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A Study on Smart Wheelchair Systems

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Abstract—Many people are suffering of temporary or permanent disabilities due to illnesses or accidents. For cases of difficult or impossible walking, the use of a wheelchair is becoming essential. Manual or electrical wheelchairs are satisfying for most of the low and medium level disability case where patients can use the wheelchair independently. However, in severe cases, it is difficult or impossible to use wheelchairs independently. In such cases wheelchair users often lack independent mobility and rely on somebody else handle the wheelchair. Researchers involved in wheelchair are aiming at designing smart wheelchairs to solve such problems. This paper is to review the recent studies on smart wheelchair systems. It aims to evaluate the current available technologies and to discuss new future directions for our ongoing research project.

Index Terms—Smart wheelchair; artificial intelligence; robotics; Embedded systems; smartphones

I. INTRODUCTION

Asia-Pacific Development Center on Disability (APCD) estimated population of persons with disabilities in Malaysia by 197,519 cases in 2007. Overseas, the Centers for Disease Control and Prevention (CDC) estimated that about 53 million people in America have a disability of some kind. Around two million people of them depend on wheelchairs for day-to-day tasks and mobility. Manual or electrical wheelchairs are satisfying for most cases. However, in severe cases, it is difficult or impossible to use wheelchairs independently [1]. These cases include people with vision problems, Tetraplegia, spinal cord injuries (SCI), Parkinson's or cognitive deficits. Consequently, wheelchair users rely on relatives, nurses or caregivers to help them with the wheelchair. To reduce suffering and the dependency of such users, some companies produce different types of what so called "smart wheelchairs". A smart wheelchair can be defined as a uniquely modified powered wheelchair which is equipped by a control system and variant sensors. It is also can be defined as a mobile robot base to which a seat has been attached [1]. Smart wheelchairs are designed to provide assistance to users in different ways. Its purpose is to reduce or eliminate the user's full responsibility on moving the wheelchair. They arealso designed for a variety of user types according to their situations and disabilities. One drawback of the Smart wheelchairs is the higher price of them comparing with the manual or the simple electrical powered wheelchairs. This paper reviewsrecent smart wheelchair systems.Commercialization issues and price estimation arediscussed.Clinicians and users' attitude toward the smart wheelchair is considered. Finally, new future directions for our ongoing research project are discussed.

II. LITERATURE REVIEW

According to the review paper published by Simpson in 2005 [1], there are many forms for designing a smart wheelchair. Early smart wheelchairs were mobile robots to which seats were added [2, 3]. Currently, most of developed smart wheelchairs are built on by modifying commercially available power wheelchairs[1]. Few smart wheelchairs are designed as "add-on" units that can be attached to and removed from the underlying power wheelchair. All these designs are sharing the same objectives which are: Easing the way the chairs are used, avoiding collisions as much as possible, increasing travel distance and decreasing travel time.

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This section reviews recent smart wheelchair systems according to three properties:
The human – machine interface.
The navigation methods and devices.
Other smart systems.

A. The human – machine interface

The main target of the human – wheelchair interface is to allow the user to control the mobility of the chair in less effort and more robustness and safety. When the patient has a severe situation like people with SCI, special tools might be needed. Moreover, smart wheelchairs may have additional technologies and facilities which need more advanced interfacing.

For mobility control, the joystick is the most common steering control interface for electric powered wheelchairs. Usually the joystick is operated by a stick on a dock. Figure 1 shows the wheelchair joystick controller from Golden Motor [4].

Some wheelchairs use other forms of joysticks. The movement of the head and/or chin is one way to steer the wheelchair as shown in Figure 2-(a) [5]. Tongue is also used in some wheelchairs [6, 7]. In [7], an intra-oral device consists of 18 inductive sensor coils is embedded in two units of 10 layer printed circuit boards (PCB) and connected to third PCB which contains a micro controller, a radio chip, and a battery as shown in Figure 2-(b). The inductance of the sensor coils changes when the user touches the sensor with a ferromagnetic tongue piercing.

