Smarter Wheelchairs Who Can Talk to Each Other: An Integrated and Collaborative Approach

Junjun Kong*†, Jiannong Cao*, Yang Liu*, Yao Guo† and Weizhong Shao†
*Department of Computing, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China
†Key Laboratory of High-Confidence Software Technologies
School of Electronics Engineering and Computer Science, Peking University, Beijing, China
*†kongjj07@sei.pku.edu.cn, *{csjcao, csyangliu}@comp.polyu.edu.hk, †yaoguo@sei.pku.edu.cn, †wzshao@pku.edu.cn

***Abstract*—Pervasive computing technologies can benefit the injured, disabled or elderly people in their daily lives, and smart wheelchair has been a representative of this kind of technologies. However, most existing smart wheelchairs have limitations on extensibility and flexibility of building new functionalities. One big reason is they are just stand-alone ones considering other wheelchairs and surrounding things as dummy objects. To address this issue, we proposed an integrated and collaborative approach: Smarter Wheelchairs that can "talk" to each other, and even "talk" to other things in the surrounding. Smarter Wheelchairs take advantages of smart objects deployed in living environment or hospital environment. Smarter Wheelchairs can harness functions provided by smart objects, therefore, their functionality can be flexibly extended. We have implemented and evaluated a prototype system of Smarter Wheelchairs to demonstrate the feasibility and efficiency of our approach.**

***Index Terms*—Smart wheelchair, Ubiquitous Interacting Object (UIO), collaboration, integration, context-awareness.**

I. INTRODUCTION

The advances in research areas such as computer science, robotics, AI (*i.e., Artificial Intelligence*), and sensor technology significantly broaden the range of applications that can support the injured, disabled or elderly people in their daily lives. Smart wheelchairs have been a representative of this kind of applications since the early 1980s [1]. Some elderly people need an assistive device to move to desired positions, and some injured or disabled individuals also need assistive navigation tools to help them navigate due to their lack of mobility [1], [2]. Consequently, electric-powered wheelchairs (*i.e., powered wheelchairs*) are invented to satisfy their needs of independent mobility. Smart wheelchairs are augmented powered wheelchairs with perception, control, communication and computation abilities, and they have more powerful capabilities in aiding those individuals that might have difficulties in maneuvering commercial powered wheelchairs [3].

A. Smart Wheelchairs

Presently, "smart wheelchairs" adopts technologies previously developed for mobile robots[1], such as obstacle avoidance, autonomous navigation, etc. Some smart wheelchair systems utilize techniques from AI such as path planning, reasoning, behavior-based control (*e.g., human gesture based navigation control*), etc., to assist the users in their daily lives.

Enhanced Navigation. Smart wheelchairs usually use sonar, infrared sensors, etc., to detect obstacles in the surrounding environment for enhancing safety and supporting autonomous navigation [1]. Some researchers employ computer vision techniques to visually detect obstacles or landmarks to assist in navigation [5].

Human-machine Interface. One promising technology to augment smart wheelchairs is computer vision. Cameras are commercially available at pretty low price, and they can be easily mounted at multiple locations on a wheelchair. Some smart wheelchairs already use computer vision as a means of head- and eye-tracking for wheelchair navigation control [1], [6]. These human gestures or activities could be used as the input of smart wheelchairs.

B. Smart Objects

Smart wheelchair itself is a kind of smart object. Smart objects are defined as "autonomous physical/digital objects augmented with sensing, processing, and network capabilities" by Kortuem et. al. [7]. Examples of smart objects include smart keys, smart shoes, smart phones, smart lights, smart watches, etc. Furthermore, many daily objects (*i.e., things or devices in daily environment*) can be converted to smart objects [8]. The concept of smart objects will be very helpful for us to build a smarter wheelchair for well-being of the wheelchair-aided people.

C. Motivations and Contributions

There are some shortcomings in the existing smart wheelchair systems:

- It's difficult to extend their functionalities in that they are designed for dedicated purposes without much consideration of extensibility. Existing systems emphasize on improving safety of navigation by adding sensors and controllers, accessibility to wheelchairs through body gesture, computer vision and speech technologies, but they don't consider much about other needs of the wheelchair-aided people.
- They cannot utilize functions provided by surrounding smart objects by reason that they are stand-alone smart objects and treat surrounding things (including smart

[1]As a result, some researchers named smart wheelchairs as robotic wheelchairs [4].

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objects) as dummy things. These smart wheelchairs don't collaborate with other things or smart objects, which results in that they cannot obtain any benefit from a service-rich smart environment.

