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TC-CPS Newsletter

Technical Articles

Summary of Activities

Call for Contributions

Cyber Physical Emulators for Power System and Power Electronics Studies

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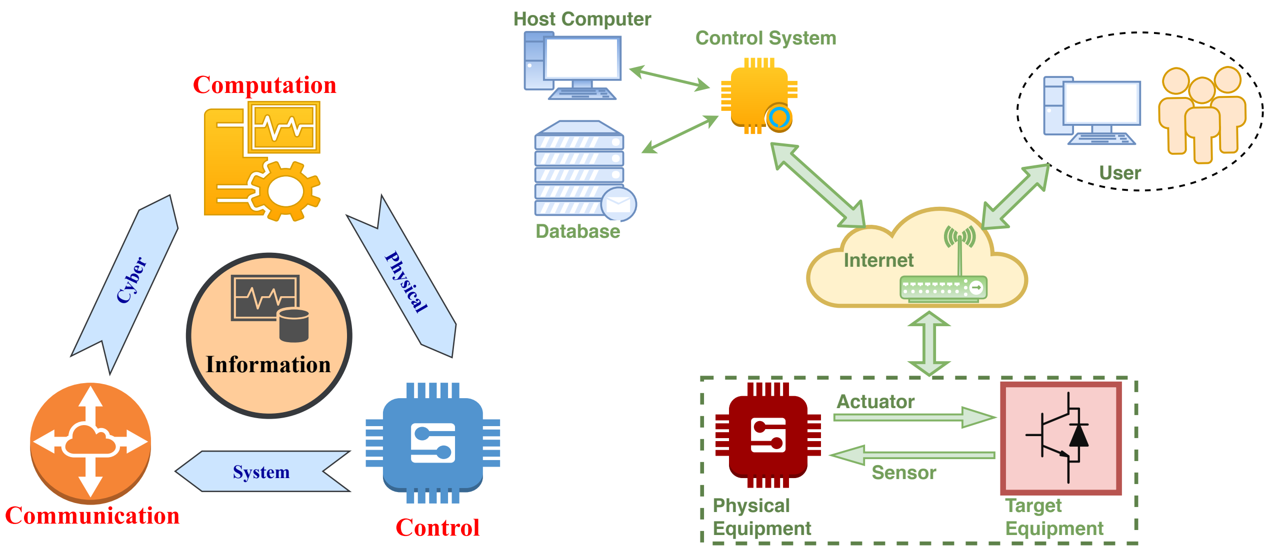
1 Introduction

The transformation in the development of functionalities in Information and Communication Technology (ICT) [1, 2], hardware, and programming brings about keen gadgets and interconnected different framework makes the training and life more intelligent. The analysts named these frameworks as Internet of Things (IoT), Cyber-Physical Systems (CPS). In training and research, the utilization of CPS brings about the virtual labs, ICT based emulators to analysis the performance of the systems. The CPS is expressed as Computations, Communications, and Control (3C's). The essential structure of CPS is spoken to in Figure 1.



(a) Block diagram of CPS flow

(b) Basic architecture of CPS

Figure 1: Block Diagram of Cyber Physical System.

CPS has the robust control ability than IoT and IoT only have the perception of sensing. The facts of introducing CPS in education and research delivers the [3, 4], (a) Continual evolution of system, (b) Integrate with cross domains, (c) Autonomy of the systems. The future energy systems is described as Cyber Physical Systems (CPS). The CPS system should behave as, (a) Intelligent, (b) Real time,(c) Adaptive and Predictive control. The Cyber Physical emulators concept has Cyber Physical Co-Simulation (CP-CS), Cyber Physical Controller Hardware in the Loop (CP-CHIL), Cyber Physical Rapid Control Prototype (CP-RCP).

- The Cyber Physical Co-Simulation (CP-CS) is the integration of different simulation engines. The data exchange between multiple simulators is carried out with common memory via network communication and remote monitoring.

- The Cyber Physical Hardware in the Loop (CP-CHIL) is the integration of hardware and software. The Plant model in host computer is communicated with processor in a co-simulated environment with online monitoring.
- The Cyber Physical Rapid Control Prototype (CP-RCP) is the online control and monitor of target equipment (physical device). Along with reconfigurable processors and data acquisition equipments.

2 LabVIEW based Cyber Physical System Emulators

The LabVIEW based Cyber Physical emulators is designed to evaluate the performance of the electrical systems. The Figure 2. shows the block diagram of cyber physical emulators for Cyber Physical Co-Simulation (CP-CS), Cyber Physical Hardware in the Loop (CP-CHIL) and Cyber Physical Rapid Control Prototype (CP-RCP). The emulators are designed with the base platform of LabVIEW. The LabVIEW is the graphical programming easy to communicate with heterogeneous systems.

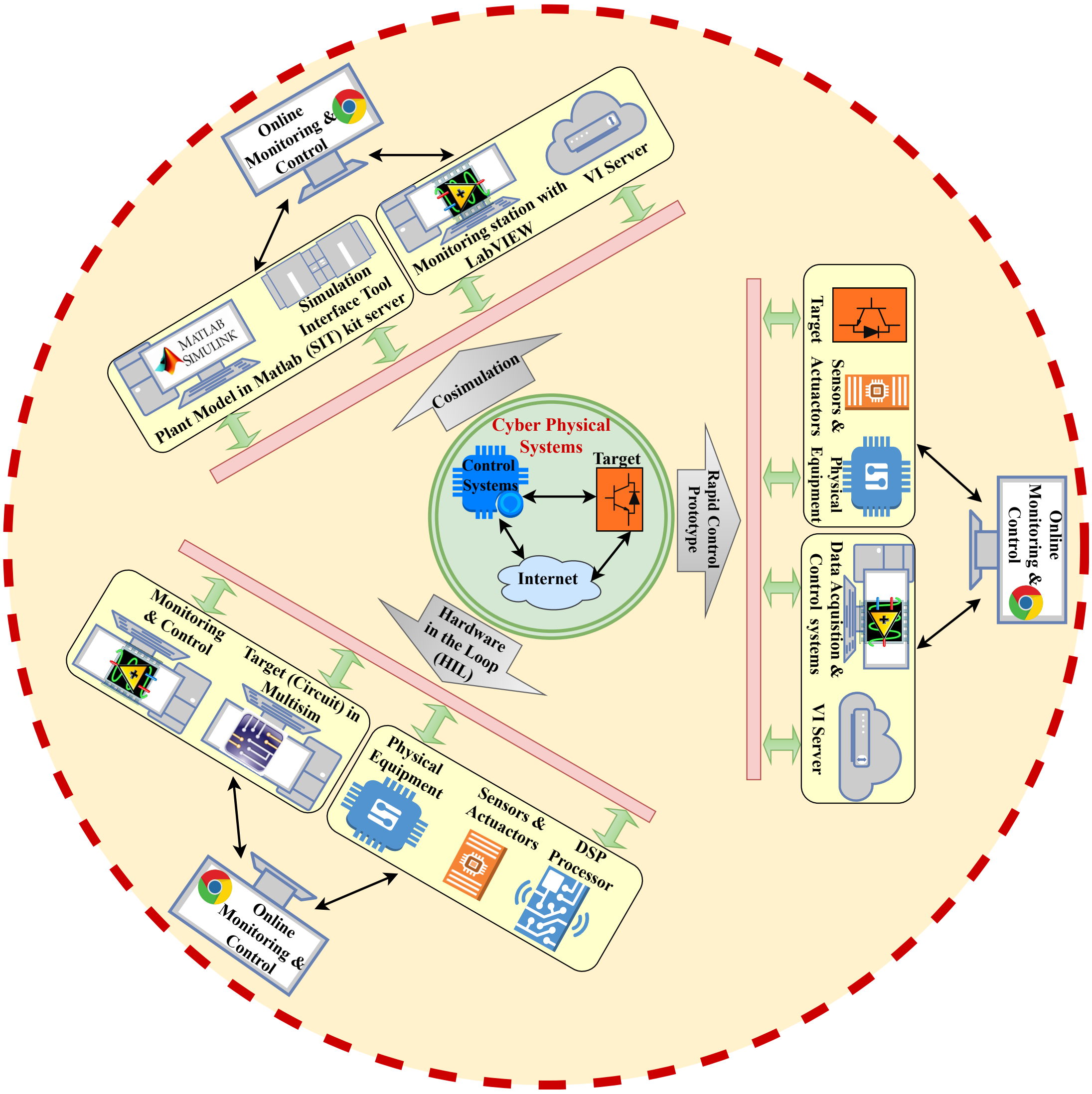


Figure 2: Block diagram of Cyber Physical System Emulators.

2.1 Cyber Physical Co-Simulation (CP-CS) of LabVIEW and Matlab

The Cyber Physical Co-Simulation (CP-CS) is modelled with LabVIEW and Matlab. The two software are interfaced with the Co-Simulation master, Simulation Interface Tool-kit (SIT) server [5]. It interfaces and exchange data between two software. In this model, the plant (power electronics/power system model) is modelled in Matlab. The control and monitoring is modelled in LabVIEW. Co-Simulation enhances the system to utilize the two software engines which reduce the solver time to analysis faster. The data's to be monitored and controlled is designed by graphical programmed with user friendly interface in LabVIEW. The SIT based master algorithm connected through the transmission control protocol/internet protocol (TCP/IP). The online monitoring also performed through the virtual instrument (VI) server, the plant to controlled and monitored is control through remote control center. This enables the analysis of the power system/power electronics models in cyber physical environment to enhance the easy implementation of the real systems. The block diagram for Cyber Physical Co-Simulation (CP-CS) of LabVIEW and Matlab is shown in Figure 2.

2.2 Cyber Physical Hardware in the Loop (CP-CHIL) with LabVIEW, Multisim and TMS320 DSP Processor

The Cyber Physical Hardware in the Loop (CP-CHIL) emulator designed based on the LabVIEW, Multisim and TMS320F2812 processor to performance evaluate of the power system and power electronics models. The power circuit model is designed in Multisim. The Multisim is the PSpice based circuit modelling tool. The control algorithm is programmed in TMS320F2812 processor. The data exchange between processor and LabVIEW is initiated by compact data acquisition (C-DAQ). The co-simulation of Multisim and LabVIEW is initiated [6]. The control pulse acquired from the processor is communicated to Multisim by co-simulation terminals and the results are monitored through the remote control center. The data from the host computer is transmitted through TCP/IP with 802.11 wireless LAN. The block diagram for the CP-CHIL is shown in Figure 2.

2.3 Cyber Physical Rapid Control Prototype (CP-RCP)

The Cyber Physical Rapid Control Prototype (CP-RCP) is the evaluation of the hardware model (target) with cyber physical features. In general, the architecture has three layers likely Physical layer, cyber-physical integration layer, and cyber layer.

- The Physical layer is the target equipment (power system/power electronics model) needs to control and monitor.
- The cyber-physical integration layer has the sensors, actuators, data acquisition(NI CDAQ 9174), physical equipment (My RIO 1900- processor) and host computer with LabVIEW. Which makes the interaction between the physical layer and host computer. The control algorithm is framed and programmed in the processor with data acquisition. Based on the operating conditions and acquired data the control algorithm will control the target.
- The cyber layer has the web service management with TCP/IP with 802.11 wireless LAN. The VI server enhances the data communication.

