Leveraging Consumer Sensing Devices for Telehealth

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Abstract—**Home telehealth applications are increasingly gaining in popularity among patients due their promise to use healthcare resources more effectively and hence to lower costs. Commercial telehealth systems usually employ patient stations and vital sign monitoring equipment in order to fulfill the need of medical professionals by enabling close monitoring of patients with severe chronic diseases. However, due their high cost, vendor lock-in, and doctor centric design, these systems are not suitable for general healthcare applications such as improving cardiac fitness, monitoring overall health, improving muscle strength and balance of elderly, or assisting with dieting programs. We argue that many of these goals can be supported in a cost effective manner by leveraging mainstream sensing devices such as game controllers and smartphones. Open-ended web-based telehealth systems can be integrated with such devices, in order to add a social component, collect health data unobtrusively, and provide feedback and health related information. In this paper, we systematically categorise and analyse consumer-level sensing devices in terms of their potential to extend the capability of telehealth systems. We show that the devices have immense potential as tools for therapy and rehabilitation activities, diagnosis, health monitoring and social support, and we reveal opportunities for professionals in computer vision, graphics and signal processing to participate in this trend.**

Keywords – telehealth, human computer interfaces, elderly.

I. INTRODUCTION

Consumer-level sensing devices can be defined as off-the-shelf devices that are owned and used by consumers in their day to day lives, most often in entertainment and communication, and which have the ability to receive and respond to an external signal. Although these devices are often designed with a single objective such as gaming, their use can be extended to other areas such as healthcare. Most of these devices are equipped with a number of technologies that can be leveraged for supporting the development of affordable and accessible telehealth systems.

Telehealth systems are increasingly gaining attention from health consumers and health professionals due to their promise to reduce healthcare costs and to make effective use of clinical resources. However, there are issues revolving around the underlying concepts of current telehealth applications, which are designed to manage diseases instead of preventing them [17]. They help to keep patients' conditions stable, but do not motivate them to improve their health. These applications do not promote self-efficacy and are expensive due to the heavy reliance on clinicians to interpret data and make decisions. Many existing systems cannot be extended by third parties, entail additional costs when adding new functionalities, and do not address the social and psychological needs of the patient. Such shortcomings motivate the development of novel online telehealth platforms, which provide inexpensive and ubiquitous care via mainstream sensing devices [17, 34].

Telehealth systems are commonly used for managing acute and chronic conditions where regular monitoring of vital signs (e.g. heart rate and weight) is crucial. However, requirements for general health support are different and include education, monitoring, psychological support (motivation), and adding social components for patient support. In previous work, we demonstrated the advantages of leveraging consumer-level devices such as off-the-shelf computers and motion-sensing input devices to make telehealth more accessible and affordable [1]. In this paper, we systematically categorise and analyse a range of sensing devices for healthcare, particularly their capability to extend the functionalities of telehealth systems. We evaluate each device based on its technology, pros and cons of its usage in healthcare, and findings from related studies. We try to answer the following research questions: 1) "how can off-the-shelf consumer-level sensing devices be categorised for healthcare applications?", and 2) "how have these devices already been leveraged in healthcare?"

Section 2 reviews and analyses common consumer-level sensing devices. Section 3 presents results of the analysis and discusses how these devices can be leveraged in telehealth systems and Section 4 concludes the paper.

II. CONSUMER-LEVEL SENSING DEVICES

There is a variety of consumer-level sensing devices available in the market. Most of them take advantage of their motion-sensing capability to provide a rich user experience. This section categorises popular consumer-level sensing devices into handheld sensing devices, handsfree sensing devices and mobile sensing devices, and analyses them from an healthcare application perspective.

A. Handheld Sensing Devices

Handheld sensing devices require users to physically hold the device to input gesture and stance information. They are usually ergonomically designed to rest comfortably in the user's palm and have a robust structure to support different movements (ranging from smooth tilts to rigorous fitness exercises). Handheld input devices resemble traditional gaming controllers except they are not constrained by wires; instead they transmit data through wireless technology, usually involving a secondary device that reads the input. These devices are not mobile. They are used within a certain distance to the reading device due to its reliance on wireless technology, which restricts users to stay within a certain perimeter when using it as sensor. Two common examples are the Wii Remote and the PlayStation Move.

