
EXQUISITUS

EXQUISITUS
Centre for E-City

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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 optimisation, 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 organised under the three research programmes: E-Sustainability, E-Mobility and E-Sensing.

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Xie Lihua received his PhD degree in electrical engineering from the University of Newcastle, Australia, in 1992. His research interests include robust control and estimation, networked control systems, multi-agent networks, and disk drive servo. He has served as an editor for IET Book Series in Control and an Associate Editor for a number of journals including IEEE Transactions on Automatic Control, Automatica, IEEE Transactions on Control Systems Technology, and IEEE Transactions on Circuits and Systems-II. Professor Xie is a Fellow of IEEE and Fellow of IFAC.

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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 Deputy 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.

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Tseng King Jet was born in Singapore. He received the B. Eng (First Class) and M. Eng degrees from the National University of Singapore, and the PhD degree from Cambridge University, U.K. He is currently the Head of Power Engineering and the Deputy Director of *Exquisitus* at Nanyang Technological University, Singapore. He oversees electrical power engineering education at both undergraduate and postgraduate levels, and manages a number of research programs in the area of electrical power and energy. He has held key advisory appointments for both Singapore Governmental and non-governmental organisations.

Cooperative Control of Networked Multi-Vehicle Systems

Cooperative control problems entail several networked autonomous players (vehicles) seeking to collectively accomplish some global objectives. With the advancement of various engineering technologies, the physical realisation of such networked systems becomes possible. A research team headed by Prof. Xie Lihua examines the deployment of large scale networks of cooperative autonomous vehicles which can offer tremendous promise for many important applications including military operations, search and rescue, environment monitoring, material handling, homeland security, etc.

A main obstacle in such large scale networks lies in that each individual vehicle lacks of global knowledge of the whole network and can only interact with its neighbors to achieve global behaviors. This makes the traditionally well-established centralised techniques of information processing and decision making inapplicable. In fact, a fundamental challenge is to design control protocols with a distributed architecture to achieve certain global objective. In addition, the distributed protocol generally imposes a stringent requirement on simplifying the computational complexity as the resource of a single vehicle may be limited. Another challenge in applications arises from the incorporation of a real-time network for the information exchange among vehicles. That is, not only the communication network topology but also the quality of the communicated information must be taken into consideration in networked cooperative control problems. The research focuses of the team are therefore on the following:

1) Efficient communication network topologies for cooperative control.
2) Cooperative control under limited and unreliable communications.
3) Application of the cooperative control in localisation, coverage control, target detection and tracking with multiple movable platforms, and dynamic road pricing for traffic congestion control.

