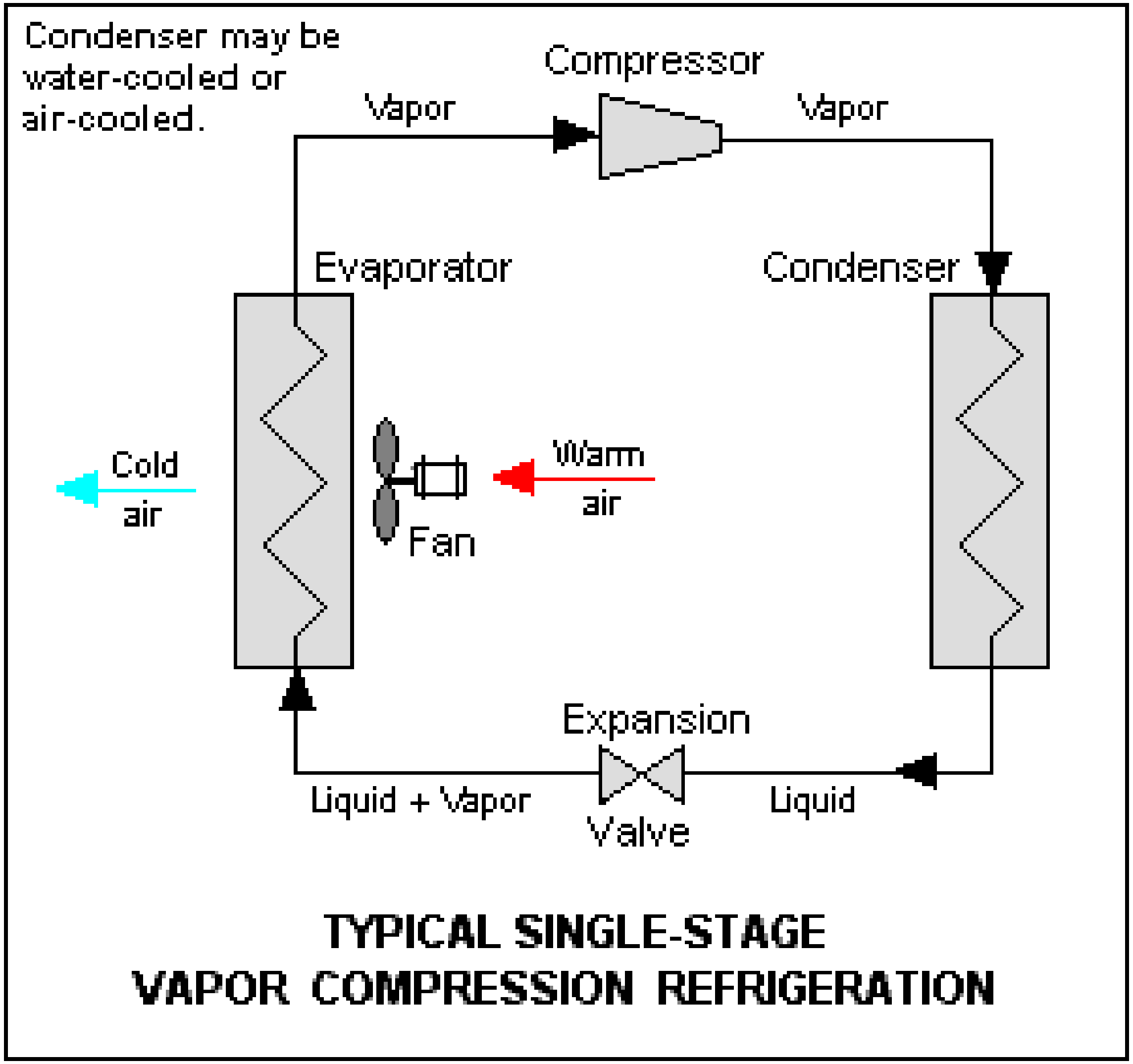
OUTLINE

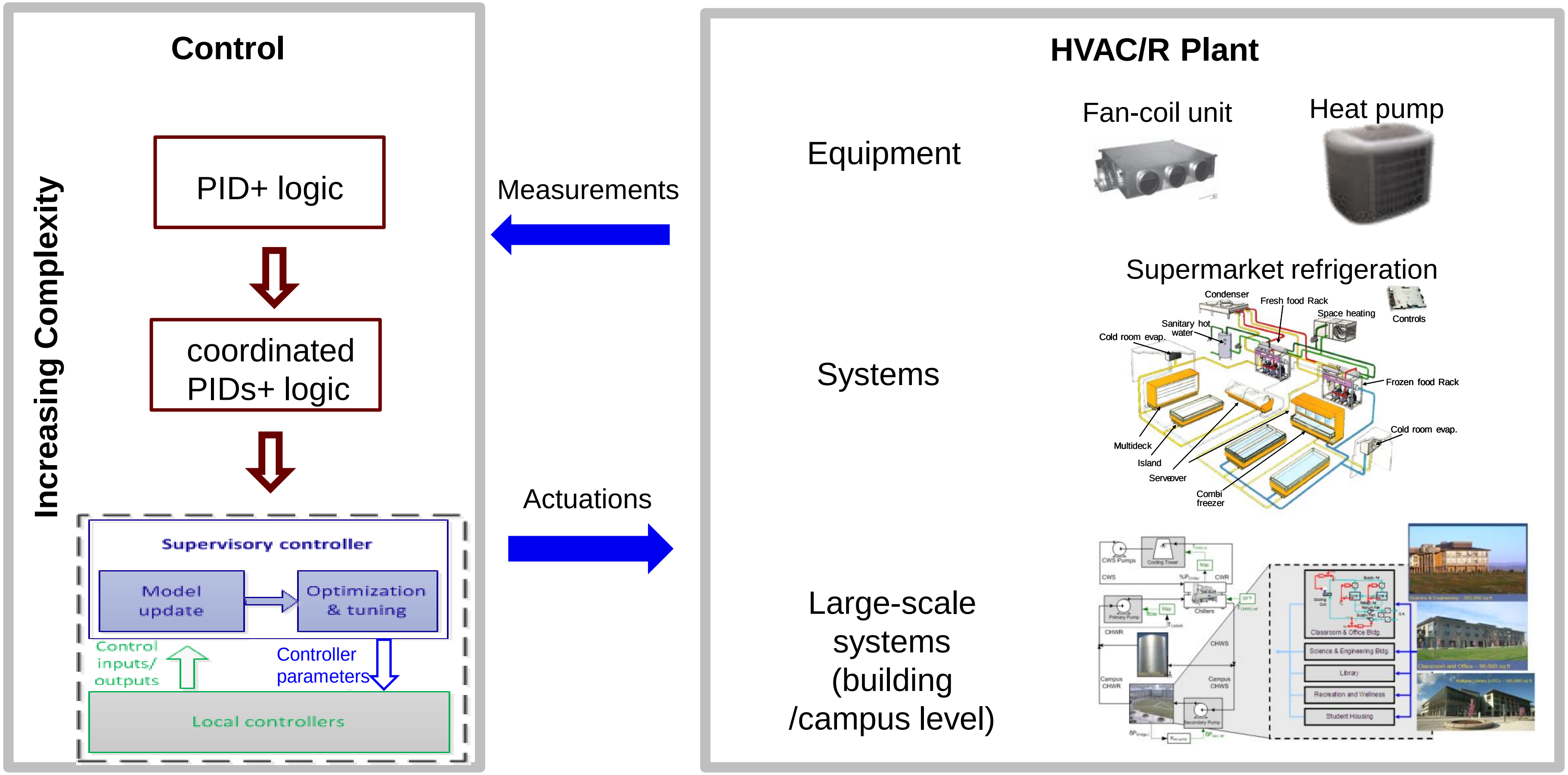
- Vapor compression refrigeration cycle
- Model Based Control Development Process
- Application Examples
  - Transportation Refrigeration
  - Commercial Refrigeration
  - Residential HVAC
  - Commercial Building HVAC
- Conclusions

VAPOR COMPRESSION REFRIGERATION CYCLE



WHAT IS CONTROL OF HVAC/R?

Reliably operating HVAC/R systems to be *functional* and *energy efficient*



What's important?

