
EXQUISITUS

EXQUISITUS
Centre for E-City

http://www.exquisitus.eee.ntu.edu.sg

The *EXQUISITUS* is a Centre of Excellence to advance research and development (R&D) in electrical systems for future cities. It will develop key technologies in power electronic devices, intelligent control and optimization, and autonomy for applications in environmental monitoring, sustainability, renewable energy systems, transportation systems, aerospace engineering, maritime engineering, and defence. The centre's research activities can be broadly divided into the following major areas, energy conversion devices, clean and renewable energy systems, energy storage, smart grids, energy efficient buildings, control system technologies, mobile robotics, intelligent transportations, and urban sensing. These activities are organized under the three research programmes: E-Sustainability, E-Mobility and E-Sensing.

Director

Professor
Wang Danwei
Email: edwwang@ntu.edu.sg

Wang Danwei received his PhD degree from the University of Michigan, Ann Arbor in 1989. Currently, he is a professor in the School of Electrical and Electronic Engineering, Nanyang Technological University, and the interim director for *EXQUISITUS*, Centre for E-City. He has served as general chairman, technical chairman and various positions in international conferences. He is an associate editor of International Journal of Humanoid Robotics and a member of editorial board of International Journal of Vehicle Autonomous Systems. He was a recipient of Alexander von Humboldt Fellowship, Germany. His research interests include robotics, automation, intelligent transportation systems, control theory and applications. He has published widely in the areas of iterative learning control, repetitive control, robust control and adaptive control systems, as well as manipulator/mobile robot dynamics, path planning, and control.

The Singapore-Berkeley Building Efficiency and Sustainability for The Tropics

The Singapore-Berkeley Building Efficiency and Sustainability for the Tropics (SinBerBEST) is an NRF-funded CREATE program which is hosted by University of California Berkeley with Nanyang Technological University as its main partner. Fourteen NTU professors have been involved as co-principal investigators. The program aims to deliver energy efficient technologies for the tropical built environment, while optimizing comfort, safety, security, and productivity. The holistic research methodology is driven by six major research thrusts as illustrated in Fig. 1. These are (1) Sensing, data mining and modeling; (2) Multi-level optimal control; (3) High confidence building operating system; (4) Human-building interaction and emissions; (5) Material, design and life cycle; and (6) Integration and test bedding. The latter is a cyber-physical test bed which integrates and demonstrates SinBerBEST outcomes from the first five thrusts. It fosters collaboration within the thrusts and across an international network with complementary capabilities.

Fig. 2 shows the architectural layout of the test-bed, which takes the form of a four room 'building' housed within the SinBerBEST laboratory in the 11th floor of the CREATE Tower. Its features include: (1) Solar daylight emulator; (2) Façade testing partition; (3) Side partition wall; (4) False ceiling grid; (5) Raised floor; (6) Permanent air tight partition wall; (7) Active chilled beam unit; (8) Controllable lighting; and (9) Fixed air tight ceiling panel. Another major feature of the test bed is a prototype of building integrated micro grid (BIMG) as shown in Fig. 3, which provides an experiment platform to support the researches on:

- Next generation of intelligent building power distribution system/topology, in terms of efficiency, quality, safety and resilience.
- Intelligent algorithms/strategies for building power flow management, in terms of economic efficiency and environment respect.
- Evaluating and verifying the relationships and interactions between the BIMG and other building service systems, e.g. air conditioning and mechanical ventilation (ACMV) system and lighting system, as well as the associated in-door thermal and visual comfort by collaborating with other thrusts.

As lighting can be responsible for about 20% of a typical building's electricity use in tropics, it is important to study optimal building performance in terms of lighting management using an energy-efficient, daylight-responsive lighting systems monitoring and control system for buildings. The study involves utilization of real-time wireless sensing technology and lighting simulation, as shown in Fig. 4.

