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# A Comprehensive Theory of Multi-Aspect Interaction with Cyber Physical Systems

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## *Abstract*

*Interaction with Cyber physical systems (CPSs) greatly differ from traditional human computer interaction. A theory that could explain multi-aspect interaction with cyber physical systems and would facilitate the implementation of highly interactive CPSs is needed. This paper tries to make the first steps in this direction and to provide insights for a necessary new theory. Four kinds of interaction which play a crucial role in the operation of CPSs and four fundamental aspects of interaction (i.e. levels, domains, contexts and modalities) are introduced. The theory explains both the aspects and the various constituents that should be considered. The novelty of the theory is in that it establishes relationships between the four aspects and supports the specification of wishful interaction profiles. Finally, a practical case of robot assisted smart bathroom is used to show how the theory can systematize and rationalize the designing of interaction with CPSs.*

**Keywords:** *Cyber-physical systems, comprehensive interaction theory, multi-aspect interaction, interaction levels, interaction domains, interaction modalities, interaction contexts*

## 1. Introduction

### 1.1. Challenges of Interaction with High-End CPSs

As highly integrating computation with physical entities and processes, Cyber Physical Systems (CPSs) could penetrate social world, even human mental world to provide services. CPSs offer services to human through the interaction among human, system, subsystems, agents, devices and software, *etc*. [1] However, CPSs feature heterogeneous components, adaptiveness, context awareness, distributed and decentralized, and multi-scale operation, all of which distinguish interaction with CPSs from traditional human computer/machine interaction.

Interaction is an evergreen topic. It always comes along when there is a change either in the involved entities and their relationships, or in the objective and context of interaction. In order to achieve optimal interaction, typically there is a need to change the reasoning model or paradigm of interaction. This happened in the past when human-human interaction (HHI) has been complemented by human-tool interaction and human system interaction (HSI). In the latter case, there are various forms of human involvement, for instance, operator, agent, and benefiter. It can be claimed that the role of human being is changing as the systems are changing. As more intelligent systems (*e.g.*, CPSs) are implemented, we can also challenge designing and using system-human interaction (SHI). This is the situation when, in home care application, an assistive robot may initiate interaction with a patient based on its autonomous decisions (*e.g.*, notify other family members, call an

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emergency cab, or displace the patient to a different room). We are moving toward the age when unsupervised system-system interaction (SSI) will be a daily reality. As shown in Figure 1, the above mentioned types of interaction can be arranged according to agents that initiate the fulfillment of a particular objective through the interaction.

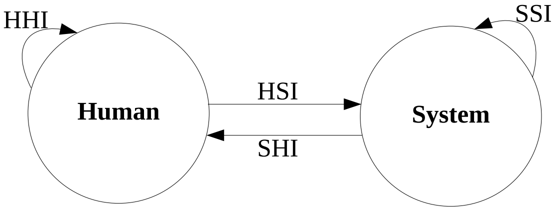

**Figure 1. Four Types of Interaction**

Multiple relationships lie inside and outside CPSs (see Figure 2). Human (users), personal profile and societal profile of users, artificial environment and artificial environment related to system operation are typical constituents of a CPS. Interactions with the CPS are detailed as follows:

- HSI: Similar to traditional HCI/HMI, users achieve certain goal by manipulating and commanding CPS. More modalities will be involved in interaction with CPS, and interaction through various modalities may be simultaneous.
- SHI: By indentifying situations and being aware of context, CPS integrate and coordinate physical ware (analogue physical hardware and digital computing hardware), cyber ware (information, contents and computing software) and synergic middleware to provide human services actively.
- SSI: Data transmission in system and among subsystems also should be seen as SSI. Furthermore, pattern recognization which is realized by analyzing and reasoning data captured from subsystems is also one kind of SSI.
- HHI: When using CPSs, interaction among users and that with the society should be considered when designing interaction with CPSs.

As more heterogeneous actors, internal and external relationships are involved in CPSs operating, and complexity of interactions with CPSs exceeds traditional HCI and HMI. Furthermore, to penetrate real life process and environments to provide service, physical entities and process are deeply merged with ubiquitous computing in CPSs. This interweaves human, devices, environments, cyber wares, and makes interaction more intricate [2].

### 1.2. Objectives and Outline of this Paper

The primary objective of the research reported in this paper is to identify new challenges posed by the emergence of CPSs and to gain insight in the phenomenon of interaction with CPSs which covers a wide range of engineered systems. It also intends to address some of the new conceptualization and development issues that system developers, users, and other stakeholders face. The aim of the first phase of the research is to construct a sufficiently comprehensive theory that can frame and underpin various methodologies for designing interaction with and efficient interfaces for CPSs.

This paper is organized into the following sections that build on each other. In the next section, we discuss the lessons learnt from traditional human-computer interaction and review the progress of human computer interaction in CPSs development. In Section 3, we use the reasoning model proposed in Figure 3 for a detailed investigation of the aforementioned aspects, and blends the aspects of interaction into a comprehensive body of knowledge. In Section 4, we validate the theory through RAIB case study. The last section discusses our conclusions and propositions, as well as future research possibilities.