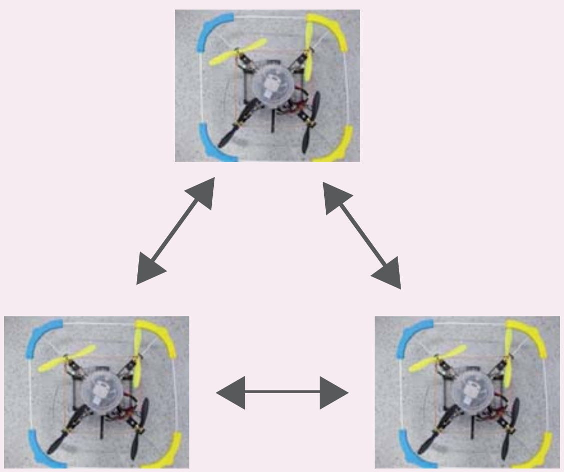


FIG. 01 Networked multiple UAV system

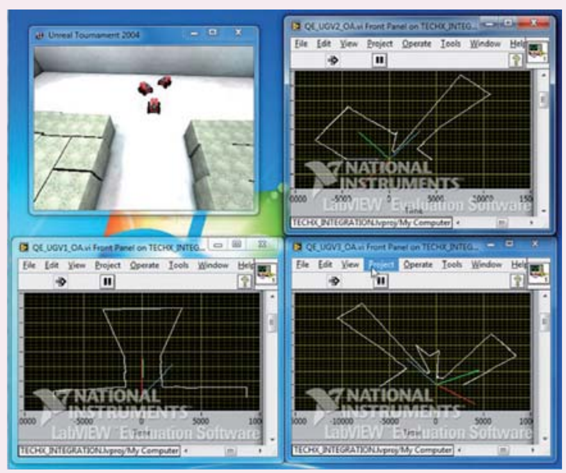


FIG. 02 Hybrid multi-vehicle platform

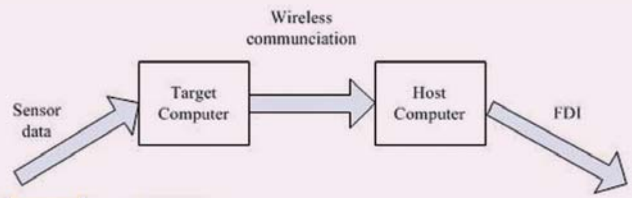
The team has made some important breakthroughs in the above research and received two best paper awards respectively from the 7^{th} Asian Control Conference and the 29^{th} Chinese Control Conference. Over 15 papers have been published in top quality journals among which 8 papers have been published as regular papers in the flagship journals of control, IEEE Transaction on Automatic Control, Automatica and SIAM J. Control and Optimisation. They have received research grants of over $1M from various government funding agencies such as DSO, A*Star, Temasek Lab, National Natural Science Foundation of China, etc.

Performance Monitoring, Diagnosis & Prognosis (PMDP) for Hybrid Systems

Prof. Wang Danwei has been working with collaborators from SIMTech on a research project funded by A*STAR to develop a framework and tools for health monitoring, as well as fault detection and failure prediction (prognosis) for complex mechatronics systems and manufacturing equipments. Such modern engineering systems are hybrid in the sense of integrating subsystems and/or components with both continuous dynamics and discrete events.

This PMDP project has generated a quantitative model-based health monitoring framework which consists of unified relations to represent system's behavior at all modes, mode tracker to identify discrete events, Fault Detection and Isolation (FDI) mechanism, fault parameter estimation and failure prognosis module. The developed framework has been applied to several hybrid systems such as electrical hybrid system with many switches and electro-hydraulic hybrid system with many components.

Furthermore, a complex mechatronics system – a vehicle steering system test-bed has been established to illustrate the effectiveness of the developed framework and algorithms. The system includes many components and subsystems including DC motor, belt, hydraulic



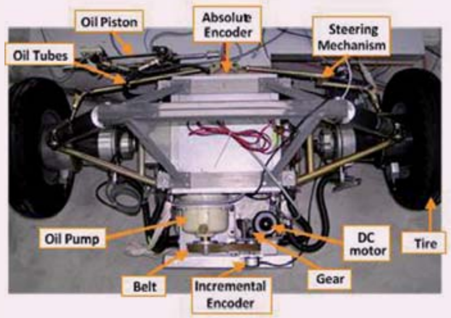


FIG. 03 **Steering system of mobile robot**

pump, hydraulic cylinder (actuator), wheels, and several sensors. Any of these components can fail and the fault needs to be detected in time so that corrective actions can be taken to avoid catastrophic consequences. Real time FDI experiments show that the developed framework and tools are performing effectively. Potential application of this method to other engineering systems is bright.

Recent Advances in Grid Integration of Wind Power

Doubly-fed induction generator (DFIG) wind turbine technology has been extensively applied by many turbine manufacturers due to the low cost of its partial-scale power electronics converter. However, enhancing ride-through capability under grid fault events has been worldwide recognised as a challenging problem of the DFIG-based wind generation systems. Recently, a team led by Assoc. Prof. Tseng KJ and Prof. Choi SS has proposed a ride-through enhancing solution based on compensation principle. The compensator is installed in the stator-to-grid interface of the DFIG in order to eliminate the impacts caused by grid voltage faults. Furthermore, an advanced ride-through control scheme based on ramp-function injection voltage is developed to significantly reduce the energy capacity requirement of the compensator, which in turn reduces the capital cost.

