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C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems

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ABSTRACT Cyber-physical system (CPS) is a new trend in the Internet-of-Things related research works, where physical systems act as the sensors to collect real-world information and communicate them to the computation modules (i.e. cyber layer), which further analyze and notify the findings to the corresponding physical systems through a feedback loop. Contemporary researchers recommend integrating cloud technologies in the CPS cyber layer to ensure the scalability of storage, computation, and cross domain communication capabilities. Though there exist a few descriptive models of the cloud-based CPS architecture, it is important to analytically describe the key CPS properties: computation, control, and communication. In this paper, we present a digital twin architecture reference model for the cloud-based CPS, C2PS, where we analytically describe the key properties of the C2PS. The model helps in identifying various degrees of basic and hybrid computation-interaction modes in this paradigm. We have designed C2PS smart interaction controller using a Bayesian belief network, so that the system dynamically considers current contexts. The composition of fuzzy rule base with the Bayes network further enables the system with reconfiguration capability. We also describe analytically, how C2PS subsystem communications can generate even more complex system-of-systems. Later, we present a telematics-based prototype driving assistance application for the vehicular domain of C2PS, VCPS, to demonstrate the efficacy of the architecture reference model.

INDEX TERMS Digital twin, cyber-physical systems, Internet-of-Things, social internet of vehicles, sensing-as-a-service, analytical modeling.

I. INTRODUCTION

Urbanization efforts of the last few decades contributed heavily in increasing the population of the city life. A United Nations report [1] forecasts that by 2050 around 66% of the world population will be living a metropolis life that can add another 2.5 billion people to the urban centers. The growing advancement and increasing adoption of the advanced technologies paving the way for the Smart Cities. The definition of Smart City is rather ambiguous and has also been addressed in the literature as the digital city, ubiquitous city, knowledge city, intelligent city, sustainable city, etc. Overall, a city can be defined 'smart' if it enhances the quality of living of its citizens by applying synergy of inhabitants' knowledge, traditional-modern communication infrastructures, information technology, efficient use of natural resources and participatory good governance [2] [3].

In a Smart City, all the physical objects (i.e. *Things*) will have embedded computing and communication capabilities so that they can sense the environment and cooperate with each other using wired or wireless communications to ensure high quality services for the users. These increasingly intelligent interconnections and interoperability often touted as Machine-to-Machine (M2M) interactions or the Internet-of-Things (IoT) [3]. Some of the important services domains in a Smart City are the Intelligent Transport Systems (ITS), Smart Water, Smart Energy, Smart Home and Waste Management [4] [5].

Sensors and actuators have become more affordable and available, which ensures ubiquitous presence of versatile sensors and subsequent data acquisition using computer networks. As a result, data analysis based control of the resources or physical environments is possible than ever before.

This phenomenon, however, is addressed as Cyber-Physical Systems (CPS). Here, physical systems collect sensory information from the real world and send them to the digital twin computation modules residing in highly capable infrastructures through communication technologies (e.g. wireless). Digital twin computation modules process these data and notify the physical systems about the findings, sometimes send control commands to make necessary changes in the physical world or reconfigure system parameters if required [6] [7]. Digital twin is an exact cyber copy of a physical system that truely represents all of its functionalities. Lee *et al.* [6] proposed a CPS architecture, 5C, to reach the goal of resilient, intelligent, and self-adaptable machines. Scalability in terms of intelligence, storage, and outreach of the 5C architecture can be improved further, by adopting cloud technology in the cyber, cognition and configuration levels.

The research community is showing tremendous interests about the CPS field these days [8]–[18]. A new model to describe the IoT is Sensing-as-a-service (SenAS) [8], where four conceptual layers are involved from the data provider to the consumption process. In this model, *Sensors* are deployed to collect data about the environment and the sensor owners have the right to publish the sensor services. Atzori et al. have introduced Social Internet of Things (SIoT) terminology and focuses on establishing and exploiting social relationships among *things* rather than their owners [12] [13]. They have identified different types of *things* relations based on location, co-work, ownership, etc. The *things* can crawl in their social network to discover other *things* or *services* which can be exploited to built various IoT applications. Such characteristics, however, matches with the online social network theme but in this case applied for the machine-to-machine (M2M) communication. Hence, we can group it as M2M social network.

The contemporary research works on CPS are mostly focused on the physical layer of embedded systems or application possibilities of the CPS domain. There lacks a clear bridge, how the embedded systems of the physical layers will be leveraged to provide both real time and delay tolerant services to the application layer of the CPS. The concept of having digital twins (i.e. cyber objects) for all the physical objects attempts to resolve these differences, where digital twins can also be used for monitoring, diagnostics and prognostics purposes. Moreover, since cloud infrastructure usage is becoming abundant in our day-to-day life, integration of these digital twins with the cloud infrastructure becomes the true bridge between the physical layer and the application layer of CPS. As a result, CPS application design, reconfiguration, and smartness become inherently scalable.

The technological intersection of digital twin based CPS, M2M social networks and cloud technology can capture the required setup for an active Smart City. Here, the physical environment can be sensed in real time and derived information can be meaningfully shared across different IoT domains, through the cloud based digital twins, to ensure efficient usage of resources to improve user experience and overall well being. The segregated cyber-physical layers of CPS allows independent evolution of both the physical and the cyber layer (i.e. digital twins) while keeping close integration among them. As a result, physical layer can provide real-time sensory fusion and the cyber layer can extend that experience to support delay tolerant applications for the Smart City. Peer-to-peer social networking capability among the physical machines through their digital twins ensures scalability across the physical networks, which accomplishes cross domain IoT data sharing while making it easily navigable and privacy sensitive. Cloud technology provides the cyber layer with high performance infrastructure resources and data analytics capability, which can improve the CPS feedback control.

The key contribution of this paper is the analytial description of a digital twin architecture reference model for the cloud-based cyber-physical systems (C2PS), where every physical *thing* accompanies a hosted cyber *thing* in the cloud. Two *things* can establish peer-to-peer (P2P) connections either through direct physical communications or through indirect cloud-based digital twin connections. We present analytical models of the key properties of the C2PS, computation, communication and control. We also provide the design details of a telematics-based vehicle driving assistance application following the proposed cloud-based CPS reference model. The rest of the paper is organized as follows: Section II describes state-of-the-art related works, Section III presents the C2PS architecture, Section IV details analytical models of the C2PS properties, Section V describes a telematics based vehicle driving assistance application and finally Section VI concludes the paper.

II. RELATED WORKS

Guinard *et al.* [19] discussed how *Web-of-Things* can share their functionality interfaces using human social network infrastructures such as Facebook, Linkedin, Twitter etc. In their system every object that wants to share its functionality on the web either has a built-in embedded web server, or proxy smart gateways (e.g. RFID tag based devices). The *Smart-Things* of an individual person share their web crawlable public interfaces with the owner's groups and friends through a social network. Friends and family get notifications about the shared smart things through the social network APIs. Operations on the shared things can be done through the RESTful `PUT, POST, GET,` etc. actions.

Smart-Its Friends [20] looked into how qualitative wireless connections can be established between *smart-artifacts*. In this system, every smart object consists of two boards: data acquisition and generic feature extraction, which is managed by the sensor unit; application specific processing, device control, and communication with other smart-its compliant devices are handled by the core unit. Their system introduces context proximity based match making and respective connections. A possible application of the system is to monitor the presence of children in close proximity of the parents.

