

A Novel Capacity and Trust Based Service Selection Mechanism for Collaborative Decision Making in CPS

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Abstract. Cyber-physical system (CPS) provides more powerful service through combining software service and physical device. It is an effective solution to organize various CPS services to realize collaborative decision making (CDM). In CPS, finding out the most competent participators for CDM sponsor is a core problem. To solve this problem, we propose a novel capacity and trust computation based CPS service selection mechanism in intelligent and automatic manners. It comprises three phases, including capacity evaluation, trust computation and negotiation selection. In the first phase, CDM sponsor describes formal semantic of decision task and computes the capacity evaluation values according to participator instructions. In the second phase, we design a novel trust computation method to calculate the values of activity trust, subjective belief, objective reputation, physical trust and recommended trust respectively. In the third phase, service selection is achieved through a negotiation mechanism according to capacity evaluation and trust computation.

Keywords: cyber-physical system, collaborative decision making, service selection, semantic, capacity, trust.

1. Introduction

Collaborative decision making (CDM) becomes a popular and feasible solution for the increasing complexity of decision making requirement from substantive users. Traditional CDM is implemented by decision support system through web service cooperation [1-2]. In such situation, CDM consists of heterogeneous and geographically distributed cyber components with different capacity. Performance and reliability of CDM depend on all the cyber capacities in virtual world [1-3]. The advent of Cyber-physical system

(CPS) enables people to make use of the facilities in physical world to make CDM more powerful.

Cyber-physical system (CPS) is a system which is tight combination of information computation and physical environment [4-8]. Software services are embedded into physical devices in order to provide more convenient and efficient services to people. Nowadays, CPS, such as smart buildings, medical devices, intelligent traffic control system, will provide a high-quality decision making through integrating computational systems in virtual world and infrastructures in physical world to cope with the increasing complex demands from people [5]. Based on the computational and physical service capacities, CPS will offer more competent services for CDM. Since both the computational systems in virtual world and the infrastructures in physical world are service providers, it is crucial to make CDM in CPS competent in virtual and physical aspects for users. Thus, a challenge of CDM in CPS is how to find out an efficient method to select competent services from the heterogeneous and geographically distributed services.

Existing researches in CPS mainly focused on architecture [6-8], middleware designing [9], system control [10-11], system security [12-14], QoS[15-16] or real-time data management [17]. However, as a service provider for users, it is critical to identify the competence degree of CPS's services for CDM, which has received limited attention in study.

In an open, relax coupling and dynamic environment, many CPS service provisions (CPSSP), including CPSSP in virtual and physical world, are not free to be available. And CDM sponsors generally have insufficient knowledge about all CPSSPs. As a result, CDM sponsor has to accept CPSSP's payment conditions without any opportunity to experience the service in advance. On the other hand, CDM sponsor may abandon a high quality CPS service because it lacks sufficient knowledge to certify service's ability. Such asymmetric position would results in inefficient and improper CPS service provision. To overcome these problems, CPS requests an effective mechanism to identify and exhibit competence degree in order to make services ease-of-use for CDM.

Trust is an effective solution for CDM service selection in CPS. CDM sponsor can decide whether a CPS service should be selected or not depending on the security or credit degree even though they do not have ample information about the service. There are many existing trust evaluation methods, such as summation/average of trust rating or past judgment ranking, to figure out their creditable degrees for traditional information systems. But these trust evaluation methods mainly focus on cyber features which are inherent properties of software, i.e. software actions or information content security, etc. Different from traditional cyber systems, CPS trust evaluation should pay attention to formulate an appropriate trust computation for both cyber and physical features. Since existing methods lack feasible ways to evaluate trust of physical components, they are not sufficient for the CPS.

In our view, the natural characteristics of CPS' service, which should be emphasized in selection evaluation, are as follows:

- 1) Capacity of software service
- 2) Trust of software service
- 3) Capacity of physical service provider
- 4) Trust of physical service provider

From above characteristics, CDM sponsor can communicate with both cyber and physical components of CPS to realize about the competence degree of CPSSP, and launch the capacity and trust evaluation.

In this paper, we propose a novel capacity and trust based CPS service selection mechanism to identify the most competent services for CDM. We address the formal semantic to describe the characteristics of CPSSP so that the communicating between CDM sponsor and CPSSPs would share a common knowledge base in our mechanism. Our mechanism comprises three phases, i.e., semantic description for CDM sponsor requirements and capacity of CPSSP, trust evaluation of CPS and negotiation selection of CPSSP. In the first phase, CDM sponsor describes formal semantic of complex requirement and estimates the capacity values according to candidate instructions from different CPSSPs. In the second phase, a novel trust computation method is adopted to calculate the trust degrees of CPSSP's different characteristics. In third phase, service selection is achieved through a negotiation mechanism based on the results of capacity evaluation and trust computation.

The rest of this paper is organized as follows. In Section 2, a brief introduction of related work is presented. Three phases of our mechanism are described in detail from Section 3 to Section 5 respectively. The service selection framework of CDM in CPS is presented in Section 6. Finally, we conclude the paper in Section 7.

2. Related Work

2.1. Collaborative Decision Making

Collaborative decision making has been widely used in many application domains, such as airport management [18-19], GIS map [20], and stakeholder research [21]. In practice, the CDM framework is proposed in three ways, i.e., Internet based CDM [22-23], multi-agent based CDM [24], and web service based CDM [25-26]. Internet based CDM is a traditional way to organize the decision making. The main challenge of Internet based CDM is how to transfer isometric data and information across wide networks. Multi-agent is a feasible and optimized solution for CDM. Agent has abilities of negotiation, decision making and knowledge interaction, which can partially realize intelligent and automatic CDM. However, because agents lack the mechanism of self-description in a machine readable format, it is difficult for agent oriented CDM to identify qualified decision making partners. In recent

studies, web service becomes a popular solution. Web service is a software program designed to support interoperable machine-to-machine interaction over a network [27]. In service oriented architecture, collaborative work can be considered to be autonomous through a set of messages and commands. In this paper, we utilize web service environment to organize the CDM.

2.2. Selection Research of Decision Making

As the core problem of CDM, service selection is constantly treated as decision model selection in traditional DSS (decision support system). Artificial intelligent (AI) techniques are widely used for model selection, such as CBR (Case Based Reasoning) [28], RBR (Rule Based Reasoning) [29], ANN (Artificial Neural Network), and GA (Genetic Algorithm) [2]. Statistical methods, such as Bayesian information criteria, are also frequently adopted for decision model selection [30]. However, these existing methods are not designed for open and distributed network. Mou et al. proposed a QoS based service selection in CDM [26], where QoS is measured as the capacity of web service. While Mou's model mainly focuses on service capacity forecasting, our capacity and trust computation strategy provides a comprehensive solution for efficient service selection.