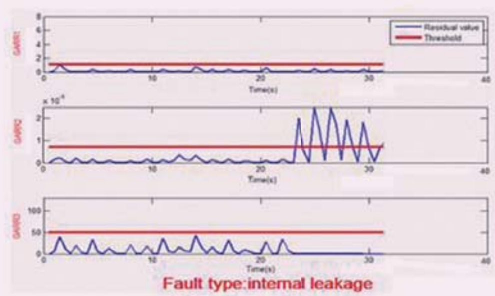


FIG. 04 **GARRs response of real-time FDI experiment**

Compared to DFIG, full-scale power electronics converter based wind generators such as those using permanent magnet synchronous generators (PMSG), exhibit superior ride-through and grid support performances. The PMSG will likely be the mainstream turbine generator in most new installations in the next decade. In the PMSG configuration, power electronics play the crucial function of power interface and buffer to bridge the PMSG and the utility. The team has proposed an integration of a three-switch buck-type rectifier and a grid-side Z-source inverter for the application of PMSG wind turbine, which aims to produce a robust design of wind power generation system. The proposed generator-side control strategy is optimised from the fundamentals of the $I_d=0$ control and the unity power factor control. In addition, voltage-oriented control is used for the grid-side inverter to decouple active and reactive power control while extracting the maximum wind power by adjusting the shoot-through duration of the Z-source network.

Regardless of DFIG or PMSG, wind power will have to meet a significant percentage of the worldwide electricity demand in the next decade. Consequently, grid connected wind power will be significant enough to affect the operation of utility in terms of voltage regulation and frequency control. Thus there is a need to devise reliable methods to accurately quantify the impacts so as to obtain the most appropriate and economical solution to mitigate the negative impacts. Hence, another of the team's recent contributions is a statistics-based analysis method for the purpose of assessing the impact on voltage quality caused by large wind power generation.

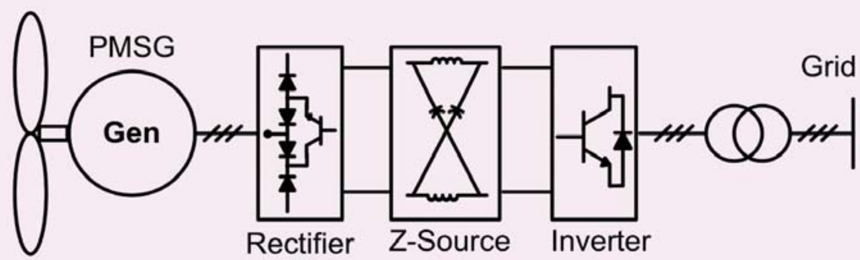


FIG. 05 **New Power Converter for Grid Interface of Wind Turbine Generators**

Herein, voltage deviation has been calculated using the probabilistic models of wind power production and grid Thevenin impedance. An index called the significance level of the voltage deviation α has been developed to provide a probabilistic measure of the voltage quality performance. By considering the contributing factor from each of the grid states that constitute α, possible solution methods to improve voltage quality can be obtained.

Robust Uncertainty Model Predictive Control of Wind Farm System

An increased number of wind farms connected to national grid, especially offshore plants, are being built with automatic controller to guarantee an active operation. However, wind farm modelling complexity and fluctuating nature of wind power impose serious challenges to controller design. An accurate modelling of wind farm dynamics is not always possible due to unknown disturbances as well as interconnected effects over transmission system. A research team, led by Prof. Wang Youyi and Assoc. Prof. Cai Wenjian, develops a new control scheme, based on the robust model predictive control (MPC), to cancel the modelling in-accuracies under the presence of aerodynamic wind power fluctuation accordingly to wind profiles.

Fig. 6 shows three individual wind turbines selected to form a cluster which has total rated power at 6 MW to fulfil power rating of a common 8 MVA Voltage Source Converter (VSC) interconnected through a local 1.6 kV DC voltage bus.

Individual wind turbines are controlled by maximum power point tracking (MPPT) algorithm which extracts maximum power from the wind. As a result, active power produced from the wind turbines fluctuates proportionally to wind profiles. The active power from generator is injected into the DC link, while the power from the other side flows into the grid.