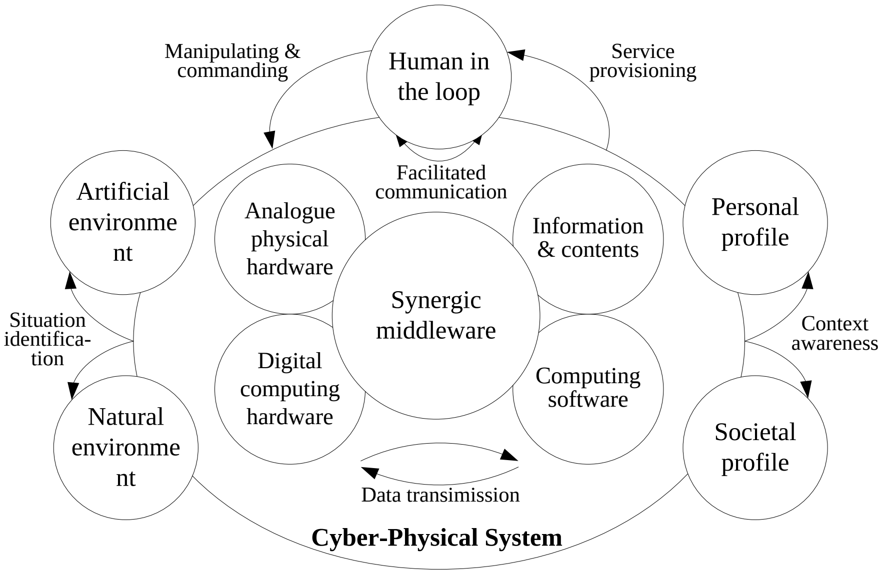

Figure 2. Interaction Areas of CPSs

## 2. Literature Review

### 2.1. Traditional Human-Computer Interaction and Human-Machine Interaction

To interpret the interaction between human and computer, researchers tried to capture and construct some models which document communication task hierarchically from the view of users and tasks. GOMS (Goals, Operations, Methods, and Selection rules) models human computer interaction process with user’s goals, actions and sequences of actions to achieve the goals, as well as the method selecting rules [3]. Norman [4] approximately describes human computer interaction with four stages: forming the intention, selecting an action, executing the action, and evaluating the outcome. While activities in the first two stages are mental for the most part, execution involves physical activities to operate machine. In the last phase, results of actions are evaluated, and the evaluation is used to direct further activities. Nielsen [5] proposes a seven-layered protocol model of computer-human interaction, and makes a comparison of proposed model and Moran’s Command Language Grammar model, Foley & van Dam’s 4-design model [6], and Buxton’s model [7]. All the 4 models agree on the distinction between the "visible" part of the dialogue (defined by its form) and the "invisible" part (defined by the meaning). Most of the differences between these models result from the placement of the question of screen layout and some low level issues. These models enable the separation of technical features of new devices from the conceptual features.

On the other hand, models are proposed to interpret human machine interaction (HMI) which is often used interchangeably with HCI. Boy [8] proposed that HMI could be represented by describing human factors, machine factors and interaction factors. In doing so, Boy developed the AUTOS framework, where human factors are user factors(U), machine factors are artifact factors (A), and interaction factors combine task factors(T), organizational factors and situational factors(O&S). With these five factors, ten interactivities are introduced to present HMI, which are task and activity analysis (U-T); information requirements and technological limitations (T-A); ergonomics and training (procedures) (A-U); social issues (U-O); role and job analyses (T-O); emergence and evolution (A-O); usability/usefulness(A-S), situation awareness (U-S), situated actions (T-S), and cooperation/coordination (O-S). Rasmussen [9] proposes a model to explain the behavior of a human operator controlling a complex dynamic system. This model is organized into three levels of behavior: skill, rule, and knowledge. In skill level, dynamic systems acquire information with sensors, and act upon environments with effectors. In rule level, systems recognize situation and then create situation based tasks, and plan procedures to execute tasks. In knowledge level, systems indentify the situations, and make decision and plans with specialized knowledge.

The reviews above readily reveal that comprehensive theories and frameworks for designing interaction with CPSs are barely visible in literature. Traditional human computer/machine interaction models take human dominance for granted, as they only interpret interaction phases and resources from the view of human and task, neglecting user’s profile and emotions. As a result, these models are too partial to be adopted in the context of CPSs where non-human objects are equivalents to human and actively initiate interaction. For the reason of these deficiencies, theoretical model and design frameworks from the holistic and general view of interaction with CPSs are urgently needed. Our research revises and advances traditional interaction models, contexts, and modalities, and propose domains of interaction to integrate these four aspects into a comprehensive theory of interaction with CPSs.

### 2.2. Progress of Human Computer Interaction in CPSs Development

Interaction with CPSs is radically affected by features of CPSs, including, among other things, ubiquitousness, adaptiveness, resilience, context awareness. However, there is no comprehensive theories and design model for interaction with CPSs. To tackle these issues, researchers and developers adopted some human computer interaction methods when designing CPSs. Some case dependent practices are presented as follows.

To provision service based on context—awareness in smart environments, Gouin [10] gathers the contextual information which includes user profiles, environment topology, device profiles, and service profiles. Cook [11] presents and empirically validates algorithms that can visualize and analyze sensor data collected in a smart space to detect multi-people social interaction. The established algorithmic approach to interaction analysis includes visualization of sensor event density, automatic detection of close-proximity interactions, and automatic recognition of activities that involve resident interaction.

To fight against traffic congestions, emergencies and accidents, reveal inefficiencies in transportation infrastructures, Dimitrakopoulos [12] proposes the concept of internet-connected vehicles Intelligent Transportation Systems, in which vehicles and objects of the transportation infrastructure are connected through an all IP-based infrastructure, capable of exchanging information directly or indirectly and appropriate for resolving several kinds of issues.

