ROBERT BOSCH CENTRE
for CYBER-PHYSICAL SYSTEMS
Indian Institute of Science, Bangalore-560012, India

ROBERT BOSCH CENTRE FOR CYBER-PHYSICAL SYSTEMS, IISC

ISSUE 3

AUGUST 2017

EDITORIAL

The Robert Bosch Centre for Cyber-Physical Systems recently conducted the **First International Cyber-Physical Systems Symposium (CyPhySS 2017)**. The three-day event started on 19 July 2017 and featured talks from researchers, policy makers and industry experts. The symposium was divided in six sessions, with a total of 16 talks.

In the course of the symposium, the around 170 participants engaged in conversations on opportunities and challenges in this promising new field and discussed their contributions to and various applications of CPS. A panel discussion was held to discuss possible areas of research and explore opportunities for collaborations between the various stakeholders present during the symposium. The event also featured posters and demonstrations of novel devices or methods using CPS.

In this newsletter, we provide a summary of the talks and share some impressions of this first symposium. The presentations are available online at: http://www.rbccps.org/symp-cps2017/talks/. We thank everyone for participating in this event and hope to see you (again) next year!

Furthermore, you can also read up on the recently completed project "Developing a framework for using electricity consumption data to drive energy efficiency in the residential sector" on the last page.

Best regards,

Prof Bharadwaj Amrutur

Chairman, Robert Bosch Centre for Cyber-Physical Systems

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Cyber-Physical Systems Symposium

News @ RBCCPS

Dr S. Sridhar joined the Centre as Member of Technical Staff in June. After B.Sc. and M.Sc. in Physics, he did a PhD thesis on nonlinear dynamics of pattern formation and control in biological systems such as the heart. He worked as PostDoc at Brandeis University, Scimergent Analytics (now known as Scisphere) and at Ghent University, Belgium.

His research interests include modelling complex systems across different domains spanning natural sciences, engineering, economics and social sciences, using tools and techniques from nonlinear dynamics, high performance computation, complex networks, and data-driven modelling.

Ten PhD students accepted their position here at RBCCPS and started on 1 August. More information is available here: http://www.rbccps.org/people/phd-students/.

Symposium schedule

WEDNESDAY, 19 JULY 2017

Keynote Address

09.00-10.00 P.R. Kumar: Security of cyber-physical systems

Session I: Autonomous Systems and Robotics

10.00-11.00 Hemendra Arya: Hardware-in-loop-simulation for multiagents

11.30-12.30 Indranil Saha: Automated task and motion plan generation for multi-robot systems from complex specifications

Session II: Control and Optimisation for Smart Grids

14.00-15.00 Prabir Barooah: Virtual energy storage for solar and wind power with distributed coordination of smart devices

15.30-16.30 Anupama Kowil: Microgrid-based operations: A new operating paradigm for utilities

16.30-17.30 Vijay Arya: Analytics opportunities in the energy sector

17.30-19.30 Poster/Demo Session

THURSDAY, 20 JULY 2017

Session III: Hybrid Systems and Control

09.00-10.00 Calin A. Belta: Formal synthesis of control strategies for dynamical systems

10.00-11.00 Eswaran Subrahmanian: Community-centric smart connected services

11.30-12.30 Stefan Abendroth: Cross-domain solutions from a connected company

14.00-15.00 Pavithra Prabhakar: Formal verification of robustness properties of hybrid control systems

Session IV: Software Engineering for CPS

15.30-16.30 Aniruddha Gokhale: Exploiting fog and edge resources for cloud-hosted cyber-physical system services

16.30-17.30 Vinai Sundaram: Resource-efficient remote monitoring and diagnostics of cyber-physical systems

FRIDAY, 21 JULY 2017

Session V: CPS Test Beds

09.00-10.00 Ram D. Sriram: The Internet of Everything and Industry 4.0 revolutions

10.00-11.00 Eswaran Subrahmanian: Category theory for CPS

11.30-12.30 Panel Discussion

Session VI: CPS Security and Anomaly Detection

14.00-15.00 Bruno Sinopoli: On the resilience of cyber-physical systems

15.00-16.00 Sandeep Shukla: Cyber security of cyber-physical critical infrastructures: A case for a schizoid design approach

Keynote Address

Security of Cyber-Physical Systems (P R Kumar, Texas A&M University)

The symposium opened with an inaugural talk by P R Kumar, College of Engineering Chair in Computer Engineering at Texas A&M University. In his lab, Kumar works on many aspects of CPS including one of the most important: Security. P R Kumar started his talk with a video of autonomous robots with collision avoidance features, moving independently and avoiding obstacles. In the next video, one of the robot's sensors is attacked by a malicious agent, which leads to a failure of the collision avoidance, resulting in a collision between the autonomous robots.

"CPS is the next generation of engineered systems in which computing, communication and control technologies are tightly integrated with many societally important future applications, like smart grid, automated transportation and telesurgery systems", remarked Kumar. "Until now, hackers could only tamper with the information in the cyber system. In CPS, however, action in the physical world are based on information from the cyber systems, allowing hackers to cause damage in the physical world, leading to more violent cyber attacks" he added.

