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iCPS-Car: An Intelligent Cyber-Physical System for Smart Automobiles

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***Abstract*—Automobiles are becoming increasingly important in our daily life. However, people usually need to cost lots of efforts and time to get their required services. On one hand, an automobile itself consists of many physical processes to achieve its traditional functionality; on the other hand, it is being integrated with more and more sensors and actuators, which makes it a typical cyber-physical system. In order to provide friendly and human-centric services for users, we proposed the Intelligent Cyber-Physical System for automobiles (iCPS-Car) for automobiles. iCPS-Car integrates people, cars and cyber spaces together and provides natural interaction manners, and personalized and continuous services. A prototype, along with several applications such as remote surveillance, gesture-based control, media migration, was built and evaluated to verify the efficiency of iCPS-Car. The prototype car has been exhibited on Beijing Auto 2012.**

Keywords-iCPS-Car; natural interaction; personalization; continuity

I. Introduction

Cyber-Physical System (CPS) is a system featuring a tight combination of, and a coordination between, the system's computational and physical elements. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa [1]. CPS has brought great influence to many application domains, such as healthcare, process control, transportation, etc.

A typical cyber-physical system is cars and its surroundings. Varieties of sensors deployed in cars provide abundant information for users in the cyber space, and in the physical space the unprecedented prosperity of hardware is no doubt coming. Plenty of information emerges in the cyber space when people interact with cars and in-car devices in the physical world. By integrating the computing, communication, and storage capabilities of the abundant information about users' actions with the monitoring and/or control of the in-car devices [2], CPS recognizes the users' requirements and provides services for users according to their intentions. The tight integration of the cyber space and physical processes help people to get rid of traditional complex operations during the interaction between people and cars. CPS creates opportunity of promoting the friendliness of the interaction between people and cars.

Nowadays people usually need to cost lots of efforts and time to get their required service. Given that CPS can integrate computation and physical processes, it is required to provide friendly and human-centric services by improving the link of cyber spaces and physical spaces. To meet this requirement, there are many challenges to overcome:

a) *Interactivity.* The traditional interaction between people and in-car devices depends on control panels, knobs and other traditional manners, and even some complex operations. The traditional interaction manners are inflexible and limited in space to a great extent.

b) *Personalization.* The traditional system can't automatically provide services according to users' intentions and preferences. Users usually need to take some operations to get their required service, which costs users lots of efforts and time.

c) *Continuity.* Some services cannot be continuous between cyber spaces and physical spaces. The services are often interrupted by users' movements or information loss.

To address these challenges, we develop an Intelligent Cyber-Physical System for smart automobiles (iCPS-Car) to provide users friendly and human-centric services. In iCPS-Car, information is ubiquitously embedded in automobile electrics and surroundings. The user with his/her surroundings and cars are pervasively connected. Interaction modalities between cars and users are more diverse and natural. The system provides personalized and right services according to users' intentions and preferences. The services between cars and other entities are continually accessible within a distance and a period of time. "Computing and Intelligent Services for Human" is the most prominent characteristic of iCPS-Car, which is a human-centric intelligent system with harmonious integration of people, cars and cyber spaces.

II. Related Work

In order to integrate computation and physical processes, many cyber-physical systems (CPS) have been developed [3, 4] in the automotive industry. With the wide use of the abundant information in the cyber space and the advance in hardware technology, many approaches have been proposed to overcome the challenges: interactivity, personalization and continuity.

1) Interactivity

Mark Weiser proposed that ubiquitous intelligence requires easier human-computer interaction that is adaptable for people's interaction idiom [5]. Some projects have proposed natural ways for users to interact with cars, such as gestures, tactile sense, voice. For example, the gestural interface for vehicles [6] not only makes it easier for the

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driver to carry out some tasks but also increase safety by significantly reducing visual demand and the cognitive workload. A vibro-tactile waist belt was also designed to give turn-by-turn instructions by using the tactile perception of the human skin [7]. Mercedes-Benz introduced the first generation of Linguatronic [8], a speech-based command and control system for cars. The speech system allows completely hands-free operation of the mobile phone.

2) Personalization

Some projects have been proposed to provide personalized service. For example, Affective Intelligent Driving Agent (AIDA), a new in-car personal robot developed by MIT researchers, can not only read the driver's mood from facial expression but also respond in a socially appropriate and informative way. Moreover, AIDA has a capacity of studying drivers' driving habits and experience, so that it can make important decisions and inferences for drivers. Ford Sync [9] can also provide navigation, traffic and entertainment information according to users' requirements and preferences.