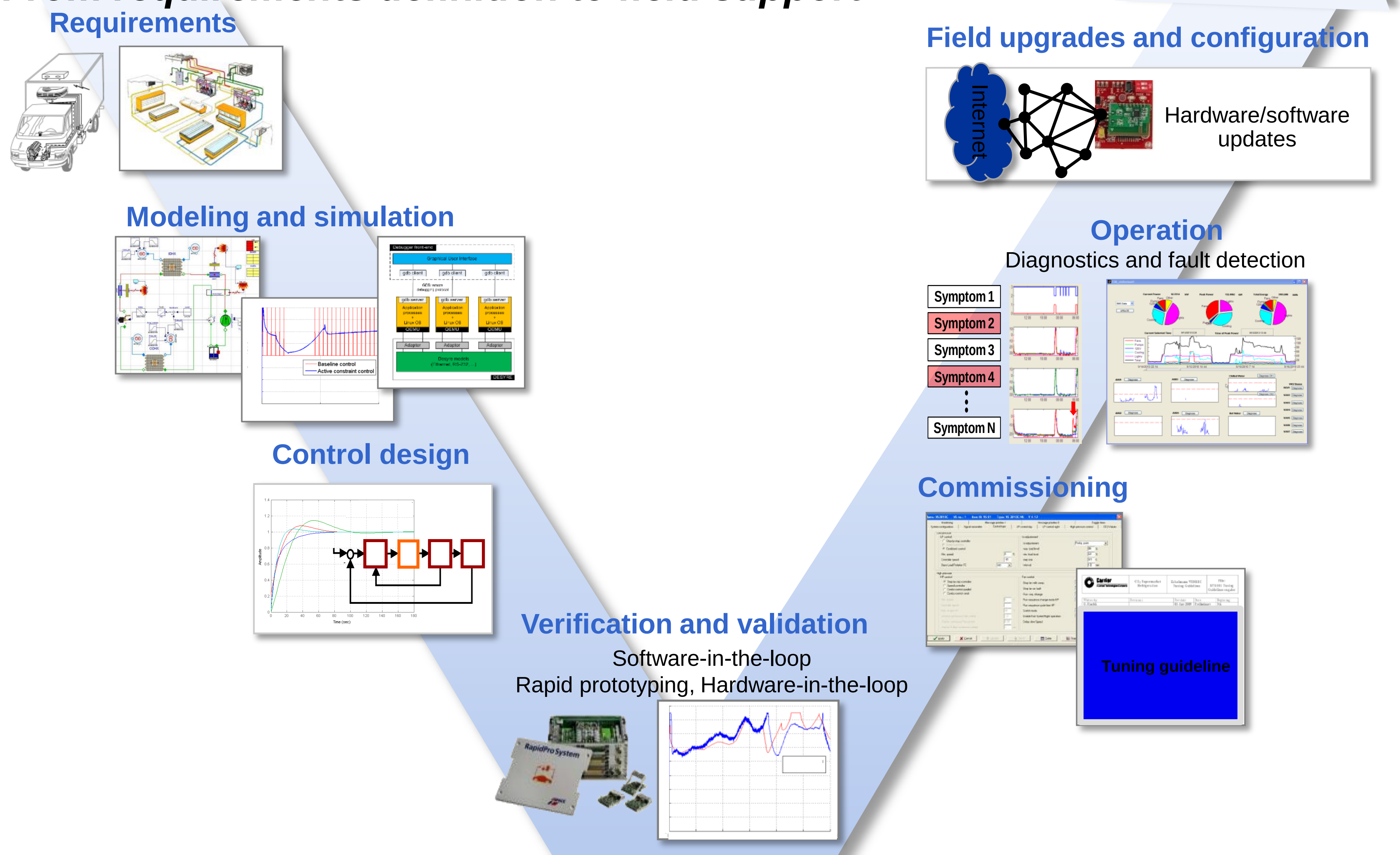
- Control architecture & algorithm design
- Implementation and test/verification
- Tuning and commissioning
- Operation & upgrading

What's important?

- Know the physics, systems objectives and limitations
- Model the physics, component to system
- System complexity

MODEL BASED CONTROL DEVELOPMENT PROCESS

From requirements definition to field support

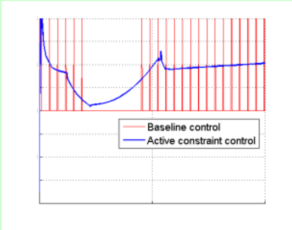


APPLICATION EXAMPLES

Equipment

__Pulsor^{TM}: Truck Refrigeration Equipment__

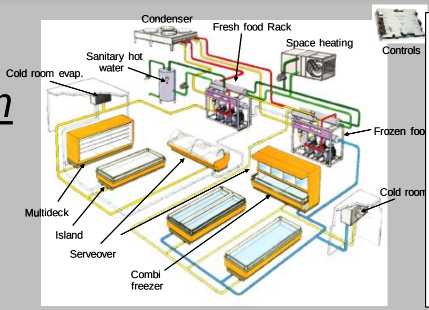
Developed control architecture and algorithm for robust system performance and optimal efficiency

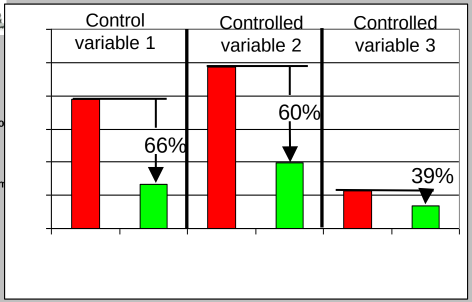


Systems

__CO2OLtec^{TM}: Supermarket Refrigeration System__

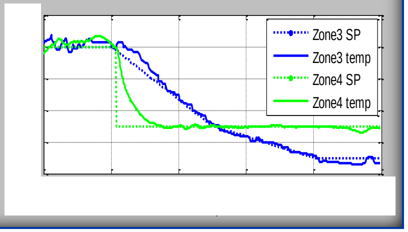
Developed control commissioning guidelines in use by Carrier installers