Sip-and-Puff is another useful technology. It uses air pressure by "sipping" (inhaling) or "puffing" (exhaling) on a straw, tube or wand to send signals to the wheelchair [8].

Other smart wheelchairs use artificial intelligence techniques like the techniques based on gaze and/or face direction tracking. Such systems track the direction in which a person is gazing and/or the head is turned. One example of how to move the chair is shown in Figure 2-(c) [9]. In this system a stereo camera is used. The user needs looks where he/she wants to go, and to start/stop the movement he/she nod and shake his/her head. The system also estimates whether the user is concentrating on the operation based on the relationship between the head and gaze movement. One drawback of the system is lacking of distinguishing method between an intentional gazing action and when the user is just looking around. Therefore, the user should continuously focus on navigating without letting his/her gaze to go astray or unfocused.

Electroencephalography is also one of the steering methods as shown in Figure 2-(d). It measures and interprets the electrical activity of the brain through electrodes attached to the scalp. It then translates the brain activity in commands to control devices [10].

Voice is also used as an input to control wheelchairs [11]. In such a system voice recognition algorithms is used. When system recognizes the voice, it is classified to one of pre-stored commands. The respective coded digital signals would be sent to a controlling unit which then controls the wheelchair accordingly.

Hand gesture controlled system is another method for interfacing humans and machines. One example is the wireless hand gesture controlled system presented in [12]. Accelerometer is used to translate finger and hand gestures into computer interpreted signals. The accelerometer data is calibrated and filtered.

Smart phones and tablet computers are increasingly becoming popular. They are equipped with many useful built-in sensors. Researchers and developers are recently using these devices for powerful controlling applications as listed in [13]. The applications include robot operating [14] besides to many other application. Wheelchair controlling is one of these applications [15, 16, 17, 18, 19]. Smartphone and its built-in sensors are used to capture and record physical activity of wheelchair users and translate it as orders to a controlling unit which control the chair. For example Authors in [15] use the 3 axis accelerometer present in most smart phones and Bluetooth wireless technology to allow patients to move the wheelchair by tilting the smart phone. The actuators for this concept are controlled by a microcontroller powering a basic servo motor for directional motion and a pair of DC motors for the wheels. Authors in [19] designed applications which can maneuver the wheelchair by receiving commands from the user. Commands to the wheelchair are delivered through the use of tactile and head movement based interfaces developed by using the smart phone.

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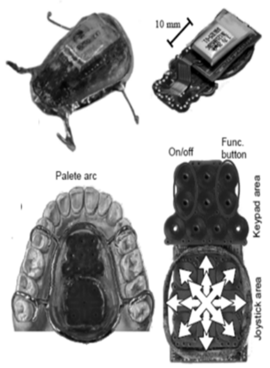
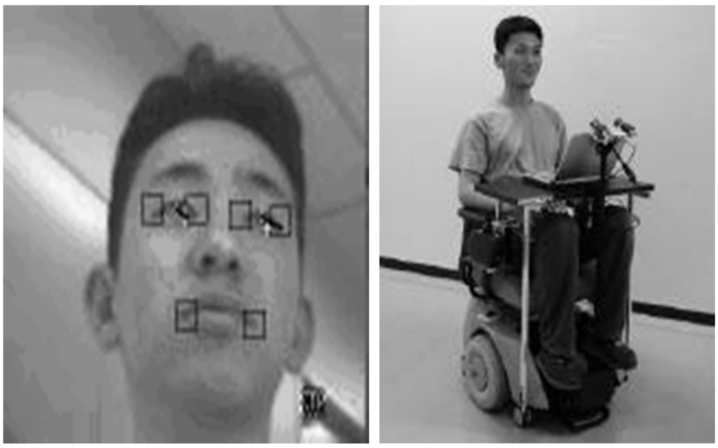
Figure1 Joystick controller from Golden Motor [4]