3 Experimental Case Studies

3.1 Case Study: Cyber Physical Co-Simulation (CP-CS) of LabVIEW and Matlab - Unified Power Quality Conditioner for distribution grid

The Unified Power Quality Conditioner (UPQC) has the ability to mitigate the power quality problems [5]. The UPQC is based on current source converter with left shunt. The Synchronous Reference Frame (SRF) theory based control strategy is implemented to control the converters . The system is implemented and analysed with Cyber

Physical Co-Simulation (CP-CS) of LabVIEW and Matlab. The UPQC model is designed in Matlab, the control and monitoring is designed in LabVIEW. The real time data exchange between the Matlab and LabVIEW is carried out with TCP/IP based protocols. The performance monitoring is done in internet browser. The Figure 3 shows the monitoring screen of the UPQC.

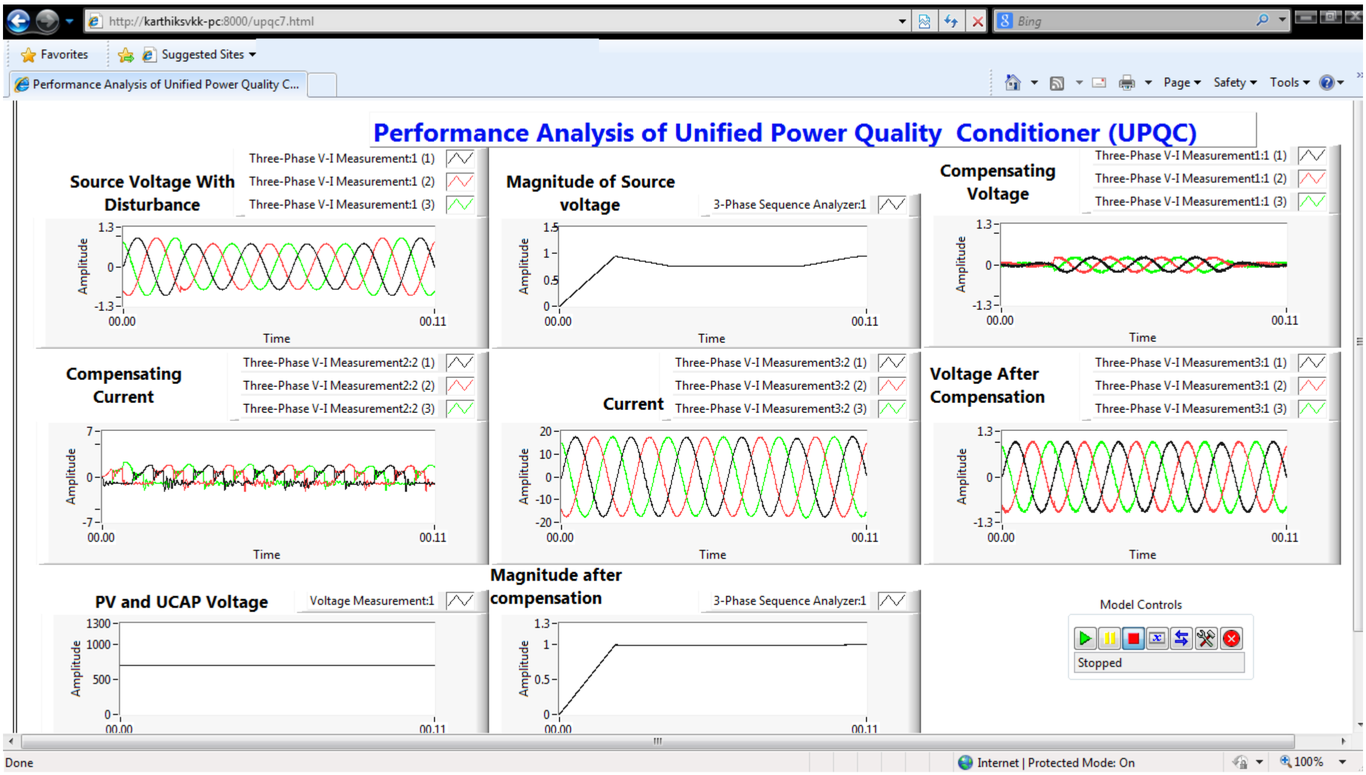


Figure 3: Online monitoring of UPQC.

3.2 Cyber Physical Hardware in the Loop (CP-CHIL)- Three phase dual output inverter

The three phase dual output inverter is designed and analysed with Cyber Physical Hardware in the Loop (CP-CHIL). The inverter is modelled in Multisim-PSpice based circuit simulator. The control pulse for inverter is programmed in TMS320F2812 processor. The communication of multisim and processor is carried out by LabVIEW. LabVIEW will act as master for data exchange of circuit and processor. The solver utilizes in LabVIEW and Multisim interface is Runge-kutta 45 ODE solver. The controller is based on hysteresis loop for inverter. The inverter is able to supply load two independent loads. The performance of the inverter under Cyber Physical Hardware in the Loop (CP-CHIL) is monitored from the remote user in browser is shown in Figure 4.

3.3 Cyber Physical Rapid Control Prototype (CP-RCP)-Single phase dual output inverter

The inverter capable of supplying two independent single phase loads is analysed with ICT based test bench of Cyber Physical Rapid Control Prototype (CP-RCP). The target equipment is dual output single phase inverter. The controller based on sliding mode is implemented in the Reconfigurable Input/Output (RIO) based processor NI MyRIO 1900. The signals from the inverter is obtained using NI CDAQ 9174 with NI 9225 voltage sensor and NI 9227 current sensor. The data acquisition from the target is collected to the host computer and using the control algorithm in the RIO will operate the inverter at desired range. The web service management in the host computer has the Secure Sockets Layer (SSL) protection with SSL x.509 certificate. The control and monitoring screen of the Cyber Physical Rapid Control Prototype (CP-RCP) is shown in Figure 5.

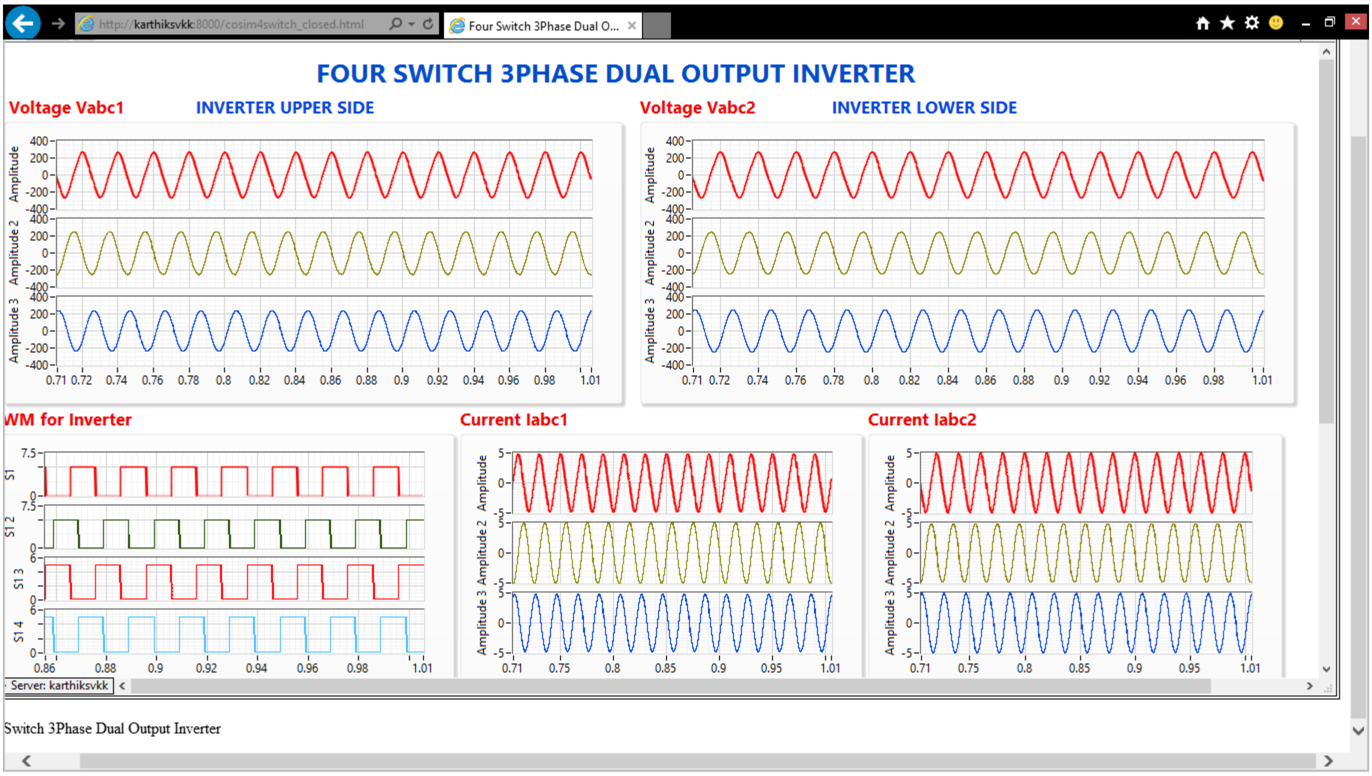


Figure 4: Online monitoring of three phase dual output.

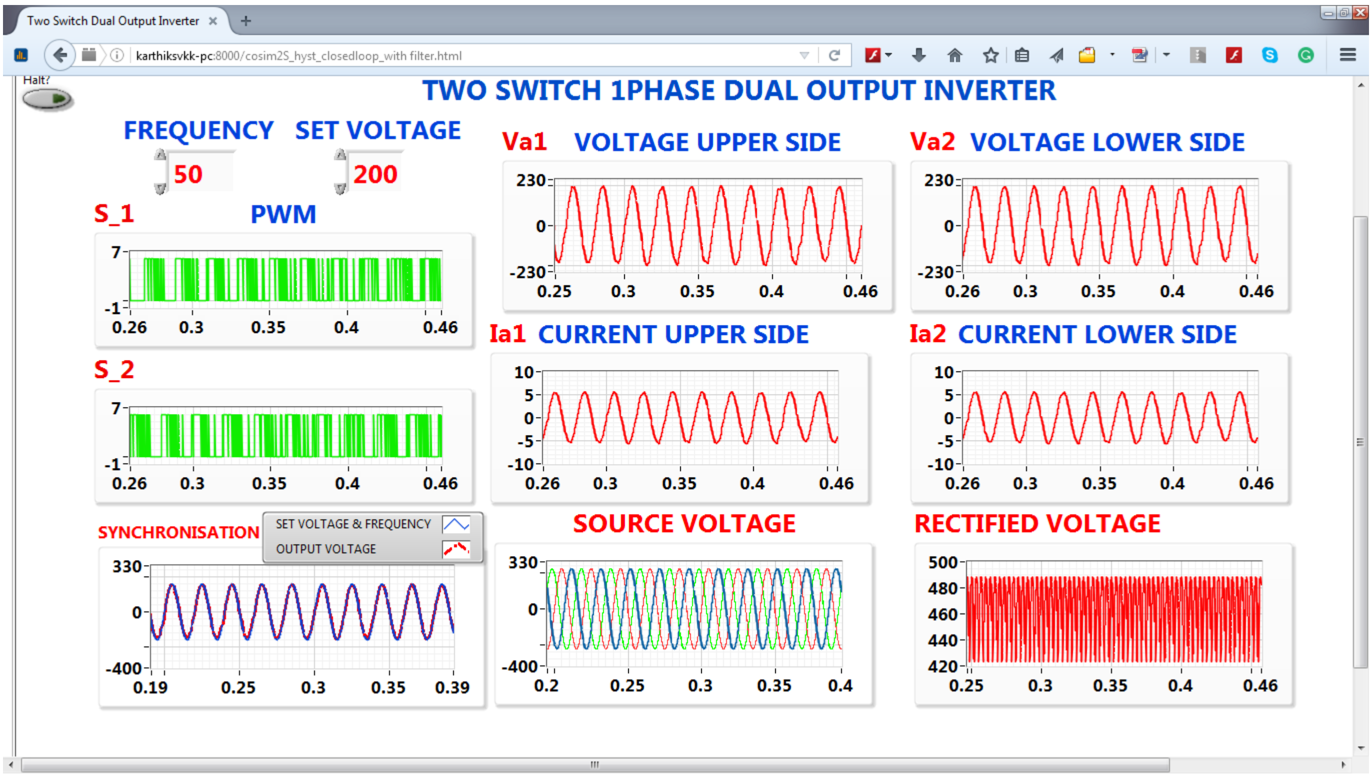


Figure 5: Online monitoring of Single phase dual output inverter.