To address these issues, we proposed an integrated and collaborative approach: Smarter Wheelchairs that can "talk" to each other, and even "talk" to other things in the surrounding. At the heart of our design is Ubiquitous Interacting Object (*i.e., UIO*), a unified model for heterogeneous smart objects. UIO means the physical entities enhanced by multiple capabilities such as computing, sensing and interacting (*e.g., smart wheelchair is a kind of UIO*). Based on this abstraction, we can build many pervasive computing systems in a more scalable and flexible way through composition of ubiquitous services, and localized and distributed coordination among UIOs. In the forthcoming future, UIOs will be popular and collectively interact to create service-rich environments. We believe that this new paradigm will be popular in the near future when plenty of UIOs are widely used, embedded into daily space, and highly connected. This motivates us to create a smarter wheelchair by considering interaction and collaboration between a wheelchair and its surrounding environment. Smarter Wheelchairs take advantages of smart objects deployed in living environment or hospital environment. They can harness functions provided by smart objects, therefore, their functionality can be flexibly extended.

Contributions of this work are two-fold: (1) a new approach to building smart wheelchairs is proposed, which alleviates the shortcomings of existing systems by adding interacting capability into smart wheelchairs; (2) a prototype of the Smarter Wheelchair is implemented demonstrating feasibility of the proposed approach.

II. System Design

A. Smarter Wheelchair System Overview

The Smarter Wheelchair system structure is shown in Fig.1. One of the major differences between our Smarter Wheelchair and other smart wheelchairs (refer to Section I-A) is its capability of interacting (discovering and talking) with surrounding Smarter Wheelchairs and smart things.

Extensible capabilities of the Smarter Wheelchair can be categorized into four groups: sensing, controlling, computing, and interacting. These augmented capabilities are achieved by adding new components including sensors for sensing, control adapters for controlling, computation modules (mote and laptop computer) for computing, and network interfaces (*e.g., ZigBee, Bluetooth, WiFi*) for interacting.

B. Navigation Subsystem

Safety and performance of wheelchair navigation can be improved by embedding several sensors into the Smart Wheelchair. Ultrasonic sensors and touch switches can be used to detect and avoid obstacles. Accelerometer and gyroscope can be attached to calculate the wheelchair speed and turning angle, which would be helpful in generating indoor map and guaranteeing stability.

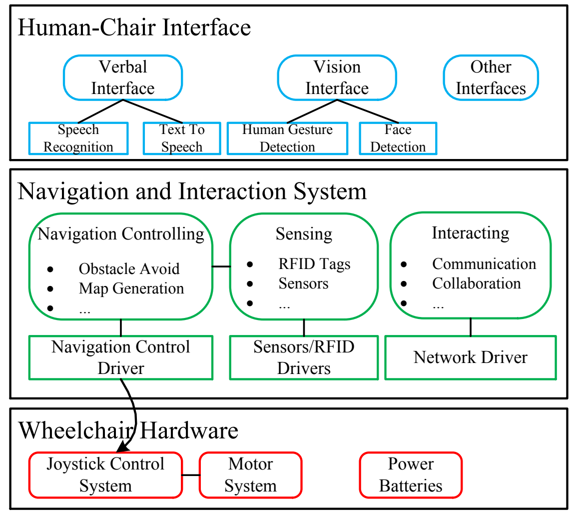

Fig. 1. The Smarter Wheelchairs system architecture. It consists of three layers: (1) wheelchair hardware supplying joystick control, motor system, and power batteries, (2) navigation and interaction system aiming at enhanced navigation and flexible interaction, and (3) human-chair interface for better accessibility of the wheelchair.

Localization and surrounding map generation. Localization and local map can be used to do (semi-)autonomous navigation. Before performing a movement, the Smarter Wheelchair should generate a surrounding map dynamically and make sure there are no obstacles within a safe range. Moreover, in order to obtain its current position, the Smarter Wheelchair integrates an RFID reader to do passive-tag-based localization.

Context-aware operation mode transition. The Smarter Wheelchair has several operation modes to control its movement. A commonly available one for commercial wheelchairs is manual maneuvering with joystick. However, it may not be safe and efficient, because under that mode, safety and performance in terms of time efficiency depend on the operator. In practice, there are a lot of operators who have limited capability to operate a wheelchair [9]. Thus some other operation modes should be introduced to improve safety and efficiency of wheelchair operations. If a smart wheelchair could obtain the map of a building, it can do autonomous navigation if only one destination is given. In this case, the operation mode is named autonomous mode. Other operation modes include wall falling (navigation in the corridor), turning, door passage, co-pilot (collaborative operation), etc. In the Smarter Wheelchair system, a context-aware operation mode transition scheme is adopted to enhance navigation. Navigation control subsystem can automatically transfer current operation mode when the operator issues a new command or the context[2] about navigation changes. Since wheelchairs are mainly designed for disabled people, they will become very helpful to those people if we enhance the functionality of wheelchairs by adding more human-aware and context-aware functions.