1) *Nintendo's Wiimote*

The Wiimote is the main interactive gameplay controller for Nintendo's Wii console. Users are able to use this controller horizontally (with two hands) or vertically (with one hand) to interact with the console or computer. The main feature of a Wiimote is its motion-sensing capability, which enables users to perform gesture-based input. Its 3-axis accelerometer is used to obtain data regarding movement direction and velocity, while its high-resolution and high-speed infrared (IR) camera captures motion and hand movement by tracking its coordinates. These spots are sent to the console using wireless short-range Bluetooth connectivity. This very technology empowers users to leverage Wiimote on other Bluetooth enabled devices such as computers. The controller has a symmetrical design that enables users to point at the sensor bar with either hand perfectly. Along with its input capabilities, the controller supports various types of feedback: a speaker, vibration motor and light-emitting diodes for auditory, tactile and visual feedback respectively. The Internal Flash Memory of Wiimote allows association of data and memory to a specific controller, which can be used to identify the user.

The Wiimote has successfully been used for health monitoring [6] and as a physical rehabilitation tool [2]. Its usage with well-designed games helps users to perform exercises such as limb movement while promoting motivation, active participation and social interaction [4]. Its wireless connectivity allows freedom and mobility for up to 5 meters from the sensor bar, encouraging group and family play. Developers have found it ideal for custom control and tracking applications due to its low cost and easy Bluetooth connectivity. Its features have attracted attention from large audiences ranging from the traditional hardcore gamers to older people. Users can leverage its functionalities for different purposes such as a pedometer or a tool for rehabilitation exercises. They need to learn to use only one controller, reducing handling burden, space requirements, time and money. Usability related research found that using the Wiimote is fairly easy, however, elderly found it frustrating when their game was interrupted from accidentally pressing any of the 12 other buttons on the controller [7]. Wiimotes have also been used for stroke rehabilitation exercises, where they are handheld or fastened on limbs to detect a variety of arm movements and to generate force feedback [2]. This can cause inconvenience and discomfort to the user, especially to the elderly [3]. Overall the Wiimote is a suitable device for realising rich telehealth applications because of its availability, large support community, and open-source device libraries.

2) *Sony's PlayStation Move*

The PlayStation (PS) Move is a wireless motion controller for Sony's PS3 console. It offers greater precision than other similar controllers via several different tracking components, mainly with its glowing orb at the top, which is tracked by the Sony PlayStation Eye camera. The PS Move is able to locate the controller in 3D space by recognising and processing the image of the glowing orb on the controller. It tracks the motion and the angle of the controller via a number of built-in inertial sensors such as a three-axis gyroscope, a three-axis accelerometer and terrestrial magnetic field sensor [21]. The PS Move can be calibrated for both left- and right-handed use. It features advanced motion sensors, a dynamic color changing sphere, vibration feedback, user-friendly buttons and Bluetooth connectivity. Although PS Move was originally designed and maintained to be exclusive to the PS3 system, recently Sony has announced the Move.me tool to enable developers to experiment with this device in other fields such as healthcare [22]. Up to 4 Move controllers can be active at the same time, where each orb will be assigned a different color, enabling the system to differentiate between players. When only one Move controller is used, the color can be adjusted to maximize contrast with the background. Developers can also use it as a feedback tool to the user, e.g. coloring the orb red when enemies are close.

Since the SDK was only recently made available to general developers, we were unable to find published research about the PS Move's use in healthcare applications. Technology wise we would expect similar applications as for the Wiimote. The PS Move's main advantage is its higher precision. However, Move.me is not available for free but is sold to developers for US$ 99.99 [24]. In addition, it cannot simply be plugged directly into the computer. Instead, it requires the user to connect their computer to the PS3 console. The PS Move's higher precision results in slight unintended movements (e.g. hand tremors) to be captured [21]. This could affect the user experience and might cause irritation to the user which eventually could be a barrier to patients, especially to the patients experiencing the Parkinson's disease. There are also some environmental constraints: In a dark room, the colored orb light can reflect on the monitor while playing, which can be annoying. If the room is too bright, the camera can have difficulties picking up the light [23].

