Cyber-Physical Systems Approach for Energy Management System in Smart Homes

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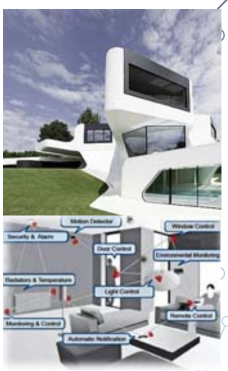
Outline

- Introduction
  - Smart Homes, Cyber-Physical Systems, Smart Energy Network
- Our Related Research Activities
  1) Home Temperature Control in Cyber-Physical Home System [ITSSA SIWM, vol.8, pp.149-166, 2012, Wai Wai Shein, et al.]
  2) Energy Efficient Thermal Comfort Control for Cyber-Physical Home System [IEEE SmartGridComm 2013, Z. Cheng, et al.]
  3) Fitting Method for Hybrid Temperature Control in Smart Home Environment [IEEE ICMIC 2014, Z. Cheng, et al.]
- Concluding Remarks

1.0 Introduction

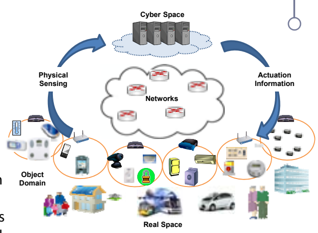
- In 1984, smart home is firstly used by the American Association of House Builders (now National Association of House Builders)
- Definition
  - Smart homes is a home-like environment that possesses ambient intelligence and automatic control, in which it responds to the behavior of residents with various facilities

    [L.C. De Silva et al., 2012]



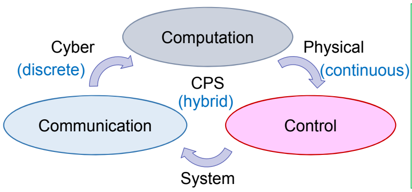
1.1 Cyber-Physical Systems (CPS)

- Definition
  - [2008, Edward A. Lee] CPS is a system featuring a tight combination of, and coordination between
    - system's computational and physical elements
  - [2008, S. Shankar Sastry] CPS uses computations and communication deeply embedded in and interacting with physical processes to add new capabilities to physical system
    - from miniscule to large-scale systems
    - dependably, safely, securely, efficiently and in real-time



1.2 More about CPS

- Interaction between the physical and virtual worlds through lots of sensors and actuators
- Physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core

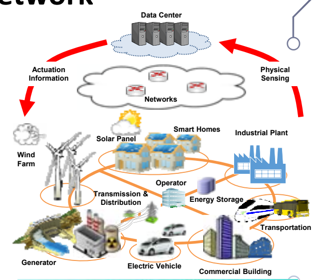


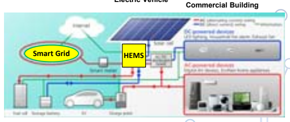
Characteristics of CPS
- CPS must deal with
  - Hardware
  - Platform
  - Software
  - Communication Network
  - Control system
- CPS must incorporate with
  - Timing
  - Concurrency
  - Dynamics

Adopted from E.A. Lee, "CPS: Design challenges," Int. Symp. on Object/Component/Service-Oriented Real-Time Distributed Computing (ISORC), 2008

1.3 Smart Energy Network

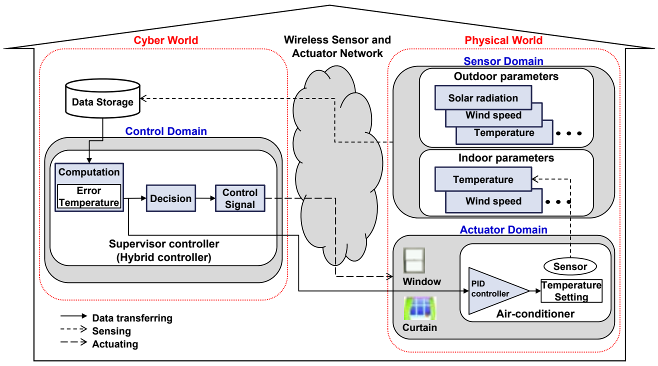
- Current status
  - Unforeseen and cascading failure: weather or disaster
  - Threat of power cut: cyberattack
  - Inefficient energy distribution and supply
- Future with CPS
  - Real-time ability to store energy, add and cooperatively control energy demand, and self-healing for energy restoring
    - Resilience to faults and attacks
    - Save energy and reduce CO_2 emission