To secure the information in CPS, the system is considered as a combination of two layers: A physical layer, containing the sensors, actuators, and routers, and a cyber layer, containing the software and the processing algorithm. To secure the entire system, both layers need to be secured.

Kumar demonstrated one of the ways in which the information from the sensors can be protected: In a third video, the robots are allowed to continue their movement, but this time Kumar introduced a 'dynamic watermarking' scheme into the programming of the robots, meant to identify an attack and avoid mishaps. This time around the infected robot is stopped in its track just before the collision.

Watermarking behaves much the same way as a watermark on images and documents. It adds an additional layer containing a particular signature that can be read by the processor to identify if information came from a sensor or from a malicious agent, allowing the users to monitor a system and alert them in case of an attack.

Session I: Autonomous Systems and Robotics

The study of a physical entity capable of acting autonomously, often called 'autonomous system', is an important sub-discipline of cyber-physical systems. Robotics can be viewed as an example of autonomous systems. The areas of autonomous systems and robotics are increasingly receiving research attention. The aim of this session was to bring together leading researchers in these areas to discuss the state of the art. The session had two talks centered around the theme of understanding coordinated activities of multiple robots.

Hardware-in-loop simulations for multiagents (Hemendra Arya, IIT Bombay)

Multiagent systems are systems that incorporate the services of multiple agents, like aerial vehicles, drones or a swarm of robots, which share the same objective. Getting the multiple agents in the system to perform their task without any mistakes or interference can be a challenge, but by using simulations this task becomes a lot simpler.

Hemendra Arya's talk focused on hardware-in-loop simulations, where a combination of actual hardware as well as computer simulations is used in a simulated environment. "Hardware-in-loop-simulation consists of virtual components as mathematical models and real components as actual hardware" explained Arya.

At his lab, he and his team are working on reducing the hardware required to successfully run a simulation. The presence of real components makes the simulation happen in real time, as dictated by the hardware components. The simulations have to react in real time to the information coming in from the sensors. This, along with the simulation of the environment where the system is set to operate, as well as simulating the

sensors and establishing a communication channel between the agents were some of the challenges faced by the team.

By changing the concept of real time to that of a 'soft-real time', where a task has to be completed anytime before a given deadline, the researchers were able to reduce the number of computers required for a simulation. To demonstrate, the team used 16 aerial vehicles, each of which could communicate with each other wirelessly, to move in a circular path within the campus. The team used open source software like JSBSIM for the flight mechanics simulations, and Xbee modules for wireless communication between individual agents. The most interesting fact of the demonstration, however, is that all the 16 vehicles were simulated on a single computer.

Another computer, connected to the first, could simulate the sensors and the environment, bringing down the resource requirement to a fraction of what was previously required. The team's work could help advance the field of automation by reducing the enormous initial investment required during the development phase of such systems, allowing simulations of several autonomous vehicles to be run on a single computer.

Automated task and motion plan generation for multi-robot systems from complex specifications (Indranil Saha, IIT Kanpur)

Staying on the topic of multi agents, Indranil Saha works on the tasks performed by the individual agents. Performing a simple task, like picking up a box and placing it at a different location, can be quite easily achieved by a robot. But in a system where multiple autonomous systems are interacting with each other, for each robot performing their individual tasks they have to be individually programmed by the user. Furthermore, the computer that is interacting with each robot also has to be aware of the constraints of each of them.

Saha and his team have built 'Antlab', a program that can receive a task from the user and then manage a swarm of autonomous agents, likes drones and robots, to complete the task. Antlab is a task and motion-planning framework, which can dictate to a swarm of robots their individual tasks and paths to follow. The program uses a method called 'Linear Temporal Logic', where formulae can be encoded for future paths. This allows Antlab to plan the task for each robot as a series of smaller motions.

The motion of each robot is achieved in a similar manner. Saha and his team developed the tool 'Compositional Motion Planner (COMPLAN)', that divides the overall trajectory a robot has to follow into smaller steps. This allows the computer to plan a path for each robot without any of their paths crossing. With a video of four autonomous robots achieving the objective of moving to a different location while avoiding obstacles, Saha demonstrated his program at work.

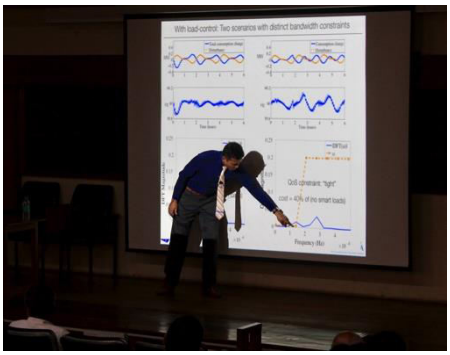
Session II: Control and Optimisation for Smart Grids

Renewable energy sources are gaining popularity due to the diminishing fossil fuel reserves and the environmental damage caused by burning those fossil fuels. Renewable energy sources, however, come with their own set of constraints and requirements, from efficiently storing the power, whenever it is generated, to efficiently supplying it to the customer. Researchers are now applying CPS to create 'Smart Grids': Efficient energy grids with ability to communicate with other grids as well as change their output based on feedback.

