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Comparing the Utility and Usability of the Microsoft Kinect and Leap Motion Sensor Devices in the Context of Their Application for Gesture Control of Biomedical Images

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in partial fulfilment of the requirements for the degree of
Master of Science in Health Informatics

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Declaration

I declare that the work described in this dissertation is, except where otherwise stated, entirely my own work, and has not been submitted as an exercise for a degree at this or any other university.

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Summary

BACKGROUND

The necessity to interact with medical images in the Operating Room (OR), along with the requirement to maintain asepsis, imposes certain restrictions on the scrubbed clinician when using traditional mouse and keyboard. Touch-free image control systems, based on Commercial off the Shelf (COTS) sensors such as the Microsoft Kinect and Leap Motion, could enable the clinician to assume direct control of the medical image navigation and manipulation while maintaining sterility.

EVALUATION

Surgeons and radiologists, resident in a large academic teaching hospital, individually trialled two controllers, Leap Motion and Microsoft Kinect for Windows v2, as part of a pre-commercial Natural User Interface (NUI) system. In a user-task-system type evaluation, the usability and utility of the two COTS motion sensor input devices were compared. The system usability scale (SUS) was used to measure the usability of each of the input devices. Additional feedback was obtained on the perceived utility of both systems. The speed and accuracy of the two controllers for anatomical structure measurement were compared with those of a standard computer mouse.

RESULTS

The results from the data analysis showed marginal to average acceptability of the two devices. Microsoft Kinect for Windows v2 was found to have better utility and usability, particularly for Surgeons and Interventional Radiologists. The accuracy of the Leap Motion sensor was established to be better and comparable with that of a computer mouse. Analysis of the internal consistency of the utility survey showed that having greater control in sterile settings is integral to the perception of usefulness. Also, a link was found between the system usability and the perception of utility with better perceived usability translating into better perceived utility. The Kinect sensor was found potentially tiresome to use but with very good potential. The Leap Motion sensor was also seen as having good potential for use in the OR but its limited *field of view* was highlighted as a disadvantage.

DISCUSSION

The system usability can be further enhanced by implementing design changes to improve its accuracy as well as its gesture vocabulary. The Kinect sensor can benefit from the implementation of voice commands. The deployment of the NUI system in the OR should be carefully assessed and planned, particularly with respect to the sensors placement and the choice of display. Integrating the input from several COTS sensors can improve the system consistency and reliability.

CONCLUSION

Advanced, touch-free commercial NUI image control systems, based on low cost COTS sensors are available and prospectively useful for interacting with biomedical images in sterile clinical setting such as the Operating Room. Further research and development is required to establish the design specifications, installation guidelines and user training requirements that can ensure successful deployment in varying clinical areas.

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Abbreviations

2D	Two-dimensional space
3D	Three-dimensional space
API	Application Programming Interface
AR	Augmented Reality
CLI	Command Line Interface
COTS	Commercial Off-The-Shelf
CT	Computed Tomography
DICOM	Digital Imaging and Communications in Medicine, a standard for managing information in medical imaging
ENT	Ear, Nose and Throat
GUI	Graphical User Interface
HCI	Human-computer Interaction
HDTV	High-definition television
HIT	Health Information Technology
ICU	Intensive Care Unit
IEEE	Institute of Electrical and Electronics Engineers
IR	Infrared
IRs	Interventional Radiologists
LCD	Liquid-Crystal Display
LED	Light Emitting Diode
MS-DOS	Microsoft personal computer operating system
NASA	USA National Aeronautics and Space Administration
NCHD	Non Consultant Hospital Doctor
NUI	Natural User Interface
OR	Operating Room
PC	Personal Computer
SDK	Software Development Kit
SJH	St. James's Hospital
SpR	Specialist Registrar - a doctor who is receiving advanced training in a specialist field of medicine
SUS	System Usability Scale
UI	User Interface
UNIX	Computer operating system

Chapter 1 Introduction

Consumer technologies such as Smartphones and video games consoles have become ubiquitous and their rapid evolution and proliferation has fuelled multi-billion euro industries. This has profoundly changed the way research and development into new and advanced technology is carried out. Commercial companies are now being able, in certain areas, to outpace traditional technology research leaders such as government institutions and the military-industrial complex. Furthermore, this has made advanced technology available at a relatively low cost, off-the-shelf.

A number of advanced, Commercial Off-The-Shelf (COTS) gesture recognition motion sensor controllers have been developed in the past several years. Since their release they have been enthusiastically adopted by the scientific community. This has resulted in the creation of a number of Natural User Interface (NUI) systems that enable gesture-based human-computer interaction. Some of these have been designed for medical applications and for use in clinical settings. One specific application of NUI systems is the use for touchless control of biomedical images.

1.1 Background

Infection control is of paramount importance in the Operating Room (OR) and it is recommended to avoid direct contact with potentially contaminated computer interface equipment such as standard computer mouse and keyboard. This requirement has resulted in complex arrangements between the scrubbed clinician and the non-scrubbed personnel during surgery. It is also the cause of time inefficiencies when the surgeon has to un-scrub in order to check patient imaging data. NUI systems based on COTS sensor devices address this issue by enabling touchless, gesture-based control of medical images. Recently, a number of such systems have been designed, implemented and evaluated:

> *This initial prototype of a touchless image control system has demonstrated that the concept of gesture-based image control in a sterile environment is feasible with cost-effective commercially available technology. (Tan et al., 2013, pE68)*

In 2013 the new Leap Motion and Microsoft Kinect for Windows v2 motion sensors were released. Both COTS interface devices have since been used in gesture-controlled NUI systems. One example is their use as part of the NUI system for touchless biomedical image control developed by the Spanish company TedCas. This naturally poses the question how suitable these motion controllers are for use in surgery.

1.2 Research Question and Study Aims

This study aims to comparatively evaluate two motion sensor devices, the Leap Motion and the Microsoft Kinect for Windows v2, as interfaces of a gesture-based NUI system for control of biomedical images and to answer the following research question:

How do the Microsoft Kinect and Leap Motion sensor devices perform and compare in terms of utility and usability in the context of their application for touchless image navigation and manipulation in sterile medical environments?

The study builds on the existing Human-computer Interaction (HCI) research in the area of Natural User Interfaces and more specifically, the design, implementation and evaluation of gesture-based systems for use in medicine and surgery.

1.3 Overview of the Dissertation

The following Chapter 2 discusses the state-of-art based on review of the literature. It provides a brief history of computer interfaces, explores the design and application of NUI systems in Healthcare, and describes the different methods for utility and usability evaluation. It also outlines the motivation for the research and reviews the earlier studies of systems for touchless control of biomedical images.

Chapter 3 describes the research design, the NUI system specification and the research trial setup. It also outlines the data analysis methods and the ethical considerations.

Chapter 4 presents the results from the comparative performance evaluation of the Microsoft Kinect v2 and Leap Motion NUI system interface devices.

Chapter 5 discusses the findings from the analysis of the experimental data. It outlines the factors impacting on the system performance and areas for design improvements.

Chapter 6 summarises the research findings, makes recommendations for future research and concludes with the principal investigator’s reflections on the study.

Chapter 2 State of the Art

2.1 Introduction

In June 2003 Microsoft released the Windows Mobile™ software for mobile devices with the intent that it will enable *"customers to take advantage of software features that are wireless-ready and easy to use, and to connect with people and information with a broader range of new device hardware -- and at attractive prices."* (Christensen, 2003). Shortly after, in November of the same year, the XDA II Smartphone running the new Windows Mobile™ 2003 operating system was launched by the European mobile phone operator O2. In the following eight months O2 had sold over 100,000 XDA II devices across its UK, Germany and Ireland markets and throughout Asia Pacific (Mobile Europe, 2004).

In November 2007 Apple Inc. launched the iPhone. Commenting on the launch, Steve Ballmer, head of Microsoft, told USA Today (2007) *"There's no chance that the iPhone is going to get any significant market share. No chance."* In the first eight weeks following the release of the iPhone, O2 had sold about 190,000 units in the UK (FT, 2008) and subsequently, in the last quarter of 2013, Apple went on to sell 51 million iPhones (Apple Inc., 2014). On the back of the strong iPhone sales, at the end of 2013 Apple had 69.1% share of the Japanese Smartphones market, 43.1% of the US market and 30.6% of the Smartphones market in Great Britain (Kantar Worldpanel, 2014).