Ning and Wang provided an architecture of Future Internet of Things (IoT) using human neural network structure [10]. They defined *Unit IoT* as man-like nervous (MLN) model that has three parts: brain (management and centralized data center: M&DC), spinal cord (distributed control nodes), and a network of nerves (IoT network and sensors). A combination of various *Unit IoT*s form the *Ubiquitous IoT* i.e. the global IoT. Global IoT includes industrial IoT, regional IoT, and national IoT. The overall global IoT is hierarchically structured and connected in a socially organized framework so that specific authority can control a small domain of IoT.

Matthias et al. describe a so-called socio-technical network for IoT where every physical object is enabled with sensors to detect activity and later synchronizes the status using human readable short texts on Twitter [11]. Here, Twitter is a medium of communication among the things and the humans. Every smart thing or a human publishes and subscribes to the twitter feed of the other smart things or humans to exchange information among them. They present a proof-of-concept twittering plant application, which shares moisture, and temperature information in the twitter. In the winter time, a light composition can be modified to suit the environment following the twitter message. This procedure is called perception-cognition-action loop.

Atzori et al. have introduced Social Internet of Things (SIoT) terminology and focuses on establishing and exploiting social relationships among *things* rather than their owners [12] [13]. They have identified different types of *things* relations based on location, co-work, ownership, and social relationships. In the SIoT, a new *thing* is first registered in the system, later the available *services* of the smart thing are explored by other interested things. SIoT things can establish various relationships dictated by the owners or through matching the things' profiles. Once a service is requested by an application agent, related service searching and subsequent service composition are completed based on trustworthiness before the final information delivery. SIoT organizes the members in four classes based on their computational, communication and mobility properties.

Lee *et al.* [6] proposed a 5-level CPS architecture for industry 4.0 based manufacturing systems, which supports plug & play smart connection; provides smart analytics for subsystem health; enables digital twin model for components and machines; instills cognition for decision making; and self-configuration for resilience. A CPS consists of two functions: 1) advanced connectivity to collect real-time data about the physical world, 2) intelligent data management, analytics, and computation in the cyber space. Tether-free and seamless connection are important for smart connections. Again, cyber space works as the central hub for data collection and processing. Cognition is achieved from thorough analysis of gathered data, which leads to feedback as configurations adjustment.

Barthels *et al.* [21] presented an intra CPS architecture to manage power in automotive systems. They represent the machine in functional state sequences, where physical input sequences transduce into different power management plan sequences. They used Moore's machine to represent power management subsystem; where a power management module is a transducing finite state, physical inputs trigger functional state transition and output functions are represented as power management plan. Engelsberger and Greiner [22] present a multi-tier architecture to integrate CPS and cloud computing to offer scalable control algorithms in the cloud and easier third party data source integration. In this architecture, embedded tiers are very lightweight and send commands, sensory value to the cloud tiers. Cloud tiers execute the control algorithms and send back results to the embedded tier. Their client tier serves as human-machine interface that can be either PC, tablet, smartphone or a web browser. They applied their architecture to improve IT and control aspects in the field of renewable energies (i.e. solar energy). Functional model based CPS design methodology is presented in [23], where authors use functional models for high-level abstraction of multidisciplinary systems.

We proposed a vehicular CPS (VCPS) architecture, Social Internet-of-Vehicles (SIoV) in [24], which was further extended in [18]. SIoV is a vehicular domain of SIoT and exploits social network like characteristics to describe the M2M relationships among vehicular CPS subsystems. We identified the social structures and interactions among VCPS subsystems and provided their detailed architectural guidelines. In the VCPS, information is shared among vehicular platoons using either DSRC [25] or 3G/LTE based communication methods. Our architecture supports both direct V2V or SenAS [8] based cloud assisted P2P data communications, which enables both real time safety and delay tolerant non-safety applications. A VCPS based entertainment application was also described in [26]. In [16], we define data workload models of various VCPS subsystems and provide dynamic adaptive algorithms to satisfy a goal. Furthermore, a cloud based CPS platform was described in [17], followed by a VCPS multi-sensory dataset in [14].

In this paper, we present a digital twin architecture reference model for cloud based CPS (C2PS), where we use the standard CPS design concepts to incorporate cloud support to it. In Table 1, we compare relevant works that present CPS architecture models. From the table, we see that researchers mostly described the integration of CPS and cloud support (i.e. C2PS) using descriptive models, which lack a formal description of the three key characteristics of a CPS: computation, communication, and control. In our work, we have followed the state machine based analytical design techniques to describe this integration. In this process, we have identified various types of computations and communications (i.e. physical, cyber and hybrid) possible in the C2PS. We also present Bayes network and fuzzy logic based reconfigurable model that considers system contexts while selecting a possible interaction mode. This kind of smart connection model has been prescribed for the CPS in [6]. Additionally, we also present a model to describe the formation of various possible cloud infrastructures.

TABLE 1. Comparison of the state-of-the-art works and the proposed C2PS model.

Related Works	Computation	Communication	Control	Cloud Integration	Configuration	Model Type
Future Internet of Things [10]	Inter and Intra CPS	Authority wise IoT infrastructure network	Distributed control node	Centralized data center	Man like neural network	Descriptive
SIoT [12] [13]	Inter and Intra CPS	Service discovery based	Owner based object relationship control	Inherently present	Service composition	Descriptive
Automotive CPS [21]	Vehicle Intra CPS	Inter-linked embedded systems	Power distribution control	N/A	Master-Slave based	State Machine Based
Multi-tier CPS [22]	Multi-tier based	Inter tier communication	Cloud based control algorithms	Software-as-a-Service	N/A	Descriptive
V-Cloud [27]	Inter, Intra CPS for vehicle	Vehicle to Vehicle/Infrastructure	Cyber-based context awareness	IaaS, PaaS, SaaS	N/A	Descriptive
VSSA [28]	Layer based computation	Service interaction	Context based	Software-as-a-Service	Service composition	Descriptive
5C Architecture [6]	Inter, Intra CPS	Smart connection	Cyber-based	Cognition functionality	Cyber-based	Descriptive
Proposed Cloud based CPS Reference Model	**Inter, Intra CPS, Smart**	**Social network like relationships among things and further complex thing formation**	**Bayes network based context awareness**	**Inherently present**	**Fuzzy rule based**	**State machine and Fuzzy rule based**

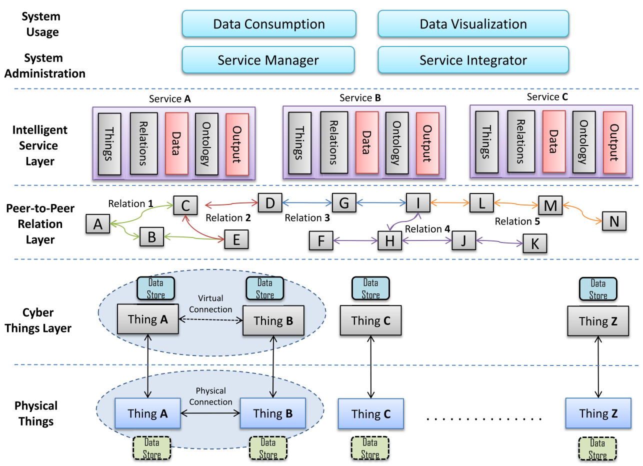

FIGURE 1. Cloud based cyber-physical system architecture introduced in [17].