3) Continuity

In some projects such as MirrorLink and Sonnenberg [10, 11], the smart phone is integrated into the smart car. MirrorLink and Sonnenberg integrated the smart phone with the car over WLAN, Bluetooth, USB or DPWS (Devices Profile for Web Services).The smart phone and the smart car are seamlessly connected, and some services and user interfaces can be migrated from mobile devices to car infotainment systems. OnStar allows people to remotely control and monitor their cars by using their smart phones. Integrating smart phones with cars can keep the continuity of services between cyber spaces and physical spaces.

In our iCPS-Car, users interact with cars in intuitive and natural ways. Users' preferences are learned and preserved by the system. Cars automatically provide personalized service according to users' requirements and preferences. The service on the mobile devices can be migrated seamlessly to the car application platforms. The service can automatically adapt to the users' movement and behavior changes to avoid service interruptions.

III. iCPS-Car: A Framework

Our iCPS-Car integrates the cyber space and the physical space into a smart environment. In the smart environment, people and cars are integrated tightly, so that people and cars can friendly interact with each other. The system architecture is shown in Fig. 1. The system architecture of iCPS-Car consists of three modules: Human, Car and Smart Environment. Every module will be introduced in details.

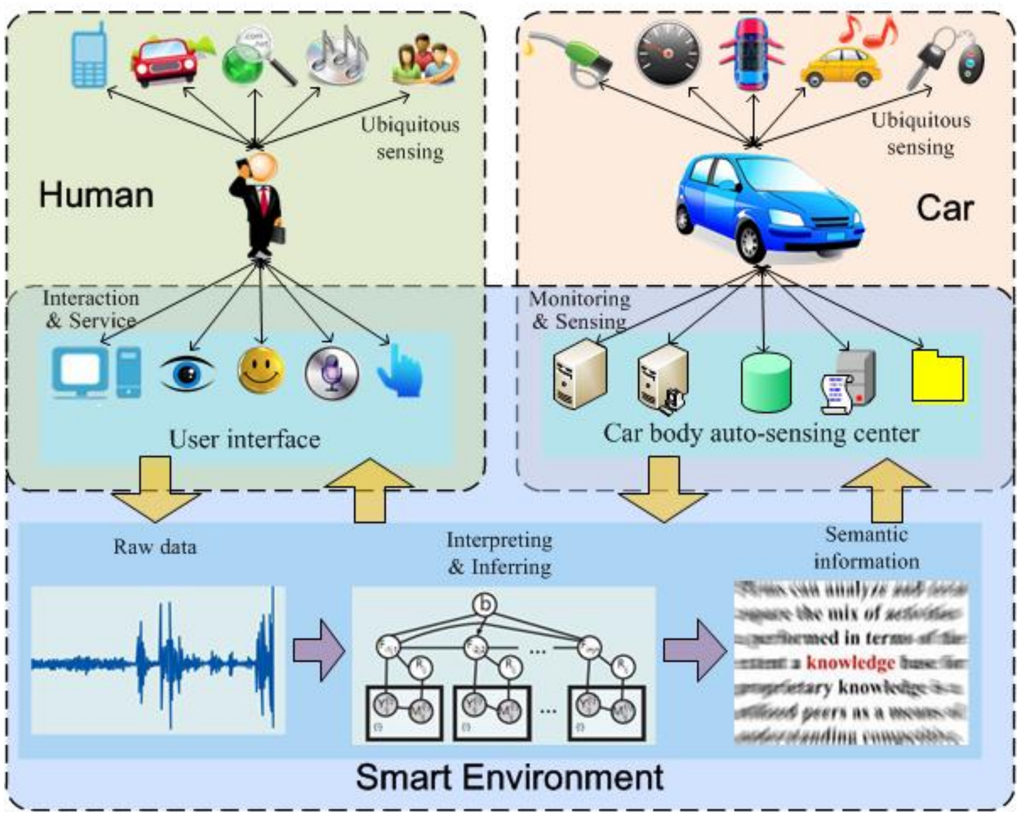

Figure 1. Architecture of Intelligent Cyber-Physical System (iCPS-Car)

A. Human

Given that iCPS-Car is a human-centric intelligent system, Human is the most important factor in the architecture. To provide personalized services, the system should automatically capture the users' requirements and accurately infer their intentions. The model of SmartShadow[12] is used to record life signal of people, including physical signal, social signal, physiological, brain signal, etc. SmartShadow, which is developed by our lab, is a digital shadow of real individuals in the cyber space and mutually aware with the real individuals in the physical space anytime and anywhere.