4 Conclusion

The cyber physical emulators for power electronics and power system studies is modelled with LabVIEW base platform. The LabVIEW supports the heterogeneous interfaces of the systems. The ICT supported emulators Cyber Physical Co-Simulation (CP-CS), Cyber Physical Controller Hardware in the Loop (CP-CHIL), Cyber Physical Rapid Control Prototype (CP-RCP) are developed to enhance the research and development of the intelligent power systems/power electronics. The case studies described the usage of emulators in different power system and power electronics studies.

5 Acknowledgements

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Simplex Architectures for Cyber-Physical Systems[1]

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1 Introduction

The Simplex architecture [10] provides run-time assurance of a plant in the presence of an Uncertified Controller (UC). A reversionary Baseline Controller (BC), which has been verified, is used as a failsafe. Given a prescribed set of unsafe states, a switching boundary is identified in the state space. Crossing the boundary indicates imminent failure, and triggers a switch from the UC, which is the default controller, to the BC, which guarantees the safety of the plant. As such, Simplex is a very powerful architecture. It assures that the plant is properly controlled even if the advanced controller has bugs. As advanced controllers are increasingly more complex, more adaptive with the use of unverified algorithms such as machine-learning, runtime assurance techniques like Simplex are becoming more important.

The Simplex Architecture [10], illustrated in Figure 1, traditionally consists of two versions of a controller, called the *advanced controller* (*AC*) and *baseline controller* (*BC*), and a physical *plant* (*P*). The advanced controller is designed for maximum performance and is in control of the plant under nominal operating conditions. However, certification that the advanced controller keeps the plant state within a prescribed safety region (i.e., region of safe operation) may be infeasible, due to its complexity or adaptiveness, or because an accurate model of it is unavailable for analysis. In contrast, the baseline controller is certified to maintain safety of the plant. When the plant is under control of *AC*, a *decision module* (*DM*) periodically, with decision period Δt, monitors the state of the plant and switches the control of the plant to the baseline controller if the plant is in imminent danger (i.e., within the next decision period) of entering a state that might lead to a safety violation.

The switching condition used in the decision module is determined as follows. A state of the plant is *recoverable* if *BC* can take over from that state (due to a switch) and keep the plant invariably safe; in other words, the composition of *P* and *BC*, denoted $P \times BC$, when started from a recoverable state, will always remain within the safety region. An unbounded time horizon is used in the definition of recoverable states because, in general, we have no bound on how long *BC* needs to take corrective actions and overcome the plant's momentum (in a general sense, not limited to physical motion) toward unsafe states.

A state is *switching* if the plant, under control of *AC*, may enter an unrecoverable state during the next decision period, i.e., within time Δt. This definition reflects the discrete-time nature of *DM*. The switching condition simply checks whether the current state is switching. Note that switching states are a subset of recoverable states which are a subset of safe states.

The earliest methodology for computing switching conditions is based on Lyapunov stability theory and reduces the problem to solving linear matrix inequalities (LMIs) [4]. The method applies to plants with linear time-invariant dynamics and a linear baseline controller [9]. This approach is computationally efficient but limited in applicability. More general approaches were later developed [3, 2], based on state-space exploration, also called state-space *reachability*. Several reachability algorithms for hybrid systems have been developed, e.g., [6, 11, 5, 1].

In this article, we formalize the Simplex architecture and describe a new approach to designing it using Barrier certificates.

2 Simplex Architecture

Consider a plant *P* that is intended to be controlled by an Advanced Controller (AC). A subset of the state-space of the plant is deemed to be *unsafe*. The composition of P and the AC, denoted by $P \times AC$, is assumed to be *uncertifiable*, i.e. it is *not* possible to verify that P does not enter the unsafe region of its state space when it is under the control of the AC. This could be due to many reasons including the unavailability of a model for $P \times AC$. However, we do assume bounds on the derivatives (with respect to time) of *P*'s evolution under the control of the AC.

[1] Joint work with Abhishek Murthy, Junxing Yang, Scott D. Stoller, and Scott A. Smolka.

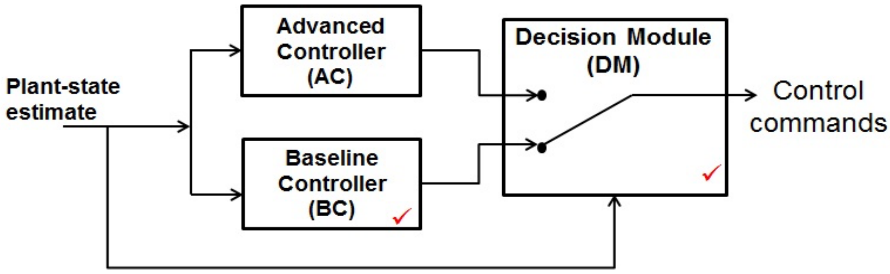


Figure 1: The two-controller Simplex Architecture.

The Simplex Architecture (SA) [10], shown in Figure 1, employs a redundant Baseline Controller (BC) and a switching logic to switch control from the AC (default) to the BC such that the safety of the plant is guaranteed at all times. A key feature of the BC is that P is provably safe under its control. In other words, it can be verified that the composition of P and the BC, denoted by $P \times BC$, does not enter the unsafe region. The proof of safety involves identifying a safety region, which is a subset of the state space disjoint from the unsafe region. The BC is guaranteed to ensure the safety of the plant within the safety region.

The switching logic, implemented by the Decision Module (DM), works as follows. The DM samples the state of the plant, which is nominally under the control of the AC, every Δt units of time. If the state-sample is found to lie outside a *switching boundary*, then the DM switches the control over to the BC. The switching boundary is derived from the safety region using $P \times AC$'s derivative bounds and its significance is as follows. Given the derivative bounds of $P \times AC$, a state lying outside the switching boundary might leave the safety region within the next Δt units of time. On the other hand, a state lying inside the switching boundary is guaranteed to stay within the safety region in the next Δt time units. Thus to ensure P's safety, the DM switches it from AC to BC when the switching boundary is violated but the plant is still within the safety region.

From the discussion above, we can see that the two central issues for designing the SA are

1. **Identifying the Safety Region**, which results in a proof of safety of $P \times BC$ and
2. **Deriving the switching boundaries**, which defines the switching logic implemented by the DM.

In our work, we model $P \times BC$ as a hybrid system. This formalism allows us to model both the continuous-time evolution and the discrete-time instantaneous changes in the behavior of the plant under the BC's control. We formally define a hybrid system as follows.

Definition 2.1. *A Hybrid System $H = (\mathscr{X}, L, X_0, I, F, T)$ is a six-tuple:*

- *$\mathscr{X} \subseteq \mathbb{R}^n$ is the continuous state space.*
- *L is a finite set of modes, also known as locations. The overall state space of the system is $X = L \times \mathscr{X}$ and a state of the system is denoted by $(l, \mathbf{x}) \in L \times \mathscr{X}$.*
- *$X_0 \subseteq X$ is a set of initial states.*
- *$I : L \to 2^{\mathscr{X}}$ is the invariant, which assigns to each location l an invariant set $I(l) \subseteq \mathscr{X}$ that contains all possible continuous states while in mode l.*
- *$F : X \to 2^{\mathbb{R}^n}$ is a set of vector fields. F assigns to each $(l, \mathbf{x})$ a set $F(l, \mathbf{x}) \subseteq \mathbb{R}^n$, which constrains the evolution of the continuous state as per the differential inclusion $\dot{\mathbf{x}} \in F(l, \mathbf{x})$.*
- *$T \subseteq X \times X$ is a relation that captures the discrete transitions between two modes. A transition $((l', \mathbf{x}'), (l, \mathbf{x}))$ indicates that the system can undergo a discrete (instantaneous) transition from the state $(l', \mathbf{x}')$ to the state $(l, \mathbf{x})$.*

Discrete mode-transitions occur instantaneously in time. We define *Guards* and *Reset maps* for mode-transitions as follows. $\text{Guard}(l',l) = \{\mathbf{x}' \in \mathscr{X} : ((l',\mathbf{x}'),$
$(l,\mathbf{x})) \in T$ for some $\mathbf{x} \in \mathscr{X}\}$ and $\text{Reset}(l',l) : \mathbf{x}' \mapsto \{\mathbf{x} \in \mathscr{X} : ((l',\mathbf{x}'),(l,\mathbf{x})) \in T\}$, whose domain is $\text{Guard}(l',l)$.

As per [8], for computational purposes, the uncertainty in the continuous flows, defined by F, are assumed to be the result of exogenous disturbance inputs such that:

$$F(l,\mathbf{x}) = \{\dot{\mathbf{x}} \in \mathbb{R}^n : \dot{\mathbf{x}} = f_l(\mathbf{x},d) \text{ for some } d \in D(l)\}$$

where f_l is a vector field that governs the flow of the system in location l and d is a vector of disturbance inputs that take the value in the set $D(l) \subset \mathbb{R}^m$.

Trajectories or *behaviors* of H start from some initial state $(l_0,\mathbf{x}_0) \in X_0$ and then the evolve in continuous time as per the dynamics defined by F until the invariant, defined by I, is violated and/or a guard is enabled resulting in an instantaneous mode switch. Trajectories are obtained by concatenating the continuous evolutions and the instantaneous discrete-time jumps between the modes.

Given a set of unsafe states $X_u \subseteq X$, H is said to be *safe* if all its trajectories avoid entering X_u. We define a mapping for mode-specific unsafe states as $\text{Unsafe}(l) = \{\mathbf{x} \in \mathscr{X} : (l,\mathbf{x}) \in X_u\}$. We also define $\text{Init}(l) = \{\mathbf{x} \in \mathscr{X} : (l,\mathbf{x}) \in X_0\}$.