Virtual energy storage for solar and wind power with distributed coordination of smart devices (Prabir Barooah, University of Florida)

Storing energy has always been a challenge. Battery technology, although considerably improved in the last few decades, is yet to see radical transformation for allowing the ability to store large amounts of energy for a long time and dispensing it when required. With the advent of CPS, the idea of smart grids could transform the way we supply energy.

Prabir Barooah and team are working on using CPS to create efficient batteries in the virtual world. They have been exploring decentralized control of loads, turning consumer devices, like air conditioners and refrigerators into smart devices that could efficiently use energy to act as a virtual battery.



The main challenge of renewable resources like solar and wind is the intermittency of supply. When the sun has set or when the wind is not blowing strongly, energy generation from these sources is at a minimum, during which non-renewable sources like coal and nuclear have to supply the deficient power. This is where decentralised load could help. By turning off devices when the demand is high and allowing devices to run when the demand is low, the power generated from renewable sources is

used efficiently, but at a cost to the consumer, who cannot use his devices whenever he wants.

Prabir Barooah's team developed the concept of virtual energy storage (VES), where the idea of decentralised loads is improved to provide the customers a better quality of service. By intentionally varying the power consumption of certain devices, like the air conditioning of large buildings, in a way that the consumer does not notice these variations, the load on the devices can be made to look like that of a battery charging and discharging. Although there is no storage of energy in VES, the behaviour of the devices is similar to a battery. For example, in HVAC systems, if the power is varied as fast as the airflow, then consumers do not realise a change in temperature while the HVAC uses less energy than it usually would.

VES still faces an uphill task to be able to work for individual consumers, but is an excellent option for large energy consumers like industries. The main challenge is maintaining the quality of service, where neither the consumers notice a significant difference due to the power variations, nor the high frequency of power variations affects the electrical components of the device. There could also be other challenges when controlling an array of devices that is spread across many buildings, each of which should contribute to the overall savings, without affecting its individual performance. Since these devices do not communicate with each other, their power supply has to be controlled by the central grid.

Barooah and his team have been addressing these challenges and are working on bringing this technology to the commercial space, where it could bring down our electricity bills significantly.

Microgrid-based operations: A new operating paradigm for utilities (Anupama Kowli, IIT Bombay)

Energy distribution is largely a state-run operation, where energy grids spread across cities and towns power the individual households. A concept that has emerged in recent times is that of microgrids, a network of consumers with a local power source that is attached to the centralized power grid, but can also function independently. Microgrids can supply to a local network in time of outages or supply back to the grid in times of high demand. Anupama Kowli and her team are working on efficiently managing a network of microgrids and centralised grids.

To efficiently use the microgrids in step with the central grid, the network of consumers connected to a particular microgrid – called the distribution grid – needs to be intelligently partitioned into smaller cells. These cells should be able to work in synchrony with other such cells and with the central grid, and be able to perform independently in case of outages. The boundaries for such cells are either static (based on the average amount consumed by a particular set of households) or dynamic (based on the supply demand conditions).

Kowli is working on developing such intelligent partitions for microgrids so that consumers face the least inconvenience during an outage. The partitioning should also take into account the various renewable energy sources like solar or wind, where the supply is intermittent. The grids need to intelligently use the power from such sources, when they are available. The microgrids also need to be communicating with each other so – in case any of the grids in the network is not able to meet the demand – other grids can support that cell.

Anupama Kowli presented an idea of partitioning microgrids dynamically, every five to 15 minutes, based on the changing supply demand conditions. Using CPS, the microgrids become smart grids, whose boundaries vary dynamically, so as to avoid grouping all low power consumers in one and high power consumers in another cell. Her work not only enables uninterrupted power supply, but also helps to move to more renewable sources and be more independent of the central grid.

Analytics opportunities in the energy sector (Vijay Arya, IBM Research)

Much of the recent news coverage on renewable energy sources and battery storage has focused on the rapid rise of solar energy production, due to falling prices of solar panels and increased awareness on the pollution caused by fossil fuels. With this new energy source now becoming ubiquitous, our existing grids need to be upgraded to keep up with the changing technologies. This can be done more effectively and efficiently when all the information about each component is available. Vijay Arya works on using this data to identify solutions to several issues faced by the energy sector.

In his talk, Arya presented examples where large data and analytics were employed to design and manage power grids efficiently. He is using such data analysis for power distribution systems, renewable energy sources, storage, microgrids and many other aspects of energy distribution. In one example, Arya presented a data-driven approach towards creating a connectivity model for energy distribution.

The connectivity model decides which household is connected to which grid or transformer. Outdated connectivity models often cause problems in managing the distribution. Using his analysis, the utility providers cannot only identify faults and keep track of errors, but also allow an interactive relationship with the consumers, where the providers can send out accurate information about the possible causes for an outage and the time it would be fixed in, guaranteeing a higher customer satisfaction. Apart from energy distribution, the methods developed by Arya were also implemented by a Canadian utility company that specialised in hydro generation. They used the analytics to reduce the operational costs arising due to uncertainty in demand and supply.

Vijay Arya brought in an industry perspective to CPS technologies, presenting current uses of CPS in various sectors and alluding to the challenges in creating many of the applications.