2.3. Trust Computation Research

In trust computation, belief and reputation are two core conceptions for creditable description. Belief is a subjective concept that demonstrates a creditable relationship between two or more individuals. On the other hand, reputation presents the whole common schema from all the qualified members. As a consequence, we think that the service selection mechanism is to identify the service with good reputation from the independent third party and the trustable ones from the sponsor's belief.

There have been a large number of research efforts on belief and reputation in the past decades [31-35]. Many methods, such as summation/average of trust rating [36] and Bayesian systems [37], have been proposed to optimize one or more aspects of trust computation performance. Based on the trust computation, there are two main types of architectures of reputation system: centralized and distributed. The former has a central authority to collect all the rating, and publish reputation score for every participant. Whereas in distributed reputation system, each member gets the belief about each experience with others, and submits the reputation on request from relying members.

In our previous research, we proposed a trust computation based model selection for decision support system, which considers the trust from subjective and objective perspective [38,39]. However, these methods cannot use both capacity and trust aspects for service selection.

For CPS, many researchers are working on security or trust issues which are important for service selection [40]. Efforts include the achievements of formalizing the definition of trust [41-42], trust management and trust negotiation methodologies [43-44]. Many researchers addressed trust issues of pervasive computing environments [45-46], trust-based communication and interoperation approaches [47-50]. However, trust computation, which should focus on the CPS substantive characteristics, has not been addressed adequately in cyber-physical systems.

In our thoughts, what is missing is a comprehensive view for cyber-physical systems that integrates both the cyber trust aspects and the physical trust aspects of CPS and allows the sponsor in the physical world to evaluate the service and interact with the cyber and physical service components based on trust value. Trust computation must be proposed for physical environments and the cyber service software should adhere to them. What is also missing is a notion of trust based interoperation for cyber-physical systems where different systems will interact in a dynamic environment to achieve CDM.

3. Semantic based Capacity Evaluation of CDM

Firstly, we provide a table (Table 1) which lists a set of nomenclatures that will be frequently used in the rest of the paper.

3.1. Semantic of Decision Requirement and CPS Service

To evaluate the quality of a candidate service, users should match the service's capacities with their requirements. In definition 1, we describe the requirements from both virtual computational aspects and the physical objects aspects so that the characteristics of CPS are shown in the definition. We define the semantic of user's requirement to as follows.

Definition 1 Requirement semantic of decision task is a 2-tuple as $\mathcal{R} = (\mathcal{R}^V, \mathcal{R}^P)$. Here \mathcal{R}^V and \mathcal{R}^P represent the user's virtual requirement semantic and physical requirement semantic respectively. Virtual requirement semantics can be defined as $\mathcal{R}^V = (\mathcal{R}^{vc}, \mathcal{R}^{vr}, \mathcal{R}^{goal}, \mathcal{R}^{cost}, \mathcal{R}^{con})$, $\mathcal{R}^{vc}, \mathcal{R}^{vr}, \mathcal{R}^{goal}, \mathcal{R}^{cost}$ and \mathcal{R}^{con} represent virtual requirement class name, structure relationships of virtual requirement, goals, affording service cost price and preconditions respectively, while \mathcal{R}^P , the physical requirement semantic, can be defined as $\mathcal{R}^P = (\mathcal{R}^{pc}, \mathcal{R}^{pr}, \mathcal{R}^{envir}, \mathcal{R}^{time})$. Parameter \mathcal{R}^{pc} denotes candidate physical service provider's class. \mathcal{R}^{pr} is the relationships of physical service provider. \mathcal{R}^{envir} is running environment

requirement of physical service. \aleph^{time} is time control criterion of physical service.

Table 1. Nomenclature

Symbol	Description
\aleph	Semantic of decision requirement
\aleph	Participator instruction semantic
$E(x (R, S, F))$	Semantic of CPS service physical environment
Ω	Semantic of CPS service activity
$capacity(\aleph^{id})$	Capacity evaluation value of CPS service
$value_{goal}(\aleph^{id})$	Goal evaluation value of CPS service
$value_{time}(\aleph^{id})$	Time forecasting value of decision making service
$match(\aleph_j^{time})$	Match function that calculates the excess time of \aleph_j^{time} relative to \aleph^{time}
$value_{price}(\aleph^{id})$	Cost evaluation value of decision making service
$over(\aleph_k^{cost})$	Function that calculates the excess cost of \aleph_k^{price} relative to \aleph_k^{cost}
$value_{environment}(\aleph^{id})$	Price environment judgment value of CPS service
$get(E_{\aleph}(x_1))$	Function that calculates number of environment requirements of \aleph^{envir} satisfied by \aleph^{envir}
$AT_{\aleph}(\Omega)$	Activity trust value of CPS service
$CT_{\aleph}(\Omega^{class})$	Class trust value of activity proposed by service \aleph
$ST_{\aleph}(\Omega^{class})$	Status trust value of service's activity
BD	Belief dependence value from sponsor to a service
BR	Belief relationship from sponsor to a service provider
RR	Reputation ranking for CPSSP
$RR_{TL}(SP)^{TL_{unit}}$	Reputation ranking value based on time limitation
$RR_{SI}(SP_1)$	Reputation ranking value based on source identity
$RR_{RD}(SP)$	Reputation ranking value based on ranking delay
$RT^{ri}(SP_2, \aleph)$	Recommended trust value
$\phi(SP)$	Confidence conformation factor
$PT(\aleph^{id})$	Physical trust of CPSSP's device
$FT(\aleph^{id})$	Fault tolerance trust value of CPSSP's device
$HT(\aleph^{id})$	Healthiness trust value of CPSSP's device

CPS service by nature consists of two components: cyber software and physical environment. We consider that semantic of CPS service should be described from above two aspects. CDM sponsor needs a decision making service whose capacity can satisfy the requirement semantic. Therefore, each CPSSP would generate an instruction to introduce its service capacity of decision making. We define the participator instruction semantic of decision making service from CPSSP for capacity evaluation as follows.