In iCPS-Car, people's actions are important information for the interaction with cars, i.e. facial expression, voice, gestures, touch actions. In order to improve the friendliness of the interaction, the system allows people to interact with cars in natural and simple ways, such as touch, gestures, etc. The system automatically captures the users' actions and accurately infers the intentions. Users' goals of actions are sent to cars via wireless network and the cars respond timely. The results will be presented in multimodal interfaces. It is needed to engage human perceptual, cognitive and communication skills to understand what is being presented in different modalities, such as visual display, audio, and tactile feedback [13].

B. Smart Environment

The Smart Environment integrates Human and Car together and computes the information in cyber spaces. The intelligence filled with the Smart Environment is the key for iCPS-Car to provide personalized and continuous services. The Smart Environment takes charge of collecting raw data, capturing and inferring intention, interpreting the intention into semantic information.

Firstly, the raw data is the information of cars, people, and people's actions. The raw data includes a wide range of information: context information of users and cars, the current state of the surroundings, etc. Secondly, the users' intention is accurately inferred on the basis of the raw data. The model in [14] is used for context reasoning, which is proposed by our lab. The model is used to generate users' plans with constraints of the current contexts. It is also responsible for replanning once the associated contexts change. Then, the users' requests are specified and interpreted into semantic information or machine-understandable language. Thirdly, the semantic information or machine-understandable language is output to Car or Human. For instance, when people make an up gesture, the gesture will be captured. The user's intention of turning up the temperature can be inferred. Then, the up gesture will be interpreted into the corresponding control command and the command will be sent to Car via wireless communication.

C. Car

Car is pervasively connected with Human via wireless communication in the Smart Environment. In iCPS-Car, Car is an intelligent agent rather than a simple way of transportation. Car has an intelligent capability of automatically perceiving users' actions, so that cars and people can be mutually aware. It can also sense its status by analyzing the collected sensor data.

Based on the intelligent capabilities of cars, people can remotely control and monitor their cars from via natural interaction ways, and cars can automatically provide personalized services for people. In the smart environment, the cars can interact with users in two modes: 1) Passive mode. Cars can respond timely to users' requests. For example, when people push a button on a smart phone to close the door, the car door will be closed timely; 2) Active mode. Cars automatically provide right services according to users' requirements. For instance, cars will keep track of users' preferences and make right plans for users.

IV. iCPS-Car: METHODS AND TECHNIQUES

In iCPS-Car, people and cars are integrated into a smart environment. Based on the integration, iCPS-Car provides natural interaction manners, and personalized and continuous services for friendly interaction between people and cars. During developing iCPS-Car, there are some challenges as mentioned in the first part: interactivity, personalization, and continuity. To overcome the challenges, we should firstly solve the following difficulties:

- *Mutual awareness:* When people leave the cars, they do not know the history information of cars.
- *Natural interactivity:* The traditional interaction relies on control panels, knobs and other traditional manners, which is not nature and inflexible.
- *Accuracy:* If users' intentions and actions are not inferred and recognized accurately, the service provided by the system will be wrong for users.
- *Continuity:* The service is often interrupted by the users' movement, behavior changes or information loss.
- *Data heterogeneity:* There is data heterogeneity between cars and smart mobile devices.

Considering the universality and smartness of a mobile phone, it holds the key to our digital identities, access rights to digital assets, personal communications, and media [15]. Therefore, the smart phone is an ideal tool for the seamless integration of users, cars and the physical environment. By integrating smart phones into cars, we summarize three key technologies to solve the difficulties mentioned above: sensor-based status monitoring and control, gesture-based environmental control, and NFC (Near Field Communication)-based media migration.