Given a set of unsafe states X_u, the safety of a hybrid system H can be proved by computing *Barrier Certificates* (BaCs) [8]. BaCs are contractive functions that capture the following safety requirements:

- The continuous-time evolutions within the modes must ensure that that the states remain safe and
- A mode-transition $((l',\mathbf{x}'),(l,\mathbf{x}))$ from the mode l' to l must reset a safe state $(l',\mathbf{x}') \notin \text{Unsafe}(l')$ to a safe state $(l,\mathbf{x}) \notin \text{Unsafe}(l)$.

Next, we define BaCs formally.

Definition 2.2. *Let the hybrid system $H = (\mathscr{X}, L, X_0, I, F, T)$, the unsafe set X_u and some fixed non-negative constants $\sigma_{(l,l')}$, for all $(l,l') \in L \times L$, be given. A BaC is a collection of functions $B_l(\mathbf{x})$, for all $l \in L$, that are differentiable with respect to its argument and satisfies:*

$$B_l(\mathbf{x}) > 0 \quad \forall \mathbf{x} \in Unsafe(l) \tag{1}$$

$$B_l(\mathbf{x}) \leq 0 \quad \forall \mathbf{x} \in Init(l) \tag{2}$$

$$\frac{\partial B_l}{\partial \mathbf{x}}(\mathbf{x}).f_l(\mathbf{x},d) \leq 0 \quad \forall (\mathbf{x},d) \in I(l) \times D(l) \tag{3}$$

$$B_l(\mathbf{x}) - \sigma_{(l',l)} B_{l'}(\mathbf{x}') \leq 0 \quad \forall (\mathbf{x},\mathbf{x}') \in \mathscr{X}^2 \text{ such that } \mathbf{x}' \in Guard(l',l) \text{ and } \mathbf{x} \in Reset(l',l)(\mathbf{x}') \tag{4}$$

Theorem 3 and Proposition 2 of [8] ensure that the BaC, as defined above, is a collection of convex functions and its existence proves the safety of H. Initial states are assumed to be safe (Eq. (1) and Eq. (2)). Eq. (3) dictates that the value of the BaC can not increase along the continuous evolution of any trajectory within a mode. Finally Eq. (4) ensures that the discrete mode transitions reset safe states to safe states. Eqs. (1) - (4) ensure that a trajectory that starts out in an initial state, and thus with a BaC value ≤ 0, can never obtain a BaC-value of > 0. Thus the zero level sets of the functions, $B_l(\mathbf{x}) = 0$, create a "barrier" between $Unsafe(l)$ and the safe states of the mode.

The convexity of the functions makes the BaC amenable to automated computation using Sum-of-Squares (SoS) optimization, as outlined Section 4 of [8].

In the following sections, the composition, $P \times BC$, will be denoted by the hybrid system H_B.

3 Identifying the Switching Logic

In this section, we identify the DM's switching logic using a BaC for H_B. The BaC also certifies the safety of H_B and the zero-level sets demarcate the safety region in each mode of H_B. In the remainder of this section, we make the following key assumption about $P \times AC$.

$$\dot{\mathbf{x}} \leq V_{P\times AC}, \tag{5}$$

where $V_{P\times AC}$ is a vector denoting the maximum velocity with which the plant's state can evolve under the AC.

Identification of a switching boundary based on a BaC for H_B and Eq. (5) is illustrated in Figure 2 and is explained below.

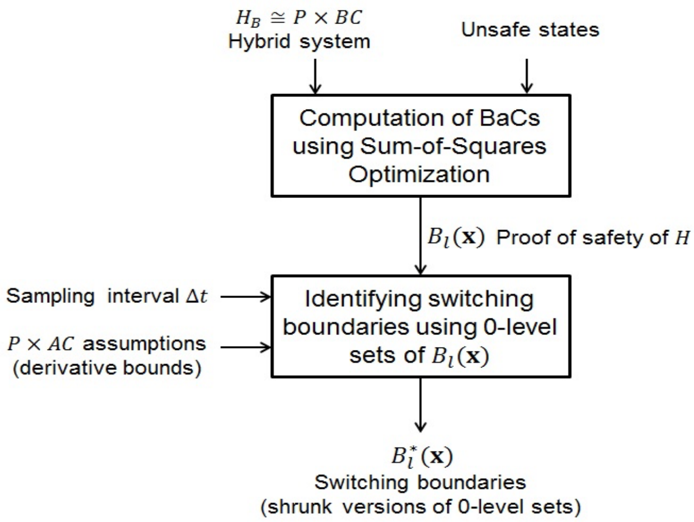


Figure 2: Identifying the switching boundaries based on a BaC for H_B and Eq. (5).

1. A BaC, $B_l(\mathbf{x}), l \in L_B$, is computed for the hybrid system H_B. Computing B_l using SoS optimization is the topic of the next section.

2. For each mode $l \in L$, the zero-level set $B_l(\mathbf{x}) = 0$ is *shrunk* uniformly by a factor of $|V_{P\times AC}|.\Delta t$. The shrunk versions, denoted by $B_l^*(\mathbf{x})$, are used as the switching boundaries.

The switching logic based on B_l^* is given in Algorithm 1.

Algorithm 1: DM's Switching Logic

1 Sampling: Obtain $\mathbf{x}_k$ = Sample at k^{th} time step (of length of Δt);
2 Using history and $\mathbf{x}_k$, estimate current mode l of H_B;
3 **if** $\mathbf{x}_k$ *outside* B_l^* **then**
4 | Switch to BC;
5 **else**
6 | go back to sampling state every Δt units of time;
7 **end**

Line 2 of Algorithm 1 employs a mode-estimation algorithm that maps the current state sample $\mathbf{x}_k$ to a mode l of H_B based on a limited history of state samples. The state $(l, \mathbf{x}_k)$ represents the state of H_B from which the BC would start controlling P if a failover was performed at the current time ($t = k.\Delta t$). The following theorem asserts that P's safety is guaranteed under Algorithm 1.

Theorem 3.1. *The SA where the DM implements Algorithm 1 guarantees the safety of P, i.e. $\forall t \geq 0$, $\mathbf{x}(t) \notin Unsafe$.*

Proof. The proof assumes the correctness of the mode-estimation algorithm of Line 2 in Algorithm 1.

Consider the k^{th} sample $\mathbf{x}_k$ obtained by the DM at $t = k.\Delta t$. If the condition in Line 3 of Algorithm 1 is not satisfied, then P is safe by definition, i.e. the state of the plant is within the zero-level set $B_l(\mathbf{x}) = 0$.

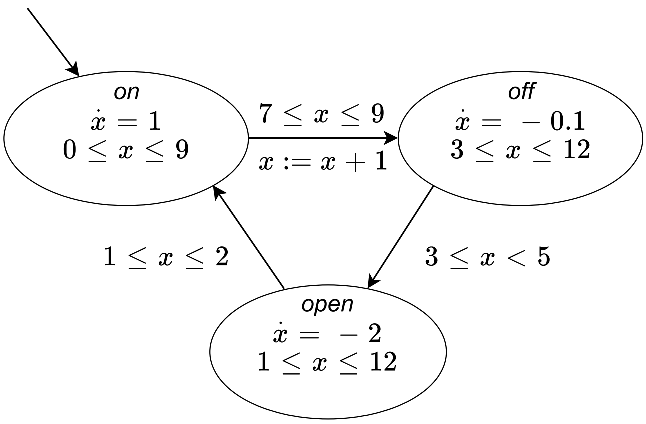
If the condition in Line 3 is satisfied, the plant is instantly switched to the BC. Thus we need to show that the trajectory of H_B starting from $(l, \mathbf{x}_k)$ remains safe. Two cases arise:

Case 1: H_B continues to be in mode l when the BC takes control of P.
Because the switching of the controllers takes place instantaneously, H_B starts from within B_l^*, and thus from within the zero-level set $B_l(\mathbf{x}) = 0$. Thus the plant is guaranteed to be safe due to Theorem 2 of Proposition 2 of [8].

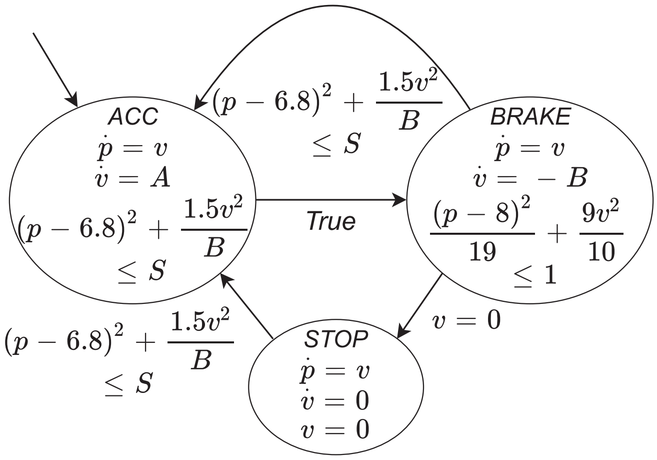
Case 2: H_B switches its mode from l to l' when the BC takes control of P. Eq. (4) ensures that a safe continuous state within $B_l(\mathbf{x}) = 0$ is always reset to a safe continuous state within $B_{l'}(\mathbf{x}) = 0$ during a discrete mode transition.

□

4 An Illustrative Example



(a) Water Tank System.



(b) Stop Sign Obeying Controller.

Figure 3: Hybrid automata of the composition H_B for the two case studies.

We consider a simple water tank system adopted from [7], where a controller seeks to keep the water level x in a tank between a certain range. Figure 3(a) shows the hybrid automaton of the composition H_B. In mode *on*, the water tank is filled by a pump that increases the water level ($x' = 1$). The pump can be turned off when $x \geq 7$, and must be turned off when $x > 9$. More water pours in ($x := x + 1$) when the pump is shutting down.

In mode *off*, the pump is off and the valve is closed, but water leaks slowly ($x' = -0.1$). We assume that the valve must be opened completely (mode *open*) before reactivating the pump. The valve can be turned on when $x < 5$, and must be turned on when $x < 3$. In mode *open*, water drains quickly, and the system closes the valve and turns on the pump when $1 \leq x \leq 2$.

We assume that the disturbance in the continuous evolution is 0. The system is not asymptotically stable as the value of x varies within a certain range without reaching an equilibrium point. Its behavior is also nondeterministic.

Due to the fact that SOSTOOLS requires the minimum and maximum degrees of an SOS to be even, we made several changes to the original model of [7]. In particular, we modified the degrees of the invariants and guards to meet this requirement without affecting the behavior of the system.

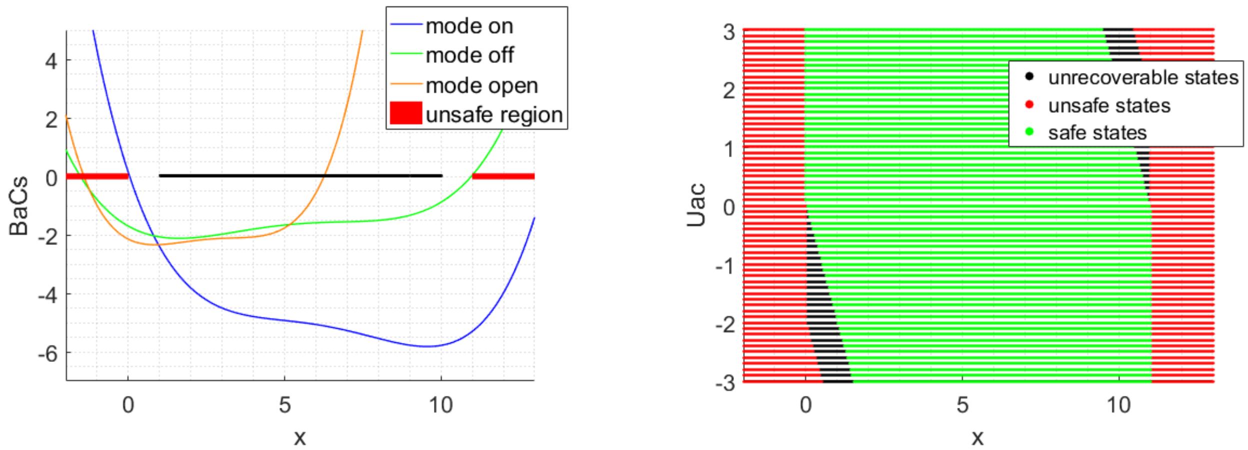
BaCs and Switching Logic.