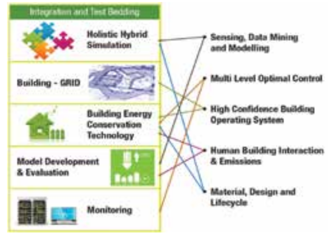


Fig. 1 SinBerBEST Research Topics

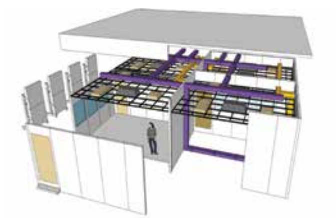


Fig. 2 The SinBerBEST Test-Bed

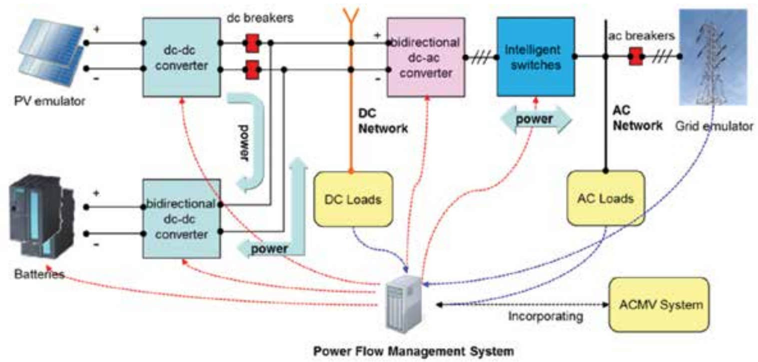


Fig . 3 Electric Power Distribution for Future Green Build

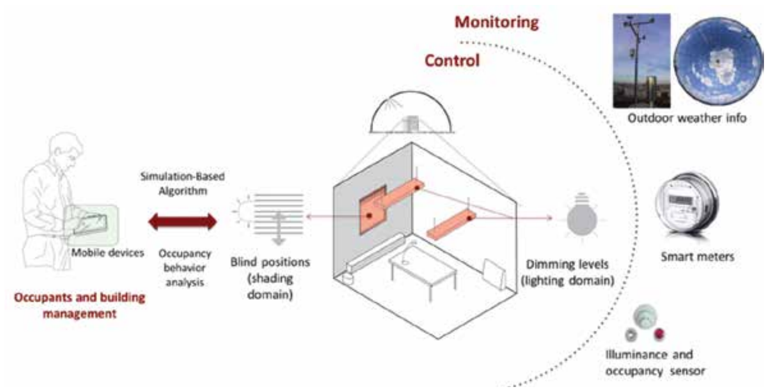


Fig. 4 Intelligent Lighting Management

Optimization And Control Of Vapor Compression Cycle

Assoc. Prof. Wenjian Cai together with collaborators have been awarded by National Research Foundation of Singapore a grant to develop a systematic methodology for optimizing and control vapor compression air conditioning systems. The vapor compression refrigeration cycle is used to remove heat from a space of lower temperature (cold reservoir) to an environment of high temperature (hot reservoir). It basically consists of four components – Evaporator, Compressor, Condenser, and Expansion Valve which are connected in a closed loop so that the refrigerant is continuously circulated.

The team will use hybrid modeling approach to model cooling coils, condensers, evaporators and ejectors. In addition, they will extend the component hybrid modeling approach to develop active devices such as compressors.

Due to the complicated relations among the system variables and the ambient environment conditions, the key trust for the system to be economically viable lies with reliable and optimal operation under different working conditions and cooling load demands. In this project, an approach for control structure synthesis will be developed to determine the types, numbers and locations of sensors and actuators such that the system variables can be effectively and economically measured and/or controlled.

Beside, the physical limitations of each device, its operation window and the interactions of each component have to be considered in the model-based performance optimization. In this project, the team will adopt two layers optimization structure to determine the operating status of each sub-cycle according to the cooling demand and outdoor environment.

The system is Multi-Input and Multi-Output (MIMO) in nature, with severe nonlinear dynamic characteristics. Thus, the controllers in the system which are used to maintain an optimal operation have to adapt to the current operating conditions. Several advanced control schemes will be applied in this research such as MIMO control, Non-linear control and multi-model control, among other techniques.