To fulfill the vision of “Pervasive Healthcare” or healthcare to anyone, anytime, and anywhere by removing location, time and other restraints while increasing both the coverage and the quality, Varshney [13] develops an application, termed comprehensive health monitoring, using wireless networking solutions of wireless LANs, ad hoc wireless networks, and, cellular/GSM/3G infrastructure oriented networks to monitor users and patients, to manage incidents and accidents, to detect certain health conditions by touchable terminals, to provide a patient or healthcare provider accesses to current and past medical information. Wood [14] develops a living assisting and residential monitoring system—AlarmNet, which integrates environmental, physiological, and activity sensors in a scalable heterogeneous architecture to enable context-aware protocols that are tailored to residents' individual patterns of living.

Human system interaction in current case dependent CPSs are mostly traditional HCI based, technical issues related, and particular for ad hoc application area. For that, interaction solutions of these researches are far from satisfaction, *e.g.*, muliple-user system interaction is not supported [10, 15, 16], defined interaction modalities are too limited to adapt to wider users and cannot collaborate each other to acheive certain objective [13, 17], and user experience is not considered [11, 18, 19]. For this, a generic interaction design model and framework is urgently needed. Our research propose modalities mapping, more higher interaction level (*i.e.*, apobetic level which related user experience), and emotional domain of interaction to develop a comprehensive theory of interaction with CPSs.

## 3. A Comprehensive Theory

Our forerunning literature study explores that there are four aspects that have strong influence on the interaction, *i.e.*, the level, domain, context and modalities of interaction (shown in Figure 3). There are intrinsic relations among these aspects. Our intention is to: (i) explore and explain the relationships among these aspects, (ii) characterize interaction with CPSs in terms of these aspects, and (iii) consider various levels, domains, contexts, and modalities in a reasoning model.

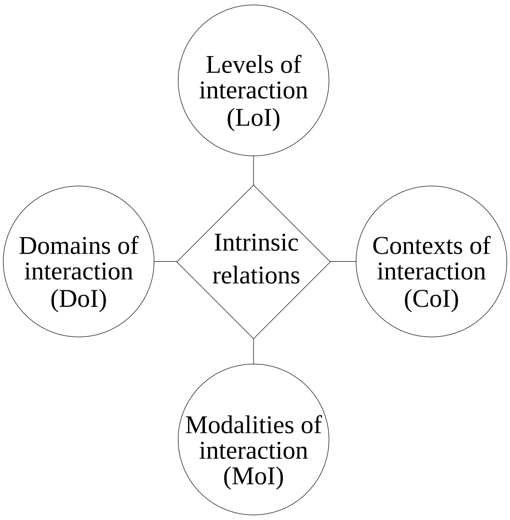

**Figure 3. Four Aspects of Interaction with CPSs**

### 3.1. Possible Levels of Interaction

Based on information theory from Gitt[20], five levels of interaction can be identified. As shown in Figure 4, information is presented and transmitted through low level interaction which based on physical or syntactic processing actions. Then, transmitted information is analyzed and synthesized to reach a comprehension through interaction in semantic level. With the assumptions that interaction actor always pursues a goal, regardless information sender or recipient, the goal of interaction is expected completed on the pragmatic level, and the concern is the way of executing the intended actions. Finally, on the apobetic level, the intended purpose of interaction, the achievement of expected results, and the positive reflections and experiences are the concerns of interaction.

In physical level, signals are transmitted and received with support from physical devices and environments. Physical entities and environmental factors are premises and basis of interaction.

In syntactic level, actors acknowledge the signals, such as the flashing signal lanterns, and the sound of water flow, *etc*. then try to understand the meaning of these signals. For human, it is a mental process. On the other hand, the output modalities of a system, *i.e.*, displayers, signal lanterns, component movements, and sounds should be considered carefully with respect to the available input modalities of human, as well as the rules that information representing should comply with. If actor A and Z can interpret what was communicated by syntax, interaction enters next level.

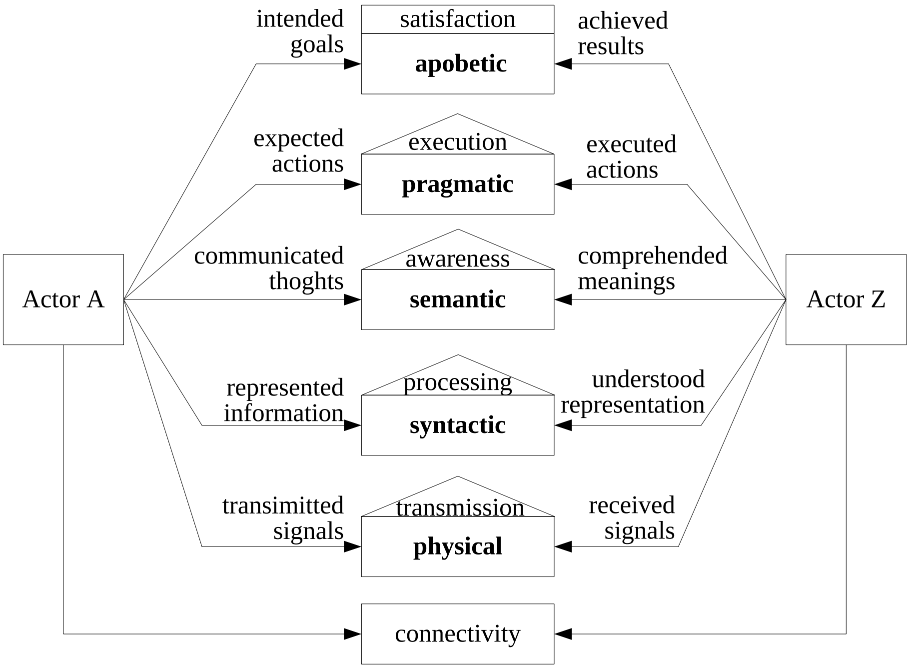

**Figure 4. Levels of Interaction**

In semantic level, actors understand the meaning of the outputs of a system, and then make a plan for interaction. The combination and metaphor of the outputs of a system is the focus of the design. If actor A and Z are aware of the meaning of what has been communicated, interaction enters next level.