Definition 2 Participator instruction semantic of CPS's service is defined as a 2-tuple as $\mathfrak{S} = (\mathfrak{S}^V, \mathfrak{S}^P)$. Here \mathfrak{S}^V and \mathfrak{S}^P represent the service's virtual capacity semantic and physical object semantic respectively. \mathfrak{S}^V can be defined as $\mathfrak{S}^V = (\mathfrak{S}^{id}, \mathfrak{S}^{vc}, \mathfrak{S}^{goal}, \mathfrak{S}^{price})$ according to its capacity. Parameter \mathfrak{S}^{id} denotes the exclusive identification of service. \mathfrak{S}^{vc} is the class of decision task which service is able to make. \mathfrak{S}^{goal} is a set of anticipated goals which can be achieved by service. \mathfrak{S}^{price} describes the price that the sponsor should pay for decision making service. \mathfrak{S}^P can be defined as $\mathfrak{S}^P = (\mathfrak{S}^{pc}, \mathfrak{S}^{source}, \mathfrak{S}^{envir}, \mathfrak{S}^{time})$ according to its capacity. \mathfrak{S}^{pc} denotes the physical class of CPSSP. \mathfrak{S}^{source} points out the source of service in CPSSP. \mathfrak{S}^{envir} represents the running environment of service. \mathfrak{S}^{time} represents the time that service would spend on decision making.

3.2. Capacity evaluation for service

The CDM sponsor may accept the service that satisfy as many as the number of goals in \aleph^{goal} under the restriction of time in \aleph^{time} , costs in \aleph^{cost} and environment requirements \aleph^{envir} . In other words, capacity evaluation for service comprises four aspects, i.e., goal evaluation, time forecasting, prices estimation, and environment judgment.

Goal evaluation. Goal evaluation aims to identify the goals of \aleph^{goal} that is achievable by a CPS service according to its \mathfrak{S}^{goal} . We measure this capacity criterion based on the number of goals which can be realized by service and the importance of the realizable goals. Firstly, we define an equalization mapping function between two semantic as follow.

Definition 3 Let x and y are the elements in \aleph and \mathfrak{S} respectively. Equalization Mapping function $N(x) \rightarrow y$ is a transfer relationship between x and y , which represents that the two elements are equal on the semantic level.

Let the set of \aleph^{goal} be $\aleph^{goal} = (\aleph_1^{goal}, \aleph_2^{goal}, \dots, \aleph_n^{goal})$. For each \aleph_i^{goal} , it has a weight w_i with the constraint $\sum_{i=1}^n w_i = 1$. Then the value of goal evaluation is calculated as follow,

$$score_{goal}(\mathfrak{S}^{id}) = \sum_{N(\mathfrak{S}^{goal}) \rightarrow \aleph^{goal}} w \quad (1)$$

Because a large number of \mathfrak{S}^{goal} can satisfy $N(\mathfrak{S}^{goal}) \rightarrow \aleph^{goal}$, the decision making task will be extremely complicated. To solve this problem, we introduce the impact factor calculation for goal evaluation. Let m is the number of \mathfrak{S}^{goal} that satisfy $N(\mathfrak{S}^{goal}) \rightarrow \aleph^{goal}$, and then the final value of goal evaluation can be calculated as follows,

$$value_{goal}(\mathfrak{S}^{id}) = \begin{cases} score_{goal}(\mathfrak{S}^{id}) \times \left(\frac{m}{n}\right)^{\left(1-\frac{1}{m}\right)} & m \geq 2 \\ score_{goal}(\mathfrak{S}^{id}) \times \frac{1}{n} & m = 1 \end{cases} \quad (2)$$

where n is the number of \aleph^{goal} set.

Formula 2 shows the gross importance of goals which can be realized by a candidate service. Here, we consider the number m and n as regulation parameters in formula 2 in order to make the result more effectively. They would influence the value of goal evaluation as adjusting parameters. For example, if there is a goal set of $\aleph^{goal} = (g_1, g_2, g_3, g_4)$ and their weights are 0.4, 0.3, 0.2, and 0.1 respectively. Service A has $\mathfrak{S}_A^{goal} = (g_2)$, while service B has $\mathfrak{S}_B^{goal} = (g_1, g_2, g_3)$. The goal evaluations of service A and B are 0.075 and 0.74 according to formula 2.

Time forecasting. Time forecasting aims to evaluate whether the CPSSP physical components response time satisfies the sponsor's requirement. Here responds time is measured as the time interval between decision and service. In general, the shorter response time in decision making, the larger value of \mathfrak{S}^{time} would be assigned from CDM sponsor.

For time forecasting, we denote maximum affording time \tilde{T} and anticipant time \aleph^{time} from CDM sponsor. Maximum affording time indicates the maximum time limit that would be acceptable by decision making sponsors. Anticipant time signifies the decision making spending time that would be the time interval sponsor looks forward to the most. Let the set of response time

given by service be \mathfrak{S}^{time} . The value of time forecasting can be calculate as following:

$$value_{time}(\mathfrak{S}^{id}) = \tilde{T} - \sum_{j=1}^l (\mathfrak{S}_j^{time})^\eta - \sum_{j=1}^l match(\mathfrak{S}_j^{time}) . \quad (3)$$

where, $\eta(\eta \in [0,1])$ is an impact factor given by sponsor, and l is the number of \mathfrak{S}^{time} set. We also propose a match function $match(\mathfrak{S}_j^{time})$ that calculates the excess time of \mathfrak{S}_j^{time} relative to \mathfrak{N}_j^{time} as follow.

$$match(\mathfrak{S}_j^{time}) = \begin{cases} 0 & \text{if } N(\mathfrak{S}_j^{time}) \rightarrow \mathfrak{N}_j^{time} \\ |\mathfrak{S}_j^{time} - \mathfrak{N}_j^{time}| & \text{else} \end{cases} . \quad (4)$$

Price estimation. Price estimation aims to test whether the service's price \mathfrak{S}^{price} is overcharge. As time forecasting, the less price service charge for decision making, the more value of \mathfrak{S}^{price} would be given from CDM sponsor. We denote maximum affording cost \tilde{C} as maximum cost limits that would be acceptable by decision making sponsors.

Let the sponsor's maximum affording cost be \tilde{C} . The price estimation can be calculated as following:

$$value_{price}(\mathfrak{S}^{id}) = \tilde{C} - \sum_{k=1}^q (\mathfrak{S}_k^{price})^\eta - \sum_{k=1}^q over(\mathfrak{S}_k^{price}) . \quad (5)$$

Here η is the same impact factor as in formula 3, and q is the number of \mathfrak{S}^{price} set. We also propose a function $over(\mathfrak{S}_k^{price})$ that calculates the excess cost of \mathfrak{S}_k^{price} relative to \mathfrak{N}_k^{cost} as follows:

$$over(\mathfrak{S}_k^{price}) = \begin{cases} 0 & \text{if } N(\mathfrak{S}_k^{price}) \rightarrow \mathfrak{N}_k^{cost} \\ |\mathfrak{S}_k^{price} - \mathfrak{N}_k^{cost}| & \text{else} \end{cases} . \quad (6)$$

We give an example here for explaining formulas of time forecasting and price estimation. Table 2 shows the related semantic values of requirement and service.