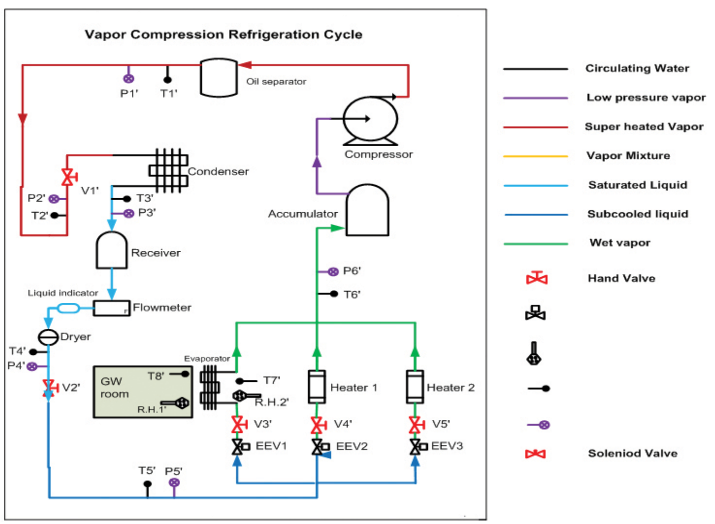
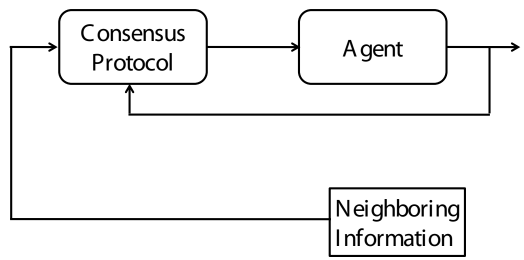


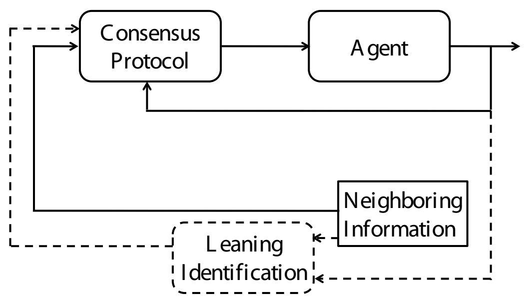
Fig . 5 Schematic of vapor compression refrigeration cycle

Identifier-Based Consensus for Multi-Agent Systems with Applications to Cooperative Control of Autonomous Robot Networks

Man-made multi-agent systems (e.g., autonomous robot networks) have been advancing apace with the help of high-performance hardware and computational technologies. Examples of such systems include teams of smart cars, autonomous robots, robot soccer players, and unmanned micro airplanes. However, despite the high-performance computing, communication, sensing, and power devices used in these systems, their effectiveness in uncertain environments appears to still fall behind the natural systems such as a swarm of ants, a flock of birds, or a team of wolves. Autonomous robot networks which use a team of networked robots



(a) Consensus



(b) Identifier-based robust consensus

Fig. 6 Comparison of two consensus block diagrams: (a) classic consensus, (b) identifier-based robust consensus using a learning identification mechanism to conduct tasks in a distributed manner have the benefits of increasing system performance and fault tolerance abilities. Such systems represent an emerging research area that will have a huge impact on the way humans design and utilize machines that work together. These systems have a wide range of potential applications in surveillance and search, highway traffic monitoring, intelligent transportation, environment monitoring, and unmanned exploration of dangerous areas.

Despite the promising future of autonomous robot networks, it is quite challenging to handle the inherent robustness and complexity issues in such systems because of the associated sensing and communication constraints, model complexity and uncertainties (e.g., external disturbances, time delays, un-modeled nonlinear dynamics, measurement noise, and dynamic network or information-exchange topologies). The robustness issue is especially important for autonomous robot networks that work in unknown environments. To bridge the lacuna between existing multi-agent system theory (e.g., consensus) and the application requirements of real-world autonomous robot networks, it is necessary to investigate the constraints and uncertainties associated with these systems and their corresponding dynamic system behaviours. In this connection, Asst. Prof. Hu Guoqiang is working towards developing new identifier-based consensus algorithms and convergence analysis methods that can be applied to cooperative control of autonomous robot networks.