In pragmatic level, actors execute a concrete interaction activity to interactive object, mostly, with the form of speech, hand gesture, and body movement, *etc*. That means, actors should complete what was communicated by doing some activities. With evaluation to the results of interaction, if actors' intention of communication is achieved, and actors are satisfied with the results and interaction process, then we come to apobetic level. With the moving of interaction from low level to high level, the goal of interaction will be achieved.

### 3.2. Domains of Interaction

Interaction domain refers to intellectual activities that be involved in interaction [21]. In perceptive domain, a mode or modality refers to receiving stimuli from a particular sense. Then, these stimuli are analyzed and synthesized in cognitive domain to form information for making a plan for peculiar activities executed in motor domain. At the end and during the process of interaction, actors may have some feelings to the interaction—this happen in emotional domain.

When interacting with simple and traditional systems, we can typically identify a dominant domain, which is usually accompanied by certain activities in the other domains. For instance, browsing pictures with an image browser is perceptive dominant and accompanied by operating the software to switch photos which is interaction in motor domain. Reading an E-book is a cognitive dominant interaction, but operating the E-book reader that running on computer or mobile devices needs motor interaction [12]. Turning on a tap is dominantly a motor interaction, but knowing the status of the tap and the rules of how to turn on it are perceptive and cognitive interaction involved. Affected by a movie is emotional interaction dominant, which realized by the perception and cognition to the plot. However, in the case of CPSs, interaction in the four domains is usually needed simultaneously and in a well-balanced manner. As indicated in Figure 5, these domains blend into a hybrid interaction domain.

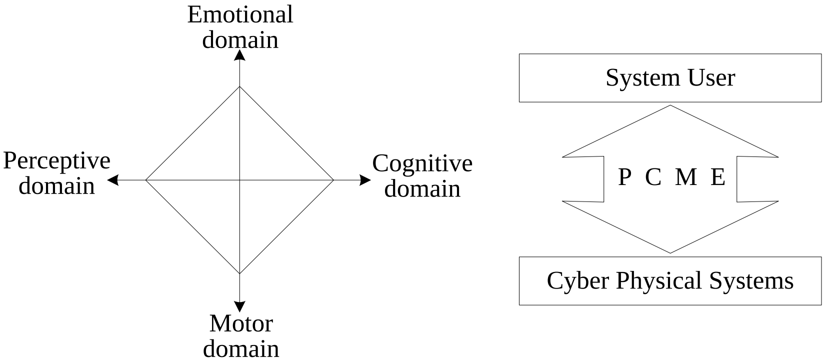

**Figure 5. Interaction Based on a Balanced Integral use of Domains**

All human interaction domains could be mapped into CPSs. In perceptive domain, systems sense environmental conditions and user's activities with sensors, and then analyze and synthesize the collected data in middleware to know the situation and to make a decision on it. After that, some of the components will operate according to the decision—that is motor interaction. One might say that the systems, non-human objects, and agents could not have emotions, but we will often be pragmatic and say that they do have, even though always neglected by human. For CPSs, emotional interaction could be based on the evaluation to the interaction results, and used as advices to improve and optimize the systems.

### 3.3. Contexts of Interaction

All interaction proceed and finish in certain space, time, location, with certain actors involved, certain goals to achieved, and some rules or conventions are followed. The compositions of some of these factors constitute the context of interaction. In the work that first introduces the term "context-aware", Schilit [23] refers to context as location, nearby person, hosts or objects, as well as changes of them over time. Brown [24] tailors the information such as location, time, season, temperature and so forth into several aspects of user's context. Chen [25] adds time context such as time of a day, week, month, season of the year, and time zone into above viewpoint. Based on above concepts, Baldauf [26] introduces physical attributes of human into context additionally. Dey [27] gives a more accurate definition—any information that can be used to characterize the situation of an entity (*i.e.*, a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves.). Based on users‘intents, Zheng[28] develops a intent system to discover and integrate services.

Aforementioned concepts and definitions of context are proposed under the premise of human-computer interfacing or human-computer interaction. In CPSs, more elements and factors involved in interaction should be included. Besides the things referred in heretofore studies and researches, social contexts, implicit factors, more detailed user contexts and environmental contexts should also be remarked.

Contexts in CPSs could be described as: all physical, environmental, spatial, temporal and social entities and factors involved in interactions, the attributes, characteristics, features, status, dynamic changes of them, and the implicit factors, such as goals, rules, approaches, procedures *etc*.

As the essence of interaction is information acquiring and feedback giving, the ease and difficulty of information acquiring have tremendous influences on interaction. According that, contexts could be categorized into two types: explicit and implicit (see Table 1).