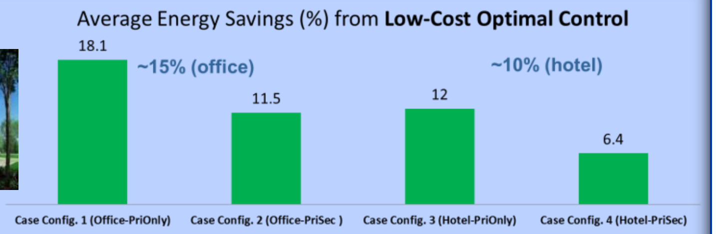
__Infinity NG^{TM}: Residential HVAC System__

Demonstrated HW-independent, model based developed control algorithm on scalable SW platform



Large Systems/Buildings

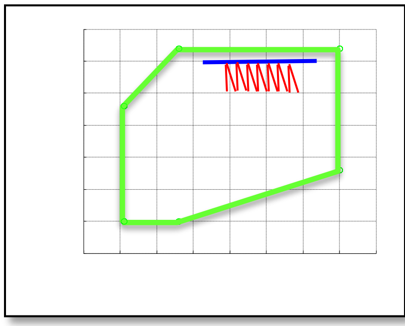
Supervisory control algorithm : 10% to 15% energy consumption reduction.



PULSOR™ ...TRUCK REFRIGERATION

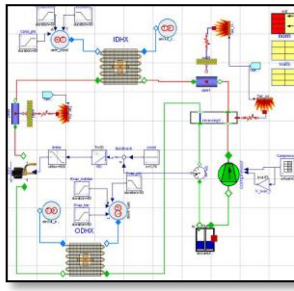
Architecture and algorithm design

Requirements

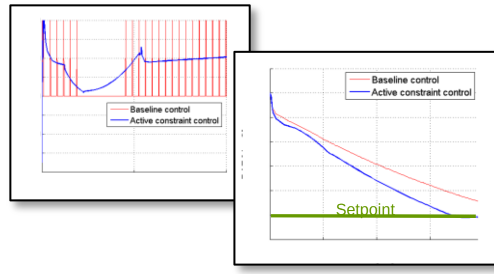


Operating constraints

Modeling and Simulation



Algorithm design



Active constraint control algorithm
- Eliminated cycling
- Better performance

Verification and Validation

Rapid prototyping

No control algorithm changes during field trials

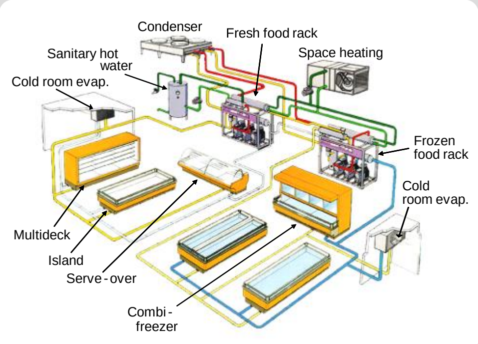
Product

- Small (~kW) capacity
- Air-cooled, standard vapor compression system
- Single-input-multiple-output control (Hybrid control solution)