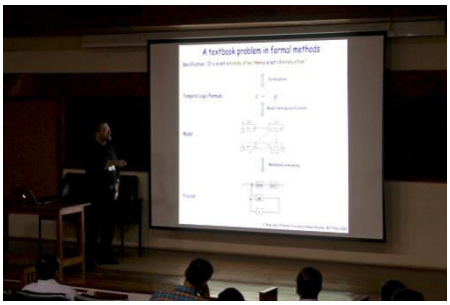
Session III: Hybrid Systems and Control

Hybrid systems involve an interplay between continuous and discrete dynamic behaviours. Algorithmic verification of qualitative properties of such systems and design of control techniques that achieve a desired property are of active research interest to computer scientists and control theorists. In the session "Hybrid Systems and Control" we learnt about various verification and control tools for Hybrid Systems.

Formal synthesis of control strategies for dynamical systems (Calin A. Belta, Boston University)

Control theory deals with the behaviour of dynamical systems like traffic systems, typically with the objective to control a system in order to obtain a desired output.

"In control theory, complex models of physical processes, such as systems of differential equations, are analysed or controlled from simple specifications, such as stability and set invariance", explains Belta. He works on developing control strategies for dynamical systems using 'temporal logic', a convenient method for specifying and verifying properties of a system. Such logic specifications can be used to specify the behaviour of very complex systems, and are widely used in 'formal verification'.



Calin Belta described techniques from game theory to obtain control strategies for low dimensional dynamical systems. He also presented methods to reduce conservativeness and improve scalability of those techniques. Multiple examples from robotics and traffic control were discussed. Belta and his collaborators have developed control strategies dynamic upgrading of the quality of these systems.

Formal verification of robustness properties of hybrid control systems (Pavithra Prabhakar, Kansas State University)

"Cyber-physical systems consist of complex systems that combine control, computation and communication to achieve sophisticated functionalities as in autonomous driving in cars and automated load balancing in smart grids", remarks Pavithra Prabhakar. Unstable components or software bugs within any of the components have resulted in disasters and product recalls. To work in the real world, CPS need to be robust, and reliable.

Simulations are commonly used to verify robustness properties of a system. Mathematical abstractions of the physical systems are derived and then analysed extensively by employing closed-loop simulations. The abstraction is improved based on the output obtained from sensors and actuators in a simulation environment. This study is repeated for various scenarios to conclude about robustness of the abstraction and hence the original system.

In her talk, Prabhakar focussed on an important robustness property: 'Stability'. In particular, she considered continuous-time switched linear systems, a mathematical abstraction for hybrid systems, and described the notion of Lyapunov stability (loosely speaking, boundedness of system trajectory) for such systems. Traditional control techniques guarantee stability based on the existence of certain functions, but often fail to provide useful insights on why a switched system may be unstable.

To address this issue, Prabhakar and her collaborators have developed a program called 'Algorithmic Verifier for Stability (AVERIST)', which evaluates the stability of a system. In addition, if stability cannot be concluded, then the program returns a counterexample that leads to instability. This feature also facilitates refinement of the mathematical abstraction.

Prabhakar concluded her talk with an example where AVRERIST has been employed to establish robustness of a cruise control system.

Cross-domain solutions from a connected company (Stefan Abendroth, Robert Bosch GmbH)

Stefan Abendroth heads the Communications and Network Technology Group at Robert Bosch in Germany. Bosch is one of the largest manufacturers of automotive components and also develops products and services in mobility solu-

tions, industrial technologies, energy and building technologies, and consumer goods like power tools and household appliances.

As the company is at the forefront of research and development in CPS, Abendroth presented several examples to demonstrate the rigorousness of the connected systems developed at Bosch: Their 'plug and secure communication' offers a simple, cost efficient, and scalable means of setting up communication channels that can be completely automated. The company is also developing ultra-reliable wireless communication services to enable Industrie 4.0 applications. The wireless systems have already been incorporated in several applications like mobile control panels, augmented reality devices and robots.

Abendroth concluded his talk by stressing on the need for CPS and communication technologies to be dependable and robust, while also encouraging the researchers to explore specific solutions for security, reliability, flexibility and simplicity of CPS systems.

Community-centric smart connected services (Eswaran Subrahmanian, Carnegie Mellon University)

With the advent of Smart Cities, the applications of CPS in implementing city-scale monitoring systems have been widely explored. But with their implementation, other aspects like governance and citizens have to be taken in to account as well. Eswaran Subrahmanian has been working on such this integration of technology and social aspects: The city is considered as a collection of commons, including road infrastructure, air quality, water, public transport, etc. A Smart City would manage these commons with citizen participation, in order to provide sustainable services.