Apple have enjoyed continued success with most of their products, sometimes against the apparent odds. There is a broad consensus among computing experts that Apple's success and the stellar market performance of the iPhone in particular have been mostly due to the company's emphasis on user experience and above all its focus on designing for humans (Vardi, 2011).

The following section introduces some important Human-computer Interaction concepts and traces the history of interfaces from the early computer systems until today's consumer Natural User Interface devices. It discusses the generic application of consumer NUI technology, applications in healthcare and focuses on the implementation of NUI for biomedical image control in the Operating Room. This provides background for the statement of the Research Question. Finally, the literature is reviewed for methods for utility and usability assessment of user interfaces and computer systems.

2.2 Human-computer Interaction

2.2.1 Preamble

The exponential advancement and proliferation of computing technology is transforming healthcare and the way people live in general. Computing devices have become an integral part of modern reality and hold the potential to greatly augment it (Kurzweil, 2013). Human-computer interfaces are more than mere attachments allowing access to the computer functionality – they enable meaningful communication and affect people's emotional experiences (Laurel and Mountford, 1990). The process of interacting with computers externalises, broadens our cognition and creates an "*extended mind*" (Clark and Chalmers, 1998). Deep knowledge of the phenomena behind these interactions is therefore essential for the design and implementation of systems which empower people by making complex technology *natural* to use, usable and ultimately useful.

2.2.2 Human Factors

It is through the interaction between people and tools that complex tasks can be accomplished successfully despite the confines of human capabilities. *"A tool addresses human needs by amplifying human capabilities"* posits Bret Victor (2011) and it is therefore a profound understanding of human characteristics that can inform successful technological design. This principle has been recognised two and a half millennia ago by the Ancient Greeks who adopted a human-centred approach to their designs in order to improve usability, safety and productivity (Marmaras *et al.*, 1999). In the present day the multidisciplinary scientific field of *Human Factors* is concerned with "*the application of what we know about people, their abilities, characteristics, and limitations to the design of equipment they use, environments in which they function, and jobs they perform"* (Human Factors and Ergonomics Society, 2011), (Figure 1).

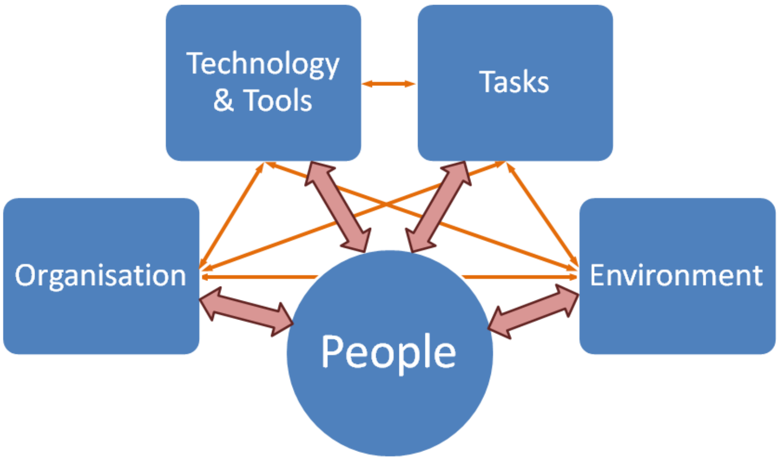


Figure 1 Human Factors. Adapted from Carayon *et al.* (2006)

The application of Human Factors principles in healthcare is not a novel concept. Hippocrates, the father of modern medicine, in his work on surgery counsels the physician on the ergonomics of the surgeon’s workplace by outlining the correct posture, position and tool placement. He also advances one of the fundamental Human Factors principles – tools design that facilitates ease of use (Marmaras *et al.*, 1999). In recent times, some Human Factors practices have gained importance and popularity in healthcare with the adoption of some aviation safety procedures. Clinical Human Factors, however, is a relatively new and developing area which aims to account for the high complexity and varied goals of healthcare (Catchpole, 2013).

2.2.3 Human-computer interaction

With the emergence of computing hardware, the field of Human Factors has been naturally broadened to encompass and account for the new interaction, communication and cognitive characteristics of computer use (Figure 2). This successively has led to the establishment of the modern discipline of Human-computer Interaction (HCI) as the subject area *“concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them”* (Hewett *et al.*, 1992).

In his seminal paper *Man-Computer Symbiosis* Licklider (1960) discusses a future of effective cooperative interaction between people and computers. Woods and Roth (1988) echo this view and see man and machine as an integrated system which maximises task performance. They point out that the design of the computer interfaces, as an "*external representation of the application world"* affects the overall system performance. The crucial importance of computer interfaces is affirmed by Newell and Card (1985) who refer to them as a "*micro-world"* which requires dedicated theories of human cognition to inform and guide the design of effective and efficient human-computer interaction.

HCI research and development aim to guide and inform quality computer system design that results in products which are both useful and usable and in addition are also desirable (Helander *et al.*, 1997). Usability is of specific importance for the design of systems for medical use. Computer systems built and implemented with due consideration for usability facilitate their adoption, are effective and efficient, and minimise errors. This, in turn, enables the provision of good quality healthcare (Staggers *et al.*, 2009).

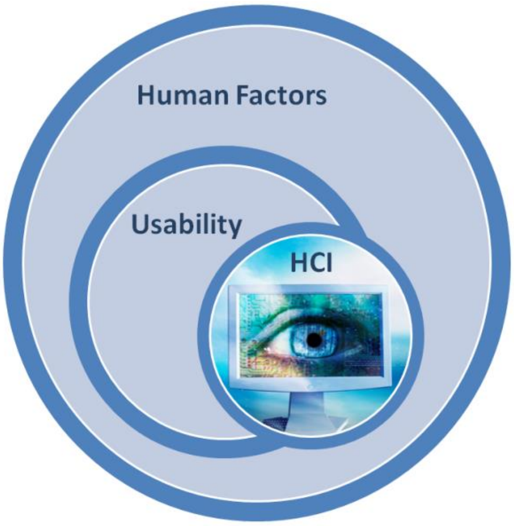


Figure 2 The relationship of Human Factors terms. Adapted from Alexander and Staggers (2009)

2.3 History of Interfaces

2.3.1 Preamble

The breakneck coevolution of Information technology and society has inspired a Pleiades of science fiction authors to attempt to glimpse our sociotechnical future. Their visions of how novel technologies are being used by people invariably pose questions of human-machine interaction and user interfaces. Successful presentation of speculative technology such as the gesture interfaces from the 2002 movie *Minority Report* or the *Star Trek* medical *tricorder* can capture people's imagination and influence future design (XPRIZE Foundation, 2013). In an equal measure, failure to see beyond the current technology and today's user interfaces can diminish the narrative believability (Shedroff and Noessel, 2012).

In his cult sci-fi classic *The Andromeda Strain* Michael Crichton (1970), a Doctor of Medicine by training, reveals his progressive vision of an advanced computer Clinical Decision Support Systems capable of correctly diagnosing a patient. Yet, when it comes to computer interfaces, his characters are confined in his present day realities of batched computer interfaces: "*He punched in instructions to the computer to wake him when analysis was finished. Then he went off to bed"*. Perhaps not hugely relevant to Crichton's story, the specified use of punched cards, or IBM Cards as otherwise known, in the future is a mere reflection of the fact that the punched card interface was the principal form of human-computer interaction in the 1960's and an established symbol of the information age for nearly half a century (IBM, 2012), (Figure 3).