(a)



(b)



(c)

(d)

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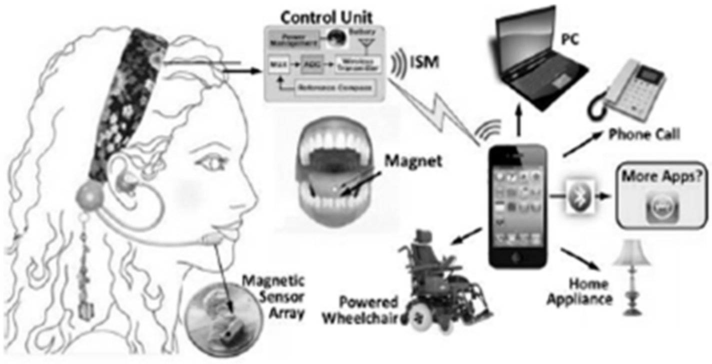

(e)

Figure 2 Other forms of joysticks: (a) Head/chin control [5]; (b) Tonguecontrol [7]; (c)Face/gaze control [8]; (d) Electroencephalography control [10]; (e) Tonguecontrol with access to common smartphone applications [18]

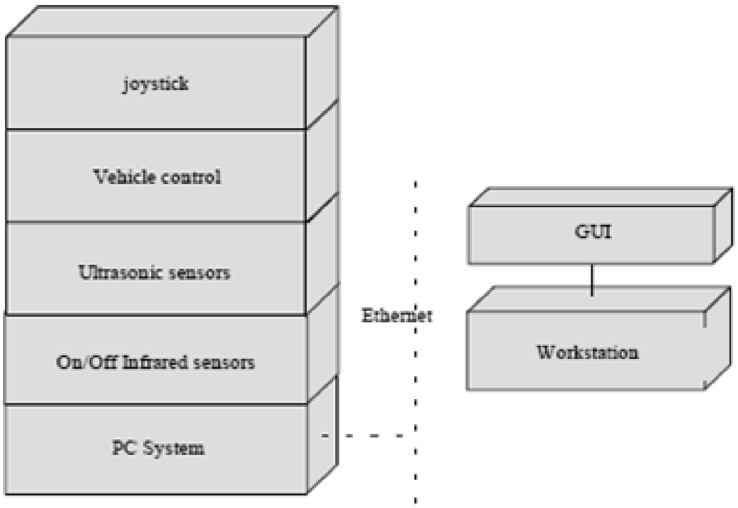

Figure 3 Modules of the "Rob Chair" system [22]

More advanced joysticks may have more add-ons technologies to facilitate other options depending on the user's abilities and situation. For example the system presented in [20] and shown in Figure 2-(e), is a wireless and wearable assistive technology that enables people with severe disabilities to control their computers, wheelchairs, and electronic gadgets using their tongue motion. The system is emulating finger taps on the touch screen. Another system uses the smart phone as a processing unit [21]. The wheelchair in this system can be controlled using the user's voice through an android based phone. Voice control commands include go, stop, turn left and turn right. These commands are responded accordingly by the robot wheelchair when the commands are issued. Users in such systems can use their voice to control their computers and mobile phones in the same way.
The "Rob Chair" assistive navigation project is using a friendly Graphical User Interface (GUI) which also works as a simulator; and introduces a voice Human Machine Interface (HMI) [22]. The system's architecture follows behavior-based control architecture. Figure 3 shows the modules of the "Rob Chair" system.