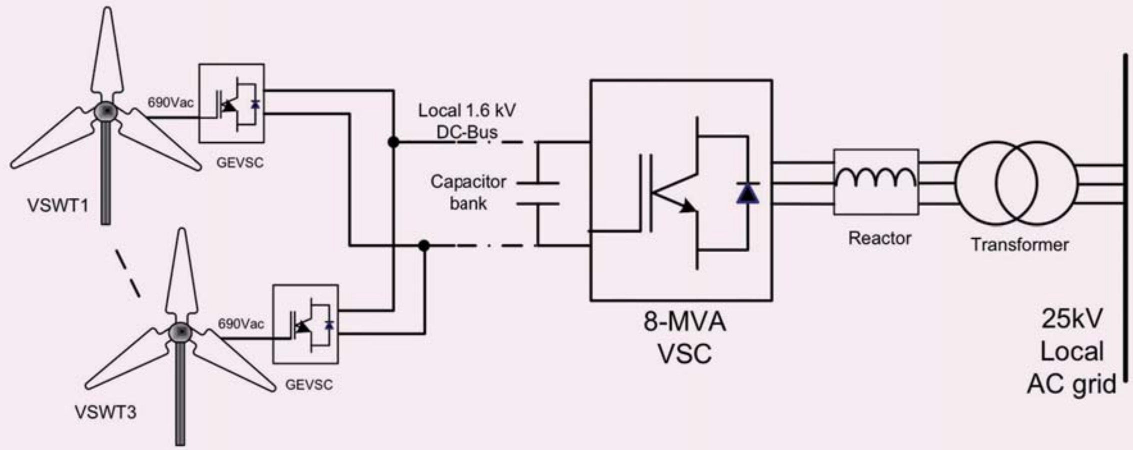


FIG. 06 A cluster of 3 wind turbines

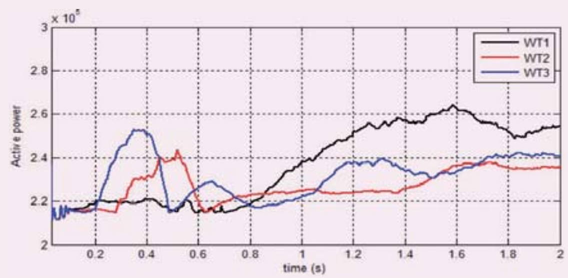


FIG. 07 Active power injected to grid from wind turbines

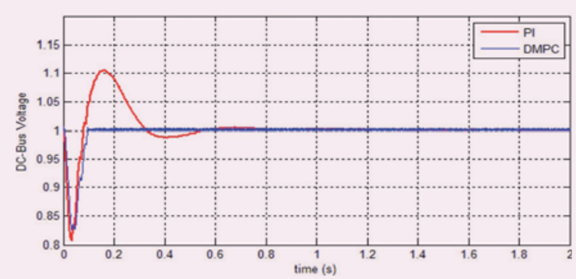


FIG. 08 DC-bus voltage response of two controllers

Simulation studies of the proposed controller for a wind farm equipped with three 2MW wind turbines has been performed. Three different wind speeds which have seasonal speed of 5 m/s experienced by the individual wind turbines producing active power are shown in Fig. 7. The DC link voltage from the proposed controller, in blue, gradually reaches the reference with no overshoot as seen in the PI controller response (red colour) shown in Fig. 8.

From the results, it is shown that the major requirements of wind farm control strategies are well performed by the proposed control scheme. DC-bus voltage is maintained constantly at steady state while less over-shot over the transient period. Most important factor is the proposed model predictive controller has a very good dynamic performance and it is suitable for practical implementation of wind farm control.

Ejector-Based Cooling Systems

In view of the exhaustible nature of the fossil energy sources and due to the environmental impact of the rising energy consumption, an increasing use of low temperature heat sources such as solar energy, geothermal energy and low temperature waste heat can be a suitable solution for a more rational energy use and ultimately lead to cost savings.

Due to the absence of moving parts, simple construction, high reliability and low maintenance costs, as well as operation driven by low temperature heat sources, ejector-based cooling systems represent an attractive alternative compared to other cooling systems.

To improve the ejector-based cooling systems performance, a research team led by Prof. Cai Wenjian is working on the technology that combines the solar driven ejector-based cooling cycle and vapour compression cycle. His group has achieved the following:

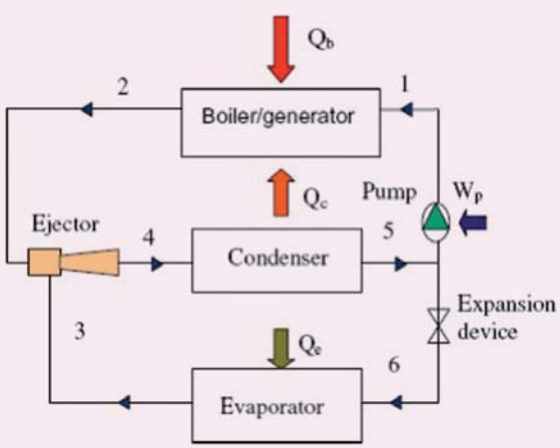


FIG. 09 **Ejector-based refrigeration cycle**

FIG. 10 **The experimental ejector cooling system**

- System integration
  The design and sizing of ejector cooling system components which maximise the use of the (varying) solar collector output and produce the highest solar contribution to the cooling load. Much research into the real-time dynamic control of the ejector-based cooling systems has also been carried out.