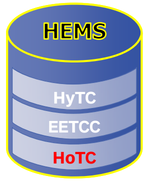


HEMS = Home Energy Management System

1.4 CPS Approach for Smart Homes

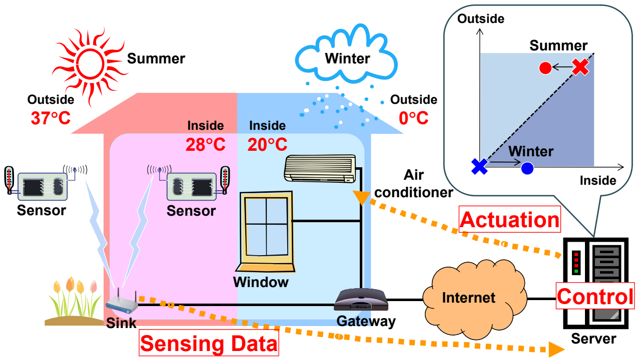


Our Related Research Activities



PART 1: HOME TEMPERATURE CONTROL IN CYBER-PHYSICAL HOME SYSTEM, 2012

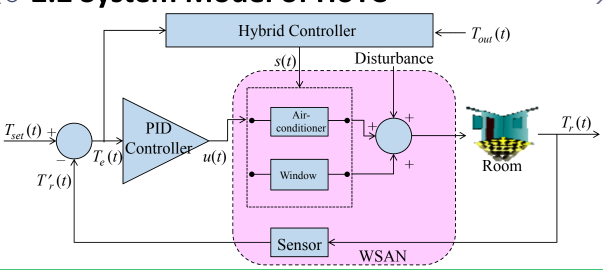
2.0 HoTC Overview



2.1 Research Objectives

- To develop a practical CPS approach for smart home system
- To design the closed-loop HTC system with 2 actuators (air-conditioner and window) by continuously monitoring the desired temperature regardless of dynamically changing environment
- To understand and analyze how the HoTC system controls the desired room temperature with PID controller and hybrid controller with minimum cost

2.2 System Model of HoTC



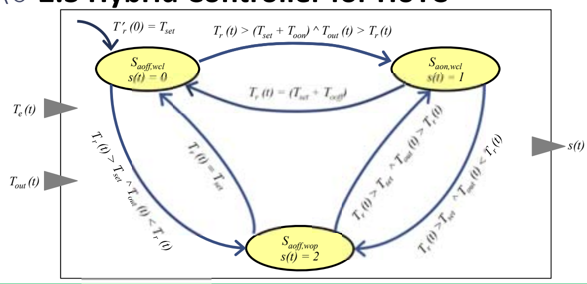
$T_{set}(t)$ = setpoint temperature
$T_{out}(t)$ = outside temperature
$T_r(t)$ = output temperature
$T'_r(t)$ = measured room temperature
$T_e(t)$ = error temperature

$u(t)$ = control input

$s(t)$ = switched control signal = $\begin{bmatrix} S_{aoff,wcl} \\ S_{aon,wcl} \\ S_{aoff,wop} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 2 \end{bmatrix}$

WSAN = Wireless Sensor and Actuator Network

2.3 Hybrid Controller for HoTC



Actuators: Air-conditioner, Window
Initial state: $S_{aoff,wcl}$
$S_{aoff,wcl}$ = air-conditioner is OFF & window is CLOSED
$S_{aon,wcl}$ = air-conditioner is ON & window is CLOSED
$S_{aoff,wop}$ = air-conditioner is OFF & window is OPENED