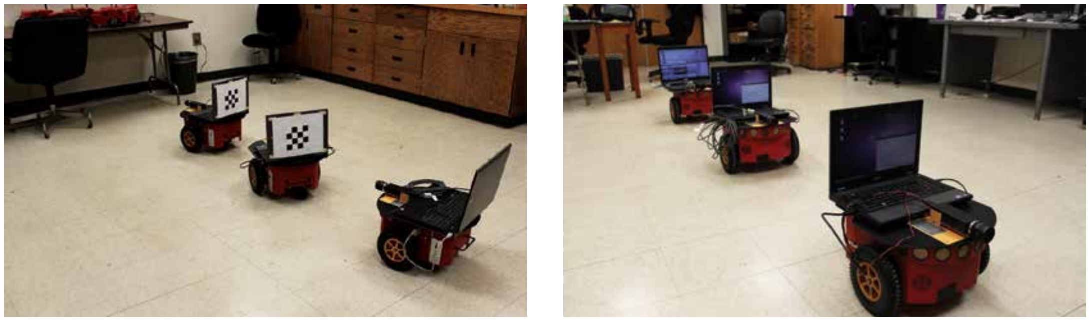


Fig. 7 A P3-DX multi-robot platform for demonstrating cooperative control of robots

Compressed Prediction of Urban Traffic

No one wants to get stuck in traffic jams. Drivers can potentially avoid such conditions if they have accurate information about the future traffic states. Traffic forecasting is also used for optimum traffic assignment which heavily relies on accurate and fast prediction of the entire network, regardless the size of that network. Traffic prediction is typically performed by developing a unique model (data driven or otherwise) for each road segment in the network. However, this might not be the feasible solution, especially for large urban traffic networks. Asst. Prof. Justin Dauwels and his team members have developed techniques, which can help to scale prediction models for large networks.

In their approach, the team predicts traffic parameters for a small subset of the road segments, instead of the whole network. They have applied proposed method in large urban network in Singapore (see Fig. 8). First, they assign a selection probability to each road segment. The selection probability depends upon the statistical properties of traffic on that road (see Eq. 1 and Fig. 9). Then, they apply data driven regression methods to obtain prediction models for the selected roads. The future state of the entire network is then inferred by extrapolating (on the graph) the predictions of the sub network (See Eq. 2). For network wide extrapolation, they learn relationship functions (matrix X) between the chosen links (matrix C) and the whole network (matrix A).

$$\mathbf{A} = \mathbf{U}\sum\mathbf{V}^T$$

$$P_S = \frac{1}{r}\sum_{j=1}^{r} v_{kj}^2$$

vkj is k-th coordinate of
j-th right singular vector.