Table 2. Example of time forecasting and price estimation

	\aleph^{goal}	\aleph^{cost}		\aleph^{time}		\mathfrak{S}^{price}	\mathfrak{S}^{time}	η
		goal	cost	goal	time			
	G1	G1	≤ 20	G1	≤ 4	15	4	
value	G2	G2	≤ 10	G2	≤ 7	8	5	0.9
	G3	G3	≤ 15	G3	≤ 4	20	5	

From data in table 2, we can calculate value of time forecasting and price estimation through formula 3, 4, 5 and 6 as follows,

$$\begin{cases} value_{time}(\mathfrak{S}) = (4 + 7 + 4) - (4 + 5 + 5)^{0.9} - (0 + 0 + 1) = 3.25 \\ value_{price}(\mathfrak{S}) = (20 + 10 + 15) - (15 + 8 + 10)^{0.9} - (0 + 0 + 5) = 14.74 \end{cases}$$

Physical environment judgment. It is crucial to check whether the physical environment of CPSSP is competent for decision making. We denote the environment semantic for decision making as follows.

Definition 4 Physical environment semantic can be described as $E(x | (R, S, F))$. In this formula, the ordered pair $x | (R, S, F)$ illustrates a set of binary relations $r_1(x, y_1), \dots, r_n(x, y_n)$ of any certain physical object x , the set of statuses $s_1(x, z_1), \dots, s_m(x, z_m)$ of x at a certain time, and the set of rules f_1, \dots, f_r of the object x . We abbreviate $E(x | (R, S, F))$ as $E(x)$.

Physical environment semantic is a describable context. This kind of semantic makes it possible that each physical object has a certain context which could be understood explicitly by sponsor.

Let sponsor's environment requirement of physical object x_1 be $\aleph^{envir} = E_{\aleph}(x_1)$, and the physical environment of x_1 which can be provided by CPSSP's service instruction be $\mathfrak{S}^{envir} = E_{\mathfrak{S}}(x_1)$. The physical environment judgment can be calculated as following:

$$value_{environment}(\mathfrak{S}^{id}) = \frac{\sum get(r_{\mathfrak{S}}(x_1)) + \sum get(s_{\mathfrak{S}}(x_1)) + \sum get(f_{\mathfrak{S}}(x_1))}{|R_{\aleph}(x_1)| + |S_{\aleph}(x_1)| + |F_{\aleph}(x_1)|} \quad (7)$$

Here, the function $|R_{\aleph}(x_1)|$ indicates the total number of binary relations of physical object x_1 . We also propose a function $get(E(x_1))$ that calculates the number of environment requirements of \aleph^{envir} satisfied by \mathfrak{S}^{envir} as follows:

$$get(E_{\mathfrak{S}}(x_1)) = \begin{cases} 1 & \text{if } N(r_{\mathfrak{S}}(x_1)) \rightarrow r_{\mathfrak{S}}(x_1) \text{ or } N(s_{\mathfrak{S}}(x_1)) \rightarrow s_{\mathfrak{S}}(x_1) \\ & \text{or } N(f_{\mathfrak{S}}(x_1)) \rightarrow f_{\mathfrak{S}}(x_1) \\ 0 & \text{else} \end{cases} \quad (8)$$

According to goal evaluation, time forecasting, price estimation and environment judgment, capacity evaluation value can be calculated as follows:

$$capacity(\mathfrak{S}^{id}) = \sigma_1 \times value_{goal}(\mathfrak{S}^{id}) + \sigma_2 \times value_{time}(\mathfrak{S}^{id}) + \sigma_3 \times value_{cost}(\mathfrak{S}^{id}) + \sigma_4 \times value_{environment}(\mathfrak{S}^{id}) \quad (9)$$

Here σ is a weight with the constraint $\sum_{i=1}^4 \sigma_i = 1$.

4. Trust Computation

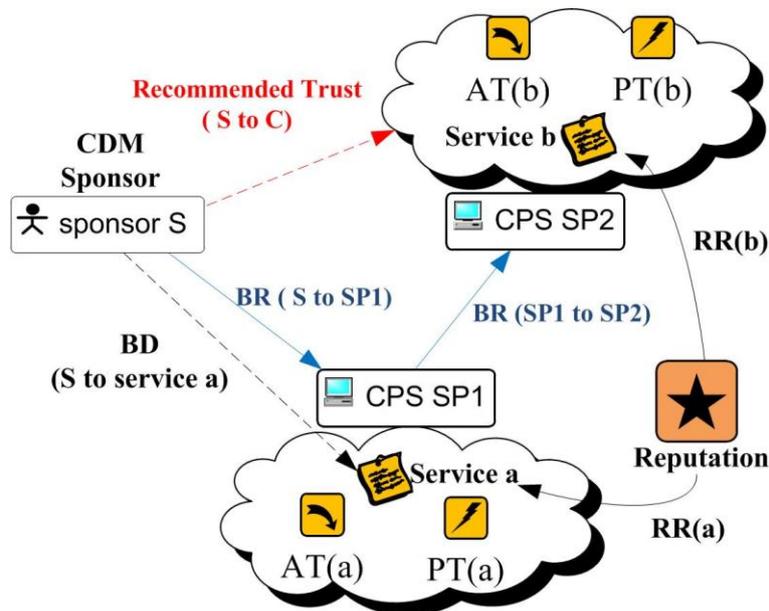


Fig. 1. Trust computation of trust

We study the trust based CPSSP selection in four aspects: activity trust, belief, reputation and physical trust. Activity trust (AT) is the trust degree of decision making process of CPS service. Belief is the subjective trust between different CPSSPs, which consists of belief dependence (BD) and

belief relationship (BR). Belief dependence is described by the trustable value from CDM sponsor to candidate services. And belief relationship means trust relationship value between CDM sponsor and CPSSP. In other hand, reputation reflects objective credit of CPSSP. Finally, physical trust (PT) is the trust that points out whether the physical device of CPSSSP is creditable or not. Furthermore, we introduce a recommended trust for CDM sponsor to study the strange CPSSPs within trust computation. Figure 1 shows an example of our trust computation framework.