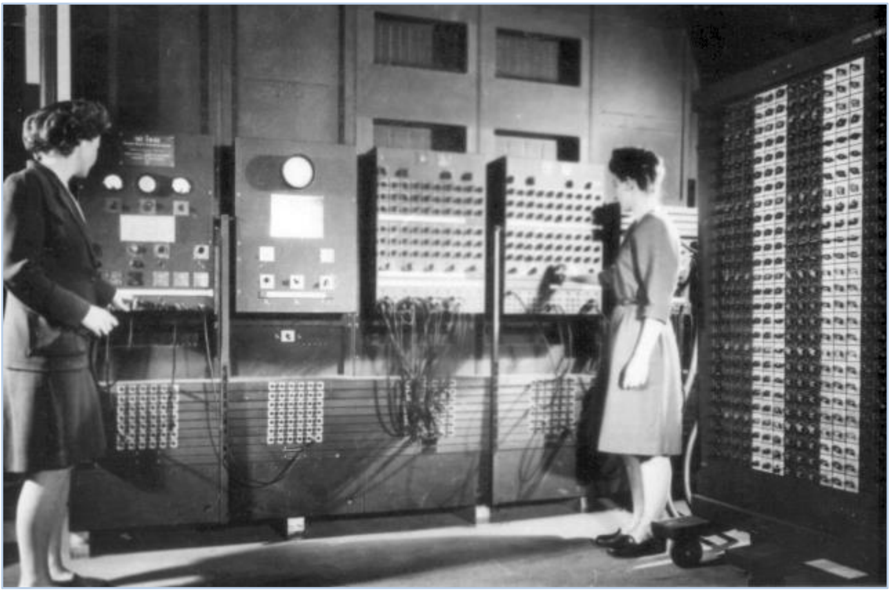


Figure 3 The control panel of the ENIAC computer. U. S. Army Photo, c. 1946 to 1955

2.3.2 Command Line Interface

In the 1970’s, the use of cardboard punched cards as means of computer data input and storage gave way to the Command Line Interface (CLI). With the arrival of keyboard equipped video terminals such as the DataPoint 3300 in the late 1960’s, CLIs were established as the principal way to interact with computer systems (Figure 4). CLI is a fully-text based interface, controlled by a keyboard and executed via a command-line interpreter or shell. CLIs give users access to large libraries of commands with various options which can be transformed into executable computer instructions. CLI implementations such as UNIX and MS-DOS are efficient and powerful computer interfaces but have poor affordance as they require prior knowledge of a large number of commands with complex syntax (Shneiderman, 1983).

Figure 4 Datapoint Corporation DataPoint 3300, 1969

2.3.3 Graphical User Interface

In March 1967, in a paper published in the IEEE Transactions on Human Factors in Electronics, the team of Douglas Engelbart at the Stanford Research Institute described the use of a mouse as a pointing device (English *at al.*, 1967). Part of their NLS/Augment system which included a graphical display, multiple windows and hyperlinks, the mouse was conceived as the input device of choice for the emerging WIMP (Window, Icon, Menu, Pointer) user interaction paradigm. In 1973, the mouse driven experimental computer Xerox Alto developed by Xerox PARC (Palo Alto Research Center) introduced the desktop graphical user interface (GUI) metaphor and heralded the era of the personal computer (Smith and Alexander, 1988), (Figure 5).

The design of the Xerox Alto computer influenced the GUI implementations of Apple MAC and Microsoft Windows of today (Tuck, 2001).

Graphical User Interfaces are "*see and point*" interactive human-computer interfaces which allow users to control information by means of selecting and manipulating graphical metaphors or widgets using a pointing device such as the computer mouse. Conventional GUIs are easy to learn and are developed to be consistent, forgiving interfaces with direct user control. Designed for use without much prior computer knowledge, GUIs enjoyed wide user acceptance and quickly came to dominate the consumer market (Grudin, 2011). For complex computer operations and information management, however, GUIs can be restrictive and burdensome. Therefore expert users every so often opt to use scripting or CLI type interactions due to their better capacity and flexibility (Gentner and Nielsen, 1996). Nevertheless, advanced and carefully designed GUIs can increase the productivity of both novice and expert users (Helander *et al.*, 1997).

Figure 5 The Xerox Alto, The Apple Pop Up Museum is in Rosewell, GA, USA

2.3.4 Touchscreen Interfaces

Touchscreens, an alternative input device to the computer mouse, have their genesis in the design and development of the compact, software configurable Super Proton Synchrotron (SPS) Central Control terminal at the European Organization for Nuclear

Research (CERN) (Stumpe and Sutton, 2010), (Figure 6). The capacitive touchscreen, first described in the 1960's (Johnson, 1965) and debuted as the interface for the "*Drinkomat*" beverage mixer at the Hanover Fair in 1977 (Stumpe and Sutton, 2010), made history as the interface of choice for the Apple iPhone in 2007 (Barrett and Omote, 2010).

Figure 6 The Touch Terminal as developed for the Antiproton Accumulator (Stumpe and Sutton, 2010)

Since 2007, multi-touch user interfaces have grown to become an integral part of most consumer computer products (Jim, 2013). The ability to directly manipulate software objects in a way which is familiar from the natural interactions in the physical world makes multi-touch interfaces intuitive and easy to use. In order to harness their full potential, they need to be designed with care so that the inherent user knowledge is utilised effectively thus minimising the effort to learn and use the interface. In addition better consistency across specific system implementations can further improve the multi-touch user interfaces affordance and usability (Ingram *et al.*, 2012).

Each step of the evolutionary path of human-computer interfaces – the keyboard driven CLI, the mouse controlled GUI and more recently the advent of touch-screen devices has profoundly changed the way people use computers and in this process people themselves. *Interface* has become a household term and there is a wide debate about what comes next. Some see the future of interfaces as one of not having any (BBC, 2013).

2.4 The “Invisible Interface”

2.4.1 Preamble

Over the past two decades Graphical User Interfaces have fuelled the democratisation of computing. Consistent, forgiving and based on familiar metaphors, GUIs have aided billions of computer users to interact with personal computers (ITU, 2013). More powerful and flexible interfaces, however, are needed for expert users and the computer savvy generation (Gentner and Nielsen, 1996). Mark Weiser (1994), while at the Xerox PARC – the research company who developed the Xerox Alto, envisages future computers as being always present but invisible; computers that employ the full range of the human’s sensory system within the suite of their interaction capabilities. Systems with multiple modalities can enable richer and more natural human-computer interaction. The use of interaction modalities such as natural speech and physical gestures can advance the design of Natural User Interfaces (NUI) that are more accessible, intuitive and easy to use (Billinghurst, 1998), (Figure 7).

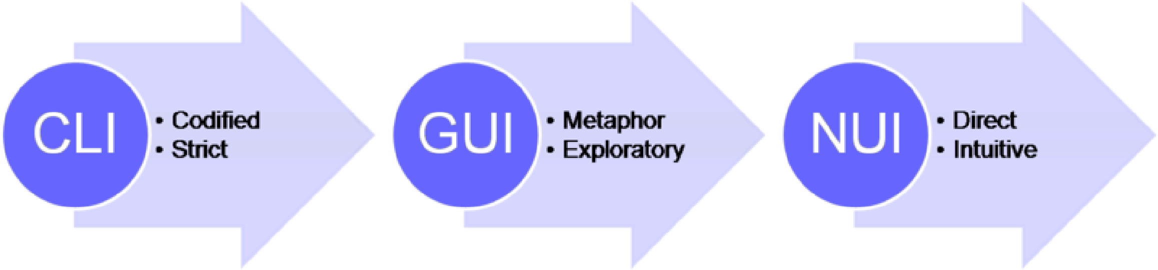


Figure 7 Human-computer interface evolution (August de los Reyes, 2009)

Safety-critical areas and healthcare in particular demand multimodal interactions that preserve the natural order and integrity of their workplace (Cohen and McGee, 2004). Furthermore, in clinical settings there is a compelling need for user-adaptive interfaces which can support collaborative work practices (Patel and Kushniruk, 1998). Gesture control NUIs based on innovative motion sensors are intuitive to use and more importantly they offer the potential to augment social interactions in general. In the context of medical surgery, for example, the collaborative practices of the surgical team can be enhanced by touchless human-computer interactions that are “*socially meaningful*” (O’Hara *et al.*, 2013).

2.4.2 Consumerisation of technology

In February 2013, the Smartphone powered CubeSat was launched into orbit on board the Polar Satellite Launch Vehicle rocket (SSTL, 2013). Developed by Surrey Satellite Technology Limited (SSTL), one of the objectives of the STRaND-1 (Surrey Training, Research and Nanosatellite Demonstrator 1) satellite is to establish the feasibility of using commercial-off-the-shelf (COTS) technology in space (Kenyon *et al.*, 2011). This initiative is a stark departure from the traditional space exploration research and development practices that is driven by the availability of very advanced and cheap commercial technology (The Economist, 2011). Along with Smartphones, the gaming industry has experienced rapid growth and progress in recent years and the video game market is expected to exceed €80 billion in 2015 (Gartner, 2013), (Figure 8). This expansion has fuelled the design and development of a new generation of advanced COTS Natural User Interface controllers.