Equation 1:
Selection probability

$$\mathbf{A} \cong \hat{\mathbf{A}} = \mathbf{CX},$$

$$\mathbf{X} = \mathbf{C}^{+}\mathbf{A},$$

$$\mathbf{A}_{pred} = \mathbf{C}_{pred}\mathbf{X},$$

Equation 2:
Network extrapolation

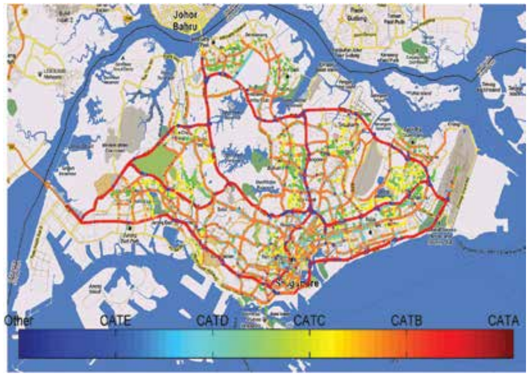


Fig. 8 City-scale traffic network of Singapore

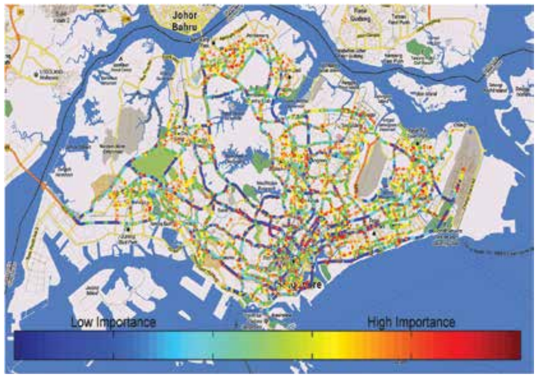


Fig. 9 Assigned importance of the road segments

Simulations have shown that the proposed approach provides competitive prediction performance and significantly reduces the computational cost (see Fig. 10 and Table 1). Consequently, the approach helps to perform real-time prediction for large networks.

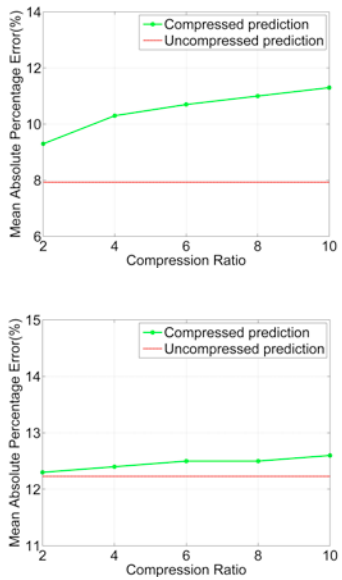


Fig. 10 Prediction performances for 5 (left) and 30 minute (right) prediction horizons. Compression ratio = size of the network divided with size of the selected subset.

Comp. Ratio (CR)	2	4	6	8	10
Time Saving	50%	75%	83%	87%	90%

Table 1: Computational savings

Fusion and Sense Making of Heterogeneous Sensor Network and Other Sources

Sense making is the process of working with a collection of data to create a deeper understanding of the scenario that generates the data. A sense-making system can be used to make sense of situations such as terrorist attacks and riots, and identifies changes of situations, which helps to speed up decision process and actions.

The fusion and sense-making system involves the combination of evidences from heterogeneous sources, including hard sensor data from sensor networks and soft sensor data from human observations, reports, news, among other sources. Assoc. Prof. Mao Kezhi and Dr. Wu Kui will study the principles that underlie human multisensory integration, explore new cognitive or biologically-inspired approaches of information processing, and develop a robust fusion and sense making system with human-like intelligence. The figure below illustrates the proposed system architecture which supports the fusion of hard sensor data via sensor networks and soft sensor data from e.g. human observations, reports, news and Wikipedia. The hard sensor data will be processed in different levels: signal level, feature level and decision level using bio-inspired algorithms and approaches. At the same time, the soft sensor data will be gathered and processed via knowledge extraction approaches such as natural language processing (NLP) and transformed into usable information that allows further processing in the proposed fusion model. Furthermore, contextual information and domain knowledge will be utilized in the situational sense-making process. An evolving learning mechanism will also be incorporated to equip the system with adaptive capability to changing environments.