III. CLOUD-BASED CYBER-PHYSICAL SYSTEM ARCHITECTURE (C2PS)

In the proposed C2PS, we assume that a number of independent systems connect together to perform a common goal, where network connections are omnipresent. In C2PS every physical *thing* is automatically accompanied by a representative digital twin hosted in the cloud. We use the terms, digital twin and cyber *thing* interchangeably in this article. There exist a direct one-to-one connection between every twin cyber-physical *thing* (Fig. 1). Whenever physical world changes, a physical sensor tries to update the current status to its digital twin representative in the cloud. Every physical *thing* and its corresponding cyber *thing* manages a *Data Store*. Every physical or cyber *thing* is identified by a unique ID (i.e. IPv6, Universal Product Code (UPC), Electronic Product Code (EPC), etc.) and is aware of the existence of its twin counterpart.

Sensor owners have the authority to control the privacy policy of a sensor by granting access to it through the services middleware layer (Fig. 1). Based on the networking or communication criteria set by the owner of the *things*, either the physical or the cyber *things* can create communication groups. Every communication group is identified by a *Relation ID*. All the communications in a particular relationship are only transferred to the members of that group. Any smart *thing* can be a member of multiple relationship groups at any given time. These communication groups are created as peer-to-peer networking groups in the *Peer-to-peer Relation Layer* of the cloud hosted digital twin objects.

The sensory information collected by the physical layer is stored in its own data store and also in the data store of the cloud based cyber layer. Interactions among the *things* can occur either through direct ad-hoc communication (e.g. Vehicular Ad-hoc Networks (VANET) in the physical layer or through the cloud layer using peer-to-peer communications among the hosted cyber objects. Important interaction information are stored by both the physical and the cyber layer. Whenever an interaction is received through the cyber layer, it is updated to the responsible physical sensor if possible. Similarly, interactions received through the physical layer are transmitted to the cyber layer.

The proposed architecture adheres to the SenAS [8] model, where the data are generated by the *things* and are finally consumed by the humans or by other machines. All the data that are useful to improve the Quality of Service (QoS) of the physical things, are stored in the cloud based *Data Center* (Fig. 2). In the C2PS, a smart thing can be both stationary or mobile and can provide various services to other smart things. All the data gathered by the smart things are stored at different levels of storage from mobile, stationary to the cloud based data center. Interactions in C2PS can be between two mobile things, one mobile and one stationary thing, a mobile thing

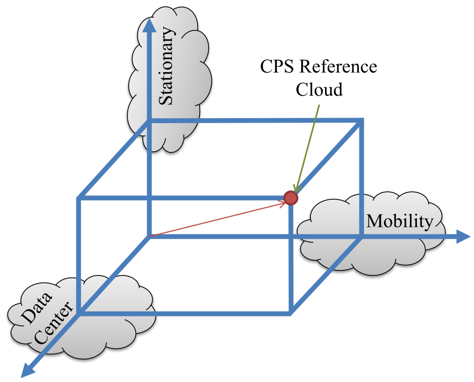

FIGURE 2. Three dimensional cloud structure for the proposed C2PS architecture.

to the data cloud directly, or from one stationary thing to the data center directly or various combinations of all of them. The proposed cloud model captures all these different combinations of data in their respective clouds.

The *Intelligent Service Layer* acts as the middleware, where the cyber *things*, their active relations, and the related ontologies are couple together. Critical understanding of the low level messages and required control actions by other receiver things can be measured based on domain specific ontologies such as description ontology [29], device ontology [30], etc. Low level reconfiguration of the C2PS is initiated by the service layer. Since data output from the intelligent reasoning stage of one CPS would be consumed across different CPS domains, ontology based data formatting ensures seamless integration of the CPS services.

In C2PS, every smart thing can provide a set of services based on its current capabilities. For example, physical systems in the C2PS can offer real time services, when the communication channel is active through the physical layer, power supply of the smart things are sufficient enough to support heavy duty operations, interacting systems are in their physical communication range. Similarly, a smart thing can decide dynamically to choose to communicate through the cyber layer when physical capacity is down. Cyber layer objects can offer near real time or delay tolerant services. Since network communication is assumed to be omnipresent, hence a hybrid case of sensor-services fusion is also possible in the C2PS architecture. Data center cloud of the C2PS can provide summary related data mining services. Different combinations of services cloud is formed in the C2PS based on the interactions of subsystems (i.e. physical level sensor cloud, cyber level services cloud and hybrid sensor-services fusion cloud).

In the proposed system, data is consumed as reports or as input to other systems. Visibility and the data privacy of the *things* are managed through the *Service Manager*. The owner of every smart *thing* can control, which part of the generated data would be shared publicly, would use subscription model or will be completely private for the owner. Access to the physical *thing* can be easily cut off from the entire world by switching off the cyber *thing* access rights. Multiple services can also be grouped together to form mashup service for the *Intelligent Service Layer* using the *Service Integrator* component.

IV. C2PS ARCHITECTURE REFERENCE MODEL

A CPS is composed of various other independent systems, which can be simple (i.e. composed of a few subsystems) and or (i.e. composed of many subsystems). The key properties of a true CPS are computation, communication, and control [31]. In the proposed model, we elaborate these key properties for a cloud-based CPS (i.e. C2PS) while we integrate cloud with the CPS. In case of C2PS computation, we derive the types of things/operation modes that are formed in a C2PS. For the control property, we describe how to select one of these operation modes based on the current system context (i.e. smart connection). The communication property describes how complex things (i.e. system of systems) can be formed by communication/interaction of the C2PS subsystems.

From here on we address the independent systems of a C2PS as subsystems and a complex thing as a collection of independent things or subsystems. The proposed C2PS, $\mathbb{S}$, is consist of the subsystems: physical things $\mathbb{P}$, a twin representative for each physical thing $\mathbb{C}$ (digital twin/cyber thing), hierarchy based composition of subsystems to form further complex things $\mathbb{M}$, relationship network among things $\mathbb{R}$, integration of web services $\mathbb{V}$. Here, $\mathbb{S} = (\mathbb{P}, \mathbb{C}, \mathbb{M}, \mathbb{R}, \mathbb{V})$.

A. COMPUTATION

In this section, we describe the computation property, where we analytically model different operational modes using Moore's [31] finite state machine.

1) PHYSICAL THINGS ($\mathbb{P}$)

We consider that every physical *thing* $p \in \mathbb{P}$ is comprised of seven elements $(S_p, A_p, F_p, E_p, N_p, P_p, D_p)$. Here, sensors S_p act as inputs to the system, at least one functional unit in the F_p that processes sensory values to identify events E_p, results are stored in data storage set D_p, actuators A_p perform actions on the physical environment, there is at least one network interface in N_p, and one power supply in P_p (Fig. 3).

$$\mathbb{P} \equiv \{p_i, i = 1...|\mathbb{P}|\} \tag{1}$$

Here we adopt the model of [32] to represent every functional unit $f_p \in F_p$ as a sequential finite state machine of 6-tuple,

$$f_p = (Q_p, I_p, O_p, q0_p, \lambda_p, \delta_p) \tag{2}$$

Where Q_p represents various states a function is comprised of and $q0$ is the initial state of computation. Different sensor values act as inputs $I_p \subseteq S_p$ to a state that initiates a transfer function λ_p (Equation 3) to other states. Every state has an associated output from the O_p following the output function δ_p (Equation 4), so that event $O_p \subseteq E_p$ can be identified.