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B. The navigation methods and devices

As mention earlier in this paper, a smart wheelchair can be defined as mobile robot with seats or as a uniquely modified powered wheelchair which is equipped by a control system and variant sensors. Therefore smart navigation methods are important aspects of smart chairs. Christina Tsalicoglou, and Xavier Perrin made a survey on navigation assistants for people with disabilities in 2010 [23].According to this survey, many projects study how a smart wheelchair can be of maximum assistance to its user. Navigation methods are divided to three categories according to levels of assistance. The three main categories are: Shared control, semi-autonomous control and completely autonomous control. The advantage of autonomous and semi-autonomous systems are that the user only needs to provide a command every once in a while and can relax once the command is given, since the navigation is automated. Shared control gives the user more independency, because user can control the motion and plan the route. The smart chair provides only emergency or corrective actions like collision prevention, obstacle avoidance and wall following.

One interesting idea is adaptive shared control systems [24, 25]. In these systems, the better the user can do by himself, the less assistance he/she receives from the shared control system. In [25], data collected through Scanning Laser Range Finder (URG-04LX) and user interface are analyzed to determine whether the desired action is safe to perform. The system then decides to provide assistance or to allow the user input to control the wheelchair.

From the names “semi-autonomous control” and “autonomous control”, it is clear that the machine assistance increases. Wheelchairs are therefore involved more in route planning in addition to collision prevention, obstacle avoidance and wall following. Semi-autonomous systems wait commands from users providing a short term *local* destination. The wheelchair then starts moving until an external flag from the navigation system informs that the command was executed. Semi-autonomous systems might be useful for cases like visually impaired users. They help them with independence mobility advantage as in “Help Star” system [26]. When the user faces an unforeseen circumstance, the “Help Star” feature can be activated. It allows a remote operator to use virtual reality technologies to provide helpful navigational instructions or to send commands directly to the wheelchair.

In autonomous system, the user indicates the final desired destination and the wheelchair system takes complete control of the navigation from the current location to the goal destination. Autonomous systems therefore need mapping and position monitoring techniques. Consequently, they usually preferred to be operated in well-defined environments. To guarantee the safety and robustness of the navigation, researchers suggested making the wheelchair to travel along a guide marker arranged in a lattice form as in the patent number US5002145 A by Hiroo Wakaumi and Tsuneo Tsukagoshi.

To make the wheelchair usable in urban Environment, synthesized landmark maps for absolute localization of a smart wheelchair system outdoors is used in [27]. First step for the project was to build a three-dimensional map. Data for the map are acquired by an automobile equipped with high precisioninertial/GPS systems, in conjunction with light detection and ranging (LIDAR) systems. The resulting map data are then synthesizeda priorito identify robust, salient features for use as landmarks in localization. The system was able to maintain accurate, global pose estimates outdoors over almost 1 km paths.

More smart options and sensors might be available in autonomous and semi-autonomous wheelchair systems. For example in [28], a panoramic camera with a 360 degree field of view and sonar sensors are added for tracking a target person. The target person is selected by the wheelchair user through a screen. The sensors, the computing power and the electronics needed for the implementation of the navigation behaviors and of the user interfaces (touch screen, voice commands) were developed as add-on modules and integrated with the wheelchair. Another example is an automatically changing behavior between indoor and outdoor environments (e.g. the speed or the threshold limits for the obstacles) [29].

A variety of sensors can be considers as add-ons navigation devices. Obstacle avoiding systems use sonars, infrared (IR)or LIDAR sensors to investigate the surroundings [27, 29, 30]. Sonar and IR sensors are often used because they are small, inexpensive, and well understood. The accuracy of

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obstacle detection is increased with laser range finders (LRFs), which provide 180°, 2D scan within the plane of the obstacles. An example of smart wheelchairs using LRF is [25].

Pattern recognition and computer vision algorithms make cameras one of the important add-ons [28, 31, 32]. For example T. H. Nguyen et al. use stereoscopic cameras. Left and right images are captured from the cameras mounted on the wheelchair [31]. The optimal disparity is computed using the Sum of Absolute Differences (SAD) correlation method. From this disparity, the map is constructed to be employed to provide an effective obstacle avoidance strategy for this system.