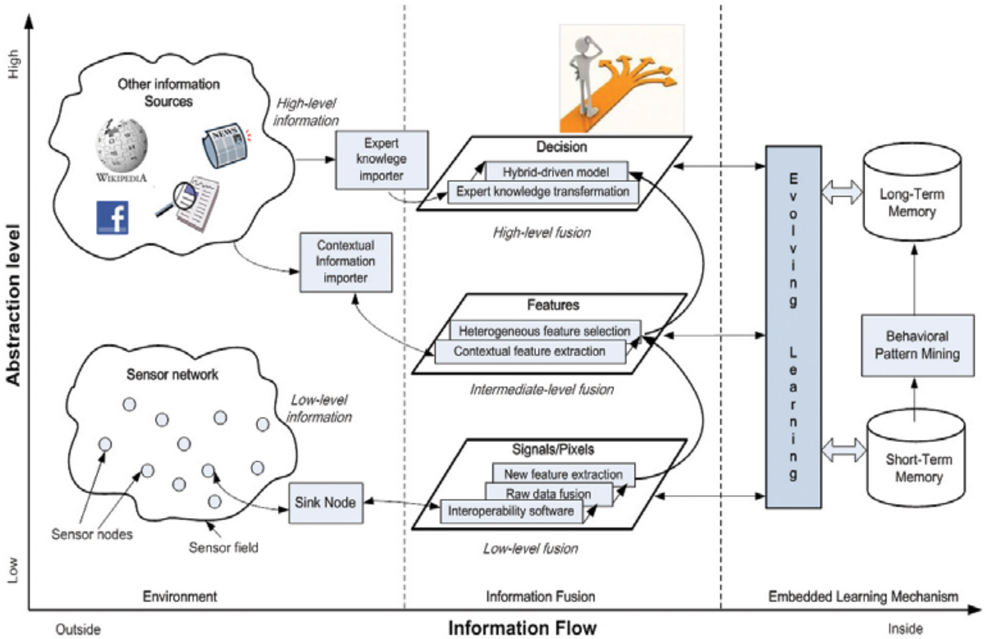


Fig. 11

Autonomous Mobile Robots For Outdoor and Urban Environments

The E-Mobile team consists of a group of academic staff, students and engineers from the *EXQUISITUS*, Centre for E-City, who are robot enthusiasts and are willing to take the challenges of robotics research frontiers. Lead by Prof. Wang Danwei, the team has developed a fleet of autonomous mobile robots for urban environments and off-road conditions to participate the TechX Challenge 2013. The team successfully passed the Qualifying Round competition by overcoming seven benchmarking functionality milestone tests and came out with the best performance among the finalists. The TechX Challenge 2013 competition scenarios are within high-fidelity urban setting, replete with realistic obstacles and conditions, and with targets placed inside buildings as well as outdoor environments. Participating teams deploy their robots from a starting point to autonomously scout the entire areas to detect and engage these targets from very complex environments and backgrounds, and return to the finish area when all missions are completed. Such remarkable capabilities are the desired attributes of future robots and are required of the participating robots. These include outdoor navigation, static and dynamic obstacle avoidance, autonomous stair climbing, static target detection and engagement, and robotic co-operation if a team of robots is fielded.

The development of such a fleet of autonomous robots includes the following main work packages: (1) design and building of two platforms: one track robot and three wheel robots; (2) sensor selections and sensor-suit designs; (3) communication system and protocol designs; (4) GPS data processing and waypoint navigation; (5) Operation Control Unit; (6) safety system and tele-operation; (7) static and dynamic obstacle avoidance; (8) G-mapping and localization; (9) target searching; (10) door entry and exit; (11) stair climbing and descending; (12) vision-based target identification; (13) vision-based odometry; (13) mission control and integrated testing. This project involves a wide range of development from specific algorithms as well as that on the system of systems.

Fig. 12

Fig. 13

PV/Battery Hybrid Power Supply with Discrete Ripple Correlation Control and Advanced Time-Sharing Switching Technique

In solar power applications, it is often desirable to track the maximum power point (MPP) of the photovoltaic (PV) array. When the load demand is higher than the power capability of PV, a hybrid power supply (HPS) system is required to realize output voltage regulation and MPPT. The second source besides the PV array may be an AC-line supply or an energy source device such as battery. In this project led by Prof. Wang Youyi, the team uses a double-input buck converter (DIBC) topology with interleaved dual-edge modulation and advanced time-sharing switching (ATSS) strategy to complete this control target.

Discrete ripple correlation control (DRCC) is simple and inexpensively implemented using analog circuits, and takes advantage of perturbation (ripple) that is already present in the system to determine the gradient of a cost function that is considered as its control objective. It does not require any prior information about the PV array characteristics to asymptotically converge to the true MPP.

The advantage of ATSS is that it imports a novel-defined coefficient α to express the power sharing factor of the DIBC based on the modified time-sharing switching (MTSS) strategy, which breaks the constraint of the MTSS to single variable control and realize multivariable control without losing any advantage that MTSS contains, such as no limitation to the number of the input-legs, equivalent circuit modeling convenience, and implementation simplicity.