Note that the zero-level sets of BaCs separate an unsafe region from all system trajectories. Thus, we need to have margins between the unsafe region and the system trajectories. The unsafe region of the system is $X_u = \{x | x \leq$

$0\} \cup \{x|x \geq 11\}$. We compute the barrier certificates for the initial states $x_0 \in [1,9]$. Since in each location l, x can only take a value within the invariant $I(l)$ of l, BaCs only need to satisfy Eqs.(1)-(4) in the invariant set $I(l)$ [8]. We take the intersection of X_u and $I(l)$ as the unsafe region for mode l.

Figure 4(a) shows the resulting BaCs. The zero-level set of the BaCs for modes *on*, *off*, and *open* is $\{x = 0.0384\}$, $\{x = 10.9709\}$, and $\{x = 6.2624\}$, respectively. Note that we only consider the zero-level set within the invariant of the mode. The recoverable regions are $\text{Recov}(on) = [0.0384, 9]$, $\text{Recov}(off) = [3, 10.9709]$, and $\text{Recov}(open) = [1, 6.2624]$. The figure shows that the intersection of the interior of the zero-level set and the invariant of each mode separates the unsafe region from all system trajectories. The validation of the BaCs using Z3, a symbolic numerical solver, proves that they satisfy all of the conditions. We obtain the recoverable

region of the system as $\bigcup_{l=1}^{M} \text{Recov}(l) = [0.0384, 10.9709]$.



(a) BaCs of the modes. The red lines represent the unsafe regions. The black line shows the system trajectory.

(b) Safe, unsafe and unrecoverable states with $\Delta t = 0.5$ under different control inputs $\mathbf{u}_{AC}$.

Figure 4: BaCs of the system and snapshot of the switching logic at run- time.

As an instance of the Simplex architecture, the water tank system could be controlled by an advanced controller with a more complex control objective. At any given time, the decision module in the Simplex architecture decides whether or not to switch to BC based on Algorithm 1. Figure 4(b) illustrates a snap-shot of the switching logic at time T across the state space. For illustration purposes, we discretize the state space and apply the switching logic for each discrete state with the corresponding control input $\mathbf{u}_{AC}$. Note that the control input is applied to the water level, i.e., $\dot{x} = \mathbf{u}_{AC}$. We have $x(T+\Delta t) = x(T) + \mathbf{u}_{AC} \cdot \Delta t$.

To check the *safety* condition in Algorithm 1, it is sufficient to check if the intersection of the line segment from $x(T)$ to $x(T+\Delta t)$ and the unsafe region X_u is empty. A red dot is used in Figure 4(b) to represent unsafe states that do not satisfy the *safety* condition. To check the *recoverability* condition, we use the recoverable region computed above and check if $x(T+\Delta t) \in \bigcup_{l=1}^{M} \text{Recov}(l)$. A black dot is used to represent the unrecoverable states that do not satisfy the *recoverability* condition. We switch to BC if the current state is unsafe or unrecoverable. If the current state satisfies both *safety* and *recoverability*, shown as a green dot, we continue with the AC. Note that if $\mathbf{u}_{AC} < 0$, then the smaller $\mathbf{u}_{AC}$ is, the larger lower bound we have for the safe states. Also, when $\mathbf{u}_{AC} > 0$, the larger $\mathbf{u}_{AC}$ is, the smaller upper bound we have for the safe states.

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A Targetless Method For Automated Calibration Of Lidar-Camera System

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1 Introduction

The main advantage of 3D Light Detection And Ranging (Lidar) is that it can accurately map 3D world without external light source but resolution of the device is limited and the price is expensive. Cameras can provide high-resolution color images but they're easily distracted by environmental factors. Registering the 3D lidars and cameras can compensate for each other's downsides. Therefore, the fusion of Lidars and cameras are often used for object detection [1] [2], navigation [3], and scene reconstruction [4] [5].

At present, several methods have been proposed to calibrate the extrinsic parameters of a camera-Lidar system. Some of them use specific planar shapes, such as polygonal plannar [6], checkboards [7] [8], perforated surfaces [9], and some others use the stereo shape like ordinary boxes [10]. The main problem is that we need to establish a specific space to satisfy calibration requirements. This disadvantage will limit the widespread use of the method in different places. Some algorithms use no calibration targets [11] [12], however, the calibration accuracy of them does not satisfy the requirements of users. For automobiles and robots, though we can calibrate the sensor pair in the specific environment and keep the calibration precision for a period of time, there is no guarantee that relative position of sensor pair does not have a random rigidity error for a long time to come.

2 Method Overview

Our targetless calibration method: In order to make the sensor calibration more convenient, we propose a new targetless method to register by repetitive controlled by the network. The basic framework is shown in Figure 1. The model is designed to generate action to find the relative position and orientation. A depth image, generated by the point cloud data based on the initial guess, and a color image are the input. The policy network is designed with a convolutional network [13], in which the output is the probability distribution of actions including translation and rotation. By optimizing the deep policy networks with respect to the expected future reward using gradient descent, policy gradient methods directly learn the policy. After the next refinement exploration is obtained, we generate a new depth image to approach the optimal solution gradually. The method achieves accurate targetless calibration without time and space constraints no matter online or off-line calculation. Furthermore, in the process of using the sensors, the sensors will be registered automatically to ensure the perception precision of the camera-Lidar system when the system triggers random rigidity error.

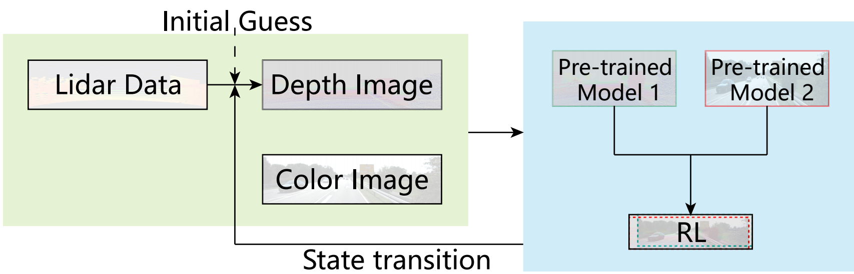

Figure 1: Method Overview.

3 Calibration Model

In the proposed method, we utilize the learning algorithms of supervised learning (SL) and reinforcement learning (RL) to train the network. In the part of SL, we train for learning the features of color images and depth images as the pre-trained network. In the part of reinforcement learning (RL), we expect that our network would select actions to calibrate the relative relationship between cameras and Lidars. At the beginning of the calibration, the data acquired by the Lidar device are transformed to the camera coordinate system according to initial guess. And the depth image is obtained by the intrinsic parameters of the camera. The initial guess ensures that there is an overlapping region between the depth image and the color image.

The Markov Decision Process (MDP) is defined by states s, actions a, state transition function s' and the reward r. We define the calibrator as an agent of which goal is to get the final transformation. The agent receives a reward for the action of frame i by deciding whether the agent succeed to get close to the ground truth or not. We define thirteen types of actions including translation steps, rotation steps and stopping actions. The translation moves include six directional moves, $\{x^+, x^-, y^+, y^-, z^+, z^-\}$. The rotation steps also include six directional moves, $\{roll^+, roll^-, pitch^+, pitch^-, yaw^+, yaw^-\}$. The action space is encoded into a 13-dimensional vector. The state s_i is defined as an array (TC_i, n_i), where TC represents the whole transformation matrix , and n_i is stored past 16 actions. After decision of action a_i in the state s_i, the next state s_{i+1} is defined as :

$$TC_{i+1} = \begin{bmatrix} rodrigues(\alpha(a_i\{rx, ry, rz\})) & [\beta a_i\{tx, ty, tz\}] \\ 0 & 1 \end{bmatrix} TC_i, \tag{6}$$

where α and β are the proportional factors that maintain the accuracy of the calculation. $r(s_i)$ is defined as the reward function:

$$r(s_i) = \begin{cases} 1, & (T - s_i) - (T - s_{i+1}) > 0; \\ -1, & (T - s_i) - (T - s_{i+1}) < 0; \\ 0, & else; \end{cases} \tag{7}$$

where T is the optimal solution. Because of the correlation between action and state in this situation, we just need to consider the state s when calculating the reward function.

4 Conclusions

In order to lower the requirements of sensor calibration for the environment, vehicles can achieve adaptive camera-Lidar system registration. A sensor registration method without calibration target is proposed. We proposed a deep neural network for adaptive registration using SL and RL, which can explore the optimal solution based on point clouds and images. In RL stage, we cascade the features of the pre-trained supervised learning model as the input. It pursues the calibration by sequential actions iteratively. Nowadays there are abundant camera-Lidar datasets, and reinforcement learning makes the usage of data possible.

5 Acknowledgment

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Model-based Control and Verification of Autonomous Vehicle Systems

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Autonomous vehicle systems, also known as self driving systems, are typical cyber-physical systems and have received enormous attention in recent years. The main goal is to design a highly automatic robot system that can safely drive itself without manual interference. In order to design such an autonomous robot, many technical issues should be properly addressed, e.g. advanced sensors and cameras that can obtain information from the environment efficiently, better algorithms to accurately recognize and classify objects from the images captured by cameras, efficient control strategies to achieve the control objective, and verification methods to ensure the stability and feasibility of the control strategies. In this report, we introduce the work we have done on the efficiency improvement of high level model-based control and verification of robot dynamics in the recent years.

Current design and verification methods of control algorithms fall into two main categories [1]: data-driven methods and model-based methods. Data-driven methods allow to design or check a control algorithm based on existing exprimental data. The basic idea of data-driven control is to learn a mapping between the state set and the input set by regarding the robot dynamic as a black box, while the data-driven verification is to check the statistical correctness by simulating the designed control strategy adequately. Without considering the concrete complicated dynamics, data-driven methods typically enjoy high efficiency and therefore can handle the systems of high dimension and high complexity. However, they cannot currently be applied in safety critical situations due to the lack of understanding of the inner mechanism. Different from data-driven methods, model-based analysis relies on the explicit robot dynamic models, rather than the simulation data, and synthesis or verify a controller by rigorous mathematical induction. Compared to data-driven methods, model-based methods can theoretically satisfy all the specification given in the blueprint, benefiting from the solid underlying theory. The drawback is that they can hardly handle large scale problems due to the intrinsic computation complexity, which impedes the widespread use of most theoretical results. Thus, in order to enable model-based methods in more practical scenarios, it is important to improve their efficiency.