$$\lambda_p : Q_p \times I_p \rightarrow Q_p \tag{3}$$

$$\delta_p : Q_p \rightarrow O_p \tag{4}$$

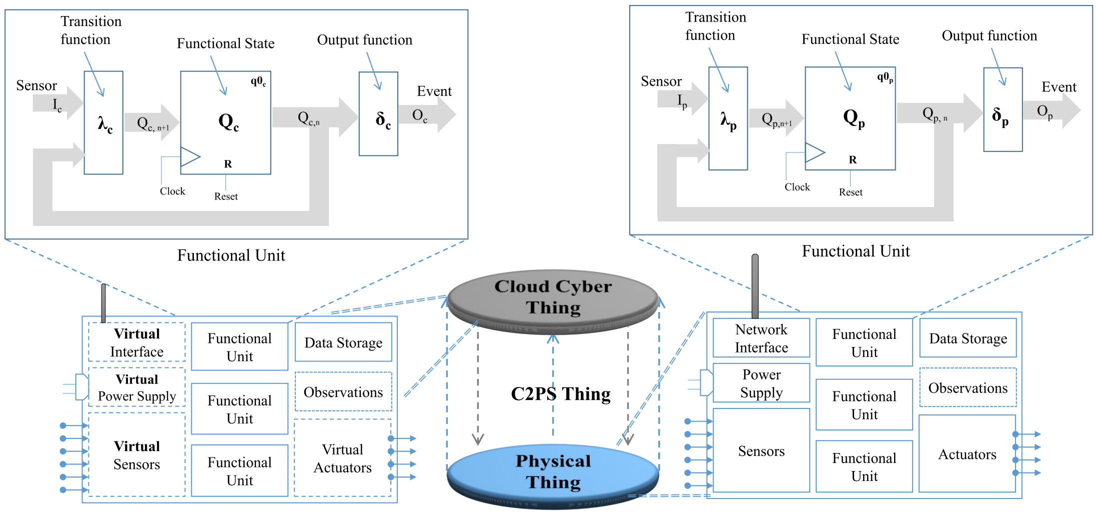

FIGURE 3. Architecture of the physical and cyber layer of a C2PS thing.

2) CYBER THINGS ($\mathbb{C}$)

In the proposed C2PS, every physical *thing* is represented by a cloud based digital twin *thing* (Fig. 3), $c \in \mathbb{C}$, that has seven elements. Here, $c = (S_c, A_c, F_c, E_c, N_c, P_c, D_c)$ consists of virtual sensors S_c, virtual actuators A_c, functional units F_c, observed events E_c, virtual interfaces N_c, virtual power supply P_c and data storage D_c. Here, virtual interface is the communication medium of the digital twin that is connected with the physical *thing* and virtual power supply indicates that the cloud based process can be easily installed or removed from the cloud.

Virtual sensors of a cyber *thing* (i.e. digital twin) are the observed outputs of a physical *thing*. These observations can be either raw data that will be processed by the cloud based functional units of a cyber *thing* to detect events or the events themselves. Equation 6 represents the relationship of a cyber *thing* to a physical *thing*. A physical *thing* can always perform operations without the helps of a cyber *thing*. Whereas, the opposite $\Delta_c^{-1} \neq \Delta_c$, i.e. replacing a physical *thing* completely by a cyber *thing* only is not possible. A cyber *thing* increases the capacity of a physical *thing*. So, there should be at least one cyber *thing* for each physical *thing*, $|\mathbb{C}| \geq |\mathbb{P}|$, in a C2PS. Sequential finite state machine Equations 7, 8, and 9 are equally applicable for the cyber things [32].

$$\mathbb{C} \equiv \{c_j, j = 1...|\mathbb{C}|\} \tag{5}$$

$$\Delta_c : \mathbb{P} \rightarrow \mathbb{C} \tag{6}$$

$$f_c = (Q_c, I_c, O_c, q0_c, \lambda_c, \delta_c) \tag{7}$$

$$\lambda_c : Q_c \times I_c \rightarrow Q_c \tag{8}$$

$$\delta_c : Q_c \rightarrow O_c \tag{9}$$

The advantage of having a digital twin for every physical *thing* is that even a low profile device, which acts as a mere sensor source can become smarter without much physical changes by developing the cyber counter part only. Cyber things can further be organized hierarchically to form much smarter things that can have understanding of a larger aspect of a problem.

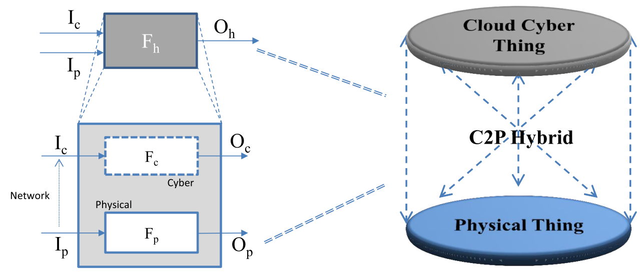

FIGURE 4. Architecture of a cloud-based hybrid cyber-physical thing.

3) HYBRID THINGS ($\mathcal{H}$)

From the above description of the physical and the cyber things (Equation 2, Equation 7), we can formulate a hybrid cyber-physical thing, $h \in \mathcal{H} \equiv (S_h, A_h, F_h, E_h, N_h, P_h, D_h)$, where part of the computations (i.e. low cost) occur in the physical layer and the rest of the computations (i.e. higher cost) occur in the cyber layer (Fig. 4). It assumes that the network communication cost is negligible and some physical sensors are acting as inputs to the cyber things while computing independently. This subsystem can be described as synchronous side-by-side composition of state machines, where $Q_h = Q_p \times Q_c$ are states, $I_h = I_p \times I_c$ are inputs, $O_h = O_p \times O_c$ are outputs, $q0_h = (q0_p, q0_c)$ is the initial state and λ_h, δ_h are transfer (Equation 11) and output (Equation 12) functions respectively [31] [33].

$$f_h = (Q_h, I_h, O_h, q0_h, \lambda_h, \delta_h) \tag{10}$$

$$\lambda_h : (Q_p \times Q_c) \times (I_p \times I_c) \rightarrow (Q_p \times Q_c) \text{ where,}$$
$$\lambda_h((q_p, q_c), (i_p, i_c)) = (\lambda_p(q_p, i_p), \lambda_c(q_c, i_c)) \tag{11}$$

$$\delta_h : (Q_p \times Q_c) \times (I_p \times I_c) \rightarrow (Q_p \times Q_c) \text{ where,}$$
$$\delta_h((q_p, q_c), (i_p, i_c)) = (\delta_p(q_p, i_p), \delta_c(q_c, i_c)) \tag{12}$$

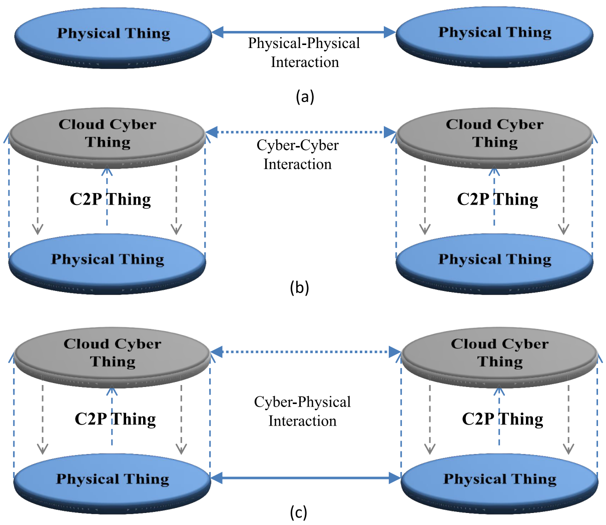

FIGURE 5. Three types of computations and interactions possible between two C2PS things: a) physical-physical, b) cyber-cyber, and c) hybrid cyber-physical.