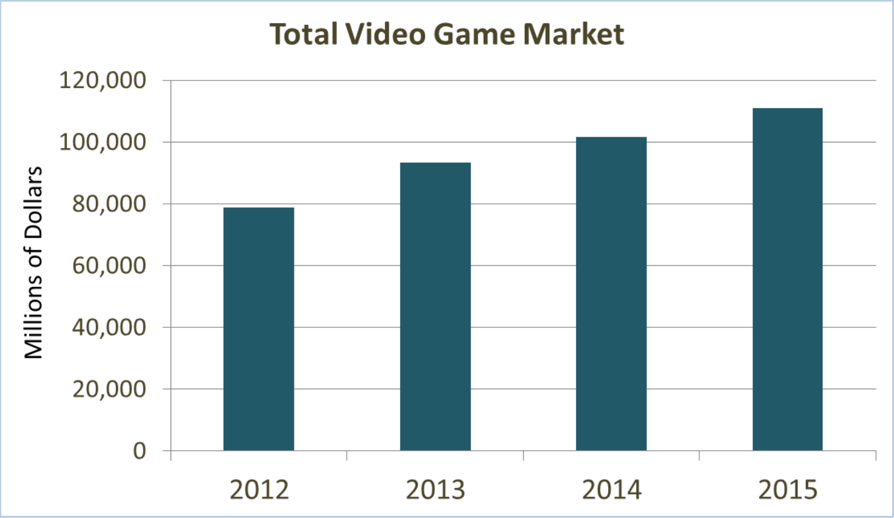


Figure 8 Total gaming industry market size (Gartner, 2013)

Hands-free consumer sensor devices such as eye and gaze tracking controllers, camera based gesture sensors and biosensors enable natural and adaptive interactions. Their capabilities promote simpler and yet more meaningful navigation. They can improve the efficiency of human-computer interaction in varied environments and broad type of user activities (Yamnitsky *et al.*, 2013). The commercial availability of these new computer interfaces has often been hotly anticipated and once released they have been enthusiastically adopted by consumers, industry and academic researchers alike (Geron, 2013, Yamnitsky *et al.*, 2013, Chen *et al.*, 2013). Table 1 shows a non-exhaustive list of notable COTS NUI sensor devices, their individual technology and manufacturers.

Table 1 COTS NUI sensor devices

Product	Company	Technology	Hardware	Launch	Reference
Kinect for Xbox 360	Microsoft	3D sensing and gesture control	IR depth camera + RGB camera	2010	Lee, 2013
Kinect for Xbox One	Microsoft	3D sensing and motion control	Time-of-flight camera with active IR sensor	2013	Sell and O'Connor, 2014
Leap Motion controller	Leap Motion	3D sensing and motion control	Common VGA camera sensors + IR illumination	2013	Yamnitsky *et al.*, 2013
Capri	PrimeSense	3D sensing and motion control	IR depth camera + RGB camera	2013	Lee, 2013, Yamnitsky *et al.*, 2014
Software	Umoove	Face and eye-tracking	Mobile device integrated camera	2014	Yamnitsky *et al.*, 2013
The Eye Tribe Tracker	The Eye Tribe	Eye and gaze tracking	Camera + IR illumination	2014	Donovan, 2013
Software or embedded hardware	Tobii Technology	Eye and gaze tracking	Camera + IR illumination	2012	Yamnitsky *et al.*, 2013
MYO	Thalmic Labs	Muscle activity motion sensing	Gesture control biosensor armband	2014	Yamnitsky *et al.*, 2013
FIN	RHL Vision	Thumb motion sensing	Thumb ring with optical sensor	2014 (TBC)	Kumparak, 2014

2.4.3 Genesis of touchless gesture interfaces

Touchless gesture interfaces made their debut in style in 1920 when Lev Termen, otherwise known as Leon Theremin, played his *Theremin* at a performance in front of the Mechanical Engineers group at the Saint Petersburg Polytechnical University (Glinsky, 2000), (Figure 9). The *Theremin*, a monophonic musical instrument allowed the musician to perform by gesturing in front of its two antennas. The touch-free controlled instrument went on to become a world-wide sensation and later inspired the first commercial synthesizers (Moog Music, 2013).

Figure 9 Leon Theremin playing his own instrument (© Sovfoto/UIG)

Half a century later, in 1970, another performing arts demonstration took place – Myron Krueger's Videoplace exhibited touchless interaction with computer graphics (Figure 10). The Videoplace "*responsive environment*" combined computer generated images with real-time participant's body movements and thus demonstrated the capability to manipulate computer objects using natural gestures (Krueger *et al.*, 1985). A similar project by the Architecture Machine Group at the Massachusetts Institute of Technology, USA successfully combined virtual environment with real space. Their "*Media Room*" installation, based on commercially available electromagnetic gesture detecting sensors and voice recognition system, showed a tangible future of computer interactions based on natural, everyday human speech and gestures (Bolt, 1980).

Figure 10 Videoplace, Myron Krueger, ©Ars Electronica Linz GmbH

Building on the initial success of the VPL Research Inc. DataGlove, in 1989 the American toy manufacturer Mattel Inc. released the Power Glove as a Nintendo video game controller (Figure 11). The Power Glove position in space was tracked by an ultrasound acoustic system comprised of two speakers, paired with three receivers placed near the display monitor. The hand position detection was complemented by a conductive-ink based sensor which tracked finger flexion, an inexpensive alternative to the more precise VPL DataGlove fibre optic sensor. Albeit not very accurate and ultimately commercially unsuccessful, the Power Glove COTS gesture controller was cheaper by a factor of 100 relative to similar contemporary systems and its low price helped it gain popularity with researchers (Sturman and Zeltzer, 1994).

Figure 11 Mattel Power Glove

In 1993, Sega Corporation, a video games company, began selling the Sega Activator (Figure 12). The full body gesture controller based on eight infrared sensors, alike the Power Glove, was not a successful product, principally due to its inaccuracy (Horowitz, 2004). The commercial failures of these early COTS gesture input devices expose the fundamental differences between natural human input based interfaces and WIMP

(Window, Icon, Menu, Pointer) GUIs. Whereas GUIs are certain and discreet type of human-computer interaction, the human gestures and speech based input is inherently uncertain and probabilistic in nature. This places an onerous task on the developers of NUI systems to optimise the use and recognition of human gestures (Oviatt and Cohen, 2000). Along with better sensing technologies, contextual knowledge and multimodal input integration are necessary to develop efficient and usable natural user interfaces (Billinghurst, 1998).

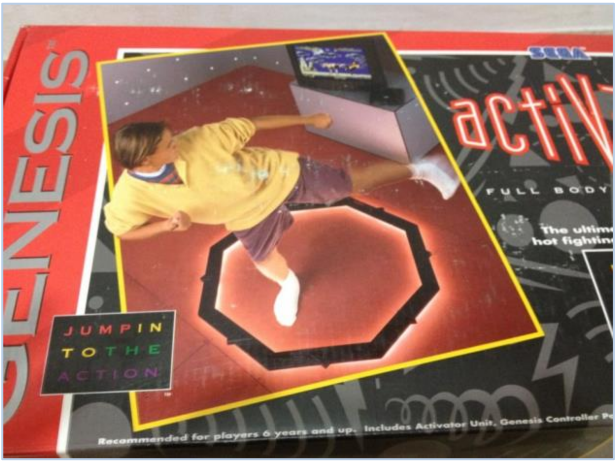


Figure 12 Sega Activator (©eBay Inc.)

During the first decade of the 21st century, a new generation of COTS motion controllers came onto the market. In September 2005, Nintendo unveiled the Wii Remote (Mirabella and Casamassina, 2005). The Wii hand held games controller enables 3D motion detection by combining three-axis linear acceleration sensing with an infrared (IR) sensor (Wisniowski, 2006), (Figure 13). The IR optical sensing allows for triangulation of distance and calculation of roll by using the standalone Wii sensor bar IR LEDs as a reference (Ohta, 2007). In 2009, the Wii Remote MotionPlus extension allowed Nintendo to overcome the limitation of only detecting movements along straight lines by adding a gyro sensor to the controller. This made possible more precise motion detection along six axes (Iwata, 2009). The following year Nintendo released the Wii Remote Plus which incorporates a more precise set of accelerometer, gyro and IR sensors within the body of the Remote (Greenwald, 2010), (Figure 13).