4.1. Activity Trust Computation of CPS Service

Activity represents statuses transition during the process of CPS service making decision. Activity trust computation gives the opportunity for CDM sponsor to realize that whether a CPS service's work is creditable or not in advance. We define the semantic of a CPS service's activity as following:

Definition 5 A activity semantic description is a kind of representation as $\Omega = (\Omega^{class}, \Omega^{exe}, \Omega^{rec}, \Omega^{pre}, \Omega^{post})$. Here, Ω^{class} denotes the class name of activity. Parameters Ω^{exe} and Ω^{rec} represent the executor and receivers of activity respectively. Parameters Ω^{pre} denotes the previous statuses before the activity being executed, while Ω^{post} denotes the post statuses after the activity being executed.

Service activity trust can be calculated based on two aspects: the past activity records and past status transitions experiences.

Let success rate of a certain class of service \mathfrak{S} activity Ω^{class} be $p_{\mathfrak{S}}(\Omega^{class})$, and the overall success rate of certain class of activity Ω^{class} be $p(\Omega^{class})$. Then, the class trust (CT) of activity proposed by service \mathfrak{S} is calculated as:

$$CT_{\mathfrak{S}}(\Omega^{class}) = p_{\mathfrak{S}}(\Omega^{class}) \times p(\Omega^{class})^{[1-p(\Omega^{class})]} \quad (10)$$

In formula 10, we add an adjusting factor which can be calculated as $p(\Omega^{class})^{[1-p(\Omega^{class})]}$. This factor denotes creditable level of Ω^{class} . Formula 10 shows that the success rate is larger the class trust value is larger. It is similar with the real world's fact that more successful times an action is executed, the more confidence such action would gain.

For example, let service \mathfrak{S} has an activity Ω_1 . And it executes this activity Ω_1 with success rate of 0.95 in past. The overall success rate of activity in same class of Ω_1 which is executed by all existing services in CPS is 0.9. Then, the class trust of activity Ω_1 can be calculated as follows,

$$CT_{\mathfrak{S}}(\Omega_1^{class}) = 0.95 \times 0.9^{1-0.9} = 0.94$$

Let the previous statuses and post statuses proposed by a service \mathfrak{S} be $\Omega_{\mathfrak{S}}^{pre} = (\Delta_{\mathfrak{S}}^1, \Delta_{\mathfrak{S}}^2, \dots)$ and $\Omega_{\mathfrak{S}}^{post} = (\nabla_{\mathfrak{S}}^1, \nabla_{\mathfrak{S}}^2, \dots)$. In past decision making, activity Ω had the set of previous statuses and post statuses be $\Omega^{pre} = (\Delta^1 | q(\Delta^1), \Delta^2 | q(\Delta^2), \dots)$ and $\Omega^{post} = (\nabla^1 | q(\nabla^1), \nabla^2 | q(\nabla^2), \dots)$. Here, $q()$ represents the status occurrence rate. The status trust of service's activity is calculated as following:

$$ST_{\mathfrak{S}}(\Omega^{class}) = \sqrt{\frac{1}{2} \times \left(\frac{\sum_{i=1}^{|in(\Delta_{\mathfrak{S}}^i)|} q(\Delta_{\mathfrak{S}}^i)}{|in(\Delta_{\mathfrak{S}}^i)|} \right)^2 + \frac{1}{2} \times \left(\frac{\sum_{j=1}^{|in(\nabla_{\mathfrak{S}}^j)|} q(\nabla_{\mathfrak{S}}^j)}{|in(\nabla_{\mathfrak{S}}^j)|} \right)^2} . \quad (11)$$

where function $in(\Delta_{\mathfrak{S}}^i)$ denotes the status $\Delta_{\mathfrak{S}}^i \in \Omega_{\mathfrak{S}}^{pre}$ can be matched in Ω^{pre} , and $|in(\Delta_{\mathfrak{S}}^i)|$ is the number of $in(\Delta_{\mathfrak{S}}^i)$.

For example, let there be an activity $\Omega^{pre} = (\Delta^1 | 0.9, \Delta^2 | 0.95, \Delta^3 | 0.95, \Delta^4 | 0.8)$ and $\Omega^{post} = (\nabla^1 | 0.9, \nabla^2 | 1.0, \nabla^3 | 0.95)$. A service has this kind of activity with statuses $\Omega_{\mathfrak{S}}^{pre} = (\Delta_{\mathfrak{S}}^1, \Delta_{\mathfrak{S}}^2, \Delta_{\mathfrak{S}}^4)$ and $\Omega_{\mathfrak{S}}^{post} = (\nabla_{\mathfrak{S}}^2, \nabla_{\mathfrak{S}}^3)$. The ST value of this service's activity is calculated as following,

$$ST_{\mathfrak{S}}(\Omega^{class}) = \sqrt{\frac{1}{2} \times \left(\frac{0.9 + 0.95 + 0.8}{3} \right)^2 + \frac{1}{2} \times \left(\frac{1 + 0.95}{2} \right)^2} = 0.93$$

Based on class trust and status trust, activity trust can be calculation as following:

$$AT_{\mathfrak{S}}(\Omega) = \varpi_1 \times CT_{\mathfrak{S}}(\Omega) + (1 - \varpi_1) \times ST_{\mathfrak{S}}(\Omega) . \quad (12)$$

where, ϖ_1 is a weight with constraint $0 < \varpi_1 < 1$.

4.2. Belief Computation

CDM sponsor prefers to identifying a service with excellent past transaction experience. As a result, belief dependence can be calculated based on the past decision making transaction evaluations between CDM sponsor and the service.

Let a decision making service semantic be \mathfrak{S} , and it has made r times of decision for the CDM sponsor \mathfrak{R} . Let $judge^{\mathfrak{R}}(\mathfrak{S})_u$ ($judge^{\mathfrak{R}}(\mathfrak{S})_u \in [0,1]$) denote the service's score of decision making from \mathfrak{R} . At the $r+1$ time, BD from \mathfrak{R} to party \mathfrak{S} is calculated as

$$BD_{r+1}^{\mathfrak{R}}(\mathfrak{S}) = \begin{cases} \frac{\sum_{u=1}^r judge^{\mathfrak{R}}(\mathfrak{S})_r}{r} & r \neq 0 . \\ 0 & r = 0 \end{cases} \quad (13)$$

Similar as belief dependence, belief relationship reflects the whole creditable relationship between CDM sponsor and CPSSP. For d services in a CPSSP SP , if all the services have made t times of decisions, the belief relationship BR at $t+1$ time is

$$BR_{t+1}^{\mathfrak{R}}(SP) = \begin{cases} \frac{\sum_{v=1}^d BD^{\mathfrak{R}}(\mathfrak{S})_v}{t} & t \neq 0 . \\ 0 & t = 0 \end{cases} \quad (14)$$

Utilizing summation or average of past evaluation to compute trust has been proven feasible and effective [36, 50]. Formula 13, 14 is proposed based on computing average value of past evaluations between two parties' interaction.