C. Other smart systems

The add-on unit approach gives flexibility in configurations of sensors, interface and input devices based on each individual user's needs. It allows the system to be modified according to the changes in the environment or the progression in the patient’s situation. It is satisfied for children in particular because their bodies grow continuously [1].

Some important add-ons may include patient monitoring systems. The authors in [33]for example discuss a cardio-respiratory and daily activity monitoring system. The paper describe using frequency modulated continuous wave (FMCW) and Doppler radar sensors embedded in a manual wheelchair to measure the cardiac and respiratory activities and the physical activity of the wheelchair user. Information is then delivered through Bluetooth communication protocol to an Android tablet computer to be processed.

Warning Devices are also important add-ons. For example a system called “BotBeep” [34], is used for wheelchair rearward safety. The rear of a wheelchair is often in a wheelchairuser’s blind spot as shown in Figure 4.Therefore, BotBeep system warns the user of elevation changes behind the wheelchair corresponding to holes, steep slopes, and staircases. Thus, Bot Beep reduces the risk of falling and turning over. Smartphone is used as computing device via an image processing technique.

Figure 4 Wheelchair user’s rear blind spot [34]

III. Commercialization and price estimation

Researches in smart wheelchairs can be considered popular in the field of robotics and artificial intelligence. However, the commercialized *smart* wheelchairs are not found easily. Searching for the term “wheelchair” in e-commerce websites yields big number of manual wheelchairs, quite a number of electric powered wheelchairs with normal joystick and very little number of smart wheelchairs. For example, one of the international e-commerce websites yields 3,345 self-propelled wheelchairs, 543 electric powered wheelchairs and only 10 smart wheelchairs. Examples of commercial products and their price estimations are shown in Tables 1, 2 and 3.Data were collected from local and international e-commerce websites.

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It is worth to be mentioned that not all the 10 smart wheelchairs found in the previous search are related to the definition of smart wheelchair in this paper. Most of them are smart in appearance or the producers call them smart due to easy folding, stair climbing, standing function and other similar facilities. We found that only Smile Smart Technology Ltd in United Kingdom is selling real smart wheelchair. This is because the robustness and safety of the technology is not 100% guaranteed yet in many researches. On the other hand, even if the reliable autonomous wheelchair technology is available, the decision to using it or not depends on the severity of the disability, the individual's overall morale and attitude towards his or her condition and the price of the technology [35]. In other words, the cost, ease-of-use and personalization are the most important factors in commercializing smart technologies.

Table 1 Examples of self-propelled wheelchairs commercial products and their prices

Product/ seller name	**Specification**	**Price Estimation**
SKU	Malaysian semi lightweight wheelchair, 15kgs	~ 60 USD
Drive Medical	Steel wheelchair, fixedarms	~ 100 USD
Hopkin	Standard aluminium wheelchair	~ 100 USD
Invacare	Reclining manual wheelchair size 18 x 16	~ 500 USD
Karman	Ergonomic wheelchair ergo flight in 18 inch seat, weighs 19.8 pound, removable footrest, anti-bacterial upholstery	~ 700 USD

Table 2 Examples of electrical powered wheelchairs commercial products and their prices

Product / seller name	**Specification**	**Price Estimation**
Invacare	Power wheelchair, adjustable height removable arms, large angle and height adjustable fold-down footboardtool-less removable shroud,charger connection conveniently located on joystick, 9" flat free drive wheels,intelligent regenerative electromagnetic brakes.	~1000 USD
BEIZ	Electric power portable wheelchairs quick-removal battery box and high strength, battery box can be taken away from body for recharging and controller can move around,when the wheelchair is out of power, it can be used manually.	~1,500 SD
Pride Mobility	Back-lit battery gauge, high intensity led headlight, auto connecting front to rear harness, easy grip tiller adjustment knob, easy access tiller-mounted charger port, comfortable, 300 lbs,weight capacity.	~1700 USD