Model-based Control: Multi-robot navigation is a typical autonomous vehicle scenario, where each robot needs to reach its target state from the original state (*stability*) and avoid collision with others (*feasibility*) by on-line input generation methods. The difficulty of this problem lies on two aspects. On one hand, it is obvious that the complexity of the problem will increase rapidly with both the number and the complexity of robots. On the other hand, since collision avoidance specification involves all the robots and is highly coupled and non-convex, it is difficult to safely decouple the multi-robot system to achieve better control performance. Model predictive control (MPC) [2], one of the most mainstream model-based control methodologies, currently still cannot address these two problems perfectly. The basic idea of MPC is to on-line predict the robot behavior in a finite time horizon and obtain an input sequence based on the current state and the dynamic of the robot, but only apply the first one. This procedure will repeat at each sampling instant until the target state is reached. Distributed MPC allows each robot to control itself based on the local information in its neighborhood. However, the limited local information always leads to dead lock or collision with non-convex constraints, which makes it less practical in the navigation scenario. Centralized MPC simply considers the global dynamic models and constraints and computes the concrete control inputs for all the robots in a central controller. Not surprisingly, it suffers from low efficiency.

In a lot of practical situations, we found that robots may be designed by different companies and thus can have different sampling frequencies. In such a case, robots can only communicate, synchronize and check the collision avoidance specification every least common multiple of all the robots' sampling intervals, which we refer to as a *collaboration interval*. In [5], we further observed that it is the states at collaboration instants, rather than the intermediate states within the collaboration cycles, that have impact on the feasibility and stability. Based on this finding, we proposed a hierarchical model predictive control (HMPC) framework for linear dynamical systems. The main idea is to first determine the robot states at collaboration instants and then to complement the trajectories by "filling" intermediate states. The key part is that we adopt reachable set at collaboration instants to describe the robot dynamic in the first step, which hides the intermediate variables and thus effectively reduce the complexity. More specifically, HMPC is a two-level framework as follows. At the upper level, a central controller is deployed to determine the next states that all the robots should achieve at the next collaboration instant, which we refer to as *control goals*, based on reachable sets by MPC strategy. At the lower level, each robot computes the concrete inputs to reach the control goal independently and in parallel. We theoretically proved that the stability and feasibility is ensured in HMPC and experimentally showed that HMPC can reduce the computation time by at least 29% compared to CMPC.

In [6], we extended HMPC to a more general case, switched linear dynamical systems. Switched linear systems are a special class of hybrid systems, which consists of several linear dynamic modes and a set of mode changing rules. They are very common in practice, e.g. vehicles with several gears. The main difficulty to apply HMPC on switched linear systems is the well-known undecidability of the reachability of general nonlinear/hybrid systems. In this work, we discussed the reachability of a switched linear system in a specific scenario and gave its computational method. The new HMPC can reduce the computation time by at least 66.4% compared to CMPC in various simulation experiments while stability and feasibility is theoretically maintained.

Model-based Verification: Verification of an autonomous vehicle systems is to check whether the robot system will reach a given unsafe state set, e.g. the state set that is too close to an obstacle, after a control strategy is designed. Since the robot dynamic system is continuous and always nonlinear or even hybrid in practice, it is difficult to do the verification. For one reason, the continuous state space makes it impossible to check the correctness by traversing through all traces. For another, as mentioned previously, the reachability of general nonlinear/hybrid systems is undecidable and therefore we cannot expect to verify a nonlinear system by comparing its exact reachable set and the unsafe set. Barrier certificate method is one of the effective ways to tackle this problem [3]. The basic idea is to find a function that maps all the unsafe states to negative reals and all the reachable states to nonnegative reals. This function then separates the unsafe region and reachable region as a barrier. The classical way to compute such a barrier certificate is to use sum of square (SOS) representation to relax the original conditions and use semi-definite programming (SDP) to solve the SOS problem. Therefore it always faces the efficiency problem due to the high complexity of SDP.

In [7], we proposed a linear programming (LP) relaxation based approach to generate polynomial barrier certificates. The main idea is to relax the non-negativity constraints derived from barrier certificate generation conditions by linear representation using Krivine-Vasilescu-Handelmans Positvestellensatz [4] and then obtain the barrier certificate by LP solvers. In experiments, we showed that our LP relaxation based approach may find a barrier certificate with lower degree and improve the efficiency by one order of magnitude in most existing examples compared to the SOS relaxation based approach.

Furthermore, stochastic systems receive more and more attention due to the various practical scenarios, e.g. the numbers and positions of vehicles in a traffic system at an instant should obey a certain distribution. The verification of a stochastic system is to compute the safety probability that the system will not reach a given unsafe state set. Currently there are few works on infinite time verification of nonlinear systems with stochastic initial states. Random testing based barrier certificate is a potential solution. It randomly chooses an initial area and verifies whether a barrier certificate exists with respect to the initial area, which we refer to as *probabilistic barrier certificate*. If the answer is yes, the probability of the chosen area is a theoretical lower bound of the exact safety probability. However, in order to achieve a tight estimation, random testing needs enormous trials and is therefore time consuming.

In [8], we proposed a template based approach to generate probabilistic barrier certificate. We first built an appropriate initial set template with respect to the initial distribution. It is worthy noting that the initial set template here should have the highest probability among all the sets with the same Lebesgue measure. Therefore the shape of the template may vary with different initial distributions. Then we tried to enlarge the template and computed the largest initial set where the corresponding barrier certificate exists. The probability of the obtained initial set is a lower bound of the exact safety probability. For a benchmark collected from related works, random testing always needs two hours to achieve a good estimation, while our approach can get a near-optimal solution within three minutes.

To conclude, we have developed several approaches on improving the efficiency of current model-based control and verification of autonomous vehicle systems. It is worthy noting that the gap between the efficiency and correctness still exists. Our future plan is to further bridge the gap by integrating model-based methods with data-driven methods.

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A Batch and Real-time Data Analytics Framework for Healthcare Applications

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1 Introduction

It is a vital proposition that patients can be rendered the necessary first aid and they are timely directed to the correct care unit. Thousands of people worldwide are losing their lives because of a lack of first aid and late intervention. Statistics [1] indicate that more than 3,000 heart attack victims could be rescued each year in the UK if 90 percent of emergency service calls were answered in that time. In the case of respiratory, in Europe, approximately 382,000 deaths occurred in 2014, accounting for approximately 7.7 % of all deaths [2]. To begin the immediate treatment for a patient in the ambulance and the transfer of the patient to the hospital with the ambulance will prevent many deaths and save lives.

There is growing interest in methods for early detection of patients at risk in order to trigger timely intervention and avoid preventable deaths resulting from late diagnoses and delayed intervention [3]. The use of Early Warning Scores (EWS) and systems is one such method. Basically, EWS systems continuously monitor patients' health status based on pre-determined indicators to derive early warnings about patient condition and, consequently, deliver timely response [4]. These systems are used to identify physiological deterioration in patients and determine the degree of illness of a patient. As an early warning score in the UK, National Early Warning Score (NEWS) was developed in 2012 and updated and as NEWS2 in 2017. NEWS2 got official approval from the NHS England and the NHS Improvement to identify early-warning systems to identify patients with acute, including sepsis, in UK hospitals [5]. NEWS is a simple aggregate scoring system that gathers six simple physiological parameters namely, respiration rate, oxygen saturation, systolic blood pressure (heart muscle pressure), pulse rate, level of consciousness and temperature from the patients when they are or were in the hospital to provide a standard platform for initial assessment of acute illness severity.

The systems deal with large amounts of real-time, heterogeneous data from patients' medical records at increasingly high velocities [3][4]. The systems, therefore, need to possess big data analytics capabilities with algorithms for automated processing, collection, analysis and sharing of data in order to achieve optimal performance. To the best of our knowledge, no such real-time, analytics solutions exist, which is an important deficiency in the field of heterogeneous data collection, monitoring patients as real-time and automatically decision-making although there exist the technologies of big data processing (e.g. Hadoop, Storm, Spark) and scalable cloud infrastructure [6].

2 Background

Advances in the omics fields such as geneomics, proteomics, and metabolomics have resulted in the production of large amounts of data [5] transformation from paper medical records to Electronic Health Records (EHR) is another reason why data is growing fast [7]. The availability of such huge data provides an ideal opportunity for physicians, epidemiologists, and health policy experts to make data-driven decisions for improving population health in general and delivering better patient care in particular [8]. It is therefore vital to develop tools, infrastructure, and techniques to leverage big data effectively [9]. A practical example of how the data can be utilised is the Early Warning Score (EWS) system, which is a timely surveillance system that aims to collect information related to patients' illness to trigger prompt public health interventions [10]. In the UK, the NEWS was developed to specify and reply to clinical impairment in patients with acute disease, and after five years, this system was updated and released as NEWS2 [5]. NEWS2 is used to establish a standard platform where assessment is made, and to provide a continuous record of the physiological condition of the patient during the ambulance journey [11], at the first assessment of acute disease severity.

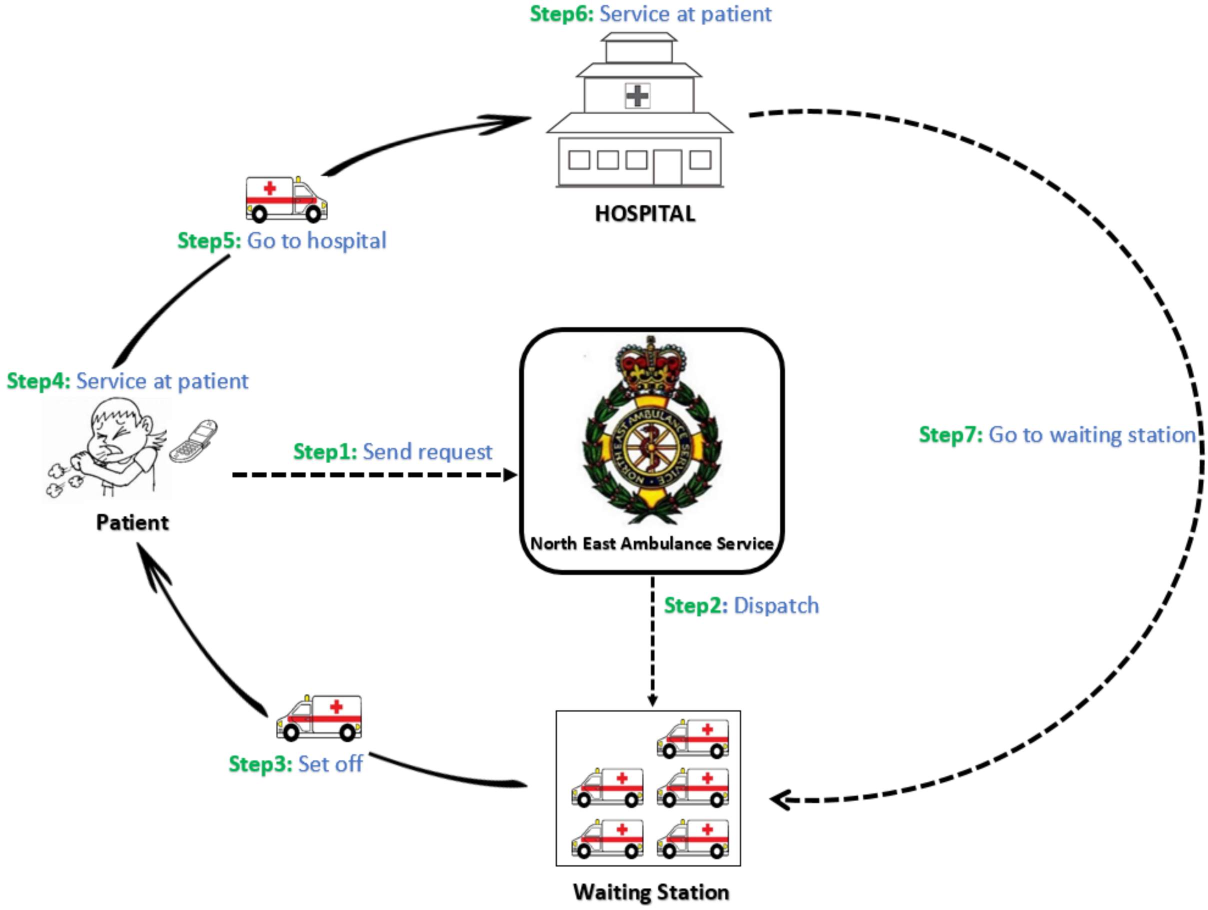

Figure 1: NEWS2 Ambulance Care System

NEWS2 process overview: During clinical evaluation, six NEWS2 physiological parameters are recorded and calculated to specify and respond to clinical impairment in patients with acute illness. A score is assigned that reflects the impact of each of the parameters.