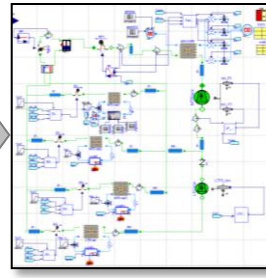
CO_2OLTEC™…SUPERMARKET REFRIGERATION

Faster and accurate system commissioning

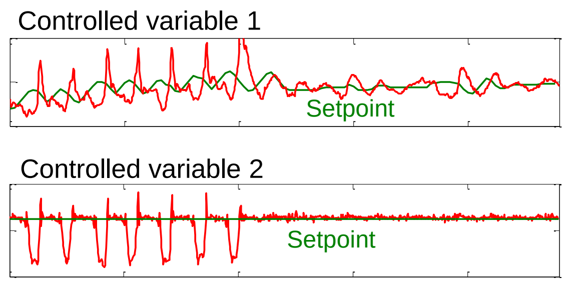
Requirements



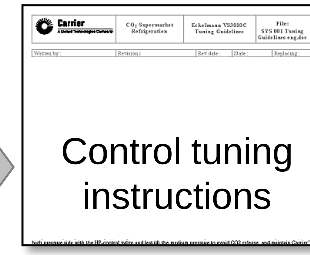
Modeling and Simulation

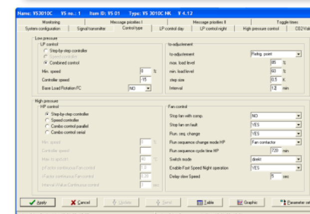


Control analysis and design



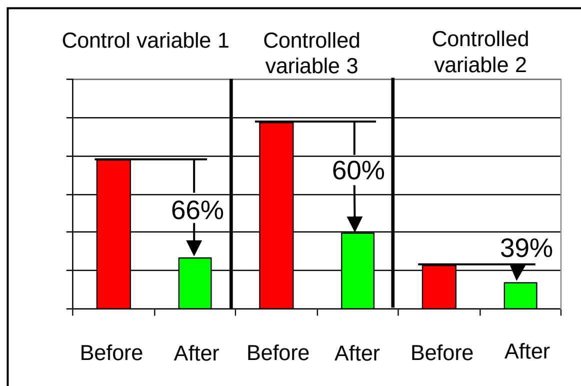
Commissioning guidelines





- Large (~100kW) capacity
- CO_2-based refrigeration system
- Multiple-input-multiple-output control (100's control loops)
- Site-specific configuration

Product



2010

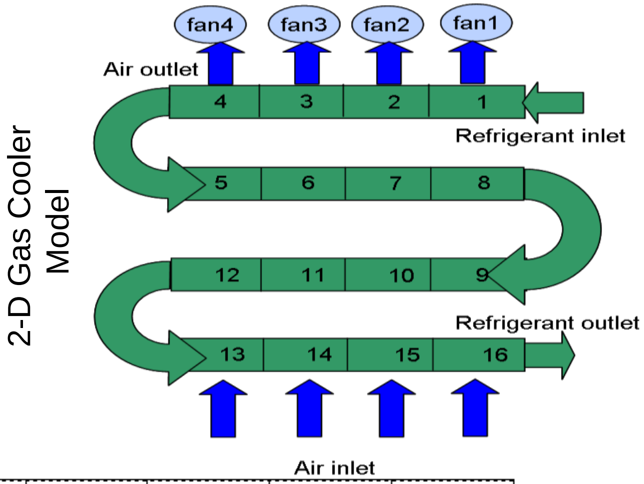
CCS using transitioned SW

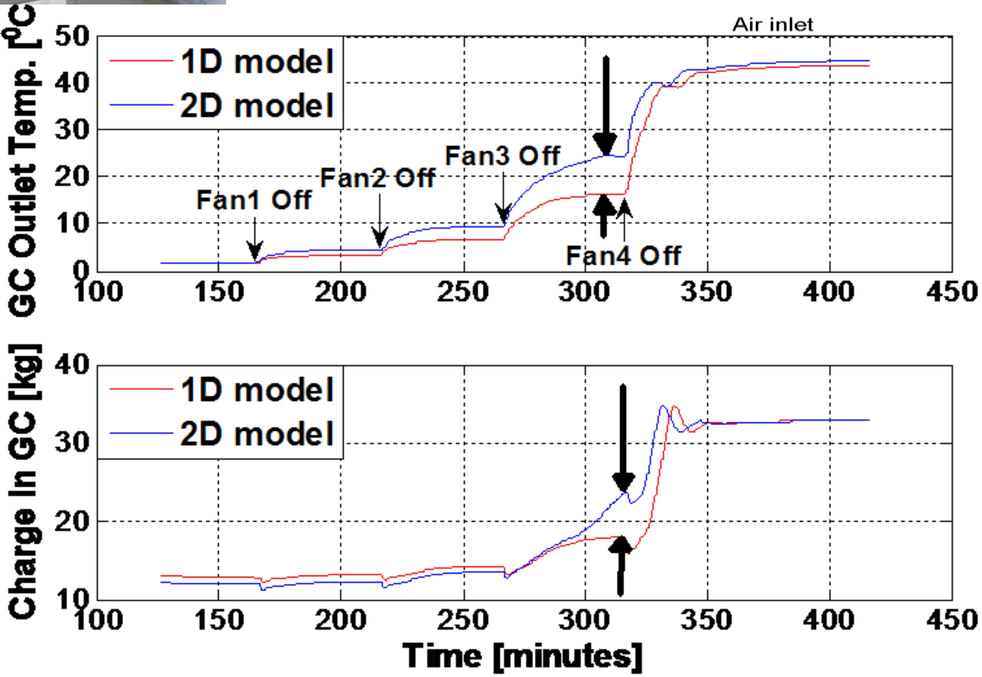
CO_2OLtec™: Gas Cooler Modeling

More physics captured by 2-D cross-flow HX model versus 1-D counter flow HX model at reasonable cost of simulation speed