T_{oon} = offset for air-conditioner is ON
T_{ooff} = offset for air-conditioner is OFF
$T_{out}(t)$ = outside temperature
$s(t)$ = status of switched control signal

2.4 Simulation Scenario

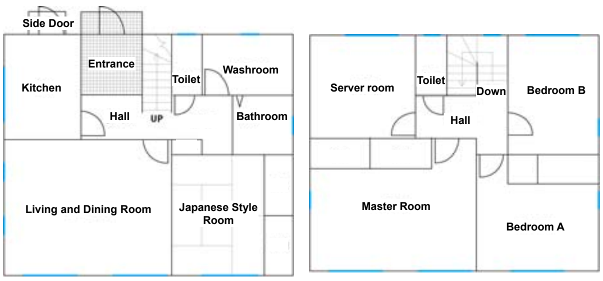
Simulation Environment
MATLAB/Simulink
PI controller
Used experiment measured inside/outside temperature of the iHouse facility during summer season (2010 August)
Living room with 4 windows

Assumption
Heat gain from the occupant and heat gain from the sun through the glass are constant
For window opening state, the velocity of air is constant
No heat loss from the room

2.4.1 Experimental Facility: iHouse

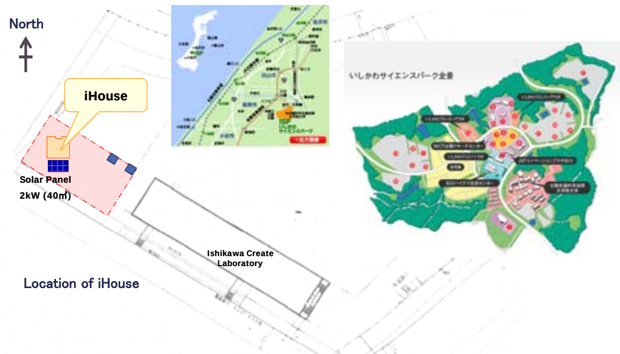
- i stands for Ishikawa, Internetted, Inspiring, and Intelligent
- Two floors with107.76 m², > 300 sensors and home appliances are connected through ECHONET v3.6 and ECHONET LITE v1.1

2.4.2 Layout of iHouse



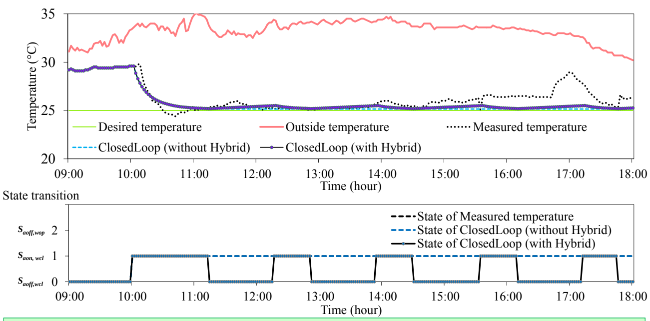
1st Floor 2nd Floor

2.4.3 Location of iHouse



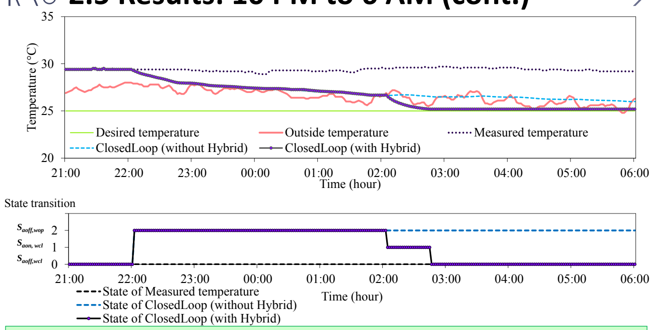
Location of iHouse

2.5 Results: 10 AM to 6 PM



**Measured: Air-conditioner is operated from 10AM to 6PM (2010 August)
**ClosedLoop (without Hybrid): Air-conditioner is operated from 10AM to 6PM with feedback control
**ClosedLoop (with Hybrid): Air-conditioner is operated with hybrid feedback control (ON/OFF)

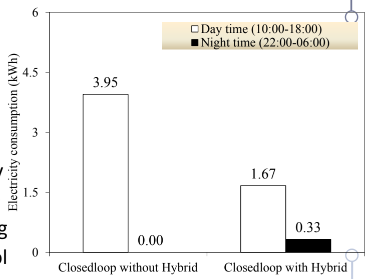
2.5 Results: 10 PM to 6 AM (cont.)