Figure 13 Wii Remote with MotionPlus and Wii Remote Plus (©Amazon.com)

In 2003 another major video game company, Sony Computer Entertainment, launched the EyeToy on PlayStation®2 (De Leon, 2011). The EyeToy, an inexpensive digital camera device, enables gesture interactions by means of three-dimensional scene analysis and reconstruction from 2D image data. Four years later Sony announced its successor, the PlayStation®3 Eye featuring a higher resolution camera able to perform in varied light conditions as well as an advanced 4-microphone array (Stocker, 2007), (Figure 14). Both controllers use motion detection computer vision algorithms and are capable of identifying gestures in an X-Y, 2D plane. The release of the PlayStation® Move motion controller in 2010 enhanced the precision of Sony's gesture recognition system (De Leon, 2011), (Figure 14). The PlayStation® Move together with the PlayStation®3 Eye facilitate *2D object tracking* which is a more exact computer vision technique (Eisenstein and Mackay, 2006). In addition, by continuously measuring the size of the RGB LED illuminated ball on the top of the controller, the system can track along the Z-axis which allows for true 3D motion sensing (Sinclair, 2010). Finally, the built-in three-axis gyroscope, three-axis accelerometer and Earth magnetic field sensor further increase PlayStation® Move gesture recognition accuracy (Sony Computer Entertainment Inc., 2010).

A comparative assessment of the Nintendo Wii Remote Plus and the Sony Move controllers has shown that both sensors have adequate accuracy of orientation and range of motion measurements suitable for clinical applications. Only the Sony Move, however, due to its built-in magnetometer, has satisfactory precision of motion tracking for use for medical assessment of human body movement (Bai *et al.*, 2012).

Figure 14 Sony PlayStation® Move (left) and PlayStation®3 Eye (right)

In 2012, Nintendo and Sony shared approximately 70% of the lucrative global Game Console market. The remaining 30% market share belonged to Microsoft and their Xbox family products (Smith, 2013). Microsoft Kinect, the Xbox motion sensor controller was released in November 2010 (Figure 15). The RGB-D camera input device along with its advanced software development kit (SDK) facilitates the implementation of various Augmented Reality (AR) applications and it is generally considered to be the "*future of game interfaces*" (Tanaka *et al.*, 2012; LaViola and Keefe, 2011).

2.4.4 Microsoft Kinect

The first generation Microsoft Kinect is comprised of a RGB colour video camera, an IR depth camera, a four-element microphone array and a motor-powered tilt system (Figure 15). The depth data is a greyscale image with each pixel representing distance from the sensor to the captured object. The Kinect device can interface with a Microsoft Xbox game console or a Windows machine. Along with the raw sensor data, the Kinect SDK provides skeletal tracking of one or two people and advanced audio processing features such as echo cancellation, noise suppression and audio beam forming for acoustic source localisation (LaViola and Keefe, 2011).

Figure 15 2010 Microsoft Kinect RGB-D sensor

The Kinect sensor effective depth range is between 0.8m and 3.5m and its horizontal angle of vision is 57.5 degrees. The vertical *field of view* is 43.5 degrees, with -27 to +27 degree variable tilt (Figure 16). Measurements of the depth sensitivity showed the Kinect device being capable of detecting object movements 1 mm in shift and 1 degree in rotation (Aoki *et al.*, 2013). Post-processing of the raw sensor data can provide real-time, accurate dense surface reconstruction (Newcombe *et al.*, 2011). Body joints location can be computed invariant to body shape, pose and even clothing (Shotton *et al.*, 2011). Overall, the quality of the Microsoft Kinect system output is considered sufficient for use in real-time medical applications in areas like radiotherapy and temporal subtraction radiography (Aoki *et al.*, 2013).

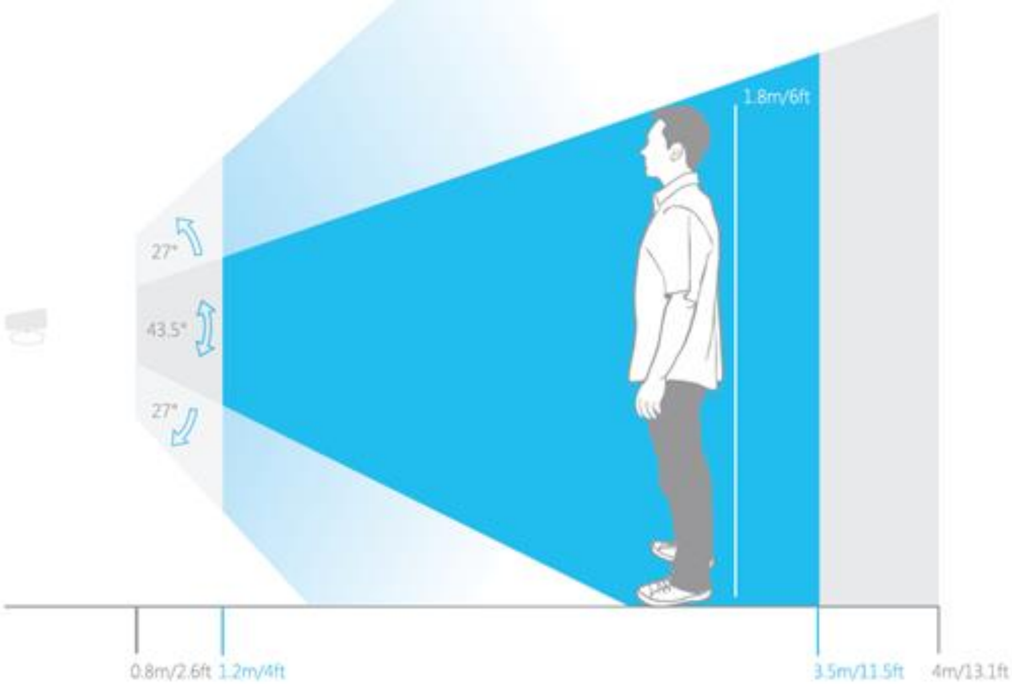


Figure 16 Kinect sensor vertical *field of view* (© 2014 Microsoft)

The second generation Kinect for Xbox One was released in November 2013 (Microsoft Corporation, 2013a), (Figure 17). However, the Microsoft Kinect for Windows v2 was only released to a small number of selected developers as part of the Microsoft developer preview program and is scheduled to be available as public beta in July 2014 (Microsoft, 2014). With the new Kinect sensor, Microsoft replaces the original PrimeSense 3D depth sensing using *structured light* (Yamnitsky *et al.*, 2013) with an in-house developed *time of flight* system (Sell and O'Connor, 2014).

Figure 17 Second generation Kinect for Windows 2 (© 2014 Microsoft)

The Kinect v2 *time of flight* motion sensing system uses a laser diode which illuminates the 3D scene (Figure 18). The light reflects off any object in the sensor *field of view* and returns back with some delay (phase shift) and attenuation. The resulting delta signal is processed by the system to produce a low latency, high dynamic range and high resolution depth image. This design also makes the depth data acquisition independent of the scene ambient lighting. In addition to the higher depth fidelity, the new Microsoft sensor has an expanded *field of view* although it is missing the ability to adjust the *field of view* using the built-in tilt motor available in the first generation Kinect. Similarly to its predecessor, the Kinect v2 has a built-in multi-microphone array which enables advance voice recognition (Microsoft, 2014; Sell and O'Connor, 2014).