Front view

Side view

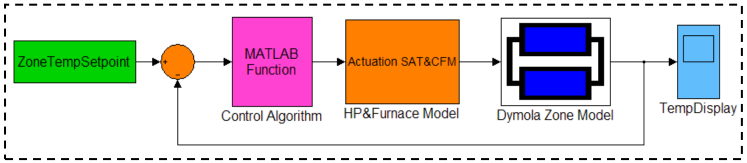




INFINITY NG...RESIDENTIAL HVAC

Software architecture and system control design

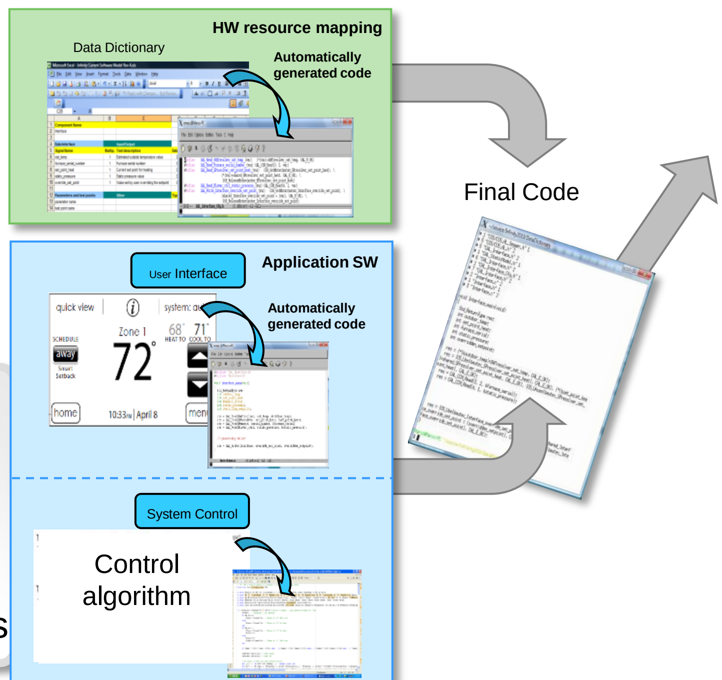
Model-based control algorithm development



Requirements

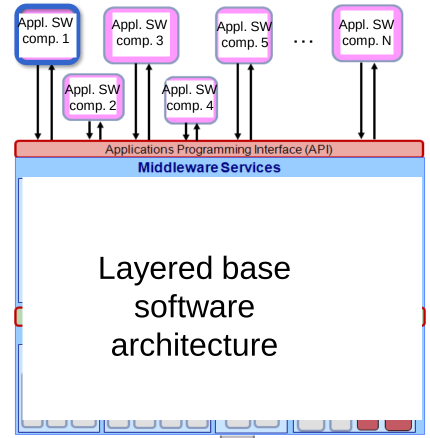
- North American residential application
- Multiple-input-multiple-output control
- Large variety of configurations