A. Sensor-based status monitoring and control

Many people care about their cars when they leave, so they hope the car status is under their control all the time. Given this, we propose sensor-based status monitoring and control. Users can check the history information about cars anytime and anywhere, for example, people can keep a remote surveillance about the in-car surroundings and out-car surroundings, and can check the alarm log according to their needs. Cars will automatically warn people when there are some unexpected things on car body. This technique is summarized into the following modules:

- *Status monitoring module:* The car status can be remotely monitored, such as mileage, the state of car doors (open /closed).
- *Surveillance module:* The job of this module is to keep a remote surveillance about in-car surroundings and out-car surroundings.
- *Lock and control module:* People can control the in-car devices by using smart phones. The smart phone can be used as a key to lock the car doors or windows.
- *Alarm module:* People will be automatically warned if unexpected things happen on cars. People can also check the alarm logs on the smart phone.

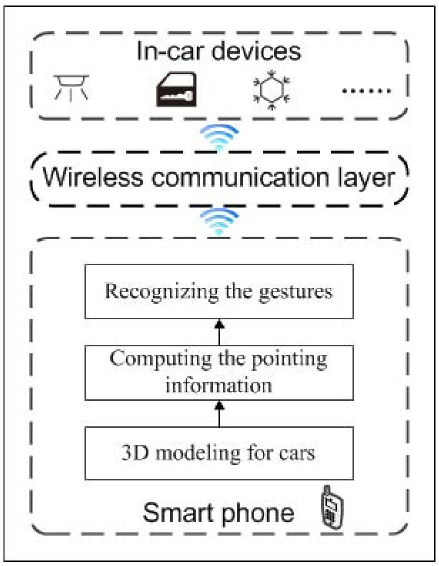

Figure 2. Diagram of gesture-based environmental control

B. Gesutre-based environmental control

Considering the intuitiveness of interaction manners, gesture is a good choice, such as pointing, flinging and shaking. The smart phone is just like a baton, and users can point their phones to any direction in the cars. More specifically, users can select any device to interact with just by pointing to it. The smart phone recognizes users' pointing direction and other gestures with the help of the built-in accelerometer and magnetometer. Gestural commands are simple and natural for users to learn and remember. Interacting with in-car devices via gestures gets rid of the special limits and saves much time. Users' intentions are inferred by accurately recognizing the gestures. We have applied the relevant technology in Smart Home and more details can be seen in [16, 17]. Gesture-based environmental control consists of three parts (Fig. 2):

- *3D modeling for cars:* We stored the 3D modeling of cars and in-car devices in a NFC tag. Besides, we also stored location information of the places seated frequently in tags and pasted the tags in the places people sitting frequently. The users are required to firstly touch the tags with their phones to read the information of the 3D model and the location of the phone.
- *Computing the pointing information:* The smart phone accurately computes the information of pointing direction. And the icon of the device pointed at by the smart phone appears on the phone screen.
- *Recognizing the gestures:* We pre-build recognizable interaction commands and the corresponding gestures of every command for in-car devices. When users get the device they choose, the users move their hands and the gestures are recognized. The corresponding control commands are sent to the devices via wireless communication.

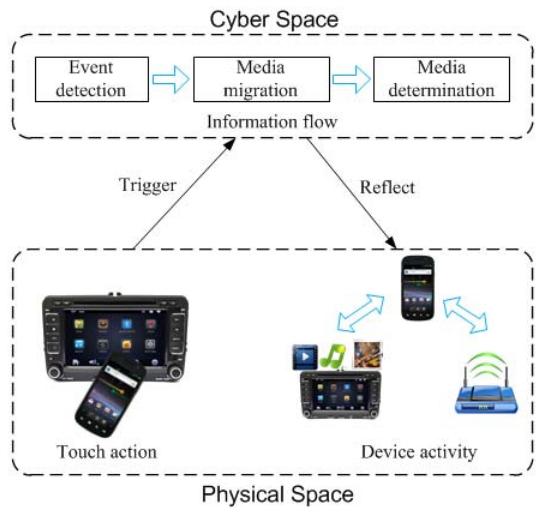

Figure 3. Illustration of NFC-based media migration

C. NFC-based media migration

Services are often interrupted by users' behavior changes or information loss. For instance, when users want the media ongoing on the phones to be continuously played on the car console, it is required to connect the phone to the car console with specialized cables or configurations. Such inconvenience interrupts the continuity of the enjoyment, wastes lots of time, and greatly reduces the media experience. Our NFC-Based media migration (Fig. 3) will help users to continuously play the media on the car. Users seamlessly migrate the media between the car and smart phone just by a simple touch. People can control the media with the smart phone. This method keeps the continuity of media without complex operations. It also successfully solves the data heterogeneity between the car console and the smart phone. Besides, users only need to touch for media migration, which is simple and natural. More details can be seen in [18]. Here, we applied this work in the vehicle environment. This work consists of three steps:

- *Event detection:* The event is captured when users use a smart phone to touch the NFC tag affixed in the car, or take the phone away from the tag. Meanwhile, the smart phone and the car console are connected via wireless communication. Information about the car console stored in the tag is read by the smart phone at the same time.