These individual parameter scores are then added together to obtain the total NEWS2 score for the patient.

Step 1: Measuring and recording the score for every physiological parameter (systolic blood pressure (heart muscle pressure), respiration rate, pulse rate, temperature, oxygen saturation, level of consciousness).

Step 2: Adding all the physiological parameter scores together (aggregate) to calculate the NEWS2 score and checking if the trigger threshold for a single parameter has been reached.

3 Motivation: NEWS2 ambulance routing as a BigData SaaS application

Ambulance routing is a critical mission, any failure in scheduling the most appropriate hospital or ambulance for the patient (e.g. closest one) may cause catastrophic consequences such as patient death. For these reasons, to identify the fastest routing ambulance and the most appropriate hospital for the patient, we need to build a big data process system based on the analysis of patient medical records to get the patient's up to date NEWS score and information about the hospital's facilities (e.g. medical staff, treatment facilities). Figure 1 demonstrates a conceptive overview of the use case scenario of real-time ambulance system. Considering a patient who needs an urgent medical attention, sends a request to the centralised ambulance service. The service then picks an available ambulance for the patient. After taking the patient and calculating the NEWS2 score of the patient in the ambulance by evaluating his/her current medical condition and historical data, the system finds the most suitable hospital for the patient. Finally, the ambulance goes to the waiting station to be available for the next patient.

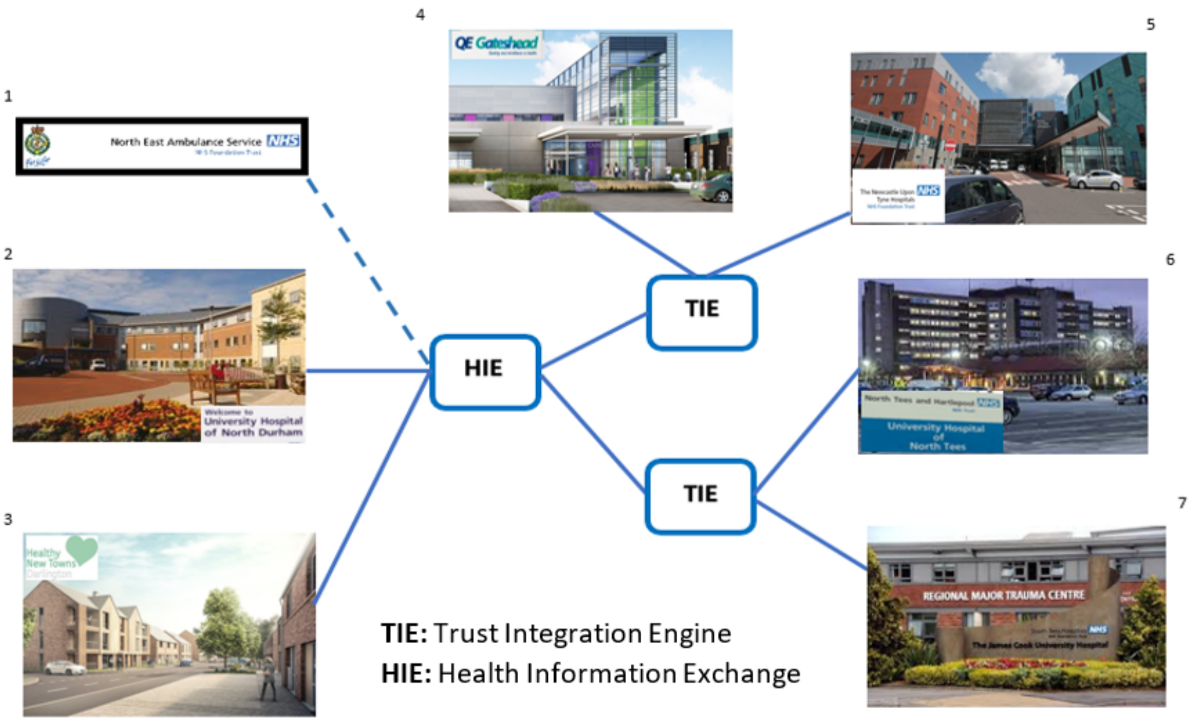

Figure 2: The systems to work on EWS data projects.

To work on the EWS data project, we considered seven prospective systems namely North East Ambulance Service[1], University Hospital of North Durham[2], Healthy New Towns[3], QE Gateshead[4], Newcastle upon Tyne Hospital[5], University Hospital of North Tees[6] and Regional Major Trauma Centres[7]. Figure 2 shows the architecture of our proposed model where each hospital can communicate using Trust Integration Engine (TIE) and Health Information Exchange (HIE) where TIE is a piece of software that handle messages between various applications and data sources and HIE allows healthcare personnel and patients to access and share securely the vital medical information of a patient electronically.

The SaaS platform implements the analysis algorithm and provision tools for the calculation of NEWS2 and sending the up to date score to staff in healthcare services to make data-driven decisions for improving patient care. The diversity and flexibility of Information and Communication Technology (ICT) functionalities considered by this project, combined with the uncertainties of its components, pose complex challenges in the effective deployment of BigData applications and provisioning of cloud resources. In particular, we will investigate the research challenges arising from real-time decision-making challenges and cloud challenges.

Using the combination of cloud and semantic technologies by analysis the data from IoT sensor within the ambulance can assist with many important ways such as: (i) analysis of very large data in real-time to reveal the necessary information in the data, (ii) the most appropriate hospital decision plan for patients, (iii) smarter and better informed decision support, (iv) timely access of patient information to healthcare providers, and (v) the processing of the analysis and decision-making automatically. Figure 3 provides an overview of how semantic technologies and

[1] https://commons.wikimedia.org/wiki/File:North_East_Ambulance_Service_Logo.png

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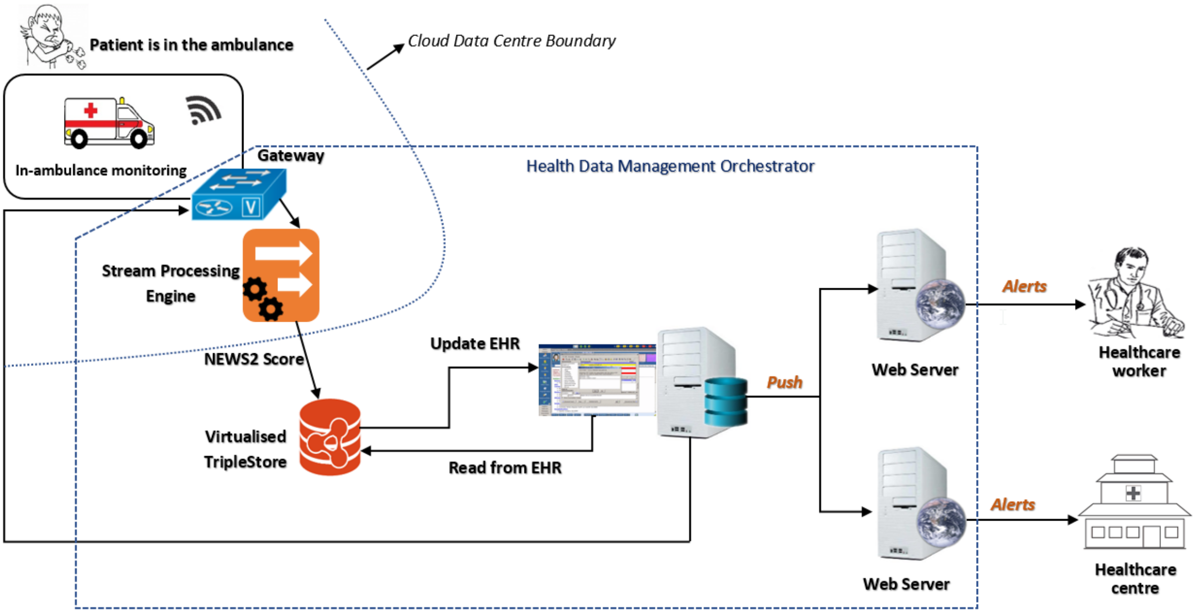

Figure 3: The overview of real-time ambulance system in a cloud-based big data analytics

cloud work in real-time ambulance systems in large cloud-based data analysis.

The main steps of an IoT-based real-time ambulance system can be summarised as follows: (i) an ambulance-based gateway, it is a piece of networking hardware, sends the data from the sensors to a stream processing cloud cluster; (ii) the stream query engine processes the sensor data, a system that can pre-processes the data which is closer to the source of the data, and the patient's status is determined by enriching the data semantically using tags and reprocessing; (iii) then this data is sent to Virtualised TripleStore, which is a purpose-built database used to store and manage ontologies that contains a copy belongs to domain knowledge base to analyse this data further to get some contextual information, such as the location of the patient, the time of the day. It also takes patient's Electronic Health Record (EHR), which contains the patient's historical data as well as the information about the current conditions, to analyse the sensor data along with the current conditions. The output is generated and then written into the HER; (iv) the output is finally sent over web services to the most appropriate healthcare units, emergency services, the patient's doctor, local health care centre etc. Health Data Management Orchestrator is a specialised software program running in the cloud that keeps all information (how to query, where the historical data are stored).

Real-time decision-making challenges: Intelligent decision-making in the real-time ambulance routing scenario considered in this project is a joint data analysis problem. The data includes i) real-time contexts (e.g. hospital facilities such as medical staff, treatment facilities and the information about ambulances to determine the closest one) and ii) historical patient data (e.g. from different health services, see Figure 2). Therefore, optimising the data analytics (i.e. query plan) to meet the requirements of real-time decision-making is a big challenge. To overcome this challenge, we need to answer the following questions: 1) How can the latency of data transfer over constrained bandwidths be reduced? 2) How can the multimodal data be efficiently processed? 3) How can the best routing solution be computed based on the available data in real-time?