- Combined cycles
  Despite recent advances in the understanding of ejector operation, the Coefficient of Performance of a simple ejector cooling system remains stubbornly low. As a result, the hybrid cooling systems incorporating combinations of ejectors and another cooling system had been proposed by the team.

- Improvement of off-design performance
  No doubt one of the key components for ejector-based air-conditioning systems is the ejector. The influence of geometry parameters on ejector performance is tremendous, as reported in the literature. Currently, variable ejector geometry parameters which can meet off-design working conditions and greatly improve the ejector performance are being investigated by the research team.

Vision-Based System to Monitor Human Eye State

A research group headed by Assoc. Prof. Wang Han investigates on a technology that develops an automatic vision system to locate human eye and monitor the eye state (open or closed). The system is aimed to improve driver safety during fatigue driving. Percent eye closure (Perclose), eye closure duration and blink frequency will change greatly when a driver becomes sleepy. The above three measurements can be continuously monitored to decide the driver's fatigue status and trigger a warning alarm when the driver becomes inattentive. It is designed to run on an ordinary webcam in real time. The proposed system consists of three modules: face detection, eye localisation and eye state recognition.

Among the three modules, the problem of frontal face detection has already been well solved. The system first adopts the well-known Viola-Jones method to detect face region. The remaining two modules, eye localisation and eye state recognition, are still interesting open