4.3. Reputation Ranking

Reputation denotes a public and authoritative trust belief from an adiaborous community. We build up an independent reputation ranking method to generate impartial reputations for CPSSPs.

Reputation of a CPSSP is the summation of evaluation scores from its all past decision making. Let CPSSP SP totally make h times of decision with evaluation score $judge(SP)$ for past decision making. Reputation ranking of SP can be calculated as follows:

$$RR(SP) = \frac{\sum_{s=1}^h judge(SP)_s}{h} . \quad (15)$$

Likewise, we introduce computing average value of past evaluations for reputation ranking in formula 15. Different with belief computation, reputation

ranking is based on all the past evaluations from parties who had interactions with CPSSP in past rather than just only between two parties. It means that reputation is an objective view from whole community, while belief is a subjective relationship between two individuals.

We utilize three factors for reputation ranking, i.e., time limitation, source identity, and ranking delay. In our previous work, we calculated the reputation from above three factors, which has been testified feasible and effective in our work [38]. In this paper, we modify the corresponding formulas according to the features of CPS.

Time limitation (TL). We authorize CPSSP a unit time called time limitation. In this time period CPSSP can only receive one appointed number of decision making evaluation from the same CDM sponsor. Time limitation can reduce the risk that vicious CPSSP issues repetitious evaluation scores to cheat well-deserved reputation.

Let the appointed number of evaluation be TL_n , and the number of decision making be TL_t . Then the reputation ranking $RR_{TL}(SP)^{TL_{unit}}$ generated by CPSSP A is calculated as follows:

$$RR_{TL}(SP)^{TL_{unit}} = \frac{\sum_{j=1}^{TL_t} \sum_{i=1}^{TL_n} judge(SP)_{ij}}{i} . \quad (16)$$

where $judge(SP)_{ij}$ denotes the evaluation score to CPSSP A in a unit of time TL_{unit} , i denotes the appointed number and j denotes the different decision making.

Source identity (SI). Reputation ranking should bind with the evaluation source sponsor's reputation. An evaluation from a source sponsor with a higher reputation generally has more impacts to the receiver CPSSP.

If a CPSSP SP_2 has reputation ranking $RR(SP_2)$, and it sends an evaluation score $judge(SP_1)$ to CPSSP SP_1 , SP_1 will get the evaluation score as follows:

$$RR_{SI}(SP_1) = judge(SP_1) \times (RR(SP_2))^{[1-RR(SP_2)]} . \quad (17)$$

Similar with formula 10, $(RR(SP_2))^{(1-RR(SP_2))}$ is an adjusting factor which relies on source CPSSP's reputation $RR(SP_2)$. And the value of factor increases with the value increasing of $RR(SP_2)$.

Ranking delay (RD). To determine that the new evaluation score is not a fake or inauthentic evaluation, we adopt a delay period mechanism. In delay period, reputation is just a temporary result ($RR_{RD}(SP)$), and such reputation ranking can be withdrawn when it is identified as any illegal or cheating trick.

Let the time for reservation of the evaluation score in delay period be RD_t , and the whole length of delay period be RD_l . The temporary ranking can be expressed as:

$$RR_{RD}(SP) = \frac{judge(SP) \cdot RD_t}{RD_l} . \quad (18)$$

From above three factors, the reputation ranking $RR(SP)^{T+t}$ can be defined as:

$$RR(SP_1)^{T+t} = RR(SP_1)^T + \sum_{j=1}^m \sum_{i=1}^n \frac{judge(SP_1) \times (RR(SP))_{ij}^{1-RR(SP)_{ij}} \times l}{i \times t} . \quad (19)$$

where T is a time point, t is the delay period¹.

4.4. Physical Trust Computation

CPSSPs communicate with each other through physical devices in relax coupling network. Physical trust computation aims to identify which physical devices are legitimate and which are not to be trusted. The threat of the fault tolerance of devices, the healthiness of devices must be considered.

Let CPSSP's device totally success rate of providing service in past be $suc(SP)$, and the fault rate occurred in past be $fault(SP)$. At the same time, the rate of CPSSP's recovering from the faults be $recover(SP)$. The fault tolerance trust (FT) of CPSSP's device can be calculated as follows:

$$FT(\mathfrak{S}^{id}) = suc(SP)^{1-fault(SP)} \times recover(SP)^{fault(SP)} . \quad (20)$$

Let the ratio of whole running period of CPSSP's device be t_1 units of time, the whole sickness period caused by device faults or connection troubles be t_2 units of time. The average sickness period and the average

¹ In this paper, we utilize unit of time to measure as the length of time. Here, we define that the length of unit of time TL_{unit} is the same as the delay period t .

mending period in sickness period be t_3 units of time and t_4 units of time². The healthiness trust of CPSSP's device can be calculated as follows:

$$HT(\mathfrak{S}^{id}) = \left(1 - \frac{t_2}{t_1}\right)^{1 - \frac{1}{t_2}} \times \left(1 - \frac{t_4}{t_3}\right)^{\frac{1}{t_4}} . \quad (21)$$

Based on the fault tolerance trust and healthiness trust mention above, physical trust of CPSSP's device can be defined as:

$$PT(\mathfrak{S}^{id}) = \varpi_2 \times FT(\mathfrak{S}^{id}) + (1 - \varpi_2) \times HT(\mathfrak{S}^{id}) . \quad (22)$$

where, ϖ_2 is a weight with constraint $0 < \varpi_2 < 1$.³

4.5. Recommended Trust Relationship Computation

In an open network environment, it is impossible for the CDM sponsor to understand all of the various CPS services. To understand the strange CPS services, the sponsor can utilize the recommendations from their acquaintances. As a result, we introduce a recommended trust to initialize the relationship between CDM sponsor and strange CPSSP. Recommended trust is built up through an intermediate CPSSP that has beliefs with both CDM sponsor and the strange CPSSP.