New programming model



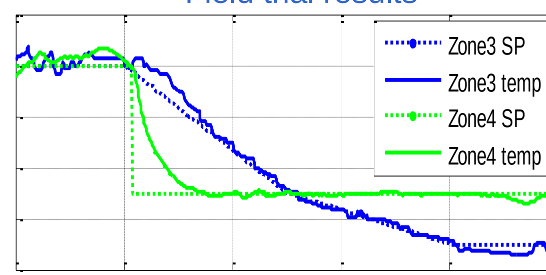
Hardware/software separation

System control algorithm



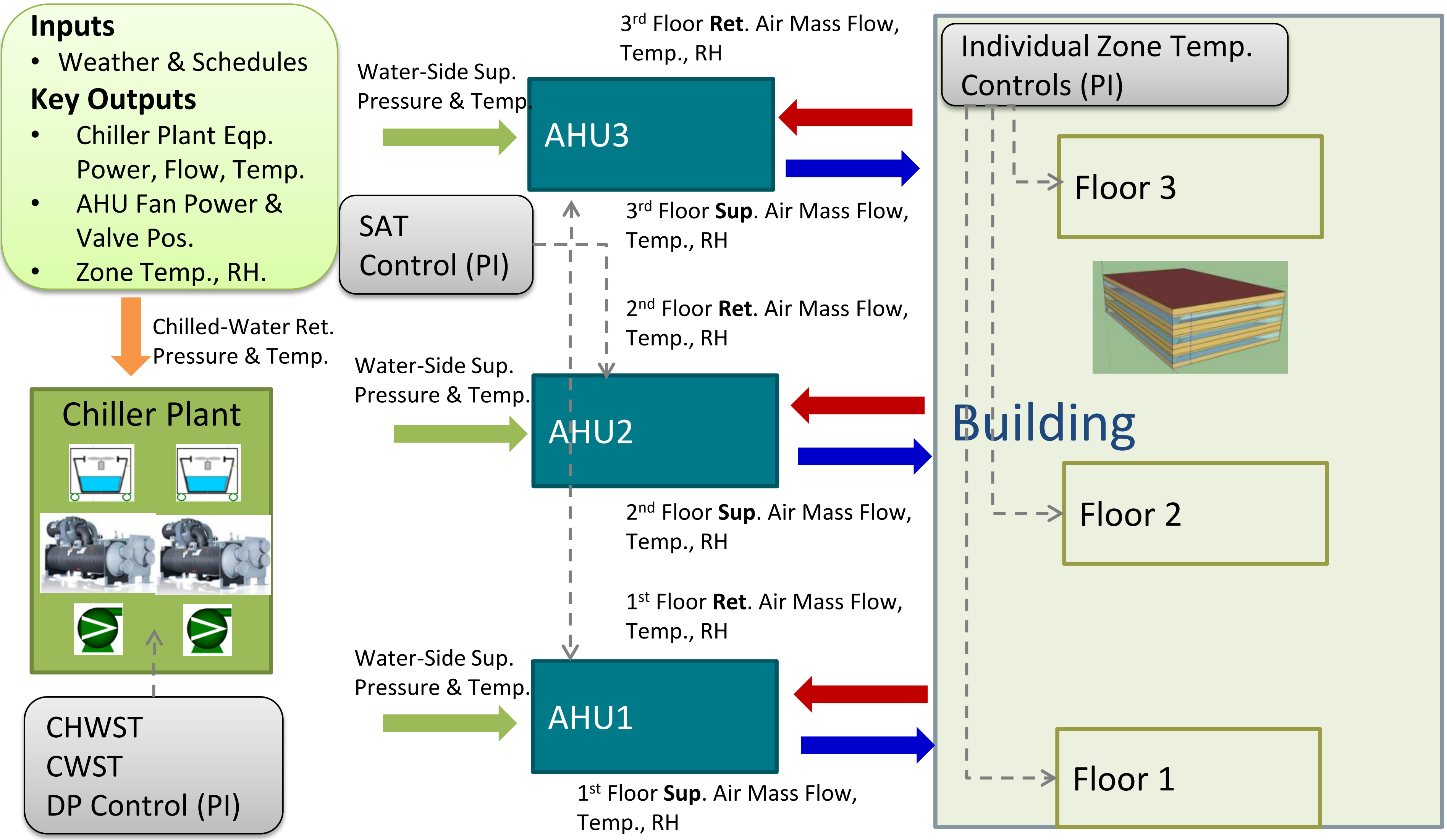
Product ...

Field trial results



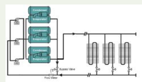
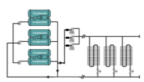
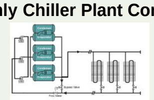
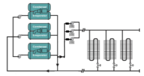
No control algorithm changes during field trials

INTEGRATED WHOLE-BUILDING HVAC MODEL



SUMMARY OF CASE STUDIES

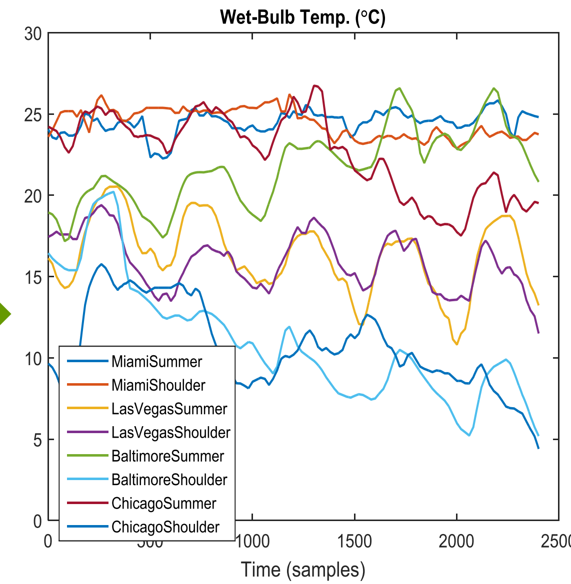
4 Case Configurations

Case Configurations	Definitions	
Case Configuration 1 **1**	Medium Office + Primary-Only Chiller Plant Configuration 	
Case Configuration 2 **2**	Medium Office + Primary-Sec. Chiller Plant Configuration 	
Case Configuration 3 **3**	Large Hotel + Primary-Only Chiller Plant Configuration 	
Case Configuration 4 **4**	Large Hotel + Primary-Sec. Chiller Plant Configuration 	

8 Test Profiles (each case config.)

Test Cases	Test Case Scenarios
Test 1	Miami Summer
Test 2	Miami Shoulder
Test 3	Las Vegas Summer
Test 4	Las Vegas Shoulder
Test 5	Baltimore Summer
Test 6	Baltimore Shoulder
Test 7	Chicago Summer
Test 8	Chicago Shoulder

Web-Bulb Temp.