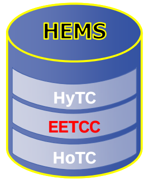
**Measured: Neither Air-conditioner nor Window is operated (2010 August)
**ClosedLoop (without Hybrid): only Window is operated with feedback control
**ClosedLoop (with Hybrid): Air-conditioner or Window is operated with feedback control

2.5.1 Results: Electricity Consumption

- Hybrid controller can reduce 57.75% compared to without hybrid controller
- Hybrid controller consumes less energy in night time because of the help of opening the window to control the desired temperature



Our Related Research Activities



PART 2: ENERGY EFFICIENT THERMAL COMFORT CONTROL FOR CYBER-PHYSICAL HOME SYSTEM, 2013

3.0 Motivation & Objective

- Motivation
  - HoTC does NOT show the actual reduction of energy consumption
  - The desired room temperature only CANNOT provide human comfort
- Objective
  - To develop a practical thermal comfort control (TCC) system using CPS approach with multiple actuators in home environment
  - To extend
    - Actuator: HTC (air-con, window) to TCC (air-con, window, curtain)
    - Parameter: HTC (temperature) to TCC (thermal comfort)

3.1 State Transition of TCC System

State	Status of Actuators		
	Air-con	Window	Curtain
0	X	X	X
1	X	X	O
2	X	O	X
3	X	O	O
4	O	X	X
5	O	X	O

O = open/on, X = closed/off

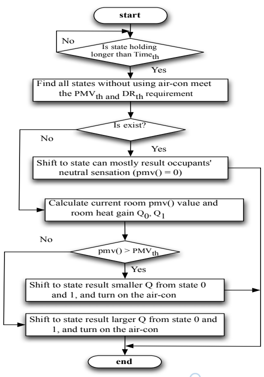
3.2 EETCC Algorithm

- EETCC = Energy Efficient Thermal Comfort Control

$Time_{th}$ = minimum time that the state has to hold

dr() and *pmv()* = the functions based on the equation for calculating *DR* and *PMV*, respectively. DR_{th} and PMV_{th} = the corresponding threshold values

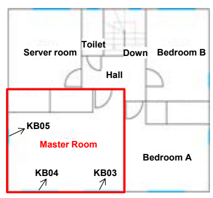
Q_i = room heat gain for state *i*.



DR = draught, PMV = predictive mean vote for thermal comfort

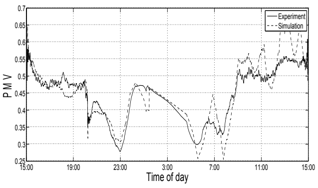
3.3 Simulation Scenario

- Master Room is used for experiment and simulation studies
- Type of window
  - KB-03, 04 Double-layer normal glass
  - KB-05 Double-layer thermal insulation glass
- Type of curtain
  - Medium translucent pastel

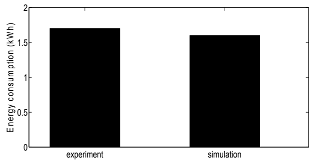


3.4 Results: Verification

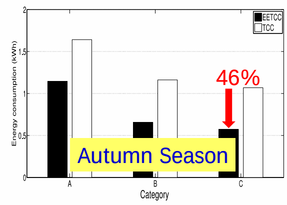
- Average value of the PMV difference between experiment and simulation is 0.029 (4.14%)

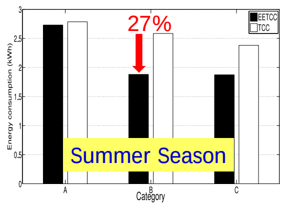


- Energy consumption between experiment and simulation is 0.1 kWh (6.25%)