- *Media determination:* By checking the relevant applications on the phone, such as Music, Video and Gallery, the media being played on the phone is determined. Then, the phone reads the information about this media.
- *Media migration:* The smart phone sends the media information to the car console and the relevant application on the car console is called. After that, the media is played continuously on the car console and can be controlled with the smart phone.

V. PROTOTYPE

A. Prototype

In order to verify the Intelligent Cyber-Physical System (iCPS-Car), we built a prototype. We implemented our prototype on Geely EV8 and Nexus S (Fig. 4).The vehicle system consists of intelligent controller, video surveillance server, and in-vehicle communication. The prototype has been exhibited on Beijing Auto 2012.

Figure 4. The prototype of iCPS-Car

B. Applications

Based on the key techniques mentioned above, we developed relevant applications, such as remote surveillance, remote status monitoring, remote lock and environmental control, remote location, gesture-based control, media migration, navigation migration, etc. We will introduce the applications in details.

1) Remote surveillance

Based on the key technique of sensor-based status monitoring and control, we developed several applications such as remote surveillance, remote status monitoring, remote lock and environmental control and remote location. The basic status of the car can be monitored on the smart phone anytime and anywhere (Fig. 5 (a), (b)), such as mileage, the state of the car doors and windows, etc. The smart phone can also be used as a key to lock the car doors or windows. Besides, the smart phone can be used as a remote controller for remote environmental control (Fig. 5(c)). We can also find our car by the application of remote location. The application of remote surveillance will be introduced in details.

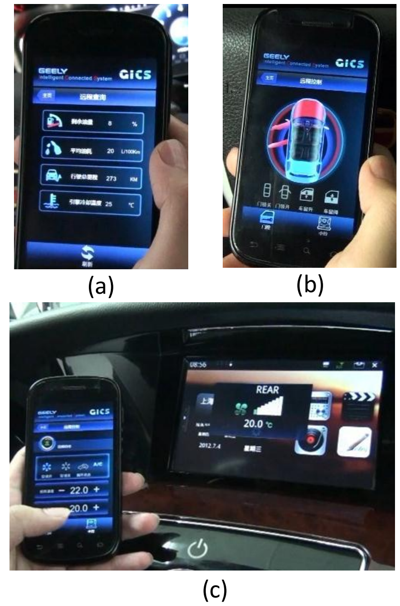

Figure 5. Remote monitoring and control: (a) remote monitoring of fuel consumption, fuel remain, mileage, the temperature of engine; (b) remote monitoring of the car doors: the left front door, left rear door and the front hood are open; (c)remote environmental control: use the smart phone to adjust the temperature of the air conditioner: the temperature of the rear air-conditioner is 20°

Figure 6. Remote surveillance of the out-car

With the application of remote surveillance, users can keep a remote surveillance about their car surroundings in the form of videos and receive alarm in the form of short messages (Fig. 6). For the video surveillance, we deployed one camera in the car and two cameras outside the car, which can rotate up, down, left, and right. The camera shooting is stored in the video surveillance server. The video of the car surroundings is viewed on the phone screen just by pushing a button on the smart phone. The viewpoint can also be adjusted by the smart phones. Cars will automatically warn people in the form of short messages when there are damages to vehicles. People can check the alarm logs on the smart phone.

2) Gesture-based control

Based on the key technique of gesture-based environmental control, we developed the application of gesture-based control. By gesture-based control, users get rid of the traditional control panel and can control the devices via gestural commands at any place in cars (Fig.7). If a user wants to turn up the temperature, he/she firstly points his/her smart phone at the air conditioner. After the icon of the air conditioner appears on the phone screen, the user continuously does the “Up” gesture until the temperature is up to his/her requirement. The most important part of this application is gesture recognition. In order to achieve an effective gesture-based interaction, we followed the requirements described in [16] and designed a set of gestures and commands for devices. We define a six-gesture vocabulary to control the frequently used functionalities of six in-car devices, as listed in Table 1. The gesture of *Forward-Backward* is performed in the *X-Y* plane, and the other five gestures are waved in the *Y-Z* plane.