B. *Handsfree Sensing Devices*

Unlike handheld or wearable sensing devices, handsfree sensing devices can read the user's gestures and stances without direct mechanical linkage between the user and the input device. This is especially helpful for reading input from activities which involve free movement of both arms. Two popular examples are webcams and the Microsoft Kinect.

1) *Webcam*

Webcam feed images in real time to a computer and are often used for video conferences and social network applications. Consumer webcams differ in quality and frame rates that can range from the typical VGA-resolution video running on 30 frames per second to the multi-megapixel resolution video running on higher frame rates of 120 frames per second. The Playstation Eye is a consumer webcam which can produce 320x240 video at 120 frames per second.

Most webcams are equipped with a microphone that allows the user to do video calls without a headset or a separate mic. Often, a webcam comes with a 58 degree viewing angle, placing user’s face in the middle of the screen. In contrast to a digital camera, a webcam does not come with a built-in memory chip. It is supported by a USB cable, which supplies power from the computer and takes the digital information back to the computer. Most laptops and desktop screens today come with built-in webcams, which makes them even more convenient to use. However, external webcams generally have higher quality image and motion when compared to built-in webcams. The features and performance of a webcam varies according to the operating system and processor capabilities of the computer. For instance, high quality video is provided to users of certain Logitech webcams if their computers have dual-core processors meeting certain specifications.

Webcams are commonly used in the healthcare industry, especially in telehealth systems. Webcams play a vital role to facilitate the face-to-face contact between patients and their clinicians. Studies show that they allow patients and clinicians to feel as if they are “in the same room together” and make it possible for patients to have frequent contact with their clinicians [13]. In addition, they help them to focus on the task at hand by making distracting contexts invisible which can make the conversation clearer than a real encounter [13]. Webcams also allows patients, especially the psychiatric patients that fear social contact, to feel more comfortable and less intimidated during the care process [14]. However, it has been reported that using webcams for telehealth only works well for patients and clinicians who know each other or have met before, and that webcams are only suitable for follow-up care, since they do not allow touching and diagnosing patients [13]. Other webcam applications in the healthcare domain include monitoring hand rehabilitation exercises [30] and activity monitoring systems for the elderly [15]. Recently, the webcam technology was used to create a tool to identify the effects of medications in real time on certain heart cells [16].

2) *Microsoft’s Kinect*

Kinect is a motion-sensing input device for the Microsoft Xbox 360 video game console, which enables users to control and interact with the console using whole body movements, gestures and vocal commands. A large community of Kinect enthusiast called OpenKinect has been exploring this device outside of its primary usage with the goal of creating open-source libraries to enable Kinect to run on various platforms such as Windows, Mac and Linux.

The Kinect sensor bar contains a traditional webcam and a structured light infrared laser and sensor system, which can produce a depth map with up to 1cm accuracy. The SDK provides algorithm for detecting human outlines and skeleton tracking [5]. Facial recognition is also possible using the traditional camera’s video feed. The Kinect is capable of recognising up to 4 people at once. Apart from its motion-sensing capability, it includes a microphone array that can distinguish between sounds of vocal instructions and other ambient or environmental sounds. This feature can be used to recognise voice commands that allow users to manipulate the controls and navigate the user interface of an application. The Kinect horizontal design makes it portable and easy to position anywhere, ensuring that it can capture a wider area. With its natural method of interaction, users can navigate menus through vocal commands and choose options based on body movements that relate to the virtual environment. More features are being added into Kinect, including the capability to capture objects from real world into a virtual environment which can be manipulated with a combination of voice and motion controls.

The Kinect is increasingly being investigated as a tool to support healthcare. It has been tested with young adults with motor impairments, to determine whether they performed exercise correctly during physical rehabilitation. Although the study uses a modest sample, results indicate reduced staff intervention and enhanced participant motivation for physical rehabilitation [3]. Using Kinect saves the users from wearing sensors that can be intrusive [3]. It does not restrict users to a specific stance, so even users bound to a wheelchair can be tracked by the system. The rich virtual environment capabilities that the Kinect provides allows clinicians to view patient notes and x-ray images without touching the surfaces, which could be infected with bacteria. The Sunnybrook Health Sciences Centre in Canada is already utilising Kinect to eliminate hygiene and infection problems in its operating rooms [8]. The motion tracking capabilities have been successfully employed detecting and monitoring children with obsessive-compulsive and attention deficit disorder [33].