As an example, Subrahmanian presented a public space waste management system he and his team implemented in downtown Washington D.C. For the waste management to be efficient, the waste has to be disposed in bins, the bins need to be collected by garbage trucks on a regular basis, and the garbage needs to be processed to recover and recycle possible materials, and all of these services have to be sustainable. CPS can be used to make 'smart bins' that detect the level of garbage and inform the garbage truck. But for effectiveness of the solution, the necessary policies need to be in place and citizens need to avoid the use of plastic and other non-degradable and non-recyclable materials for the system to be effective. Subrahmanian used a combination of CPS, which provided information on the trashcans and garbage trucks, and social media applications to get citizens involved. Citizens could report on the status of the trashcans and their immediate environment (i.e. whether trash was disposed next to them) in their locality, thus supporting the sensors in the trashcans to schedule the correct pick-up time.

Citizens are actively participating in managing the commons within a city, which – coupled with CPS – could enable effective sustainable services throughout the city, from clearing the trash to checking the quality of air in a neighbourhood.

Session IV: Software Engineering for CPS

The 'cyber' part of CPS refers to the virtual part of the system. This is where lines of codes enable control over the physical world through a set of sensors and actuators. This software forms the backbone of CPS, telling each of the individual components its role. Physical constraints like availability of server, distance to the server, or computing power of the processor still play a major role in developing effective software, but researchers are always looking to find efficient ways of using available resources most efficiently to engineer the required software.

Exploiting fog and edge resources for cloud-hosted cyber-physical system services (Aniruddha Gokhale, Vanderbilt University)

The amount of data generated from CPS like traffic control or air quality monitoring systems is enormous. To make useful predictions or to find solutions from the data requires analysis, which in turn requires significant computing power. One of the preferred methods of getting such analysis done without investing in supercomputers is using cloud computing. Services like Google Cloud Platform, Amazon Web Services and Microsoft Azure already provide cloud services for the analysis of large data. But cloud computing comes with its own drawbacks, mainly due to the distance between server and user. The time required for the information to travel between the user and the server may interrupt CPS services, as they work on real-time data.

Aniruddha Gokhale is working on reducing this transit time through fog and edge computing, where data, computation and storage are all distributed between the user and the cloud. Once the user sends a request, the serve allocates some of the computing-intensive task to edge/fog services closer to the user. Once the desired objective is achieved, the results are sent back to the user, thus reducing the transit time. The fog/edge services act as 'micro data centres (MDC)'. For such a system to be effective, the centralized data centre, which receives the request from the users, should allocate the tasks to MDCs in an efficient manner.

To achieve this, instead of building a model for such a data sharing system and testing it, Gokhale and his team used a machine learning approach. The

machine learned from a vast amount of available data and then built a model, which was further improved in successive steps from additional data. This way, the efficiency of the system allocating the tasks and resources can keep evolving as the available data increases.

"Many of the coffee shops like Café Coffee Day and Starbucks can start providing an additional service of starting MDCs, which will ensure quick analysis for users and good business for the owners", concluded Gokhale.

Resource-efficient remote monitoring and diagnostics of cyber-physical systems (Vinai Sundaram, SensorHound)

Software errors are frustrating when occuring on our computers; in CPS, however, they can have devastating effects when rendering the system incapable of performing. In systems like autonomous vehicles, telesurgery, or other medical applications of CPS, such an error could even cause fatalities. Protecting the software and ensuring its robustness and effectiveness is crucial for wide applications of CPS, for example in a Smart City, where millions of devices and software must perform efficiently. Vinai Sundaram founded SensorHound, a company that provides security and reliability solutions for CPS and IoT, ensuring the software works before and after deployment.

The company provides programs to continuously monitor the state of the software in a system, alerting when the software fails or when intrusions are detected. The company offers products that can be incorporated into several devices, like sensors and drones, and also provides software to diagnose the source code to find defects and malwares. "Prior attempts to monitoring of CPS are specialised for individual types of defects, require continuous manual intervention, or impose high overhead. We developed novel tools and techniques that enable CPS developers to automatically detect anomalous behaviours in deployed systems, and will allow them to efficiently diagnose the problem such that it can be quickly and confidently corrected", remarked Sundaram.

Session V: CPS Test Beds

Ever since its inception back in the 1990s, the Internet of Things has transformed the way we view the world. If every object, from humans and animals to buildings and utilities, could be electronically tagged, then a computer could inventory them. Add control to this structure and we have CPS: A system with the ability to interact and control the physical world through an IoT platform. With CPS we can performs tasks in a virtual space, which can have an impact in the real world, allowing for many applications in medicine, transportation, space exploration and even personal health care devices. The future of this technology will be on an industrial or even city scale, with researchers already implementing some of these systems.

The Internet of Everything and Industrie 4.0 revolutions (Ram D. Sriram, National Institute of Standards and Technology)

The power of the Internet to transform our world and become as ubiquitous as it is now, was not foreseen by many, who believed the Internet would mainly be used only for emails. Today, with readily available mobile computing devices, the time is right to exploit the interconnectivity of those devices to introduce new services and products. With IoT, we can monitor aspects of the real world, like people's health, air quality or the amount of trash in your trashcans. Today, with CPS, we can not only monitor but also control this physical space remotely from a virtual space. Ram Sriram discussed some of the important applications of CPS in the coming years, including setting up the Internet of Everything and Industrie 4.0

In Europe, industry had gone through four stages of revolution: The first, when steam powered engines were introduced; the second, when mass production and assembly lines began; the third was the rise of computer and automation; and the final revolution is currently happening: Industrie 4.0 or the introduction of CPS. This concept enables processes like smart manufacturing, where advanced intelligence systems can dynamically respond to a product demand by enabling rapid manufacturing of new products. These modern factories can be connected with the customers, suppliers and distributors to create a highly efficient and dynamic production line.