**Table 1. Explicit and Implicit Contexts of Interaction**

| **Categories** | **Explanations** | **Affects on interaction** | **Instances** |
|---|---|---|---|
| Explicit contexts | Objects of which information could be sensed, detected and explored directly and easily. | The fundamentals and necessaries to support interaction. | Robot, human being, spatial information of a bathroom, humidity, and temperature, etc. |
| Implicit contexts | Factors that should be perceived by prediction, deduction, analysis and synthesis etc. | Influence fluentness and effectiveness of the interaction. | Potential user needs, emotions, and attitudes, etc. |

Explicit contextual information includes objects, temporal, spatial, and environmental factors *etc.*, which could be sensed, detected, explored by actors directly and easily, and configuration data which are required to support system operating. On the other hand, implicit context awareness involves synthesis, analysis, reasoning, prediction, and making decision etc. Interaction involves explicit context is the basic and low-level interaction which could be automation. During this kind of interaction, according to the defined rules, system directly gives feedback correspond to captured information. Interaction involves implicit context is high-level interaction which will result in smart solution. In this kind of interaction, based on low-level interaction, system synthesizes and analyses captured data to understand the situation, then deduces the optimal solution.

### 3.4. Modalities and Channels of Interaction

As the threshold of interaction, modalities determine what and how information is transmitted. Interaction modality refers to the type of communication channel used to convey (output) or acquire (input) information. It also covers the way an idea is expressed (output) or perceived (input), or the manner an action is performed (output) [29]. For human, we experience external stimuli through sight, hearing, touch, and smell, and give feedback through speaking, facial expressions, gesture, and body movements *etc.*, [30]. Traditional human computer interface convey information with graphics and text, sound, and vibrations, which correspond with human vision, audition, and tactile sense [31]. Human computer interaction communities traditionally pay most attention on researches that enable computers to receive instructions through intermediate equipments (such as mouse, keyboard and touch screen, *etc.*,) and middleware that could recognizing and analyzing human speech, facial express, behaviors, and brain waves, *etc*. Recently, multimodal human computer interaction (MMHCI) arises to study information processing of multimodal combination, such as the combination of vision and audition, to which, multimodal fusion and fission are key problems to solve [32].

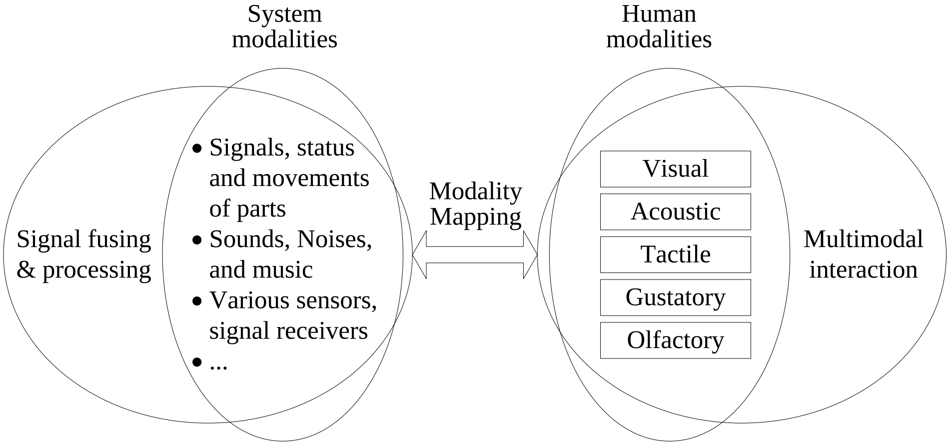

**Figure 6. Modalities of Interaction with CPSs**

In the context of CPSs, equipped with various sensors (input modalities) and more powerful computing abilities, systems could acquire more diversified information, such as humidity, temperature, air pressure, composition of air, and gas density, *etc*. Furthermore, services and information should be provided and represented in accordance with the capabilities of human input modalities (see Figure 6). Assuring the correspondence of modalities of human and system is called modality mapping. For instance, images and texts on the displayer should be accessible to human, frequency of notification sounds should be recognized by human audition, and amplitude and frequency of vibration cannot exceed human perceptual threshold.

### 3.5. Blending the Aspects of Interaction into a Comprehensive Theory

Intrinsic and inherent interrelationships reside among the four aspects of interaction. To achieve certain level of interaction, certain domains and modalities are required, and the ease of achieving this level and which modalities should be involved are affected by interaction context.

To achieve physical level, input modalities of information receiver, such as vision and hearing of human, and output modalities of information sender, such as displayers and operation sounds of a system or the agents, are required to be involved in interaction. Perceptive domain involved in the interaction to percept information. Therefore, the contextual condition should promise the interaction success by afford enough lighting and quietness.

Through syntactic level to achieve semantic level, the rules of display information and procedures of interaction activities (*i.e.*, send information) should be comprehended and assimilated by actor in the domain of cognition.

To achieve pragmatic level, actors should make interaction plan with related knowledge and information at first, which process happened in cognitive domain. Then execute concrete activities (such as say a word, push a button, and make a hand gesture, *etc.*,) to carry out interacting—which happened in motor domain.

Contexts information is determining factors that decide what and how these activities to carry out.

In a context based interaction, an actor receives information (through modalities in perceptive domain), analyzes it and makes a plan (with cognitive and analysis abilities in cognitive domain), execute an interactive activity (through modalities in motor domain), then enter in next loop, receives feedback information, analyzes and evaluates received information, makes a plan… Experience in every step and on the whole process will result in certain emotions (activities in emotional domain) to an actor. If goals are achieved and actors have positive feelings about interaction, then, apobetic level is achieved.