Drawbacks of the Kinect are its limited field view (57.8 degrees) and range, which varies from 2 to 16 feet depending on the application. The environment must be well lit and unobstructed. Bright sunlight can influence the IR sensor and laser system. The Kinect is of limited use outdoors [25] and for small cramped rooms where space is limited. Using a second Kinect device can improve recognition, but requires non-trivial merging of sensor information. Connection is done using USB ports and the number of active Kinect's is only limited by the number of ports and the available processing power. However, only two users can be active at any one time.

C. *Mobile Sensing Devices*

The increasing availability and reducing cost of mobile Internet enables new opportunities for using mobile consumer-level devices in health management. Two of the most common mobile devices in the market are smartphones and handheld gaming consoles. In this section, we focus on the iPhone (Android-based Smartphones have similar capabilities) and Nintendo DS as examples.

1) *Apple’s iPhone*

One of the most popular smartphones today is Apple’s iPhone range. It is based on the iOS operating system, which provides a standardised user interface and the capability to run applications. In contrast traditional mobile phones, the iPhone has a larger screen and more powerful processors. Its main use is for communication, but it has also become a popular mobile gaming platform, and it contains functionalities resembling a handheld computer. The different models of iPhone hardware are heterogeneous by nature, implying that not all applications made for one can run on another. For instance, the iPhone3Gs does not include a front camera, therefore, may not be able to take advantage of two-way video calling applications, as opposed to the iPhone4, which has front and back cameras. The iPhone is equipped with an accelerometer, which can track movements and gestures of users. For instance, the iPhone uses the accelerometer to control applications such as a bowling game by enabling the user to swing or flick the device as if throwing an actual bowling ball [11]. The iPhone also supports natural input through the use of touchscreens. It improves the interaction between the user and the device by allowing direct manipulation of objects on the screen. Touchscreens are intuitive, easy-to-use, and eliminate the need for traditional buttons, which effectively optimises the display area. The latest iPhones consist of 3G, Wi-Fi, Bluetooth, IR and GPS technologies, which allow them to connect and operate with various networks, platforms and other devices. Although they come in slightly different sizes, they are all pocket-sized and designed to be portable. Other features commonly found on iPhones include speakers, microphone, vibration motor, flashlight and additional tactile buttons (e.g. volume, power, home and lockscreen).

The Apple App store offers more than 500000 iPhone applications including health and fitness-related applications, such as monitoring heart rate by placing a finger gently over the camera for 10 seconds [26]. Research shows that 9% of mobile phone owners have software applications on their phones that enable them to track or manage their health [9]. The use of mobile phones amongst the elderly is increasing and is becoming a promising avenue to improve their quality of life [10]. Smartphones like iPhones are ideal devices for developing innovative health monitoring and support tools for health consumers due to their ability to deliver health improvement interventions to traditionally hard-to-reach populations [19]. The availability of iPhones' iOS SDK enables third-party developers to create native health applications. Furthermore, every model release exhibits the same look and feel; therefore, upgrades will not require users to learn a new interface. Direct manipulation of objects on the touchscreen (i.e. touch-drag-drop) effectively reduces the number of key strokes to perform basic tasks. The iPhones are also found to be an ideal tool for collecting patient data for online health platforms [12]. Applications such as OsiriX, an image processing software, has potential to expedite diagnosis and treatment planning while facilitating communication among radiologists and referring clinicians [18].

Although iPhones, offer tremendous opportunity to develop healthcare interventions via accelerometers, they are not as robust as Wiimotes to be used as a device to perform rigorous activities such as a bowling game. There are high chances for it to slip and break from the user's hand, especially for the elderly who will have weaker grips, while performing rehabilitation exercises. Furthermore, even though they come with a touchscreen, buttons in most user interfaces are relatively small, which makes it difficult for the elderly to use them with ease. There are other little glitches with iPhones that could be annoying to the user, such as its short battery life span that requires users to charge it constantly [20].