An often neglected part of the CPS architecture is the social element. Availability of social media networks makes it easy to also keep track of the social aspects within a CPS system, allowing a system to achieve customer satisfaction along with quality. Sriram also discussed some of the IT challenges in building CPS, including designing the system. He concluded his talk with an optimistic look at the future of the technology where a collective intelligence of all human beings, connected through the Internet, could enable designing and developing better devices and technologies.

Category theory for CPS (Eswaran Subrahmanian, Carnegie Mellon University)

To successfully design CPS, it needs to be considered as two distinct types of composition. First, the system with its set of sensors and actuators is a CPS system by itself: An autonomous vehicle, for example, is a CPS, with brakes, engine, etc. being the individual compo-

nents. Second, the system could also be a part of a larger CPS: In the case of the car it would also be a part of the traffic CPS, where it needs to interact with other cars, which are separate CPS systems like it.

This is generally referred to as the 'systems-of-systems' approach, and is one of the key features of CPS. Designing the framework for such a system at two different scales is a complex problem. Eswaran Subrahmanian and his team have been using 'Category Theory (CT)' for their approach, a branch of abstract mathematics that allows representing mathematical concepts and structures using a collection of objects and arrows: "CT has the potential to provide a rigorous and systematic foundation for engineering of CPS", remarked Subrahmanian.

As an example, he demonstrated the evolution of brake systems in automobiles, along with presenting a CT design for the modern day anti-lock brake systems. He ended his talk with a look at future research efforts in CT, which included formalizing a CPS framework for the National Institute of Standards and Technology (NIST), developing crystallographic databases as well as developing the methodology for using CT. It has already been used in certain CPS implementations at DARPA, Airbus, Dassault and MIT, and appears to be an effective tool to form the framework and foundation for CPS.

Session VI: CPS Security and Anomaly Detection

The final session of the symposium looked at another crucial aspect of IT: Security, the concept with which the symposium started. CPS is a combination of software, hardware, and networks, all working in harmony. Ensuring the security of each of these components is essential for the functioning of the whole system. The topic is especially important in CPS implementations, which will be in charge of city scale services and whose disruption could end in calamity. Ensuring the software and components are safe from attacks, as well as detecting anomalies is the difference between an effective CPS and a dangerous system.

On the resilience of cyber-physical systems (Bruno Sinopoli, Carnegie Mellon University)

With a growing market for CPS implementations, many of the components are being mass manufactured. CCTV cameras, GPS sensors and temperature and climate controls are just some of the examples that have already reach the mass production stage, with off-the-shelf products for easy implementation of CPS for our homes and vehicles. But such off-the-shelf products also bring in their own set of problems, most important of which is the security aspect, as most of such devices are susceptible to intrusions.

Bruno Sinopoli is working on addressing such security concerns of CPS. One of the major concerns in designing the security for such systems has been in the independent design of the control, communication and computing components of the CPS. Since all these components form parts of a whole and need to interact with each other, Sinipoli and his team have been addressing the security of the CPS rather than addressing the security measures for each of the individual components.

Some of the challenges in the area include the inability of the security algorithms to address the underlying physical dynamics, the difficulty of updating the security systems and ensuring graceful degradation of components that are under attack. Sinopoli presented some of the possible solutions and future efforts. The solutions involved leveraging the design of the physical dynamics, using the information from sensors and degrees of freedom of the components as a measure of the health of the system and performing resilient control to ensure the performance of a component under attack.

He also presented an example of securing system from sensors under attack by using physical watermarking, much like the watermarking on images, where a signature attached to the information allows us to verify its validity.

Cyber security of cyber-physical critical infrastructures: A case for a schizoid design approach (Sandeep Shukla, IIT Kanpur)

A CPS design usually involves a model-based engineering approach, where a mathematical model of the physical system is created with it objectives, functional safety and reliability, while cyber security and defence are incorporated at a later stage. Sandeep Shukla advocates a change to this design approach, considering cyber security and defence aspects during the design of the system. A CPS allows several entry points for an attacker to get in to the system, from attacking the sensors and actuators to provide wrong information to incorporating malicious software, that can send wrongful commands to the sensors. Thus it is crucial to monitor the system at every level, and, more importantly, design the system in such a way that it

becomes difficult for a hacker to access the various levels within the system.

Shukla helped setting up the Centre for Cyber Security and Defence of Critical Infrastructure at IIT Kanpur, dedicated towards developing security solutions for various digital platforms, including CPS. He advocates a schizoid approach to cyber security, which assumes the coexistence of disparate or antagonistic elements within the society. Such an approach would require designers and engineers to consider the actions of such elements once their systems are ready for implementation. This way, safety measures are built right into devices and software to safeguard against attacks, and in the case of an attack, contingencies ensure the functioning of the system in the presence of malicious agents in the system. Shukla and his team also developed an integrated test bed for power system utility security modelling and simulation.