For CDM sponsor \mathfrak{R} and two CPSSPs SP_1 , SP_2 , if $BR^{\mathfrak{R}}(SP_2) = 0 \wedge BR^{\mathfrak{R}}(SP_1) \neq 0 \wedge BR^{SP_1}(SP_2) \neq 0$ and $\exists \mathfrak{S} \in SP_2 \wedge BD^{\mathfrak{R}}(\mathfrak{S}) \neq 0$, the recommended trust ($RT^{\mathfrak{R}}(SP_2, \mathfrak{S})$) is:

$$RT^{\mathfrak{R}}(SP_2, \mathfrak{S}) = \alpha(BR^{\mathfrak{R}}(SP_1)) + \beta(BR^{SP_1}(SP_2)) + \gamma(BD^{SP_1}(SP_2, \mathfrak{S})) . \quad (23)$$

where α , β , and γ are parameters which are set by the system to demonstrate the importance degrees of different trust values for recommended trust.⁴

For CDM sponsor, recommended CPSSP is an unfamiliar service provider with full confidence. So we propose a confidence conformation factor for recommended CPSSP based on objective reputation with impartial nature. We suppose that there are d intermediary CPSSPs SP_i^{in} recommending

² Here, the length of each unit of time is same as the length of delay period in formula 19.

³ In this paper, the parameters of weight σ_i , ϖ_1 and ϖ_2 in formula 9,12 and 22 are given by system in advance.

⁴ $\alpha, \beta, \gamma \in [0, 1], \alpha + \beta + \gamma = 1$

same CPSSP SP to CDM sponsor. The confidence conformation factor $\phi(SP)$ of the recommended CPSSP SP is as follows:

$$\phi(SP) = \frac{(\sum_{i=1}^d (RT^{\mathfrak{R}}(SP) \cdot RR(SP_i^{in}))) \cdot RR(SP)}{\sqrt{\sum_{i=1}^d (RT^{\mathfrak{R}}(SP)_i \cdot RR(SP_i^{in}))^2} \times \sqrt{\sum_i (RR(SP))^2}} \quad (24)$$

In our consideration, confidence conformation factor $\phi(SP)$ aims to show the similarity between recommendation trust and recommended CPSSP's reputation. So formula 24 is proposed based on Cosin method which is widely used to calculate similarity between two vectors. We give an example here to present our formula. Let there be 3 CPSSPs SP_1 , SP_2 and SP_3 who recommend same CPSSP SP_4 to sponsor \mathfrak{R} . Related values of trust and reputation are given in table 3. According to formula 23 and 24, we can calculate the recommended trust ($RT^{\mathfrak{R}}(SP_2, \mathfrak{S})$) and confidence conformation factor $\phi(SP)$ as follows,

Table 3. Example of recommended trust

	$BR^{\mathfrak{R}}(SP)$	$RR(SP_i)$	$BR^{SP_i}(SP_4)$	$BR^{SP_i}(SP_4)$	$RR(SP_4)$	RT	$\phi(SP)$
SP_1	0.9	0.95	0.95	0.9		0.955	
SP_2	0.8	0.85	1.0	1.0	0.95	0.94	0.99
SP_3	0.9	0.95	0.9	1.0		0.94	

Here, we appoint the parameters value of α , β , and γ as 0.3, 0.3 and 0.4 respectively.

5. Service Selection Negotiation for CPSSP

In order to make the best decision, CDM sponsor always wants to find the most competent services. Capacity and trust represent two critical aspects for candidate services. Our service selection mechanism is based on the principles of capacity and trust.

CDM sponsor selects desirable services from candidate services based on the CPSSPs' applications for decision tasks. As a result, negotiation between sponsor and CPSSP is a feasible solution. Negotiation would render both CDM sponsor and CPSSPs opportunities to query, discuss, explain or revise the decision tasks.

First, we define a set of message primitives for negotiation as follows.

- $send()$: sending a message.
- $reject(a,b)$: informing to reject event a and sending event b .
- $Send_value(a,value)$: sending the value of event a .
- $Accept()$: sending a set of acceptable events to the other.
- $revise(a,b)$: revising the event a and modifying it to event b .
- $query(a)$: querying the state of event a .

Our service negotiation selection mechanism consists of 12 steps as follows:

Step1: CDM sponsor decomposes the complex decision problem according to the structure relationship in semantic $\aleph.SR$ and forming sub-problems semantic sub_N_i of \aleph .

Step2: CDM sponsor sends sub_N_i to CPSSPs who have belief relationships $BR^{st}(SP_k) \geq \vartheta$ through primitive $send(sub_N_i)$ ⁵. And CPSSPs who receive the sub_N_i also transmit sub_N_i to sponsor's strange CPSSPs with well-deserved belief relationships.

Step3: While CPSSPs receive sub_N_i , they reply CDM sponsor whether the tasks would be accepted. If sub_N_i is acceptable, CPSSP would send a message $Accept(sub_N_i)$ to CDM sponsor. Otherwise, CPSSP would send a message $reject(sub_N_i)$ to CDM sponsor to inform that CPSSP would surrender the opportunity to take part in sub_N_i .

Step4: If a CPSSP wants to recommend another CPSSP SP to CDM sponsor, it uses $send(SP.\aleph)$ to send message and recommend the service \aleph of CPSSP SP to CDM sponsor. While sponsor receives such recommendation, it will query the recommended CPSSP SP through primitives $query(SP.\aleph)$ and $send(sub_N_i)$ to inform decision task and confirm if SP would take part in CDM.

Step5: All the affirmative services from different CPSSP SP_k send their service semantics through $send(\aleph_j)$ to CDM. For each candidate service semantics \aleph_j , sponsor computes evaluation scores of $capacity(\aleph_j)$, $AT(\aleph_j)$, $BD^{st}(\aleph_j)$, $RR(SP_k)$, and $PT(\aleph_j)$. Moreover, sponsor computes scores of $RT^{st}(\aleph_j)$ for the recommended services.

⁵ Here, ϑ , ζ and ρ are thresholds given in advance.

Step6: Sponsor selects candidate services \mathfrak{S}_j for each sub_N_i with $capacity(\mathfrak{S}_j) \geq \zeta$. If no \mathfrak{S}_j is selected for a decision task sub_N_i , sponsor selects the \mathfrak{S}_j who has the maximum value of $capacity(\mathfrak{S}_j)$. The selected services are in a set Γ .

Step7: Sponsor sends messages $reject(\mathfrak{S}_j)$ to the CPSSPs whose services are not in Γ .

Step8: For service in set Γ , sponsor sends messages with primitive $revise(\mathfrak{S}_j^{id}, plan)$ to CPSSPs to ask for the detailed revising plans.

Step9: Upon revising claims, CPSSPs will determine whether modify their plans. If CPSSP modify the plan, it sends the new plan with $revise(\mathfrak{R}, plan)$ to sponsor. Otherwise, it sends the rejection claim $reject(\mathfrak{R}, plan)$ to sponsor.

Step10: Sponsor repeats the negotiation steps 8 and 9 until at least one service in set Γ modify its plan.