2) *Nintendo DS*

Portable video gaming consoles have been extremely popular amongst young people and since the emergence of Nintendo DS (in short known as DS), the trend has spread to other age groups. Unlike its predecessors, the DS introduces state-of-the-art motion-sensing technology with its 3-axis accelerometer and the pair of internal and external VGA digital cameras. The DS console has a double screen interface, with one being a LCD display and one being a stylus input touchscreen display. It is also equipped with a number of ways to engage users in social networking. This is done using Wi-Fi technology and Nintendo's proprietary communication protocol, which allows the DS to connect to another DS.

The DS has also been explored for health-related applications. Brain Training, a game designed for the DS with the purpose of providing mental exercise, has received attention from health professionals and is claimed to be beneficial for the elderly [27]. MyHealthCoach, a health management application developed for the DS, uses the accelerometer of the console as an active pedometer and records movement data for its user. Likewise, the game can monitor a user's BMI by explicitly asking for input from the users and keep track of their progress. These data can be shared with other users of the system for comparison, ultimately encouraging social interaction [32]. The DS also allows children with diabetes to connect in a social network called DIDGET, which rewards the user for building consistent blood glucose testing habits and meeting glucose targets [31]. Recently, researchers in Korea have designed a system that used the DS for on-the-go patient monitoring [28]. The system collects the monitored data and displays it either on a computer or on the LCD of the DS.

The idea of preventing cognitive declination of the elderly by using brain and memory games such as DS's Brain Training is well received, but there is limited evidence to prove such games actually work [29]. Similar to iPhones, the DS has a fragile structure which limits its suitability for intensive physical activities. Its official development SDK is not open source and comes at a high cost and with multiple prerequisites such as having to sign a gaming contract from a large game publisher. However, there are many available homebrew libraries and compilers provided by enthusiasts that enable developers to program the device without breaching any copyright laws.

III. DISSCUSSION

Our analysis of existing consumer-level sensing devices reveals three categories: handheld, handsfree, and mobile. Each of these categories differs in terms of the portability and handling of the devices. Since there are different needs to meet for a wide variety of users and settings, this classification provides developers with a better understanding of their usage and interaction from a broader perspective.

It is apparent from the previous section that almost all of the devices are widely being investigated in the healthcare industry. They are familiar to users and therefore their operation has a short learning curve. Table 1 summarises their features, capabilities and potential in telehealth. The key advantages of these devices are their motion-sensing capabilities that can be integrated into the user's physical environment to collect on-body, freehand, and mobile health monitoring information and to initiate corresponding actions or alarms. Most of them make use of accelerometers, a powerful technology that can be used as monitoring devices such as

TABLE I. COMPARISON OF COMMON CONSUMER-LEVEL SENSING DEVICES

Categories	Handheld Sensing Devices		Handsfree Sensing Devices		Mobile Sensing Devices	
Devices	***Wiimote***	***PS Move***	***Kinect***	***Webcam***	***iPhone***	***Nintendo DS***
Main purpose	Gaming	Gaming	Gaming	Online video conferencing	Communication	Gaming
Motion detection	Yes	Yes	Yes	Yes	Yes	Yes
Open source	Yes	No	Yes	Yes	No	No
Range	Wireless short-range	Wireless short-range	Wireless short-range	Wired short-range	Limited to its connection method	Limited to its connection method
Feedback	Yes	Yes	Yes	Yes	Yes	Yes
Microphone	No	Yes	Yes	Depends on product brand	Yes	Yes
Voice recognition	No	Yes	Yes	No	Yes	Yes
Buttons	Yes	Yes	No	No	Yes	Yes
Camera	No	Yes	Yes	Yes	Yes	Yes
Accelerometers	Yes	Yes	No	No	Yes	Yes
Connectivity	Bluetooth	Bluetooth, USB	USB	USB	Bluetooth, Wi-Fi	Wi-Fi
Other technology	Optical sensor, Infrared	Gyroscope , Terrestrial magnetic field sensor	Infrared	Image sensor (CCD or CMOS)	Touchscreen, GPS, 3G, Infrared	Touchscreen, Nintedo proprietary communication protocol
Potential in telehealth	Rehabilitation (e.g. arm exercise) [2], Monitoring [6], Social support [4], Fall detection	Rehabilitation (e.g. arm exercise), Monitoring (e.g. fall detection), Social support	Rehabilitation (e.g. physical body exercise, weight control) [3], Handsfree imaging tool [8], Diagnosis [33], Video calling, Social support, Therapy	Rehabilitation (e.g. hand exercise) [30], Video call [18,19], Monitoring [15], Social support, Diagnosis	Rehabilitation (e.g. arm exercise) [11], Monitoring (e.g. heart monitor, diet tracker) [26], Data collection [12], Diagnosis [18], Medication reminder, Video calling, Social support	Rehabilitation (e.g. mental exercise) [27], Monitoring [28], Data collection [31], Fall detection [31], Social support [31], Video calling