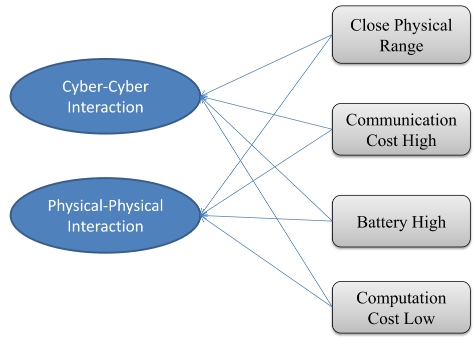

FIGURE 6. DAG model of context aware interaction controller showing causal influences.

B. CONTROL

For the C2PS, we consider every sensing or actuation request as a physical event. For any physical sensing event, a smart *thing* is involved in data collection, computation and data transmission. Here, data transmission means data sharing among connected *thing*s that are in a relationship (r). Many control decisions are required in a C2PS. For example, there can be three modes of computations and subsequent interactions possible in a C2PS subsystem (Fig. 5): physical-physical, cyber-cyber, and cyber-physical hybrid. An important control application is to select one of these computation-interaction modes that can be regarded as context aware self-reconfiguration.

1) CONTEXT AWARE SELF RECONFIGURATION

In the `physical-physical` interaction of a C2PS, all the computations occur in the physical thing. In this case, data sharing takes place in the direct physical communication channel (Fig. 5.a). Whereas, for the `cyber-cyber` type of interactions, all the computations take place in the cloud level digital twins, where *thing*s interactions use the cloud-based cyber layer. All computation updates are notified to their respective physical things from their corresponding cyber things (Fig. 5.b). The other type of interaction is `cyber-physical`, where computations are split in both the physical and the cyber layers and data sharing also occurs simultaneously in both the layers. At the end of each operation session, the physical layer of a thing is updated with the results of the digital twin layer and vice versa (Fig. 5.c). A smart C2PS thing can automatically decide to select any of these modes considering current system contexts. The probabilistic framework of Bayesian networks (BNs) is a popular choice to model uncertainty of context awareness for a long time [34] [35] [36], which motivated us to select BNs to design the smart connection controller.

a: BAYESIAN NETWORK-BASED CONTEXT MODEL

At any moment, a smart thing can choose either of the three operation modes based on the current system contexts. Here we assume, the contexts of a smart *thing* at any time can be battery power, computation cost, communication cost, communication range, etc. The decision system uses a Bayesian network represented as a directed acyclic graph (DAG) in Figure 6.

In the DAG model, the immediate contexts of a thing are considered for example as "*close physical range*", "*communication cost high*", "*computation cost low*" and "*battery high*" that are represented as Cr, Ch, Cl, and Bh respectively. The direct complement of these events can be described as "*out off range*", "*communication cost low*", "*computation cost high*" and "*battery low*" which are represented as Cr', Ch', Cl', and Bh'. In order to select the `physical-physical` communication mode, we consider the contexts Cr, Ch, Cl, and Bh. Similarly, a *thing* can choose the `cyber - cyber` mode based on the contexts Cr', Ch', Cl', and Bh'. Since the proposed DAG (Fig. 6) is a polytree (i.e. singly connected network) [37], hence the joint probability distribution of any node can be represented as [38],

$$\begin{aligned}P(X_1 &= x_1, \ldots, X_n = x_n)\\ &= \prod_{i=1}^{n} P(X_i = x_i | X_{i+1} = x_{i+1}, \ldots, X_n = x_n)\\ &= \prod_{i=1}^{n} P(X_i = x_i | X_j = x_j \text{ for each } X_j \text{ which is parent of } X_i)\end{aligned} \tag{13}$$

Here, the conditional probability of selecting `physical-physical` communication mode is,

$$P(PP|Cr, Ch, Cl, Bh) = \frac{P(PP, Cr, Ch, Cl, Bh)}{P(Cr, Ch, Cl, Bh)} \tag{14}$$

Also, the conditional probability of selecting `cyber - cyber` communication mode is,

$$P(CC|Cr, Ch, Cl, Bh) = \frac{P(CC, Cr, Ch, Cl, Bh)}{P(Cr, Ch, Cl, Bh)} \tag{15}$$

Once we have the joint probability distribution values from Equation 13, we can find the probabilities of selecting `physical - physical` and `cyber - cyber` modes. We further use them as inputs to a fuzzy logic decision system that can select either of them or the `cyber - physical` option. As `cyber - cyber` is the opposite mode of the `physical - physical` communication mode, we use a fuzzy logic based decision system to describe the intermediate ranges. Also, fuzzy logic rules can be easily updated to instill higher degree of reconfiguration in the control method.

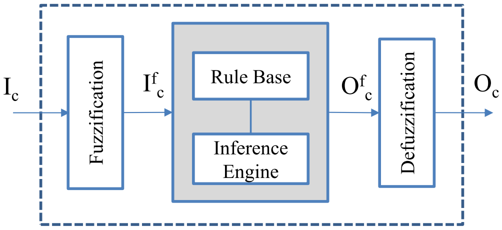

FIGURE 7. **Abstraction of a basic fuzzy logic based decision system.**

b: FUZZY LOGIC BASED CONTROLLER MODEL

Figure 7 shows the architecture of a fuzzy logic based control system, where the input I_c is first fuzzified to I_c^f and after the rule base association and inference application, it generates output O_c^f which is later defuzzified to O_c [39]. We have selected fuzzy logic since its rule base can be always updated, which suits the nature of C2PS hybrid computing reconfiguration.

$$I_c^f = \{(i_c, \mu^f(i_c)) | i_c \in I_c\} \tag{16}$$

Here every fuzzy input is an ordered pair of the input (i_c) and its grade of member function ($\mu^f(i_c)$). Member functions can be of type triangular, gaussian, bell-shaped, sigmoid, polynomial, etc [40]. The rule base of a Multiple Input Single Output (MISO) fuzzy system can be written as,

$$\begin{aligned}
R_1 &: \text{ if } i_1 \text{ is } A_1 \text{ and } i_2 is B_1 \text{ then } o_1 \text{ is } C_1 \\
R_2 &: \text{ if } i_1 \text{ is } A_1 \text{ and } i_2 is B_2 \text{ then } o_1 \text{ is } C_2 \\
R_3 &: \text{ if } i_1 \text{ is } A_2 \text{ and } i_2 is B_1 \text{ then } o_1 \text{ is } C_3 \\
R_4 &: \text{ if } i_1 \text{ is } A_2 \text{ and } i_2 is B_2 \text{ then } o_1 \text{ is } C_4
\end{aligned}$$

Here i_1, i_2 are sensor variables and o_1 is an output variable respectively. A_i, B_i, and C_i are linguistic values of the linguistic variables i_1, i_2, and o_1 in the universe of discourse of W, X, and Y respectively. Here, a fuzzy control rule such as R_1 can be defined as,

$$\begin{aligned}
\mu_{R_i} &\equiv \mu_{(A_i \text{ and } B_i \rightarrow C_i)}(w, x, y) \\
&= [\mu_{A_i}(w) \text{ and } \mu_{B_i}(x)] \rightarrow \mu_{C_i}(y)
\end{aligned} \tag{17}$$

Where A_i and B_i is a fuzzy set $A_i \times B_i$ in $W \times X$; $R_i \equiv (A_i \text{ and } B_i) \rightarrow C_i$ is a fuzzy implication (relation) in $W \times X \times Y$ space. Each of the fuzzy relation represents a fuzzy logic controller. The values of W, X, and Y are selected based on new smart *thing* is to be designed. The output of the fuzzy relations can be defuzzified using centroid of area, mean of maximum, bisector of area, etc. [41]. In the following section we design a MISO controller to smartly select one of the interaction modes.