The influences that context has on interaction are vary, which are reflected in modalities choosing and involvements, as well as interaction domains involvements. Explicit contexts, such as information related to lightness, temperature, and detectable objects could be obtained by interaction involves a certain modality, such as vision or optical sensor, temperature sense or sensor, vision and tactile or identifier. The obtaining process usually proceeds in perceptive domain. Implicit context, such as meaning of a sound, user’s statues, and meaning of combination of signals should be processed in cognitive domain which requires analysis and synthesis to information obtained by multiple modalities.

Interactions in perceptive domain are processes of information acquiring by modality, such as vision, auditory, and various sensors, *etc*. In cognitive domain, actors analyze and synthesize information obtained by multiple modalities, then make a plan to execute interactive activities. In motor domain, concrete interactive activities are carried out. In emotional domain, actors have the feelings of whole experiences of interaction process, which will affect the interaction efficiency and user satisfaction to CPSs.

## 4. Validation

### 4.1. Application case to Validate the Theory

To validate the proposed theory, RAIB will be used to examine the appropriateness of the theory. After that, we will check if the theory could provide sufficient information for interaction design (IxD) with CPSs, and illustrate the implementation of the design methodology in the case of RAIB.

Robot Assisted Intelligent Bathroom in nature is a Cyber Physical System. Compared with traditional bathroom, it has more advanced functions, such as perceiving the environments and contexts, understanding human language, logical reasoning, and leaning the knowledge to achieve the goal. All of these functions claim the sensors that could observe the situation in the bathroom, the software that could fuse the captured data to make logical reasoning and decision, and the actuators that can execute certain function according to the decision.

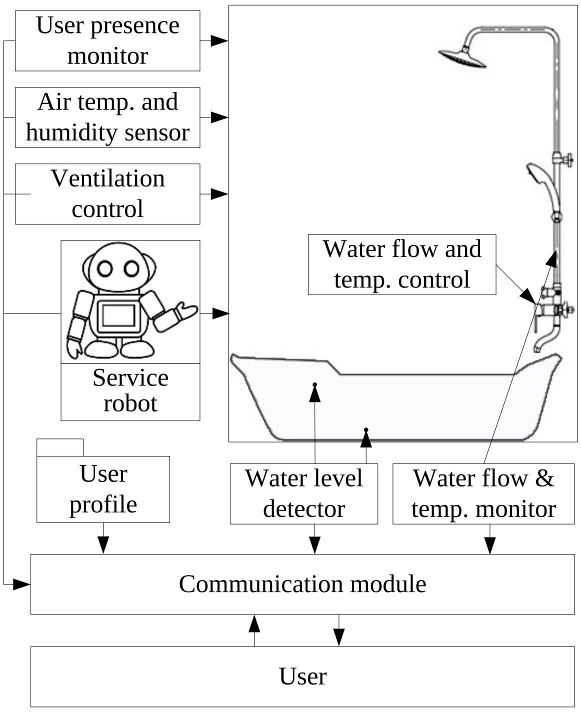

Figure 7. Application Case: A Robot Assisted Intelligent Bathroom

As shown in Figure 7, air temperature and humidity sensors are adopted to perceive the local environment. A user presence monitor is used to sense if there is human in the bathroom. Water flow, temperature and level monitors to sense water information. To penetrate user daily life and social life to provide adaptive service, system needs store user profile, such as agenda, healthy conditions, and preference to water flow and temperature. These data also could be read from external data source, such as smart phone and personal health record database. All perceived information and data of user profile are transmitted to communication module to be shown or sensed by user, and then adjust ventilation, local temperature, water flow and temperature according user’s command or usage history. As an intelligent agent of the system, service robot equipped with various sensors and has the ability to receive command from user (through speech) and perceive context information (*e.g.*, there are too much water on the floor after user taking bath), and provide service accordingly (*e.g.*, to carry something for user or clean bathroom).

### 4.2. Appropriateness Validation with a Challenging Application Case

To validate the appropriateness of the proposed theory, a scenario of interaction with RAIB was used as an exemplification, in which we consider the process of taking a bath.

With the intent of taking a bath, firstly, user needs to switch on shower or facets, and then adjust water flow and temperature. During this process, user percept the water flow by vision and sound, sense water temperature by sense of touch and temperature—this is physical level interaction with input modalities, which occur in perceptive domain. Before adjust water flow and temperature, user should to understand the meaning of current status of the regulator, and the relations between the status of regulator and flow and temperature of the water—this is syntactic and semantic level interaction occurred in cognitive domain. This understanding may come from prior knowledge or learned from some tries in which user try to understand the mechanism of RAIB by investigating and analysis—also syntactic and semantic level interaction in perceptive and cognitive domain. After user has the related knowledge, he could make a plan to switch the regulator to achieve his goal. Then, he switch the regulator in accordance with his knowledge to get the water flow and temperature he wants—this is pragmatic level interaction with output modalities, which occur in motor domain. When doing all things above, user has some kind of feelings about the ease of adjusting water flow and temperature with regulator, and after bath, he will have a whole experience of this bath taking process—this is apobetic level interaction which occurred in emotional domain. All of this interaction steps and phases are affected by context. If lighting (explicit context) is not enough for user to see (visual modality) the location and status of regulator clearly, or, if the user is a blind (explicit context), other modality should be adopted. If big noise outside bath room (explicit context), or user thinking other things or talk with other people (implicit context), then user may fail to make the correct plan of regulator operating, or fail to understand the meaning of the status of the regulator—these are syntactic level interaction and semantic level interaction occurred in cognitive domain. In pragmatic level, user may fail to operate the regulator successfully, for the reason that his/her hands are too slippery (implicit context), don’t have enough strength to operate it (implicit context), or can’t hold the regulator result from Parkinson's disease (explicit context), which in turn block the interaction in motor domain. If user have a good mood (implicit context) when taking bath, no matter for what reasons, then the apobetic level will be reached easily through interaction in emotional domain.