pedometers and fall detectors. Most of the devices are open, enabling developers to take these devices beyond their traditional usage (e.g. gaming) into areas such as physical therapy and rehabilitation. They support common connectivity such as USB or Bluetooth, which make it possible to transfer data into a computer.

Handsfree sensing devices such as the Kinect are likely to be suitable for a wide range of patients, especially the elderly who often face anxiety when confronted with technology. Such devices can aid them to interact with a health application with ease and confidence. Most of the devices are created for gaming and they support multiple co-located players simultaneously. This enables health consumers, especially the elderly, to connect with their family members or other patients to play health-based games together, which helps to address social isolation. Mobile sensing devices such as iPhones and DS can be used to deliver ubiquitous care to health consumers.

Unlike handheld and handsfree sensing devices, which constrain the user to perform rehabilitation activities within a specific location, mobile sensing devices gives the freedom to do it from anywhere. However there is a trade-off between their portability and the nature of their display. So far, we have developed and tested two iPhone games which fulfill two purposes at once: therapy and monitoring, supporting patients to perform rehabilitation exercises involving the arm's joints and muscles [16]. Both games make use of the accelerometer. Apart from using the iPhone as an exercise tool, it is possible to use this device to monitor and collect vital signs data (e.g. heart rate). The touchscreen technology supported by both iPhone and Nintendo DS makes interaction with them convenient for the user.

It is clear that there are more advantages of leveraging existing consumer-level sensing devices for health reasons. Each of them has different unique capabilities, which we need tap for the development of novel telehealth systems. Often, the amount of activity or exercise performed using a particular device is recorded within the individual device or system. Such data is crucial and need to be shared to allow health consumers to keep track of their health-related activity. The integration of existing sensing devices would make it possible to accumulate health data (e.g. monitored data) from different sources [17]. Therefore, it is worth to investigate data integration using existing consumer-level sensing devices to realise an affordable and unobtrusive care for health consumers.

Consumers are more likely to use devices they already have with them or in their home to take care of their health, rather than buying special hardware. Hence, the integration of consumer-level devices for proactive healthcare is a crucial step to make telehealth more accessible and more effective for health consumers, especially the elderly. Apart from making telehealth systems more accessible, the usage of other types of devices besides the keyboard and mouse will expand the range of applications that can be made available, i.e. it will help to satisfy unique health needs. Currently, we are working on an open-ended system called Healthcare4Life that envisions to host a range of health-related applications that can be added by third-party developers [17].

IV. CONCLUSION

In this paper, we have systematically grouped popular mainstream sensing devices into handheld, handsfree and mobile. For each category, we have specifically looked into the motion-sensing technology, the general hardware specifications, architecture and connectivity. Although these available and inexpensive devices are usually created for a specific purpose such as gaming, there is immense potential in the healthcare industry. These devices are found to be easy and fun to use, and with their innovative technologies, can be used as part of novel telehealths systems, such as tools for therapy and rehabilitation activities, diagnosis, health monitoring and social support. Hence, when these devices are integrated with native health applications, they can achieve innovative and effective healthcare systems for the future. We are currently working on integrating various devices into an online telehealth platform called Healthcare4Life. This novel system is built to leverage the discussed mainstream sensing devices to increase its accessibility and expand the range of health applications available to health consumers.

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