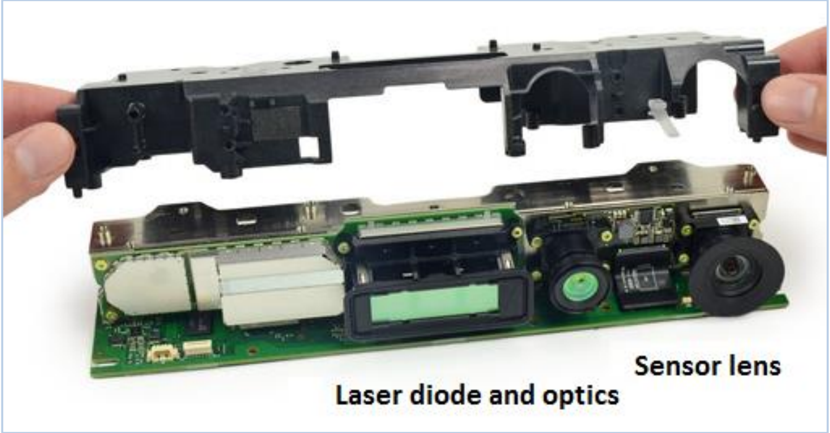


Figure 18 Kinect v2 hardware (sensor image ©iFixit)

The sensor standard SDK provides functions for high precision skeletal tracking of up to six people, hand tracking (enabling the identification of gestures such as gripping, releasing, and pressing), human muscle and forces model, heart rate measurements, and face expression recognition (WIRED, 2013; Microsoft, 2014). The new Kinect v2 controller has an impressive set of capabilities but it is how these are put to use in the context of human-computer interaction that will ultimately decide whether in time it will attain the iconic status of some of Apple's inventions.

2.4.5 Leap Motion

Inspired by the success of Apple's touchscreen products, a start-up from the USA called Leap Motion have designed and developed a motion sensor with the ambitious goal of one day replacing the computer mouse (Satariano, 2012). The Leap Motion controller, released in July 2013, is a gesture recognition interface device which enables computer interactions based on hand and finger motion (Leap Motion, 2013b), (Figure 19). Since its announcement, the Leap Motion sensor has got positive reception from both developers and electronics equipment manufacturers. In 2013 the company successfully signed deals to embed the controller in some of the high end products of two of the world largest PC makers, ASUS and HP (Leap Motion, 2013a; Chacos, 2013).

Figure 19 Leap Motion controller

The Leap Motion controller comprises of two IR cameras and three IR LEDs which allow it to track motion based on *stereo vision* processing, in contrast to the Kinect v2 sensor which uses *time of flight* method. The positions of recognised objects within the controllers' conical *field of view* are calculated relative to the centre point of the device which is where the middle of the three IR LEDs is located (Figure 20). These are exposed via the Leap Motion Application Programme Interfaces (APIs) for use by application software developers.

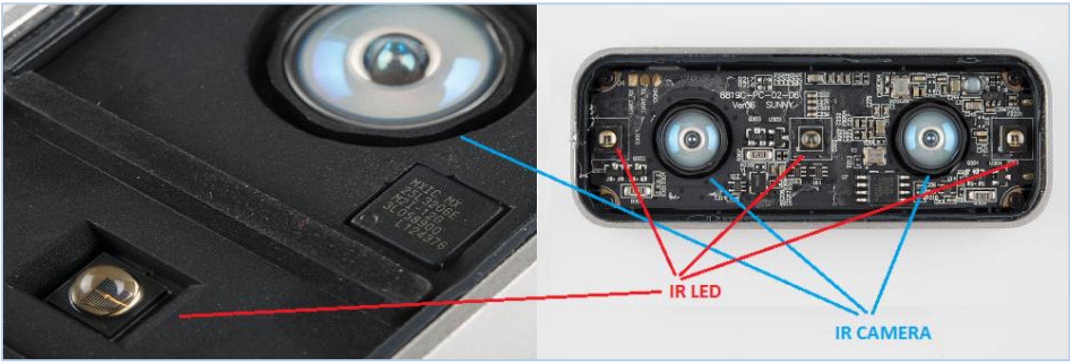


Figure 20 Leap Motion controller hardware (sensor images ©SparkFun Electronics)

The Leap Motion sensor has a wide, 150° *field of view* (Leap Motion, 2014), (Figure 20). A study of the Leap Motion controller using a high precision industrial robot reference system found that the sensor has accuracy of static positioning less than 0.2 mm and 1.2 mm for dynamic positioning (Weichert *et al.*, 2013). This is considered sufficient for use of the device as a natural user interface controller. In another assessment of the sensor, Guna *et al.* (2014) established that its effective range extends between 2.5 to 60 centimetres above the device. Their study also revealed that the accuracy of the sensor diminishes significantly with the hand moving away from the device and that the sampling frequency is highly variable, with an average of 40Hz. Despite these shortcomings, the Leap Motion controller is usable as gestural interface and it provides "*fine control*" for activities such as air painting (Sutton, 2013).

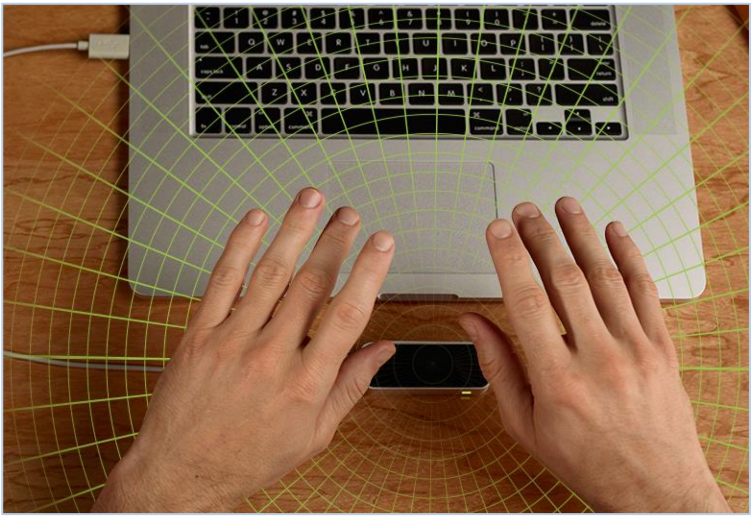


Figure 21 Leap Motion sensor *field of view* (© 2014, Leap Motion, Inc)

2.4.6 Microsoft Kinect and Leap Motion applications

The Microsoft Kinect and Leap Motion controllers have both been adopted by developers and researchers well in advance of their respective commercial releases (Microsoft Corporation, 2013b; Leap Motion, 2012). Applications for the motion controllers have been developed in a diverse range of areas such as entertainment, learning, health and engineering. For example, in their research Zafrulla *et al.* (2011) and Potter *et al.* (2013) investigate the feasibility of utilising the Kinect and Leap Motion sensors respectively for sign language recognition and translation. Both studies acknowledge the viability of cost-effective sign language translators based on the two COTS devices. Another example is the use of the two controllers by the NASA Jet Propulsion Laboratory Operations Lab (OpsLab JPL), the research centre where the software for command of space exploration vehicles and robotic devices is developed. At the start of 2013, researches from OpsLab JPL (2013a) demonstrated how Leap Motion can be used to operate a planetary rover (Figure 22). Later that year, OpsLab JPL (2013b) revealed their successful experiment of controlling a robot arm using Microsoft Kinect v2 and Facebook’s Oculus Rift virtual reality headset (Figure 22). This setup provides first-person view for the operator and can facilitate the remote control of Robonaut 2, the NASA International Space Station's robotic crew member.

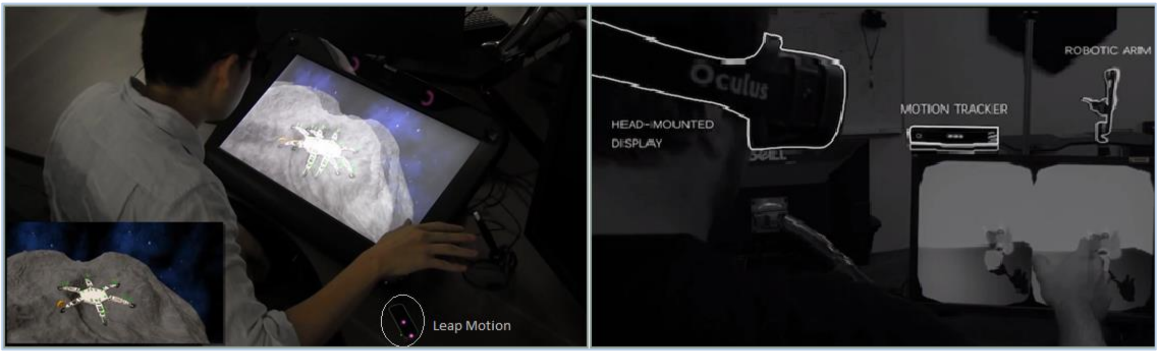


Figure 22 Leap Motion (left) and Microsoft Kinect v2 (right) sensors controlling robotic devices (© 2013 OpsLab JPL)

2.5 Use of Consumer NUI Technology in Healthcare

2.5.1 Preamble

There is a broad spectrum of applications of COTS motion sensors. One specific field where successful implementations have been demonstrated is healthcare. The usefulness of NUI systems based on consumer devices has been established in a diverse range of health-related areas – form training and education of healthcare professionals through medical diagnostics to medical treatment and rehabilitation.