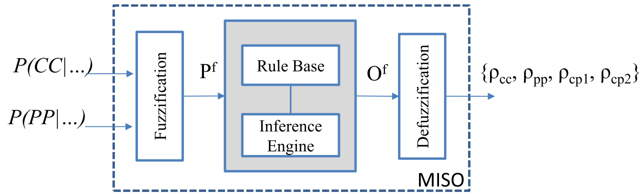

FIGURE 8. **Fuzzy logic based smart interaction type selection model. It is a MISO (Multiple Input Single Output).**

Physical-Physical (columns); Cyber-Cyber (rows)

	VL	L	M	H	VH
VL	CP2	CP2	PP	PP	PP
L	CP2	CP1	CP1	PP	X
M	CC	CP1	CP1	X	X
H	CC	CC	X	X	X
VH	CC	X	X	X	X

Very Low (VL)	=	0.000 - 0.250
Low (L)	=	0.175 - 0.425
Medium (M)	=	0.350 - 0.650
High (H)	=	0.575 - 0.825
Very High (VH)	=	0.750 - 1.000

Physical-Physical (PP)	=	0.000 - 0.500
Cyber-Physical-1 (CP1)	=	0.300 - 0.500
Cyber-Physical-2 (CP2)	=	0.500 - 0.700
Cyber-Cyber (CC)	=	0.500 - 1.000

FIGURE 9. **Fuzzy logic rules matrix to select the communication mode. Here each color represents a mode to be selected. Don't care combinations (X) represent the situations that are not possible (i.e. $P(CC) + P(PP) > 1$).**

c: INTERACTION CONTROLLER DESIGN

In order to select one of the communication modes, we design a MISO controller, where there are two inputs $P(PP|Cr, Ch, Cl, Bh)$, $P(CC|Cr, Ch, Cl, Bh)$ and one output $\{\rho_{cc}, \rho_{pp}, \rho_{cp1}, \rho_{cp2}\}$ (Fig. 8) and the rule base matrix is Figure 9. As an example, we divide the probability space as *Very Low (VL), Low (L), Medium (M), High (H)*, and *Very High (VH)*. Here the input space for `physical <-> physical` and `cyber <-> cyber` is $W = \{VL, L, M, H, VH\}$ and $X = \{VL, L, M, H, VH\}$ respectively. The output space is again considered as *physical-physical (PP), cyber-cyber (CC), cyber-physical-1 (CP1)*, and *cyber-physical-2 (CP2)*, where $Y = \{\rho_{pp}, \rho_{cc}, \rho_{cp1}, \rho_{cp2}\}$. The input and output space can be configured according to a system manufacturer.

C. COMMUNICATION

Multiple C2PS things can work as subsystems of a further advanced C2PS ($\mathcal{M}$). Mode of interaction of a C2PS subsystem is transparent to other subsystems. We can easily build an advanced system through the cyber layer, where a digital twin *thing* communicates with other digital twins by following a topology or relationship. For simplicity, we take the total number of possible advanced systems to be the power set of $\mathcal{C}$, $\mathcal{P}(\mathcal{C}) = 2^{|\mathcal{C}|}$. Every advanced thing is denoted by an unique Id $\mathcal{T}$ so that $M_{\mathcal{T}}^{-1}(c)$ for $c \in \mathcal{P}(\mathcal{C})$ returns an unique $\mathcal{T}$. Each of this master things works as a hub of other networked digital twin things. Every network is uniquely tagged by a relationship Id $\mathcal{R}$ and fulfils a specific goal $\mathcal{G}$. The subsequent advanced things fulfill the Equation 18;

$$f_r : \mathcal{M}_{\mathcal{T}} \rightarrow \mathcal{R}, \exists g \in \mathcal{G} \tag{18}$$

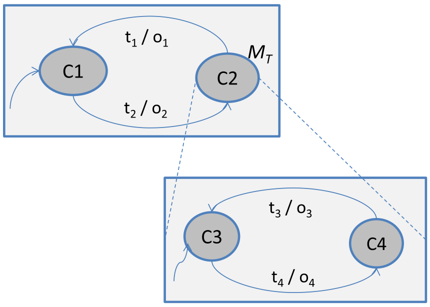

FIGURE 10. Abstraction of hierarchically organized things.

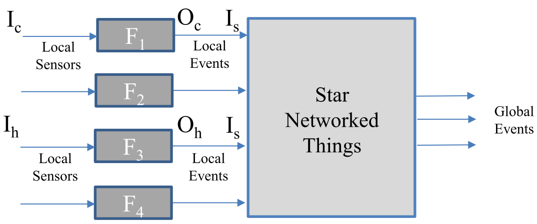

FIGURE 11. Architecture of the advanced star networked things.

1) HIERARCHICAL COMPOSITION OF C2PS THINGS

A possible structure of complex systems is to organize them hierarchically. In this case, a higher level cyber thing is composed of further lower level digital twin things Fig. 10. Here, one higher level thing works as the master of the lower level slave things. And, any state transition to a master thing means a state transition for any of the slave things. We can define such a complex system using hierarchical composition of finite state machines (Equation 19), where $\mathcal{T}$ is a set of unique IDs for the cyber things. We follow the methods of [32].

$$\mathcal{M}_{\mathcal{T}} : \mathcal{C} \to \{\{\emptyset\} \cup \mathcal{C}\}, \quad \mathcal{M}_{\mathcal{T}}^{-1} : \mathcal{C} \to \mathcal{P}(\mathcal{C}), \ f_r \tag{19}$$

Here we see that every cyber thing can be a composition of other cyber things $c \in \mathcal{P}(\mathcal{C})$. The maximum number of subsets of the $\mathcal{C}$ is $\mathcal{P}(\mathcal{C})$ denotes the power set of the cyber things that is $2^{|\mathcal{C}|}$. As a result, we might need to create more logical entities of some cyber things to build a complex thing which is easy for C2PS. But in any case $\mathcal{M}_{\mathcal{T}}^{-1}(c)$ will return the unique $\mathcal{T}$ and related $\mathcal{R}$.

If we represent Equation 8 as Λ_c and Equation 9 as Δ_c then we can assume mean $\bar{\mathcal{C}}$ and define transfer and output function as Equation 20 and 21 respectively [32],

$$\Lambda_{\mathcal{M}_{\mathcal{T}}^{-1}(\bar{\mathcal{C}})} \equiv \prod_{i=1}^{\mathcal{M}_{\mathcal{T}}^{-1}(\bar{\mathcal{C}})} \Lambda_i \tag{20}$$

$$\Delta_{\mathcal{M}_{\mathcal{T}}^{-1}(\bar{\mathcal{C}})} \equiv \prod_{i=1}^{\mathcal{M}_{\mathcal{T}}^{-1}(\bar{\mathcal{C}})} \Delta_i \tag{21}$$

2) STAR NETWORKED C2PS THINGS

A complex thing can be organized as a star networked topology (Fig. 11), where a master cyber thing acts as a hub of other cyber things and the outputs of the lower level subsystems are

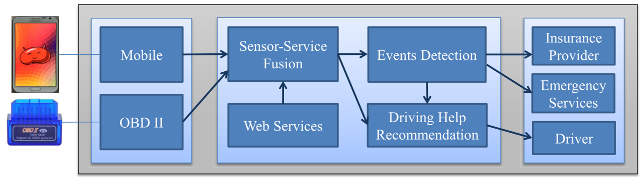

FIGURE 12. Telematics based driving assistance application.

inputs to the higher level system. We can define the system by Equation 22, where transfer and output functions are similar to the general synchronous finite state machine.

$$\begin{aligned} f_s = (Q_s, I_s, O_s, q0_s, \lambda_s, \delta_s), f_r \text{ where } V_c \subseteq V_s \\ \text{assume, } V_c \text{ is data type of } O_c \\ \text{and, } V_s \text{ is data type of } I_s \end{aligned} \tag{22}$$

$$\lambda_s : Q_s \times I_s \to Q_s \tag{23}$$

$$\delta_s : Q_s \to O_s \tag{24}$$

This type of advanced *thing* takes the lower level event information and process them to find further regional or global knowledge. The lower level systems generate the type of information that the higher level system can process. Hence, the higher level system can be replicated and new lower level things can be plugged in as long as the data type matches. For example, if we have four smart temperature sensors deployed to four corners of a room then the individual temperature data collected in the four digital twin things of the respective sensors can be fed into a higher level master cyber *thing* that recognizes temperature data and can produce an aggregated temperate of a room.