### 4.3. Sufficiency Validation for Design Methodology Development

There have been some examples of intelligent bathroom developed under previous researches [33-35]. When developing the concepts and prototypes of these instances, designers and engineers considered human system interaction on the basis of traditional human computer interaction design theory and methods, which results the intelligent bathrooms that either featured the functions that do not meet user needs or have interfaces that cannot enable fluent interaction between human and systems. The proposed theory tries to solve these problems by inspecting the interaction from the new viewpoint of levels, contexts, domains, and modalities of interaction. Some benefits it will bring to designers and engineers are shown in Table 2.

**Table 2. Improvements can be Achieved by Using the New Theory**

| **Aspects** | **Benefits** |
|---|---|
| Levels of interaction | Pragmatic. Meet user needs with the intelligent functions.<br>Apobetic. Satisfy and entertain users through using and interacting with the system. |
| Contexts of interaction | Explicit. Consider the temporal, environmental, and spatial factors, and user profile, etc.<br>Implicit. Consider user needs, emotions and attitudes, etc. |
| Domains of interaction | Deploy the perceptiveness, reasoning, executing, and affecting of the system. |
| Modalities of interaction | Modality mapping. Adapt systems to user abilities of information receiving and activities performing. |

When using traditional interaction design methods, system designers and engineers just considered the physical, syntactic, and semantic levels of interaction, *i.e.*, the communication channels of information, the representing of the information, and the meaning of the representing. By comparing with this, the proposed theory offers some new implications on the pragmatic and emotional issues, *i.e.*, how to meet user need with the intelligent functions and how to satisfy and entertain users through using and interacting with the system.

The contexts are categorized into explicit contexts and implicit contexts which are not covered in traditional interaction methods, and provide a new viewpoint of the contextual issues in interaction design. When these two kinds of contexts being considered, designers will be inspired in designing the context awareness of the system to achieve advanced system features.

The proposed theory gives some insights on the domains of interaction, which could be seen as the requirements of the resources of the actors. With this, designers could be clearer on how to deploy the perceptiveness, reasoning, executing, and affecting of the system.

Modalities are not only the channels human used to communicating with systems, but also various sensors systems used to capture data and information. This gives birth to a new way to consider the communication between human and system, named modality mapping which supply a clearer vision on how systems adapt to user abilities of information receiving and activities performing.

## 5. Conclusions and Future Research

The intricate and unclear interrelations among components, systems, subsystems, and users of CPSs result in that designing interaction with CPSs is a challenging work. Literature review on traditional HCI and HMI and review on the progress of interaction design in CPSs development result in the conclusion that traditional human computer interaction models and design methods are not suitable for designing interaction with CPSs. To tackle with this, we propose a new reasoning model of multi-aspects interaction with CPSs, in which interaction levels, interaction domains, interaction contexts, and interaction modalities should be taken into consideration in design process. The intrinsic relationships lie in the four aspects and elements in each aspects are discussed and explained, based with we construct a new interaction theory and give the methodological implications of the theory. To give a clearly explanation we interpret the theory with an example of Robot Assisted Intelligent Bathroom.

The paper proposed the multi-aspect theory which could be a framework for designing interaction with CPSs. Obviously, elaborating design process and steps to construct a standard design procedure need more research, as well as the implementation of the design procedures. Moreover, some design tools are needed to tackle with the complexities lie in the interaction with CPSs. The following recommendations are offered for future research:

- Methods to elaborate interaction levels are needed to explain the transition of interaction from lower level to higher level.
- Models to illustrate the composition of the domains are needed to define the domains involved in each interaction level.
- Criteria and guidelines for modality selecting should be constructed in a specific interaction context.
- Methods of prototyping interaction with CPSs should be built to help designers express their ideas.
- Methods and criteria for design evaluating should be proposed to finalized design processes.

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## References

[1] I. Horváth and B. H. M. Gerritsen, "Outlining Nine Major Design Challenges of Open, Decentralized, Adaptive Cyber-Physical Systems", ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, **(2013)**.

[2] T. Koskela and K. Väänänen-Vainio-Mattila, "Evolution towards smart home environments: empirical evaluation of three user interfaces", Personal & Ubiquitous Computing, vol. 8, no. 3-4, **(2004)**, pp. 234-240.

[3] K. Stuart Card, T. P. Moran and A. Newell, "Computer text-editing: An information-processing analysis of a routine cognitive skill", Cognitive Psychology, vol. 12, no. 80, **(1980)**, pp. 32-74.

[4] D. Norman, "Stages and levels in human-machine interaction", International Journal of Man-Machine Studies, vol. 21, no. 84, **(1984)**, pp. 365-375.

[5] J. Nielsen, "A virtual protocol model for computer-human interaction", International Journal of Man-Machine Studies, vol. 24, no. 3, **(1986)**, pp. 301-312.

[6] J. D. Foley and A. Van Dam, "Fundamentals of interactive computer graphics", Reading, MA: Addison-Wesley, **(1982)**.

[7] W. Buxton, "Lexical and pragmatic considerations of input structures", Computer Graphics, vol. 17, no. 1, **(1983)**, pp. 31-37.

[8] G. A. Boy, (Ed.), "The handbook of human-machine interaction", A human-centered design approach Ashgate Publishing, Ltd., **(2012)**.