Step11: Sponsor re-computes all $capacity(\mathfrak{S}_j)$ of services in set Γ after negotiation and selects the services \mathfrak{S}_j satisfying constraint $capacity(\mathfrak{S}_j) + AT(\mathfrak{S}_j) + BD^{\mathfrak{R}}(\mathfrak{S}_j) + PH(\mathfrak{S}_j) \geq \rho$ or $capacity(\mathfrak{S}_j) + AT(\mathfrak{S}_j) + RT^{\mathfrak{R}}(\mathfrak{S}_j) + PH(\mathfrak{S}_j) \geq \rho$. For the services that do not satisfy the constraint, sponsor rejects them and removes them out of set Γ .

Step12: For each decision sub-problems sub_N_i , sponsor selects the services \mathfrak{S}_j as the final victor with the maximum reputation values of CPSSP $RR(SP_k)$. If the selected service is a recommended one, sponsor computes its confidence factor $\phi(SP)$. If $\phi(SP)$ is acceptable, sponsor ascertains that the recommended service is victor. Otherwise, sponsor selects the second highest value of reputation.

6. Proposed Framework

In summary, we propose a framework of service selection for CDM in CPS. Our service selection mechanism is shown in Figure 2. In the figure, blue lines indicate the releasing of sponsor decision making task semantics, the dashed lines indicate the negotiation between sponsor and CPSSPs, and red lines indicate the services from CPSSPs in selection process. As shown in Figure 2, there are three phases, which are the semantic based capacity evaluation for CDM sponsor, trust computation of CPS, and the negotiation selection of CPSSP. In the first phase, the formal semantic of complex

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decision task is described through ontology in sponsor machine. Each CPSSP analyzes the decision task semantic and generates participator instruction according to its service capacity and physical environment automatically. Moreover, CPSSP sends the participator instruction to the CDM sponsor. In the second phase, trust computation is launched when the sponsor receives all the participator instructions from CPSSP. Trust computation consists of two steps: trust evaluation for virtual software service and trust evaluation for physical service objects. In the last phase, CDM sponsor would negotiate with CPSSPs and identify the most competent CPSSP participants through trust and capacity criterions.

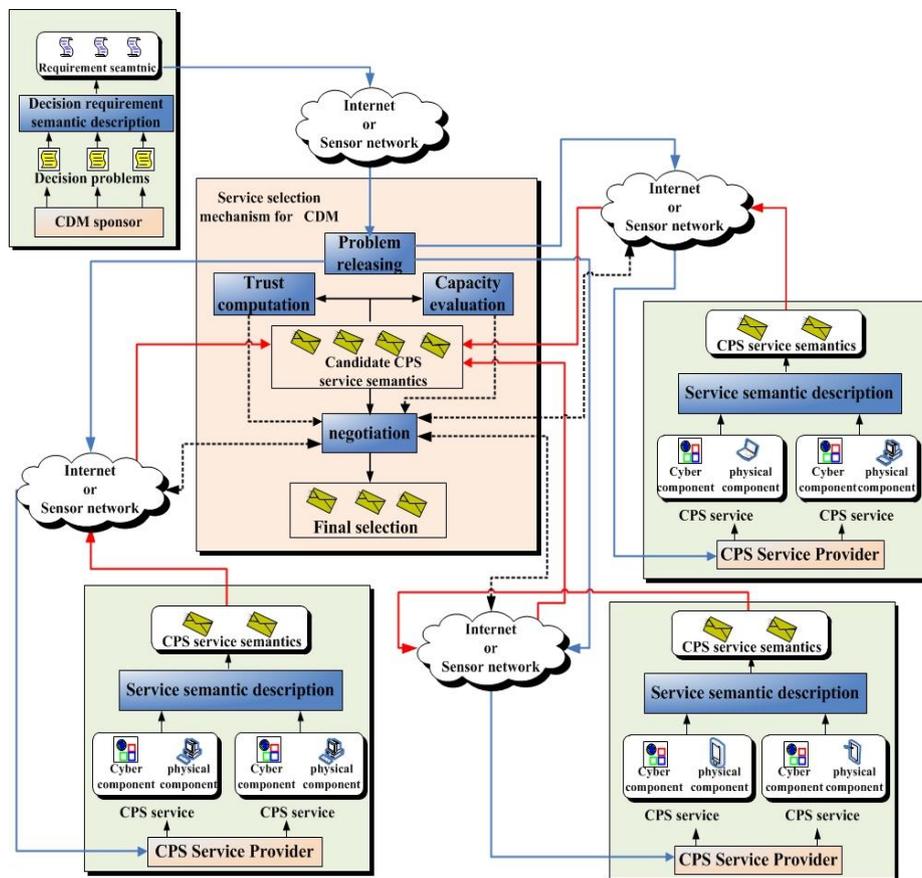


Fig.2. Service selection mechanism from CPSSP for CDM

CPS service selection framework aims to enable CDM sponsor to identify their desirable service from candidates automatically in virtual and physical environment. It comprises 6 elements as follows.

- 1) Semantic description is responsible for representing semantic of sponsor's requirements and CPS's services.

2) Asynchronous message communication is responsible for the e-communication among organizations.

3) Capacity evaluation of CPS's service provides the capacity reference value.

4) Trust computation offers trust reference value.

5) Negotiation activities are the protocols for negotiation during decision making. The negotiation is divided into 6 steps: handshake negotiating, releasing of user's requirements, negotiating conformation of requirements, negotiating exchange of service plans, and negotiating revising of plans, final service selection.

6) Other functions mainly include service rules, data storage, physical environments watch, and device log maintenance.

Currently, in order to exhibit and examine the effects of our framework, we are working on the implementation of a real-world application: smart connected cars. We utilize the capacity and trust evaluation of cyber software and physical device proposed in our framework of this paper to select CPSSP, such as car or on board device that best fits the service requirements. This work can be used in smart vehicle scheduling or smart traffic controlling.

7. Conclusion

CDM-based CPS service now faces the embarrassment to identify the most competent services from candidate sets due to insufficient prophetic knowledge for a specified decision making. In this paper, we utilize the capacity and trust computation for the service selection. Our methodology comprises three phases. First, capacity evaluation of decision service is achieved based on formal semantic description of decision problem and CPS service's software as well as physical characteristics. Second, we address the trust computation composed by service's software activity, subjective belief trust, objective reputation, physical trust and recommended trust. Based on above two criteria, we present an automatic negotiation framework for service selection. Our future works will focus on the challenges that have not been discussed in this paper as following:

- Measure the trust value for the dynamic environments and statuses of cyber and physical components in CPS.
- Measure the service's activity trust based on the nature of activity, just like logic, motivation or consistency of activity.
- Define how trust evolves in a dynamic setting.

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