3.4.1 Results: Energy Consumption



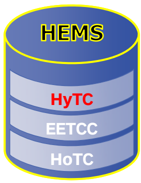


- Autumn, good weather
  - energy saving is obvious
- Summer, bad weather
  - energy saving is NOT very obvious

Category	PPD (%)	PMV
A	< 6	-0.2 < PMV < +0.2
B	< 10	-0.5 < PMV < +0.5
C	< 15	-0.7 < PMV < +0.7

EETCC: using EETCC algorithm
TCC: using air-con only, window & curtain are closed

Our Related Research Activities



PART 3: FITTING METHOD FOR HYBRID TEMPERATURE CONTROL IN SMART HOME ENVIRONMENT, 2014

4.0 Motivation & Objective

- Motivation
  - How to use the sensed data to estimate actual room temperature felt by occupants?
    - General method is using average value of the sensed data, which is NOT accuracy and it can affect system's performance
- Objective
  - To improve the sensing accuracy without increasing system implement cost

Proposed Solution in this Research

Build a **fitting function** to estimate the actual room temperature instead of using its average value

4.1 Fitting Function

- Fitting function is using a linear regression method based on the training data of December 9-15, 2013

$$T_r^f = 0.347T_1 + 0.0726T_2 + 0.398T_3 - 0.0446T_4 - 0.290T_5 + 0.385T_6 - 0.0300T_7 + 0.200T_8$$

T_r^f : room temperature felt by occupant that is obtained by fitting function method
T_1 to T_8: data obtained from sensors located at north east, north west, south east, south west of the ceiling and floor, respectively

T_r^m: measured room temperature from sensors near the occupant from experiment
δ_f, δ_a: sensed error for using fitting function method and average value method, respectively
N_f, N_a: normal distribution with the same μ and σ as δ_f and δ_a, respectively

4.2 Indices for Control Performance

- Indices for sensing accuracy
  - μ: mean of the probability density function of sensed error
  - σ: standard deviation of the probability density function of sensed error
- Indices for control system performance
  - Energy Consumption

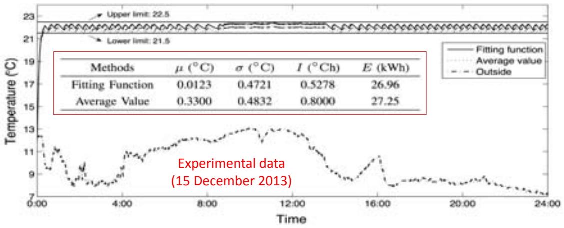
$$E = \frac{1}{COP}\int_{t_s}^{t_e} |Q_{aircon}(t)|\,dt$$

where
COP = the coefficient of performance of air-conditioner
t_s, t_e = the starting and ending time of a control period
Q_{aircon} = the cooling/heating load of air-conditioner

  - Discomfort Index

$$I = \int_{t_s}^{t_e} [\min\{|T_r(t) - T_{th}^l|, |T_r(t) - T_{th}^u|\} \cdot 1_{L^c} T_r(t)]\,dt$$

4.3 Results: Control Performance



Methods	μ (°C)	σ (°C)	I (°Ch)	E (kWh)
Fitting Function	0.0123	0.4721	0.5278	26.96
Average Value	0.3300	0.4832	0.8000	27.25

- Both methods can maintain the actual room temperature felt by occupants in the desired interval (30 sec)
- μ of average value method is much larger than fitting function method
- σ of average value method is merely larger than fitting function method
- Fitting function method improves 34% in I and 1.1% in E that is compared to average value method

5. Concluding Remarks

- Conclusion
  - CPS have been introduced
  - HEMS using CPS approach for smart home environment also have been presented
- Future works
  - To investigate the optimization theory (e.g., MOO) for CPS-based smart homes
  - To further find out the new model for CPS
  - To extend our findings for large-scale systems
    - Smart Communities (or Smart Cities) with Smart Grid
    - Smart Transportation Network

Thank You for Your Attention!

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