[2]Context is defined as "any information that can be used to characterize the situation of entities" by Dey and Abowd [10].

C. Human-Chair Interface

Advances in computer vision and machine speech technologies make it possible to take human gestures or verbal commands as input of a wheelchair to control its movement.

Vision interface. Vision interface makes the Smarter Wheelchair human-aware. It relies on a digital camera placed in the front of the wheelchair and a powerful computer, such as smart phone or laptop (in our prototype, we used a laptop). Potentially, this technology can be useful for human identification, body gesture recognition, and even health monitoring. Face orientation can be used to control movement of the wheelchair. Three different kinds of face orientation should be detected: left, frontal, and right. Two kinds of head gestures can also be recognized: nodding and head-shaking. Both of them are used as command input. For example, nodding stands for agreement (YES), and shaking for disagreement (NO).

Verbal interface. The operator says some words, and the wheelchair can understand and perform some actions accordingly. There are two issues here: converting human speech (human-friendly) into text (computer-friendly) and converting text to human voice, which are named speech recognition and speech synthesis separately. With the help of this interface, human operator can control the wheelchair in a natural way. However, this method has a penalty: longer latency compared with manual maneuvering. Therefore, human-chair interface should work with navigation subsystem collectively to avoid some dangerous conditions and yet pursue better performance.

D. Interaction and Collaboration

The capability of interacting with other Smarter Wheelchairs and surrounding smart objects is the most distinguishable feature of the proposed Smarter Wheelchairs. To accomplish it, a ZigBee-powered module is added to the Smarter Wheelchair. Besides, a lightweight middleware system called UIOCore is developed for discovering neighboring UIOs (including Smarter Wheelchairs and other smart things such as smart light) and supporting collaboration among multiple UIOs. The UIOCore supplies programming interface to applications, and interaction interface to neighboring UIOs. The programming interface makes our Smarter Wheelchair easily extensible, and the interaction interface makes our Smarter Wheelchairs able to use services/functions provided by other smart objects. Taking a smart light as an example, our Smarter Wheelchair can collaborate with it in this way: when the wheelchair detects it's dark, it can actively "talk" to the light asking it to turn on or increase brightness. As we can see, this Smarter Wheelchair can aid the elderly or disabled in a better way, not merely a navigation tool.

III. Implementation

We have implemented a prototype system of the Smarter Wheelchair based on a commercial electric-powered wheelchair, HBLD2-16, manufactured by Shanghai Hubang[3]. Fig.2 shows some photos of the Smarter Wheelchair prototype,

[3]Detailed specification can be found: http://www.hubang.net.cn/en/product

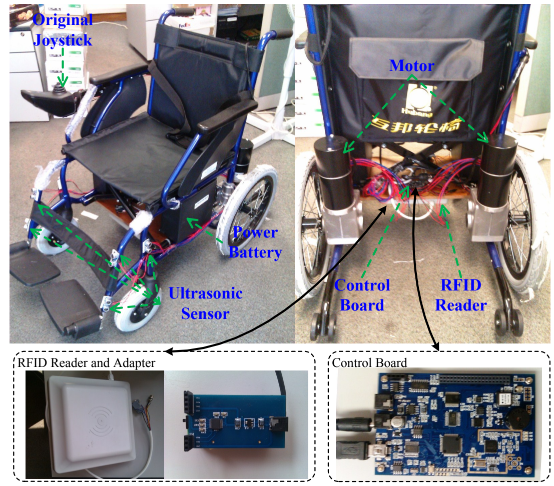

Fig. 2. The Smarter Wheelchair prototype based on a commercial electric-powered wheelchair. This prototype integrates many sensors (including ultrasonic sensor, pressure sensor, accelerometer, gyroscope, touch switch, light sensor, etc.) for enhanced navigation, an RFID reader for indoor localization, and a laptop computer for advanced human-chair interaction.

TABLE I
INTEGRATED SENSORS ON THE CONTROL BOARD OF OUR PROTOTYPE.