Panel Discussion

Participants: Anurag Kumar (IISc), PR Kumar (Texas A&M), Harald Hoenninger (Robert Bosch GmbH), Ram D. Sriram (NIST), Sandeep Shukla (IIT Kanpur)

Moderator: Amrutur Bharadwaj (IISc)

"One important area that needs to be addressed is the rapid global rise of cyber-physical systems. But we can turn it into a huge opportunity by research, training and skilling in robotics, artificial intelligence, digital manufacturing, big data analysis, deep learning, quantum communication and Internet of Things. (…) We need to develop an Inter-Ministerial National Mission in the Cyber-Physical Systems to secure our future by creation of basic R&D infrastructure, manpower and skills." remarked Narendra Modi, Prime Minister of India, during the Inauguration Address of the 104th Session of the Indian Science Congress earlier this year. Consequently, the Department of Science and Technology, set up an Interdisciplinary Cyber-Physical Systems (ICPS) Division, and is providing funds for research into application of CPS with societal impact. The Government of India is planning to invest heavily in future research in CPS.

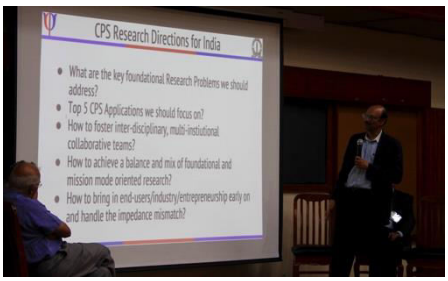
The panel came together to discuss some of the future directions of this exciting new technology and to identify opportunities for nationwide and worldwide collaborations. Some of the key issues discussed were: (1) Foundational research problems to be addressed, (2) main CPS applications to focus on, (3) how to foster interdisciplinary, multi-institutional teams, (4) how to achieve a balance and mix of foundational and applied research and (5) how to involve industry and end users as early as possible in the research effort.

The discussion began with each of the panellist presenting their views on those key issues. Anurag Kumar, Director of the Indian Institute of Science, provided an overview of the Institute and different areas of research that could be enhanced with the introduction of CPS. He stressed on the need for collaboration between the different institutes working on CPS, while also maintaining the importance on socially relevant innovations.

P. R. Kumar followed the talk with a take on the future directions for research in the country. While research is important, he also emphasized the need for the infrastructure necessary to implement such technologies including the creation of right policies, standards security frameworks.

Harald Hoenninger, a Senior Advisor at Bosch spoke next, focusing on the future challenges of CPS, especially in the Indian context. Those included the engineering framework for CPS, addressing the need and problems of the customer, and designing security features for CPS systems. He also stressed on the need for industry and academia to come together and set a long-term goal that can advance the research in the area.

Ram D. Sriram echoed those ideas and highlighted the need for collaborations. He further implored participants to collaborate with institutions like NIST. He also mentioned a few key areas of applications of CPS, most importantly healthcare. From managing overall health to addressing specific illnesses, Sriram presented several examples of innovations in CPS, which could be implemented in the country.



Sandeep Shukla concluded the opening statements of the panel discussion. He focussed on the need for translation of research and innovations into applications: While the country has been leading the way in research in CPS and IoT,

those results need to produce applications to improve communities and lives. Shukla also spoke about the security aspect of CPS, the lack of which could undermine years of research and incur huge losses to investors and the public.

During the discussion, the various panellists strongly emphasised the need for new technologies to have a positive societal impact. This includes research in areas like agriculture, medicine, energy management or smart grids. They also underlined the need for a National Institute for Standards and Technology in India to set the guidelines and standards for the current industrial revolution. India missed out on previous technological revolutions, including the industrial revolution, 3G, 4G etc. Now, however, it is well poised to implement CPS systems successfully. Perhaps it is time for the country to lead the way in this crucial technology of the future.

Posters and Demonstrations

The CyPhySS poster session provided a forum for researchers to showcase ongoing work and obtain feedback from the CPS research community. The following posters have been selected for presentation:

Intelligent communication between autonomous surface vehicles (ASVs): **Monica Palla**, Vamsi Krishna Kollu, Sri Harsha Gajavalli, Hrishikesh Venkataraman (IIIT Sri City) and Shunmugham R Pandian (IIITDM Kancheepuram)

Two-step clustering mechanism for communication in less disciplined cehicular traffic: **Surekha Ananthapalli**, Aishwarya N Reganti and Hrishikesh Venkataraman (IIIT Sri City)

Performance limits of delay constrained communication systems: Sharu Theresa Jose and **Ankur A. Kulkarni** (IIT Bombay)

Separating the good from the bad in rating systems: Smita Solanki and **Ankur A. Kulkarni** (IIT Bombay)

Observation based diagnosability of discrete event system: **Reshmila S** and Rajagopalan Devanathan (Sree Narayana Gurukulam College of Engineering)

A smart device to monitor quality and measure quantity of water flowing in pipeline: Hari Krishnan, **Madhav Mundhe** and Manish Arora (IISc)

Remotely operated vehicle (ROV) – IRIS for underwater inspection tasks: **Alok Sahu**, Debasish Ghose and P.S. Sastry (IISc)