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Phenol	Drive medical wildcat 450 heavy duty folding power wheelchair, 24 sea, anti-tipwheelsbatteries: 2x12v 50ah, batteryweight - 73 lbs, brakes electromechanical.	~2000 USD
Jazzy Select GT	Active trac suspension, in line motor technology, 40 amp pggc controller, battery removal thru side panel, easy access charger port and circuit breaker	~2600 USD
Wheelchair88	Stylish heavy duty foldable wheel with a thick & tuff travel bag, foldable in 2 seconds, 55 lbs with polymer li-ion battery, powerful and quiet motors with bigger rear tires (10"), which is just right without feeling bulky, 4 spring suspensions, easy-to-detach connector on the joystick controller, quick release anti-tilt support for safety.	~3000 USD

Table 3 Examples of smart wheelchairs commercial products and their prices

Product/seller name	**Specification**	**Price Estimation**
Karman	Full power stand up chair, 18”power wheelchair with standing function, drive mode available while in standing position, relieves pressure, promotes blood circulation, and overall health	~ 8,400 USD
Wheelchair 88	4 wheel drive stairs climbing wheelchair with li-ion battery pack, able to climb stairs and slopes,durable rigid rubber tires to overcome obstacles or rough surfaces, equipped with li-ion battery, performance controller system ensures smooth operation at all times, top quality precision controller with lcd display, adjustable racing car seat with auto suspension, led head lights.	~12,500 USD
Smile Rehab Ltd	Controlled by switch joystick or scanner, sensor options for environment & user safety, line following ability, voice confirmation of outputted commands, collision safeguard, easy to set up for multiple users, wide range of options available	N/A

IV. CLINICIANS AND USERS’ ATTITUDE TOWARD SMART WHEELCHAIR

The cost, ease-of-use and personalization are the most important factors in commercializing assistive robotic technologies as mentioned in previous section. Another factor that should be taken into consideration is the clinicians and users’ attitude toward the smart wheelchair. Medical doctors and clinicians in general support the use of services offered by a smart wheelchair according to surveys [35,36]. Nearly half of patients who are unable to control a power wheelchair by conventional methods would benefit from an automated navigation system according to the clinicians who treat them. On the other hand, the clinicians indicated that 9 to 10 percent of patients who receive power wheelchair training find it extremely difficult or impossible to use them for daily life activity. The percentage of patients who finds steering and maneuvering tasks difficult or impossible is 40 percent. Taking into consideration that the wheelchair users are elder people or people with special needs makes these findings understandable. Therefore, friendly interfacing techniques are very important for smart wheelchairs.

V. CONCLUSION AND FUTURE WORK

This paper presents different smart technologies for wheelchairs. It focuses on two main properties: The human - machine interface and the navigation methods and devices. Also it reviews other smart

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systems like monitoring and safety systems. From the review of many published papers, it is concluded that researchers are continuously trying to build a powerful and helpful wheelchairs to ease the daily life activities and to give more independent mobility for people with different types of disabilities.

Unfortunately there are very few commercialized wheelchairs with the smart technology available. One reason is because the robustness and safety of the technology is not 100% guaranteed yet in many researches. However, the main reason is maybe related to marketing and feasibility issues. Using high-tech smart wheel chairs depends on the severity of the disability, the individual's overall morale and attitude towards his or her condition and the most important is the price of the technology. Moreover, smart wheelchairs are complicated for many users. Therefore familiarization and training sessions are needed as after sales services. This makes the investment in smart wheelchairs less interesting for stockholders.

Future work should maybe focus more on the add-on approach which gives flexibility in configurations of sensors, interface, and input devices based on each individual user's need s and budget. Other options for making the wheelchair friendlier can be added in future also. For example, entertainment and social communication facilities might be added to the wheelchair. Health monitoring, first aid, muscle relaxing and rehabilitation tools might be considered as useful add-ons too.

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