D. CLOUD SERVICES

From the above design models, we see that there can be three types of cloud setup: physical sensor cloud, digital twin process cloud and finally sensor-service integration cloud. The sensor cloud is formed by real world level ad-hoc communication among the C2PS things. Every physical *thing* involved in a C2PS communication has its own data storage and communication infrastructure. These storage and network facilities can be accessed in the physical level sensor cloud by ad-hoc network members. So at this level, we have Storage-as-a-Service, Network-as-a-Service or Software-as-a-Service (SaaS) supports. Physical sensor cloud setup can provide real time or near real time services to the physical layer members.

In the cyber level digital twin process cloud, we get delay tolerant services that cannot be provided through the physical sensor level. These services take the sensor inputs from the lower physical layer, take heavy duty decisions using scalable cloud infrastructures and provide services to its own physical level things or to other things through the peer-to-peer digital twin process cloud layer. Digital twin processes in the cloud layer can be updated, upgraded or can add new functionalities that are accessible from the low level physical layer. Digital twin process layer can provide Virtual Network-as-a-Service, in order to create relational networks out off the

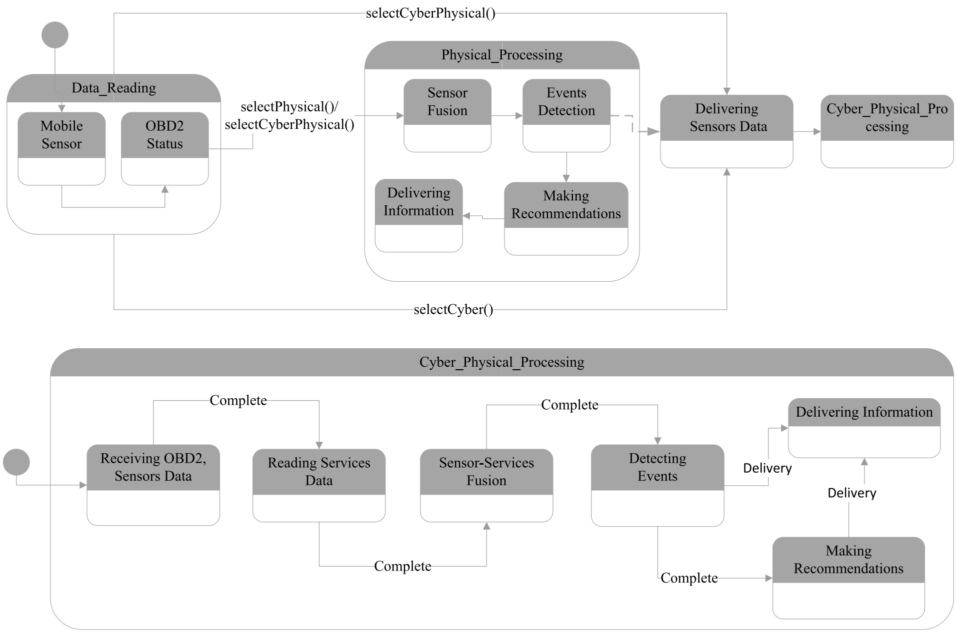

FIGURE 13. **A simple state machine representation of the telematics system. (Implemented in Qfsm).**

physical communication range. We assume that the physical things will use cellular networks (i.e. 3G/LTE) to communication with the cyber digital twin layer. Other possible services from the cyber cloud layer are Storage-as-a-Service or SaaS.

The data center can also provide various types of cloud services such as Storage-as-a-Service, SaaS, and Data-as-a-Service, so that various data mining applications can be accessed from the physical layer or by different monitoring authorities.

V. PROTOTYPE SYSTEM IMPLEMENTATION

In this section, we describe a telematics based driving assistance application for the vehicular CPS (vehicular domain of C2PS) (Fig. 12) to demonstrate the efficacy of C2PS design. In this application, we consider two sources of sensory values: 1) Mobile sensors that capture the user interactions, GPS location of the vehicle, speed, acceleration, etc. 2) On Board Diagnostic II (OBD-II) scanner that reads the real time status of the vehicle such as fuel consumption, airbag status, etc. We show the usage of different types of C2PS computations that applies sensors and services fusion to identify various driving events and/or driving related situational recommendations for drivers, insurance or emergency service providers.

A. COMPUTATION

We have designed the finite state machine (Fig. 13) of the telematics system using Qfsm[1] that can translate the graphical design to SMC[2] enabled format. SMC file format is later transferred to source code such as JAVA. At first, the system stays at *Data_Reading* state, where it reads data from the mobile and/or the OBDII devices. Later based on the current context of the system one of the *Physical_Processing*, the *Cyber_Processing*, or the *Cyber_Physical_Processing* computation model is selected. This decision is taken by the control part of the system. For the *selectPhysical()* action, all the processing occur in the physical layer that is in the vehicle. Several real time driving and usage events are detected in this level of operations and subsequent driving recommendations are made based on the available sensory data.

In case of the *selectCyber()* action, all the processing occurs in the digital twin cloud layer. As a result, this type of processing can not provide real time event detection or driving recommendations. But, time delayed operations can benefit from the cloud computing infrastructure for their horizontal scalability. The *selectCyberPhysical()* action expects a hybrid operation, where real time processing occurs in the physical layer and the resource heavy processing occurs in the cloud layer. Cloud based processing can provide cost effective and timely integration of web services which is not readily available in the physical layer. Both the *cyber* and *cyber-physical* modes enable sensor-services fusion, an extension to the sensor only fusion available to the physical layer, which ensures higher degree of driving support recommendations.

B. CONTROL

The control part of the system is divided into two sections. The first part is a Bayesian network (Fig. 14) that takes input about system contexts such as communication range, computation cost, system battery level and communication cost.