Towards an automated deployment framework for large-scale CPS co-simulations in the cloud: Yogesh Barve, Himanshu Neema, **Aniruddha Gokhale** and Janos Sztipanovits (Vanderbilt University)

Exponentially stable position tracking control schemes for a class of underactuated vehicles: **Rakesh R Warier** (IIT Bombay), Amit K Sanyal (Syracuse University), Srikant Sukumar (IIT Bombay) and Sasi Prabhakaran Viswanathan (Akrobotix LLC)

In addition, the following demonstrations were presented to the participants:

Cyberglove and robotic arm control (IISc, Department of Electronic Systems Engineering)

ECG module and health platform (IISc, Department of Electronic Systems Engineering)

Sparse signal recovery based channel estimation in OFDM systems (IISc, Department of Electricial Communication Engineering)

Channel estimation for the drone to ground communication at 2.4/5 GHz (IISc, Department of Electrical Communication Engineering)

RBCCPS project demos in the areas of healthcare, water, energy, and Smart Cities.

Developing a framework for using electricity consumption data to drive energy efficiency in the residential sector

During the five years from 2010-15, the electricity consumption of Kerala had grown by about 33%. At this growth rate, the net consumption in about a decade's time from now is likely to be about 75% over today's levels. The cost of generating power increased by 31% during the 2010-15 period, and is likely to increase further. It is therefore essen-

tial that utilities actively engage with consumers to manage the growth in demand. Most domestic consumers, however, spend very little time understanding their consumption. Statistics from surveys indicate that only about 5% of consumers have a good recollection of their consumption for the previous month. A significant fraction (a third of the sampled respondents) is unaware of energy efficient alternatives while making an electrical appliance purchase. Among those that are aware, a significant fraction doesn't take up the efficient alternatives.

RBCCPS, IISc's ECE and ESE departments, Clytics Technologies (a start-up focused on energy information management and analytics) and the Kerala State Electricity Board embarked on a consumer engagement project involving about 25,000 consumers in the town of Aluva, close to Ernakulam, in Kerala. The goal of the project was two-fold: (1) understand the data analytic research challenges in building a prototype consumer engagement platform; and (2) quantify outcomes due to behavioural changes that are based on feedback to consumers on consumption patterns. Personalised feedback on consumption was given, along with their consumption bill, to about 25,000 households for the duration of a year. The personalised feedback included usage trends, comparison with similar households, targeted suggestions on better usage practices, and a gamification involving a pet plant whose growth reflected the energy conservation steps taken by the consumer. These conservation steps were deduced from the decreased consumption or bill amount.

The team of engineers working on this project had to solve several technological challenges. The experimental households could not all be instrumented with smart meters for that would have been prohibitively expensive. Instead, the team combined smart metering data from a minimal set of about 30 representative households, survey data on dwelling type, family size, appliance ownership and consumption patterns from about 3,000 households, billing data from the 50,000 households in a portion of Aluva, daily weather parameters, appliance specifications, and significant amount of modelling to arrive at the bi-monthly personalised feedback to the 25,000 experimental households.

Data logger: Smart meter and data logger being fixed in a 1BHK home in Kalamassery, South Aluva. The unit measured the consumption every second and logged the parameters into a memory device.

The team used this data to cluster households into various abstract categories. Households were surveyed to get information on the number of individuals in the household, age-groups, basic appliances and numbers, building material types, floor, etc. The unsurveyed users were then associated with a certain number of 'nearest neighbour' surveyed consumers, and the factors representing their consumption were imputed based on the factors of the associated nearest neighbours. Using these, the team identified targeted interventions for this household, and also arrived at disaggregation algorithms to identify consumptions for various appliance categories, such as lighting, cooling, heating, refrigerator, others, again for this household.

The project lasted 16.5 months and compared the reduction in consumption in the aforementioned 25,000 experimental households to that in approximately a similar number of control households. The overall impact of the pilot programme was estimated to be around 1% reduction in the consumption of the experimental group (with respect to the control group) leading to an estimated reduction of 2.70 lakh units of energy. This amounts to about Rs. 14 lakhs at the levelised cost of Rs. 5.26 per unit of energy. The average sale price for the domestic segment for the project period is a subsidised Rs. 3.76 per unit of energy leading to a revenue gap of Rs. 1.50 per unit. If the programme could be extended to the entire state of Kerala comprising of over one crore low-tension domestic connections, the financial impact is estimated to be to the tune of Rs. 41 crores and a reduction in subsidy is estimated to be about Rs. 12 crores.

For more details, please see the project report on the RBCCPS website: http://www.rbccps.org/energy-efficiency-residential-sector/.

The project was led by Rajesh Sundaresan and his team in IISc and by Shuvashish Chatterjee and Viney Kaushik of Clytics Technologies. The team acknowledges generous funding support from the Shakti Sustainable Energy Foundation.

A photograph with some of the consumers (second and third from right) at Aluva West after conducting programme assessment survey. From left to right, Viney Kumar (Clytics), Rajesh Sundaresan (IISc Bangalore), Abdul Salim and his spouse, Pradeep (meter reader).