1) The gesture of *Forward-Backward* is performed as if pushing an ON/OFF switch button on a control panel of in-car devices.
2) The swinging gestures of *Up* and *Down* are very natural to express the meaning of up and down, e.g. volume up/down, temperature up/down.
3) The two gestures of *Left* and *Right* are also natural to represent the meaning of ‘previous’ and ‘next’.
4) The gesture of Clockwise Circle suggests ‘Play’ or ‘Pause’ operations, e.g. stopping a video, continuing to play a video.

All of the gestures we designed are simple and natural. The gesture commands for different devices are consistent, i.e., similar operations of different devices are defined as the same gesture to reduce the size of gesture vocabulary. In this case, the application of gesture-based control employed the algorithm FDSVM [17] to recognize gesture commands from acceleration data.

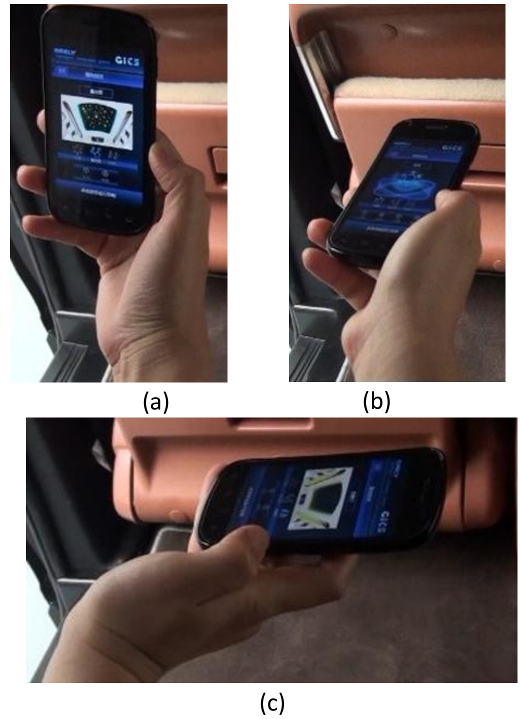

Figure 7. An example of gesture-based control: (a) choose the starlit sky roof; (b) choose the air conditioner; (c) choose the ambience lighting.

Table 1 DEFINITION of GESTURE FOR IN-CAR INTERACTION

In-car Devices	Gesture Commands			
	Forward-backward	Up; down	Left; right	Clockwise
Car door	Open/Close			
Car window	Open/Close	Wind.up Wind.down		
Air conditioner	ON/OFF	Temp.up Temp.down		
Player	ON/OFF	Vol.up Vol.down	Media.prev Media.next	Pause/Play (Media)
Starlit sky roof	ON/OFF			
Ambience lighting	ON/OFF			

Vol, ‘Volume’; Temp, ‘Temperature’; Wind, ‘Window’; Prev, ‘Previous’

3) Media migration and navigation migration

Based on the key technique of NFC-based media migration, we developed the application of media migration and navigation migration.

a) Media migration

With media migration, media can be seamlessly migrated from the smart phone to the car. The touch-driven migration application upon a NFC enabled phone is capable of migrating media from the smart phone to the car console just by a simple touch (Fig. 8). The migration application contains the following parts:

- *Touch&Connect:* Touching the phone with a tag fixed in the car and the phone and the car being connected.
- *Touch&Watch:* Sharing photos and videos to the display equipment and supporting photo reviewing, video playback, and other control commands from the phone.
- *Touch&Listen:* Streaming music played on the phone to the car and supporting the playback progress and other details.

b) Navigation migration

We also developed a navigation migration application, with similar principle of media migration. The route on the phone can be migrated to the car console by a simple touch.

Figure 8. Media migration from the smart phone to the car

We also developed similar applications on Galaxy Tab (GT P7310): remote surveillance, remote status monitoring, and remote location, etc. Given the fact that pad is much heavier and bigger than the smart phone, it is not convenient for users to touch and point with pad. We did not develop the applications of media migration and pointing-based control on the pad. (Fig. 9).

Figure 9.Using the Pad to turn up the volume, and the volume is 15.

VI. EVALUATION

We designed two experiments to evaluate the performance of the applications mentioned above. The first experiment is to evaluate the gesture recognition rate of gesture-based control and the second one is to test the speed of the media migration.