The Simulink model is given in Fig. 14, which consists of 30V-battery-bank model served as V_{s1}, 190W-PV-array model served as V_{s2}, DIBC circuit, changeable resistive load bank, ATSS switching function generation module with 3 flip-flops, and

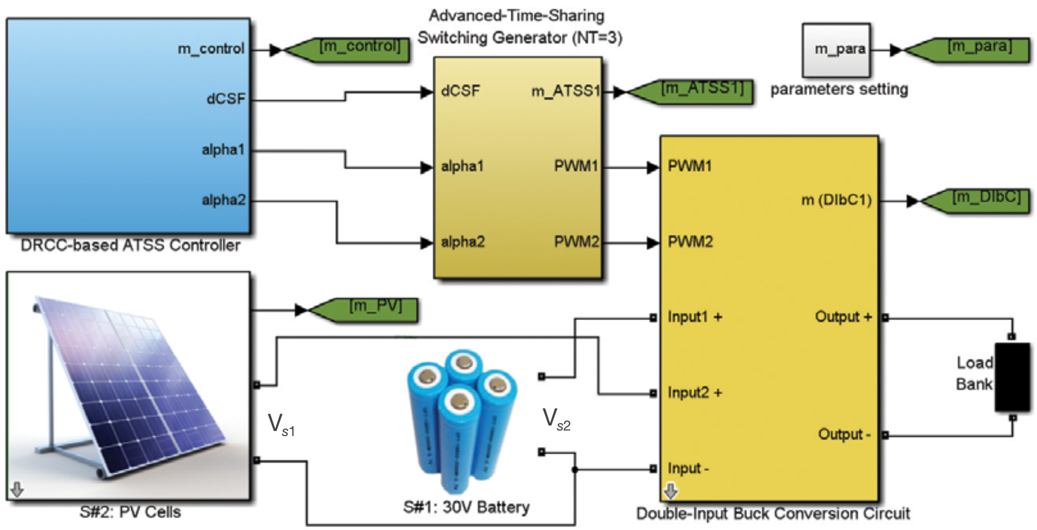


Fig. 14 Schematic of the PV/battery hybrid power supply system based on DRCC and ATSS techniques.

controller module. The battery model was taken from the library with its nominal voltage 26 V and rated capacity 10 Ah.

The waveforms shown on Fig. 15 illustrate the steady-state of the PV panel and control-related parameters. From the results, one can see that the panel is regulated at its MPP 197.5 W since the instantaneous power passed through the maximum twice in each switching cycle, once while the current was increasing and once while the current was decreasing, which accords with the DRCC theory. The averaged voltage and current of the panel were about 37 V and 5.33 A. It verifies that MPPT for the PV panel has been realized by applying DRCC technique to the ATSS strategy for the DIbC circuit. By taking α_2 as the objective of the control law, the DRCC approach was successfully applied to the ATSS strategy to realize MPPT of the PV panel, meanwhile, the output voltage can be regulated by another controller designed independently.

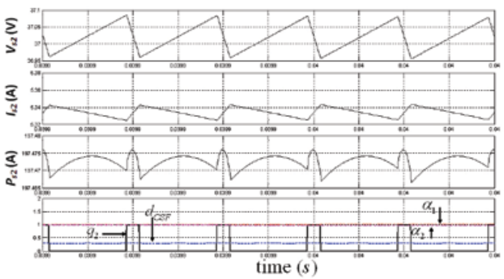


Fig. 15 Waveforms of the steady-state of the PV panel and the related parameters

Indoor Quadrotors Formation Flight with Vicon Motion Capture System

Formation flight of quadrotors has drawn much interest in the research community recently. This is especially prominent with the maturity of motion capture system for unmanned aerial vehicles (UAVs) application. The objectives of this research, led by Prof. Xie Lihua, are to develop the capabilities of such formation flight with the Vicon Bonita system in the Internet of Things Lab. The superior accuracy of the system will also provide a good benchmark for algorithm testing or to evaluate other technologies such as vision-based navigation.