2.5.2 Enhancing medical training

Along with enabling the control of robots during space exploration missions, virtual reality (VR) systems can be an effective tool for medical education. Augmented reality applications such as the Kinect based virtual mirror Mirracle can be used for anatomy training (Blum *et al.*, 2012). A review of virtual environment based surgical training has demonstrated that it can be effective in improving the performance of surgical trainees (Gallagher *et al.,* 2005). Using COTS 3D depth camera sensors can provide a cost effective way of developing VR systems for surgical training (Yang *et al.*, 2014) as well as for training and procedural skills development for all types of medical professions (Tolk *et al.*, 2013; Bartoli *et al.*, 2012).

2.5.3 Medical diagnostics support

The NUI input sensors' capability to accurately track body movement, face expression and gaze can be utilised for physical and neurological assessment of patients. Eye tracking sensors such as the Tobii and the Eye Tribe Tracker can be used for automated visual field defects identification (Table 1). This can help diagnose young children and elderly patients who cannot be tested using standard tests (Murray *et al.*, 2009; BBC, 2012). Integrating the multimodal input of motion sensors enables the analysis of nonverbal behaviour and aids the diagnosis of psychological and neurodevelopmental conditions such as depression and Autism Spectrum Disorders (Scherer *et al.*, 2013; Domínguez *et al.*, 2013; Walczak *et al.,* 2012). Using Microsoft Kinect for motion analysis has been shown as an effective tool for postural control and physical health assessment in the clinical setting (Staiano and Calvertb, 2011; Clark *et al.*, 2012).

2.5.4 Supporting Physical Medicine and Rehabilitation

COTS motion sensors can be utilised for physical and neurological assessment. They can be also part of the therapy. For example, gesture interface systems can be developed to facilitate the treatment of Autism Spectrum Disorders and other sensory processing disorders (Zalapa and Tentori, 2013; Surapa and Dwivedi, 2013). They can predict the risk of falls and deliver fall prevention training (Garcia *et al.*, 2012). Commercial game controllers have sufficient speed and accuracy for use in exergames for rehabilitation (Tanaka *et al.*, 2012). A considerable number of Kinect based systems for physical rehabilitation have been developed and studies of their therapeutic application have shown that they are an effective alternative of or a complement to conventional therapy (Roy *et al.*, 2013; Parry *et al.*, 2013; Chung *et al.*, 2014).

2.5.5 Minimising the radiation dose exposure

Another area of application of 3D motion sensors is diagnostic radiology. Radiation exposure due to radiography imaging brings a risk of cancer for both patients and medical professionals. Epidemiological studies have established that the use of several CT scans over a course of treatment results in an increased risk of cancer (Brenner and Hall, 2007). This risk is significantly higher for the growing child and the Image Gently campaign is trying to heighten awareness of the need to adjust radiation dose when imaging children (Goske *et al.*, 2008). Using the Kinect sensor data can help accurately determine the patient’s volume and enable the use of lower, patient-specific radiation doses (Cook *et al.*, 2013). Similarly, by facilitating the registration of intra-operative images with pre-operative planning data, a Kinect-based system can help shorten some surgical interventions. This can reduce the surgical procedure related radiation exposure for both patients and clinicians (Mersmann *et al.*, 2011, Müller *et al.*, 2013).

2.5.6 Computer and robotic aided surgery

Advancements in biomedical imaging and robotics allow for a greater number of treatments to be delivered using minimally invasive procedures. The US Computing Community Consortium and the American Robotics Virtual Organization in their *Roadmap for U.S. Robotics* predict that robotic technologies will transform medical imaging and surgery in the same way they have radically changed manufacturing in the last few decades (Robotics-VO, 2013). For this to be achieved, the human operators would need interfaces which are not only effective but also natural and transparent. NUI based on gesture recognition and haptics can be successfully used to facilitate telerobotic surgery (Ryden, 2012), (Figure 23).

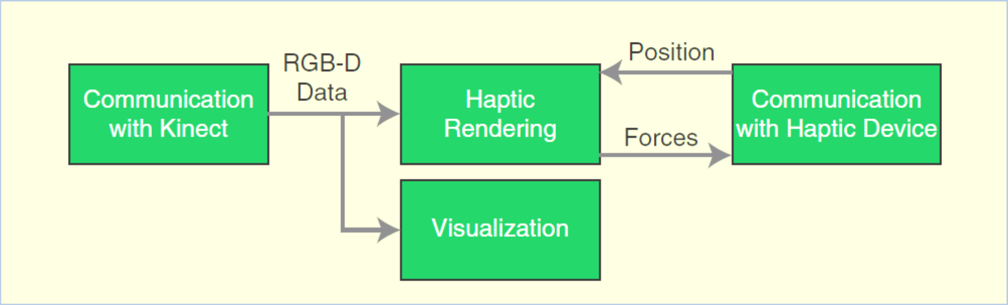


Figure 23 Use of Kinect for control of robotic devices (Ryden, 2012)

2.6 Application of Natural User Interfaces in the Operating Room

2.6.1 Preamble

In the previous section some of the various uses of NUI devices in healthcare were outlined. This section examines the motivation for use of gesture technology in the OR and its application for image navigation and manipulation during surgery.

2.6.2 The requirement for sterility in the operating room

Infection at the surgical site is the most frequently acquired hospital infection in the Republic of Ireland, contributing to more than 18% of all cases (Burns *et al.*, 2012). Environmental surfaces are one of the three most likely routes of infection spread in the OR (Woodhead *et al.*, 2002). Furthermore, Hartmann *et al.* (2004) found that the computer keyboard and mouse have a greater rate of microbial contamination compared to other physical objects within a surgical ICU. Schultz *et al.* (2003) reported that 95% of the tested keyboards in a tertiary hospital have confirmed positive for microorganisms. It is paramount that scrubbed members of the surgical team avoid contact with such potentially contaminated surfaces (Mangram *et al.*, 1999).

2.6.3 Maintaining asepsis while accessing medical images

Biomedical imaging is an area which is rapidly evolving and this has resulted in a significant rise in the use of diagnostic imaging (Smith-Bindman *et al.,* 2010). In addition, image guided, minimally invasive surgical procedures require the implementation of controllable real-time imaging and computer-assisted surgical intervention workflows (Linte and Yaniv, 2014). Using traditional mouse and keyboard to interact with computer systems and medical images within the OR along with the strict requirement to maintain asepsis has led to complex arrangements between the scrubbed clinician and the non-scrubbed personnel (Jacob *et al.*, 2012; Ogura *et al.*, 2014). Image interaction via delegation of control to a non-scrubbed member of the team can result in workflow inefficiencies (Figure 24). One example is the reported by Grätzel *et al.* (2004) 7 minute long procedure to enact a single mouse click. Furthermore, lack of direct control over the image manipulation can negatively impact on the ability of the clinician to interpret the image (Johnson *et al.*, 2011).

Figure 24 Existing arrangements between the scrubbed clinician and the non-scrubbed personnel. © 2013 BskyB; filmed in the Hermitage Clinic Dublin

When the scrubbed clinician needs to take first hand control of the imaging system he or she would have to un-scrub and then scrub again. This increases the time of the operation and therefore both the overall financial cost and the risk to the patient. The conflict between attaining additional diagnostic information and keeping the time of the surgical procedure to a minimum has in some cases led to questionable "workarounds" such as the one shown on Figure 25.