A. The evaluation of gesture-based control

To evaluate the performance of pointing-based control, we collected a data set with six gestures (Forward-backward, Up/down, Left/right, Clockwise circle) of 10 individuals aged 21-25 years over three days, including seven males and three females. The experiment required the 10 participants to perform each gesture for 6 repetitions per day. Thus there were 6 x 3 x 6 x 10= 1080 samples. The result of user-independent gesture recognition test is shown in Fig. 10. Obviously, the recognition rate of all the gesture commands is above 90%. And the recognition rate of Clockwise Circle is lower than the other three groups, which reveals that the complex gesture command is more difficult to be recognized than simpler gesture commands. The result indicates that the gesture should be simple and terse, which is easy be recognized. Compared with the experimental result in [16], our results are a little worse than that. The reason may be that the wireless communication in automotive environment is not so stable as it is in the Smart home.

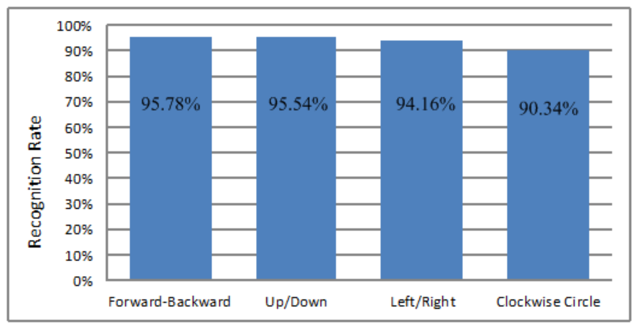

Figure 10. Recognition rate of gesture-based control

B. The evaluation of media and navigation migration

To evaluate the response time of media and navigation migration, we collected a data set of 20 participants aged 20-26 years with diverse education backgrounds. Each participant was asked to perform the following tasks twice, and there were 20 x 2=40 samples. For comparison, it is also required to perform each task in a traditional way, without using the application of media and navigation migration based on NFC.

- *Video migration from a phone to a car console.* The car computer can be connected the smart phone via Wi-Fi. An NFC tag is attached to the steering wheel (Fig. 8). A data cable is also provided to allow wired connection of the phone and the car computer.
- *Navigation migration from a phone to a car console.* The console can be connected via WiFi, and the tag is also attached to the steering wheel. To allow manual input of navigation target, a control panel

with buttons and knobs are provided as a traditional interface.

Fig. 11 shows the average time taken to perform the two migration tasks. We can conclude that the touch-driven approach is about 20 times faster than the traditional methods on average. The reason is that using traditional methods, users have to connect devices, copy files, input URLs and destinations manually. Compared with the traditional methods, our touch-driven migration just needs a simple touch, which is quick and convenient.

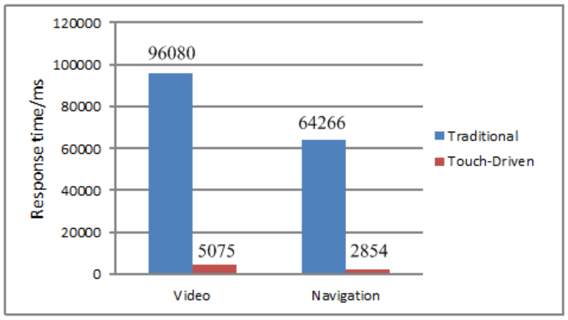

Figure 11.Average time taken to perform the two migration tasks

VII. CONCLUSIONS

In this paper, we proposed the Intelligent Cyber-Physical System for smart automobiles (iCPS-Car) to provide friendly and human-centric services for users. On the basis of the integration of computation and physical processes, iCPS-Car provided natural interaction manners, and personalized and continuous services for users. We built a prototype to verify iCPS-Car and developed several applications based on the prototype to show the efficiency. For the interactivity, people can control in-car devices via gestures, which are simple and natural. The smart phones can be used as a key or a remote controller, which can get rid of the special limit. For the personalization, cars can actively warn users when there are damages to cars. For the continuity, the media and navigation can be seamlessly migrated from mobile phones to cars, and it saves lots of efforts and time. In order to perfect the human-centric service of iCPS-Car, our future work is to deepen the knowledge of human behaviors and mind, and to enhance the communication between cars and other entities.

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