[1]Qfsm: a tool to design finite state machines, http://qfsm.sourceforge.net/
[2]SMC: State machine compiler, http://smc.sourceforge.net/

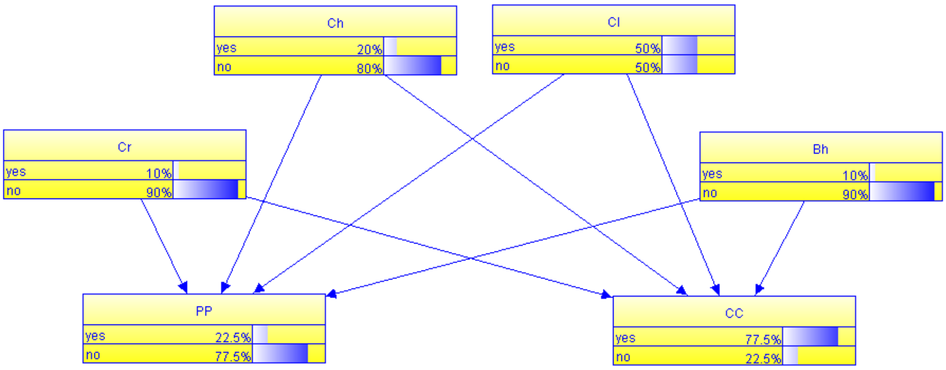

FIGURE 14. Selection of one of the two context based connections using a Bayesian network.

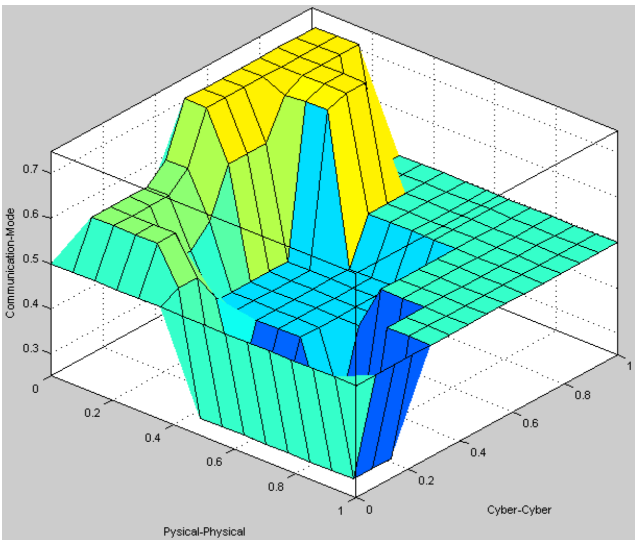

FIGURE 15. Rule base of the fuzzy logic based controller of the telematics based system.

The Bayesian network decides which one of these two modes (i.e. *cyber-cyber*, *physical-physical*) will be selected. As the *cyber-physical* mode is a hybrid organization, it can have many possible combinations. In order to tackle this issue, we take the previous two opposite modes as inputs to a fuzzy logic based controller. We have selected fuzzy logic since its rule base can be always updated, which suits the nature of C2PS hybrid computing reconfiguration. Figure 15 shows the surface view of the entire fuzzy logic rule base. For this example, we have selected two hybrid computing modes *CP1*, and *CP2*. Some of the rules of this setup are:

$$R_1: \text{ if } P(PP) \text{ is } VH \text{ and } P(CC) \text{ is } VL \text{ then } O^f \text{ is } \rho_{pp}$$
$$R_2: \text{ if } P(PP) \text{ is } H \text{ and } P(CC) \text{ is } VL \text{ then } O^f \text{ is } \rho_{pp}$$
$$R_3: \text{ if } P(PP) \text{ is } M \text{ and } P(CC) \text{ is } VL \text{ then } O^f \text{ is } \rho_{pp}$$
$$R_8: \text{ if } P(PP) \text{ is } L \text{ and } P(CC) \text{ is } H \text{ then } O^f \text{ is } \rho_{cc}$$
$$R_{12}: \text{ if } P(PP) \text{ is } L \text{ and } P(CC) \text{ is } L \text{ then } O^f \text{ is } \rho_{cp1}$$
$$R_{15}: \text{ if } P(PP) \text{ is } VL \text{ and } P(CC) \text{ is } VL \text{ then } O^f \text{ is } \rho_{cp2}$$

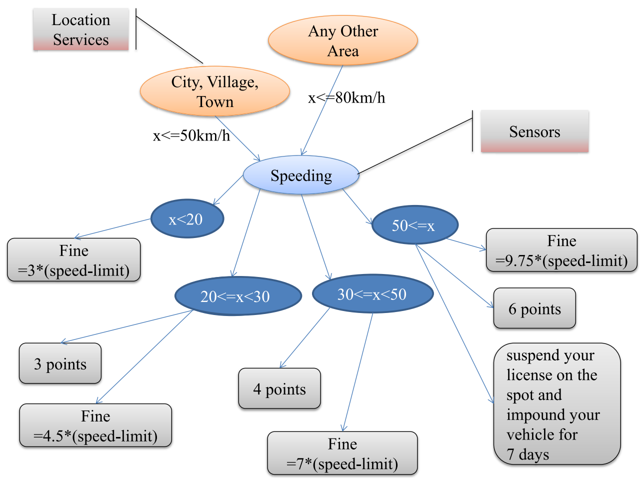

FIGURE 16. An example driving assistance model for Ontario, Canada region based on speeding event.

Here, *Very High*, *High*, *Medium*, *Low*, and *Very Low* are presented respectively as *VH*, *H*, *M*, *L*, and *VL*.

C. SENSORS AND SERVICES FUSION

Three possible types of data fusions are possible for this situational driving support recommender system that follows C2PS design philosophy. At first, physical layer based sensors only fusion that can provide near real time driving events detection as well as render situational assistance to the driver. We use the MUDVA multi-sensory dataset (accelerometer, gyroscope, barometer, GPS of mobile or data from OBD2 scanners) [14] to detect *speeding* and *turn* events using models from [42]. Identification of these critical events can elicit color based warnings to the driver through the vehicle dashboard if required.

Secondly, cloud layer based services only fusion can provide delay tolerant services such as nearby parking or hotel or restaurant information, location based deals, accident statistics etc. For this purpose, we follow the model from [15]. Finally, C2PS hybrid sensor-services fusion can extend both of the sensors or services only fusions. This kind of fusion is a true application of fog computing. For example, the speeding event detected by the physical layer can further be fused with the location and weather services information coming through the cloud layer. As a result, the system can provide location specific speeding related possible fines and/or demerit points. Figure 16 shows an Ontario, Canada based model for such an application, where the system can determine whether the vehicle is in a city/village/other areas and can provide the driver with warnings such as speed-wise possible fine, demerit points or even accident statistics of the upcoming road segment.

VI. CONCLUSION AND FUTURE WORKS

Cyber-Physical System is considered as the next generation of Internet-of-Things, where computation, communication and control features of the physical systems get distributed and physical devices mostly act as data sources for the computation modules (i.e. Digital Twins). Digital twins analyze the current context of the system and recommend control actions for the physical environment if required. As a result, there exist a twin feedback loop that is always active to improve the quality of service of the physical systems. This approach further becomes more scalable, once computation and control are featured by the cloud computing infrastructures. In this paper, we propose a digital twin architecture reference model to design cloud-based cyber-physical systems (C2PS). In this case, we divide the system into three operational modes, physical level sensors-fusion mode, cyber level digital twin services-fusion mode and a deep integration of sensor-services fusion mode. We provide a system context based control decision scheme that uses Bayesian network and fuzzy logic based rules to select any of these system modes for inter-system interactions. We have analytically modeled the computation, communication and control properties of the C2PS. A telematics based driving assistance application is also described to prove the efficacy of the C2PS design philosophy.

The lessons learned from the vehicular CPS application development can be used to build similar C2PS applications for other domains such as smart home, smart office, smart agriculture, smart waste management, etc. Here, the C2PS architecture reference model works as a template so that cross domain integrations can be seamless. This integration requires a common language, which can be formulated from an upper level meta ontology. Later, domain specific ontologies can be developed to facilitate these integrations. As a result, a true Smart city can be formed, where data can be accessed easily across domains by different stakeholders.

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