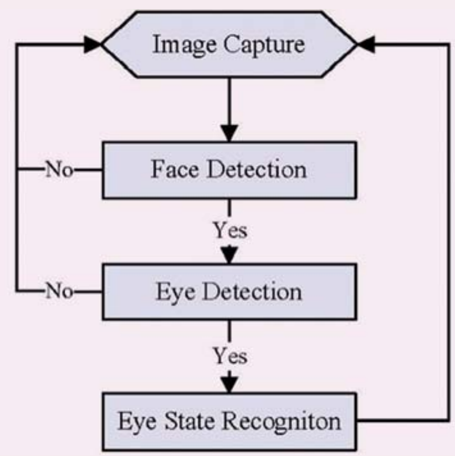


FIG. 11 **The framework of eye state recognition system**

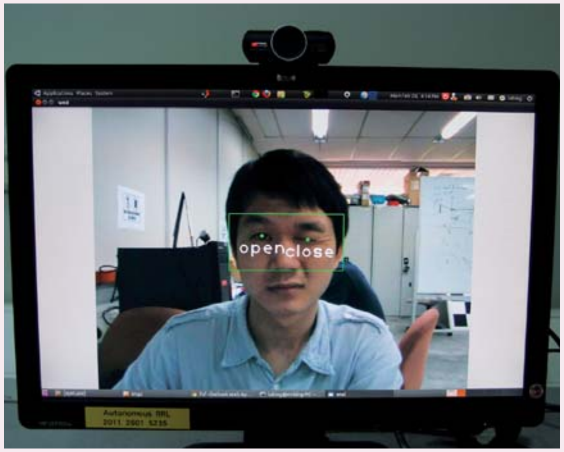


FIG. 12 **An illustration of the real-time eye recognition system**

challenges due to various difficulties, such as low image resolution, varying lighting interference, and changing eye appearances. Given detected face region, eye localisation is realised using a coarse-to-fine framework. First two rough eye window detectors are trained by boosting local binary pattern (LBP) features. Face region is scanned with a sliding window at different locations and scales, and the position with the highest confidence level in the detection is considered as the rough eye window. Subsequently, accurate position of the eye center is obtained by a novel projection function, the Selective Projection Function, which selectively picks low-intensity pixels from nearby rows and columns to produce the sum response. Accurate eye center is located at the positions with the lowest SPF responses. Eye image is then cropped and normalised to a standard size for eye state recognition. The proposed eye-state recogniser contains two vital aspects: feature descriptor and classifier design. The eye descriptor relies on a new local feature: the local binary increasing intensity pattern (LBIIP). LBIIP assigns each pixel with eight binary bits according to the intensity increasing trend in eight orientations, and a decimal pattern label is given to encode the local pattern. LBIIP can specify the intensity increasing tendency of the local region around each pixel. It inherits the merits of LBP and gradient feature. Given an eye image, the LBIIP histograms are extracted from the numerous sub-windows and concatenated together to a feature vector. For classifier design, Discrete AdaBoost is applied to select a few most discriminative features and learn the open/closed eye classifier. Experimental results show the proposed system achieves excellent performance in static face databases with large variations. Furthermore, it also demonstrates reasonably high accuracy and speed in real time video processing.

Real Time Route Guidance

As the cities grow so do the problems they face. And Singapore is no exception. Transportation and Mobility issues dwell at the heart these expanding metropolitans. Asst. Prof. Justin Dauwels and his team, in collaboration with Prof. Patrick Jaillet from MIT (LIDS/ORC) are working on creating novel and robust solutions for the mobility challenges that a cosmopolitan city like Singapore would face in future. They have been awarded grant from Future Mobility interest group of the Singapore-MIT Alliance for Research and Technology (SMART) to carry forward their work.

One of the prime goals of the project is to tackle the problem of traffic congestion, which commuters face on every day basis. The goal is to come up with real time route guidance system, by coalescing machine learning, and data mining techniques with Operations research models and methods. In order to develop effective on-demand route guidance, the team is developing intelligent systems and algorithms, using heterogeneous data sources such as video sensors, radar detectors, and GPS-enabled mobile devices, to track, predict and forecast traffic flow and potential traffic jams in real time, and find route guidance schemes to avoid them.

Public transportation systems, such as buses and taxis, are nowadays often equipped with GPS technology. For instance, in Singapore there is a total fleet of 25,176 taxis operated by eight taxi companies and independent drivers (as of May 2010), collectively completing close to 1 million trips daily across the island. All taxis in Singapore are equipped with a GPS system, which records the location and speed every few minutes. A crucial step in harnessing the data is *map-matching,* where the goal is to accurately reconstruct the sequence of road segments traversed on the map based on location, speed and time measurements which are noisy and sparse. Accuracy of data sensors (e.g. GPS probes) is also a major issue. To mitigate such errors, correct modelling of driving behaviour of agents (taxi drivers in our case) is essential. The team applies dynamic programming to incrementally solve for the maximum likelihood path using hidden Markov models. The algorithm integrates spatial, temporal and topological information with a novel combination of probabilistic scoring functions. For real time prediction, they utilise SVR's capability to map non-linear relations using kernel functions to perform short term traffic speed prediction for different prediction horizons. The prediction model developed offers the

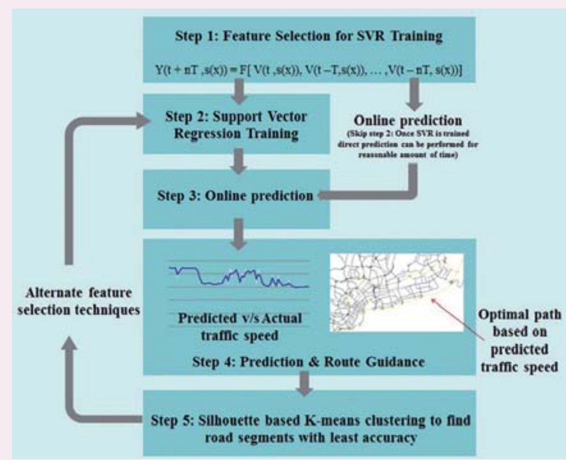


FIG. 13 **Real time Route Guidance System Overview**

advantage of scalability without compromising accuracy and is able to predict in real time. Prototype models for Data acquisition and traffic parameters prediction have been developed and show promising results. Other forms of data being utilised are Link data from LTA and Loop Detector data for traffic flow calculations; with more data sources to be integrated in future.