[9] J. Rasmussen, "Information processing and human-machine interaction: an approach to cognitive engineering", North-Holland series in system science and engineering, **(1986)**.

[10] C. G.-Vallerand, B. Abdulrazak and S. Giroux, "A context-aware service provision system for smart environments based on the user interaction modalities", Journal of Ambient Intelligence and Smart Environments, vol. 5, no. 1, **(2013)**, pp. 47-64.

[11] D. J. Cook, A. Crandall and G. Singla, "Detection of social interaction in smart spaces", Cybernetics and Systems: An International Journal, vol. 41, no. 2, **(2010)**, pp. 90-104.

[12] G. Dimitrakopoulos, "Intelligent transportation systems based on internet-connected vehicles", Fundamental research areas and challenges(C)//ITS Telecommunications (ITST), 11th International Conference on. IEEE, **(2011)**, pp. 145-151.

[13] U. Varshney, "Pervasive Healthcare and Wireless Health Monitoring", Mobile Networks & Applications vol. 12, no. 2-3, **(2007)**, pp. 113-127.

[14] A. Wood, J. A. Stankovic and G. Virone, "Context-aware wireless sensor networks for assisted living and residential monitoring", Network, IEEE, vol. 22, no. 4, **(2008)**, pp. 26-33.

[15] J. C. Wang, H. P. Lee and J. F. Wang, "Robust environmental sound recognition for home automation", Automation Science and Engineering, IEEE Transactions, vol. 5, no. 1, **(2008)**, pp. 25-31.

[16] M. Bezold and W. Minker, "A framework for adapting interactive systems to user behavior", Journal of Ambient Intelligence and Smart Environments, vol. 2, no. 4, **(2010)**, pp. 369-387.

[17] M. Tentori and J. Favela, "Activity-aware computing for healthcare", Pervasive Computing, IEEE, vol. 7, no. 2, **(2008)**, pp. 51-57.

[18] D. Zhang, Z. Yu and C. Chin, "Context-aware infrastructure for personalized healthcare", Studies in health technology and informatics, vol. 117, **(2005)**, pp. 154-163.

[19] M. Mansoorizadeh and N M. Charkari, "Multimodal information fusion application to human emotion recognition from face and speech", Multimedia Tools and Applications, vol. 49, no. 2, **(2010)**, pp. 277-297.

[20] W. Gitt, "In the beginning was information", New Leaf Publishing Group, **(2006)**.

[21] P. Dourish, "What we talk about when we talk about context", Personal and ubiquitous computing, vol. 8, no. 1, **(2004)**, pp. 19-30.

[22] J. R. Gersh, J. A. McKneely and R. W. Remington, "Cognitive engineering: Understanding human interaction with complex systems", Johns Hopkins APL technical digest, vol. 26, no. 4, **(2005)**, pp. 377-382.

[23] B. Schilit, N. Adams and R. Want, "Context-aware computing applications", Mobile Computing Systems and Applications", WMCSA 1994. First Workshop on IEEE, **(1994)**, pp. 85-90.

[24] P. J. Brown, J. D. Bovey and X. Chen, "Context-Awareness Applications: From the Laboratory to the Marketplace", IEEE Personal Communications, **(1997)** October, pp. 58-64.

[25] G. Chen and D. Kotz, "A survey of context-aware mobile computing research", Technical Report TR2000-381, Dept. of Computer Science, Dartmouth College, **(2000)**.

[26] M. Baldauf, S. Dustdar and F. Rosenberg, "A survey on context-aware systems", International Journal of Ad Hoc and Ubiquitous Computing, vol. 2, no. 4, **(2007)**, pp. 263-277.

[27] A. K. Dey, "Understanding and using context", Personal and ubiquitous computing, vol. 5, no. 1, **(2001)**, pp. 4-7.

[28] C. Zheng, W. Shen and H. Ghenniwa, "An Adaptive Intent Resolving Scheme for Service Discovery and Integration", Journal of Universal Computer Science, vol. 20, no. 13, **(2014)**, pp. 1791-1812.

[29] J. Coutaz, "Multimedia and Multimodal User Interfaces", A Taxonomy for Software Engineering Research Issues". In Proc. Second East-West HCI conference, **(1992)**, pp. 229-240.

[30] M. Turk, "Multimodal interaction: A review", Pattern Recognition Letters, vol. 36, **(2014)**, pp. 189-195.

[31] B. Dumas, D. Lalanne and S. Oviatt, "Multimodal Interfaces: A survey of principles, models and frameworks", In Human Machine Interaction. Springer Berlin Heidelberg, **(2009)**, pp. 3-26.

[32] B. Schuller, M. Lang and G. Rigoll, "Multimodal emotion recognition in audiovisual communication", In Multimedia and Expo, 2002. ICME'02. Proceedings. 2002 IEEE International Conference, vol. 1, **(2002)**, pp. 745-748.

[33] S. Mann, "Intelligent bathroom fixtures and systems: EXISTech corporation's safebath project", Leonardo, vol. 36, no. 3, **(2003)**, pp. 207-210.

[34] A. Bujnowski, A. Palinski and J. Wtorek, "An intelligent bathroom", In Computer Science and Information Systems (FedCSIS), 2011 Federated Conference, **(2011)**, pp. 381-386.

[35] W. Maass, T. Kowatsch, S. Janzen and A. Filler, "Applying Situation-Service Fit to Physical Environments Enhanced by Ubiquitous Information Systems", In ECIS, 221, **(2012)**.

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