Sensor Name	Num	Function
Ultrasonic	8	measuring distance with obstacles
Touch	4	detecting collisions with obstacles
Pressure	1	detecting whether there is a user sitting on the wheelchair
Accelerometer	1	measuring acceleration speed of three dimensions and for calculating speed of the wheelchair
Gyroscope	1	detecting deviation angle of the wheelchair relative to its original direction and guaranteeing accuracy of navigation
Light sensor	1	detecting brightness of indoor environment
Temperature	1	detecting temperature of indoor environment

and its major components are highlighted with blue text. The major components are (1) control board integrating several sensors listed in Table I, (2) RFID reader and adapter, and (3) a standalone laptop computer connected with a digital camera and headphone, which is not fixed on the wheelchair. Both the control board and RFID adapter are enabled by TinyOS (v2.1.0), and the laptop (Fujitsu SH560 with Intel Core i5 processor and 4 GB memory) is powered by Windows 7.

A. Integration

Integration of new components is the basic approach to build smart wheelchairs. New capabilities are added to a powered wheelchair converting it to a smart wheelchair by integrating new hardware and software modules. There are 7 different kinds of sensors embedded into the prototype, and their total number is 17, as listed in Table I.

B. Interaction and Collaboration

Human-wheelchair interaction. We use Java Speech API to program voice control user interface. Text-to-speech feature

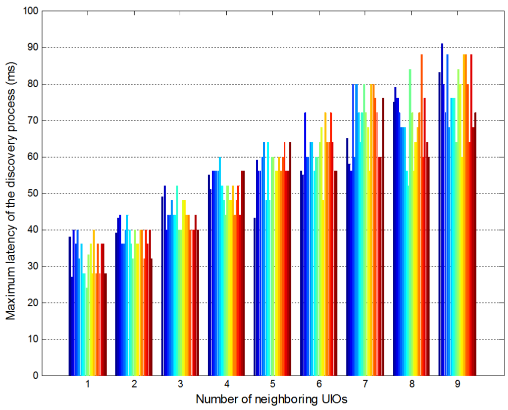

Fig. 3. The UIO discovery latency in total increases linearly as the number of locally discoverable UIOs is from 1 to 9.

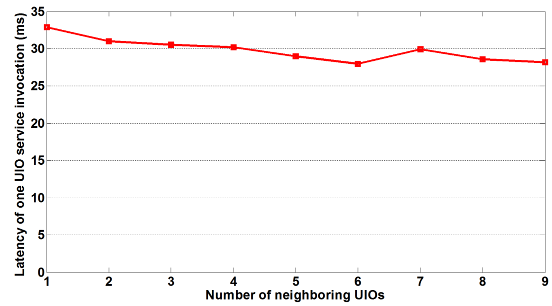

Fig. 4. The average time needed for a UIO service invocation.

is implemented by reusing FreeTTS. Speech recognition is based on a third-party implementation, CMU Sphinx. OpenCV library is used to implement vision interface of the wheelchair UIO. Three categories of human gesture can be recognized, that's hand-waving, face orientation (left, frontal, and right), head gesture(nodding, shaking).

Wheelchair-SO Collaboration. Collaboration between wheelchair and other smart objects (SO) is supported by UIOCore as mentioned in Section II-D. UIOCore is implemented on two different kinds of devices: sensor mote and laptop. Laptop UIOCore can interact with mote UIOCore (SensorUIOCore) via ZigBee network. SensorUIOCore, implemented with nesC, provides fundamental mechanism for device collaboration. SensorUIOCore performs discovery, communication, and SO service discovery and invocation. In our prototype, both the attached RFID reader and control board are powered by TinyOS and SensorUIOCore.

IV. Evaluation

In this section, we briefly evaluate our prototype. Due to the limitation of paper length, we just evaluate the most important and valuable part of the Smarter Wheelchair: UIOCore. The results show that UIOCore performs UIO discovery and UIO service invocation (*a basic mean of collaboration*) efficiently. Fig. 3 shows the performance results of UIO discovery when the number of locally discoverable UIOs is from 1 to 9. The average latency of one UIO discovery is approximately 10 milliseconds. Fig. 4 shows that the average time needed for one UIO service invocation to its neighboring UIOs is about 30 milliseconds. Besides, the prototyped wheelchair can directly interact with UIOCore-powered smart things such as laptop computer, smart light, and RFID reader.

V. Conclusion

In this paper, we proposed Smarter Wheelchairs to overcome the shortcomings of existing smart wheelchair systems. Most existing smart wheelchairs have limitations on extensibility and flexibility of building new functionalities, because they merely consider other wheelchairs and surrounding things as dummy objects. We abstract such smart wheelchairs and other smart objects into a unified model, namely UIO, and as well build a lightweight middleware (UIOCore) based on the concept of UIO. We have implemented a prototype system of Smarter Wheelchairs to demonstrate its feasibility. Preliminary performance results show that UIOCore performs interaction and collaboration efficiently. Further study is needed to explore the potentials of the Smarter Wheelchairs.

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