Cloud challenges: Analysis of uncertain, multi-modal data volume requires cloud resources' optimal provisioning. Provision of cloud-based software and hardware resources to a real-time ambulance system is a complex undertaking because it requires a resource provider to calculate the best hardware (IaaS) and software (PaaS) configuration to achieve QoS (Quality of Service) targets (e.g. availability, fairness, reliability, response time, etc.). While achieving energy efficiency and utilization to the maximum, the objectives of the implementation (QoS targets) are achieved. There are two aspects to the uncertainty about providing cloud resources. First, in terms of an ambulance service, it is difficult to forecast the data volume, the rate of data arrival, data types, time distributions for data processing, the behaviour of I/O system, and the number of healthcare systems connected to the application. Moreover, with the improvement of the Internet of Things, real-time big data systems demand data synchronisation because of the comprehensive heterogeneity of big data from different sources [12]. Second, it is difficult to determine from the perspective of a cloud source about the size of the resources to be provided at any given time, without knowing the requirements and behaviour of real-time ambulances. In addition, the availability, efficiency of cloud resources, and load can change by unpredictable reasons because of failure, network congestion or malicious attacks.

Aims and objectives:

This project builds on the recent advances in the areas of real-time ambulance routing, big data analytics and the facilities provided by cloud computing. In spite of the evolution of big data processing technologies (e.g. Hadoop, Storm, Spark) and scalable infrastructure (e.g. Clouds), there remains a significant gap in heterogeneous data collection, real-time patient monitoring, and automated decision-making in healthcare. The goal of this project is to develop a system to support diffusion and analysis (detection, collection, storage, processing, extraction, and reporting) of massive datasets from multiple sources using cloud resources.

In this project, we aim to:

1. Develop efficient techniques and an early warning system called News4Ambulance, which will enable real-time data management application over cloud resources.

2. Develop an innovative approach for diffusion and analysis (detection, collection, storage, processing, extraction, and reporting) of data from multiple sources, including the devices in the ambulance and healthcare services, whereby those devices can interact with cloud-based resources.

3. Validate News4Ambulance by developing application demonstrators for NEWS2, deploy the ambulances, and decide the healthcare services and deploy them on private cloud as SaaS applications.

4 Conclusion

IOT, cloud and big data analytical systems, are the technologies that make new applications easier in the fields of health services, smart cities, intelligent production etc. Since these systems involve multiple computing paradigms, designing and developing them is extremely difficult.

In our work, we emphasized the resource management and real-time ambulance system for the patients with acute disease. We discussed the research gaps and the difficulties of this system. We envision a remote healthcare application that will be available in the future, including patients' past and current health conditions, and we use a combination of IoT detection, cloud, and big data processing technologies to help healthcare workers. As we emphasize in the paper, this will require a multitude of research and development efforts in the disciplines of computer science in collaboration with health science experts.

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Energy Harvesting Powered Embedded Systems

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1 Introduction

Historically, battery is the power source for mobile, embedded and remote system applications. However, the development of battery techniques does not follow the Moore's Law. The large physical size, limited electric quantity and high-cost replacement process always restrict the performance of the application such as embedded systems, wireless sensors networks and lower-power electronics. Energy harvesting, a technique which enables the applications to scavenge energy from RF signal from TV towers, solar energy, piezoelectric driven by motion of people and thermal energy from the temperature difference, which could dramatically extend the operating lifetime of applications. Thus, energy harvesting is important for the sustainable operations of an application.

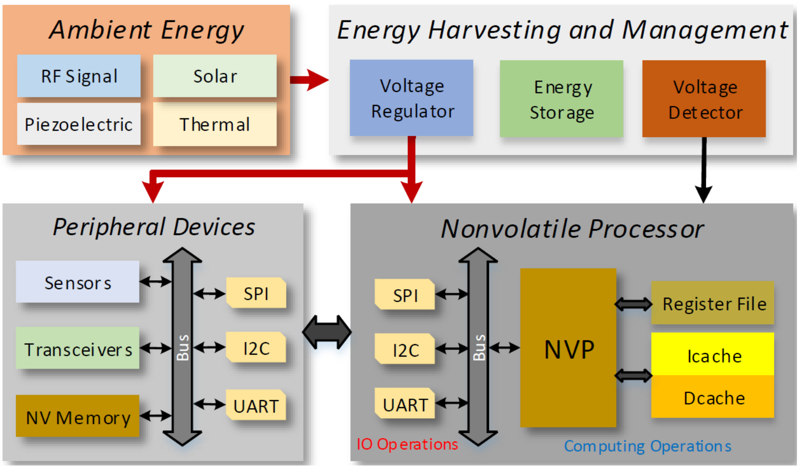

Figure 1: *Architecture of Energy Harvesting Powered Sensing System.*

Energy harvesting powered sensing systems are emerging as a key technology for Internet of Things (IoT) and Wireless Body Area Network (WBAN) [1]. The power consumption of a typical sensor node in such systems ranges from several uW to hundreds of mW, based on the task undertook by the node. Figure 1 is the typical architecture of an energy harvesting powered sensing system. Ambient energy can be harvested by a harvester, which has high manufacturing complexity and low energy utilization. Fortunately, small on-chip inductors make energy harvesting circuits easier to implement and further improve the energy conversion efficiency [2, 3, 4, 5]. The energy management module regulates the harvested to power processors and multiple peripherals. The processor, which is usually a Nonvolatile Processor (NVP) [6] equipped with Nonvolatile Memory (NVM), can budget the overall energy for each module and manage the behavior of the energy management module. One advantage of NVP compared with conventional processor is it can survive power shortage without losing their status, which fits well with the intermittent characteristic of the ambient power. The peripheral devices includes sensors, transceivers and NVM. Sensors are used to collect data, such as temperature, humidity and barometric pressure from the environment. Transceivers transmits the collected data to a remote node or router node, which forwards the data further to a server. NVM is used to maintain in-process data between power outages and store configurations such as local address for communication.

2 Related Works in Energy Harvesting

In this section, we will first introduce the energy harvesting applications, which harvest energy from ambient power sources and use the harvested power to complete operations. Then we will introduce several optimization techniques to energy harvesting based systems, which improve system stability and computing performance.

2.1 Energy Harvesting Applications

The Ultra-Low Power Sensor Evaluation Kit (ULPSEK) [7]-for evaluation of biomedical sensors and monitoring applications, is a wearable, multi-parameter health sensor powered by an efficient body heat harvester. ULPSEK could measure and process electrocardiogram, respiration, motion and body temperature. The key component of ULPSEK is the thermal harvester, which is placed at the forearm or the chest. The harvester consists of a heat sink, a thermal-electric module and a DC-DC converter circuit. As for mechanism energy, a Piezoelectric Energy Harvester (PEH) is proposed to be used in cantilever configuration and Structural Health Monitoring (SHM) [8]. It harvests energy from the vibration of bridge caused by the passing vehicles in the form of concrete vibration sensor for reinforced concrete structure. RF energy scavengers are the field attracting a great deal of researchers' attention, especially in low-power wireless sensors networks. Researchers from the University of Tokyo propose a deign of low-cost sensor nodes harvesting energy from TV broadcast signal and storing excess power in capacitors [9].

2.2 Advances in Optimization and Design Process

There is an intrinsic drawback with energy harvesting application, that is they are intermittent. Since almost all traditional computer systems are designed to be with a stable power supply, they could not make much progress with the intermittent power sources. Thus, it is necessary to implement optimizations in different perspectives to enable the devices to complete assigned tasks with intermittent power sources and other constraints.

Progress Accumulation: To make progress, we have to accumulate the computing across intermittent power cycles. One of the key techniques to achieve the goal is checkpointing, which save the processor's states to a non-volatile memory before a power failure and resume from the stored state when power comes back on.The domain of intermittent computing contains a significant amount of work, which address power loss during a devices operation and make a checkpointing [6]. The adoption of NVP in energy harvesting devices is emerging as a decent solution to the intermittent computing. There are several compiler optimization techniques have been published and these works show a promising results for the utilization of NVP [6].

Power Management: The energy buffer in energy harvesting devices is typically recharging batteries and capacitors, which all have limited capacities and so any energy generated when the energy buffer is full will be wasted. Thus, it is necessary to develop an efficient power management to achieve the maximization usage of the harvested power. There are several power management achieved by tuning different software and hardware parameters in the energy harvesting devices, such as duty cycles [10], sensing rate and transmitting power.

3 Challenges and Research Opportunities

Although the recent advances in energy harvesting powered embedded systems, there still exists challenges and opportunities for future researches.

Energy Harvesting Sensing Network with Multiple Nodes: Although extensive researches have been carried on energy harvesting sensor node, there are still some challenges when adopting these techniques to the whole sensing network consisting of multiple nodes. When sensor nodes are dispersively deployed in the field, some far-away nodes cannot communicate with the router node directly due to signal dissipation. Low power routing algorithmis desired to forward the information from the unreachable node back to the router. Multi-hop informationeven energy relay and overall information and energy cooperation applicable to energy harvesting node communication are still challenging because of symmetry of energy consumption of transmitting and receiving data per time unit. But relatively longer time window for receiving in Time Division Multiple Address (TDMA) network leads to higher energy consumption than transmitting the same length packet.

Health Concerns: It has been long recognized RF exposure can cause heating of materials including biological tissues. Some research [11] shows that genes can be affected when RF power approximates the upper bound of international security levels. Although there are some studies on the effects of RF exposure from mobile and cellular networks, health effects caused by dedicated RF power transmitter which emits much higher power than cell phones are still required. Moreover, one way to mitigate health concerns is to decrease the transmitting power of a dedicated power source. However, this evicts challenges to the RF harvesting sensor node on how to leverage the limited power to finish predefined task efficiently.

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Technical Activities

1 Conferences and Workshops

- Asian Hardware Oriented Security and Trust Symposium (AsianHOST 2018)
- IEEE International Conference on Embedded and Real-Time Computing Systems and Applications (RTCSA)
- IEEE Non-Volatile Memory Systems and Applications Symposium (NVMSA)
- IEEE International Workshop on Smart Energy Cyber-Physical Systems
- DAC-2018 Workshop on Design Automation for Cyber-Physical Systems (DACPS-2018)

2 Special Issues in Academic Journals

- ACM Transactions on Cyber-Physical Systems (TCPS) special issue on Human-Interaction-Aware Data Analytics for Cyber-Physical Systems

Call for Contributions

Newsletter of Technical Committee on Cyber-Physical Systems (IEEE Systems Council)

The newsletter of Technical Committee on Cyber-Physical Systems (TC-CPS) aims to provide timely updates on technologies, educations and opportunities in the field of cyber-physical systems (CPS). The letter will be published twice a year: one issue in February and the other issue in October. We are soliciting contributions to the newsletter. Topics of interest include (but are not limited to):

- Embedded system design for CPS
- Real-time system design and scheduling for CPS
- Distributed computing and control for CPS
- Resilient and robust system design for CPS
- Security issues for CPS
- Formal methods for modeling and verification of CPS
- Emerging applications such as automotive system, smart energy system, internet of things, biomedical device, etc.

Please directly contact the editors and/or associate editors by email to submit your contributions.

Submission Deadline:

All contributions must be submitted by **Jan. 1st, 2019** in order to be included in the February issue of the newsletter.

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