The main technical challenge in this research is the real-time control of the quadrotors. As the latency of the Bonita system is minimal at 2ms, the bottleneck is the computing power of the workstation to post-process the optical data, and to execute the Simulink at near real-time. Telemetry is another main challenge.

Fig. 16 Unique passive markers arrangement on quadrotors

A custom-built quadrotor of X330 with 8-inch propellers shown in Fig. 16 is used as a test platform. The hover test for the platform was performed to evaluate its position-hold accuracy. A good position-hold is a pre-requisite for formation flight. The formation flight is challenging in terms of aerodynamics disturbances, synchronization, collision avoidance and telemetry interference. In a formation flight setup, one workstation is responsible to control up to six quadrotors due to bandwidth limitation. The telemetry module was chosen to be the XBee-Pro 2.4GHz for its superior performance in latency and data throughput rate. The Simulink is used as a Ground Control Station to receive the Vicon processed data (position and attitude) and to perform outer loop control (position control) for all quadrotors. Fig. 17 shows an example of formation for five quadrotors. The quadrotors formation flight and other Vicon-related capabilities will be showcased in the Singapore Airshow 2014.

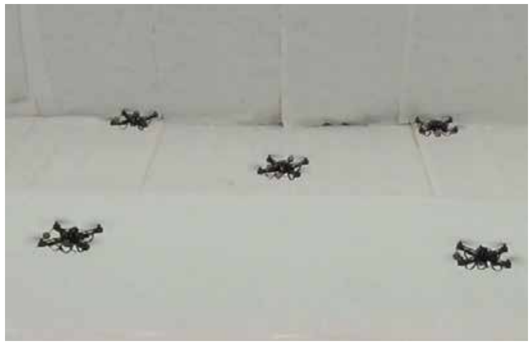


Fig. 17 Formation flight of UAVs

Investigation on Vanadium-Redox Flow Battery Energy Storage System (VRB-ESS)

Energy storage is essential in the development of smart grids and the utilization of the renewable energy resources. The large-scale energy storage have the potential to contribute to (1) improve energy efficiency and flexibility of national electricity grids, through load leveling/peak shaving, and (2) grid stabilization due to variations in the power derived from renewable energy based sources. The all-vanadium redox flow battery energy storage system (VRB-ESS), as shown in Fig. 18 and 19, has to date shown the greatest potential for large-scale energy storage applications because of its long cycle life and high energy efficiencies of over 80% in large installations. Using the same element in both half-cells, it prevents cross contamination and has a theoretically indefinite electrolyte life. It also exhibits a low cost for large storage capacities. This on-going research led by Asst. Prof. Zhao Jiyun proceeds in two areas: (1) Investigation on the operational characteristics of the VRB-ESS; (2) Coupling of VRB-ESS with renewable energy resources to achieve smoothing of the generated renewable power. Both the experimental tests and the mathematical modeling and simulations are ongoing in the two areas. Thermal-hydraulic modeling of VRB energy storage systems is an important issue and temperature has remarkable impacts on the battery efficiency, the lifetime of material and the stability of the electrolytes. A thermal-hydraulic model was developed and benchmarked with the experimental tests to investigate the thermal behavior, especially for tropical weather applications. It was found that the temperature at stack and tanks rises up about 10 °C under normal operating conditions for the stack design and electrolyte volume selected. It is also found that the electrolyte flow rate has significant impact on the battery efficiency. A methodology on the flow rate optimization has been developed.

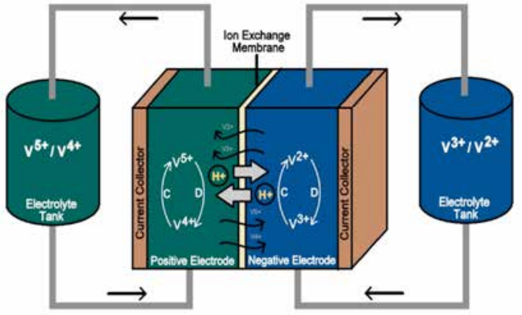


Fig. 18 VRB Configuration

Fig. 19 A 10 kWh VRB module