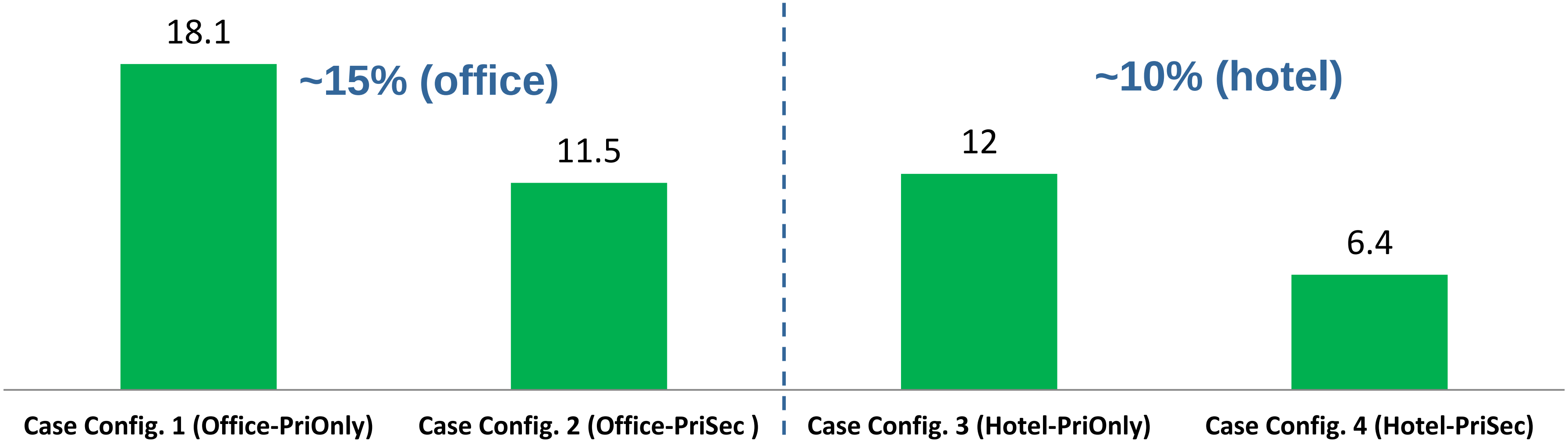
4 Chiller Plant Control Algorithms

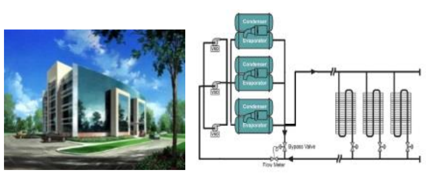
Control Algorithms	Descriptions
1. Baseline Control	**Constant** chilled-water supply temp. (CHWST) setpoint of 7°C. Load based chiller staging logic.
2. OAT-Based Reset (ASHRAE 90.1)	A **linear schedule** to reset CHWST setpoint based on outdoor air temperature (ASHRAE 90.1). Load based chiller staging logic.
3. Heuristic-Based (Trim-Respond)	Trim-Respond logic resets CHWST setpoint based on the demand measured by AHU's **chilled-water valve position**. One request is generated when one chilled-water valve position becomes greater than a prescribed threshold (e.g., 90%). Load based chiller staging logic.
4. Low-Cost Optimal	Maximize CHWST setpoint while performing real-time **load estimation**. Load based chiller staging logic.

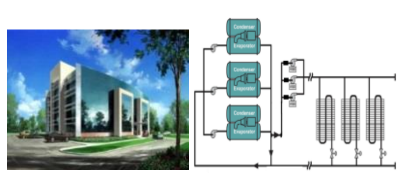
LOW-COST OPTIMAL CONTROL

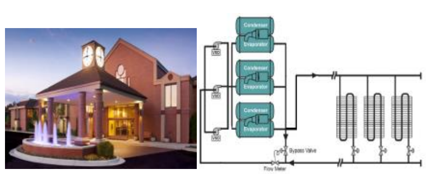
$$Average = 100\left(\sum_{test\ no.}^{1\ to\ 8} E_{total,base} - \sum_{test\ no.}^{1\ to\ 8} E_{total,optimal}\right) / \sum_{test\ no.}^{1\ to\ 8} E_{total,base}$$

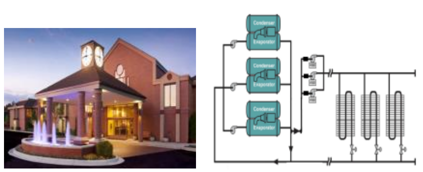
Average Energy Savings (%) from **Low-Cost Optimal Control**











CONCLUSIONS

Better performing and more robust products

- **Physics based dynamic modeling and control enabling**
  - Control architecture (actuation/sensing) trade-off analysis
  - Algorithm analysis and design
  - Installation/commissioning guidelines development
  - Software robustness testing
  - Equipment diagnostics development

- **No turn-backs or surprises after the products are developed/deployed**