Stability Analysis of Supercritical Water Cooled Reactors

The supercritical water-cooled reactor (SCWR), as shown in Fig. 14, is one of the six reactor types that are being investigated in the GEN-IV international advanced reactor development program. The SCWR is a combination of the traditional Light Water Reactor (LWR) and the supercritical FPP (Fossil Power Plant). It will operate at high pressure (25MPa) and high temperature (500°C average core exit). The high coolant temperature, as the coolant leaves the reactor core, gives the SCWR the potential for high thermal efficiency (45%). However, near the supercritical thermodynamic point, coolant density is very sensitive to temperature which raises concerns about instabilities in the supercritical water-cooled nuclear reactors. To ensure the proper design of the SCWR without incurring the instability problems, the stability feature of a proposed SCWR design is under investigation by Asst. Prof. Zhao Jiyun in the centre. The objectives of this work are: (1) to develop a methodology for stability assessment of both thermal-hydraulic and nuclear-coupled stabilities under supercritical pressure conditions, (2) to compare the stability of the proposed SCWR to that of the Boiling Water Reactor (BWR), and (3) to develop guidance for SCWR designers to avoid instabilities with large margins. A stability map that defines the neutral stability boundary has been constructed for the SCWR. This is shown in Fig. 15.

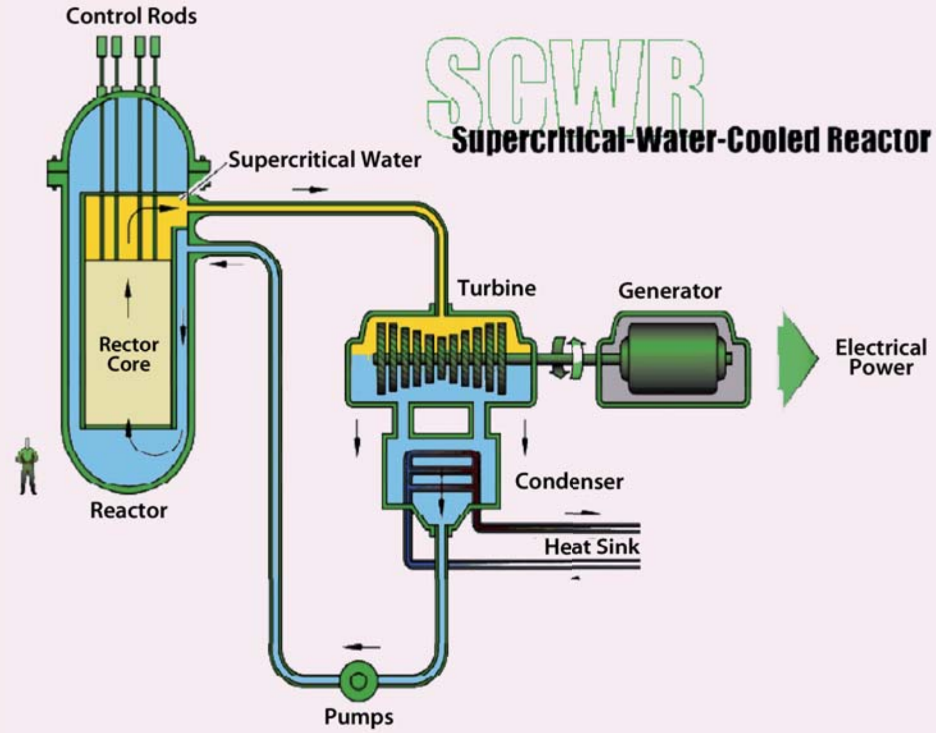


FIG. 14 Schematic diagram of a proposed SCWR design

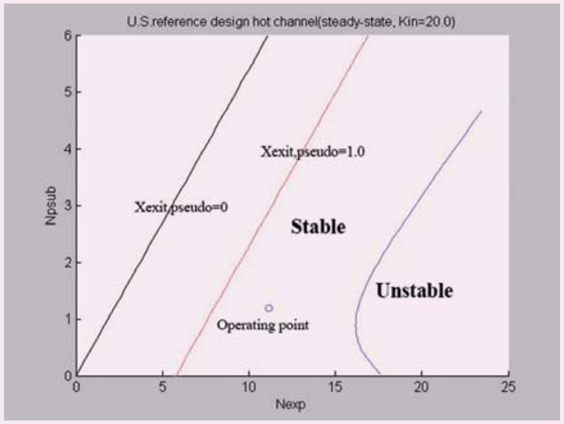


FIG. 15 Stability map for a proposed SCWR design