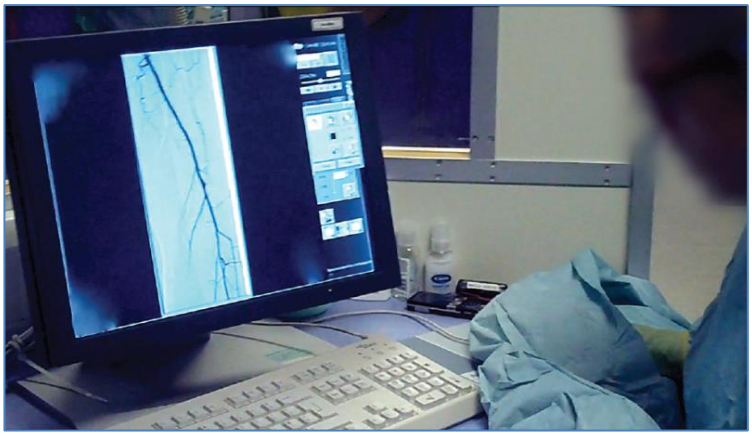


Figure 25 An interventional radiologist using the mouse through his gown during angioplasty (Johnson *et al.*, 2011)

There are exiting solutions such as sterile computer mouse and keyboard covers, touch operated tablets protected in sterile bags or fully sealed and washable mouse and keyboard which can potentially address some of the described issues of maintaining sterility in the OR. These, however, will not resolve the problem entirely as there is a risk of damage to the barrier and the interface device cannot be operated by both scrubbed and non-scrubbed personnel (Johnson *et al.*, 2011).

Touchless, natural user interfaces for image interaction can provide the scrubbed clinician with direct and dynamic image control while minimising the risk of surgical site infection (Tan *et al.,* 2013; O'Hara, 2014a). Gesture recognition systems for image manipulation in surgery began to emerge over a decade ago. Graetzel *et al.* (2004) demonstrated a gesture based "*non-contact mouse*" for use during minimally invasive procedures. Three years later, a system for touchless image navigation using real-time web camera video analysis was trialled during live neurosurgery (Wachs *et al.*, 2007). Soutschek *et al.* (2008) established that a camera based hand gesture recognition system based on a pixel-wise *time of flight* measurements of an active reference signal (the Kinect v2 framework) is feasible for use in the clinical environment. Gallo *et al.* (2011) implemented an open-source PACS image viewer system using the Kinect sensor as the sole input device. In 2013, Strickland *et al.* (2013) successfully trialled a NUI image control system during live surgical procedures, both minimally invasive and open, at the Sunnybrook Health Sciences Centre in Toronto, Canada.

To date, several proof-of-concept deployments of Microsoft Kinect v1 based touchless image control systems have been successfully completed in various real surgical settings (O'Hara *et al.*, 2014a; Strickland *et al.,* 2013; Ruppert *et al.*, 2012). Despite its recent release in July 2013, already a few research studies have demonstrated the viability of a Leap Motion based NUI system for use in the OR. Mauser and Burgert (2014) have established the potential of the Leap Motion input device for use in the clinical environment. Ogura *et al.* (2014) determined that the Leap Motion application for angiography is practicable and it can even outperform the traditional computer mouse in terms of speed of operation. Presently, there are several companies which offer commercial NUI medical image interaction systems, based on the Microsoft Kinect and Leap Motion sensors, such as GestSure Technologies (gestsure.com) and TedCas Medical Systems (tedcas.com), with others imminent to launch their products in the near future (Siemens, 2012).

2.6.4 Ownership of need and action

Employing gesture recognition systems for computer interaction can enhance the way healthcare professionals use imaging data in the OR by reducing the need for representation when manipulating images. Using NUI can also decrease the cognitive load when interacting with 3D virtual environments (Roupé *et al.*, 2014). For example, Kirmizibayrak *et al.* (2011) found that certain tasks such as volume rotation and target localisation are performed more effectively using hand gestures rather than traditional computer mouse. In addition, the use of NUI can create new opportunities for imaging practices and surgical team collaboration. Specific examples are the ability to hand over control between a consultant (lead clinician) and junior doctors (assistants) or to discuss and collaboratively interpret medical imaging and review intervention plans (O'Hara *et al.*, 2014a).

2.6.5 Implementation of NUI in the OR

In order to successfully realise the potential benefits from the NUI systems in clinical settings, the technology has to be both useful and usable. Effective convergence of utility and usability in the implementation of an interactive computer system is essential (Grudin, 1992) and both factors are considered of equal importance

(Grinstein *et al.*, 2003). The perceived usefulness of an information technology system is established as a key determinant of its use and acceptance in the healthcare setting (Holden and Karsh, 2009). Equally, the usability of a clinical information system is essential for its adoption and use (Staggers *et al.*, 2009). BenMessaoud *et al.* (2011), in a study exploring the factors influencing surgeons' acceptance and use of robotics, confirmed that negative views on the *Effort Expectancy* and the *Perceived Usefulness* are the two main barriers to adoption of robotics in surgery. It is therefore important that a NUI image control system devised for use in the OR is evaluated in terms of its utility and usability. This can in turn ensure the success of its ultimate design and implementation (Shackel, 2009; Alexander and Staggers, 2009).

2.7 Review of the Literature on NUI Systems for Medical Image Control

Studies evaluating the utility and usability of touchless NUI technology for use in clinical settings were reviewed. The Google Scholar, Web of Knowledge and Engineering Village research databases were searched for the following keywords: "Kinect", "Leap Motion", "gesture" or "Natural User Interface" AND "operating theatre", "operating room", "surgery", "sterile", "hospital", "radiology" or "medical imaging". The full text of all potentially relevant articles was retrieved and read. None of the reviewed studies utilised an existing, formal usability or technology acceptance evaluation method (Table 2). All research projects have developed their own set of questions for assessing the utility and usability of the evaluated system. Other studies of Kinect based NUI systems designed for non-clinical applications have used the After-Scenario (ASQ), the Computer System Usability (CSUQ) questionnaires and the USE questionnaire for usability evaluation (Francese *et al.,* 2012; Cuccurullo *et al.*, 2012).

Table 2 List of NUI system evaluation studies

Device	Type of Assessment	Evaluation Type	Reference	Trial Setting	Comment
ToF camera	System implementation	Usability questionnaire	Soutschek *et al.*, 2008	Design lab	
Kinect v1	System implementation	Feasibility study	Gallo *et al.*, 2011	Design lab	

Device	**Type of Assessment**	**Evaluation Type**	**Reference**	**Trial Setting**	**Comment**
Leap Motion	System implementation	Feasibility study	Mauser and Burgert, 2014	Design lab	
Kinect v1	Trial evaluation	Task completion time. Usability questionnaire	Ebert *et al.*, 2012	Non sterile setting	Comparison with PC mouse
Kinect v1	Trial evaluation	Task completion time & error rate. Usability questionnaire	Jacob *et al.*, 2012	Non sterile setting	
Kinect v1	Trial evaluation	Usability questionnaire	Tan *et al.*, 2013	Non sterile setting	
Kinect v1	Trial evaluation	Task completion time. Usability questionnaire	Juhnke *et al.*, 2013	Non sterile setting	Comparison with PC mouse
Kinect v1	Trial evaluation	Task completion time & accuracy. Usability questionnaire	Chao *et al.*, 2014	Non sterile setting	Comparison with tablet & gyroscopic mouse
Leap Motion	Trial evaluation	Task completion time	Ogura *et al.*, 2014	Non sterile setting	Initial comparison with Kinect v1
Kinect v1	*In-situ* evaluation	Ethnographic study	O'Hara *et al.*, 2013	Operating Room	
Kinect v1	Trial evaluation & *in-situ* evaluation	Cognitive Walkthrough + Ethnographic study	Strickland *et al.*, 2013	Operating Room	
Kinect v1	*In-situ* evaluation	Ethnographic study	O'Hara *et al.*, 2014b	Operating Room	

2.8 Research Question

2.8.1 Research Motivation

There are a number of studies evaluating touchless, NUI image control systems in the operating room (Table 2). The launch of the Leap Motion controller in July 2013 and the release of the new Microsoft Kinect motion sensor in November 2013 naturally pose the question how these new devices compare as interface controllers of a NUI system for medical image navigation and manipulation in clinical settings.

External expert opinion on this research topic was sought from Dr. Helena Mentis, a research fellow at Harvard Medical School. Dr. Mentis' current work is on the design and coordinated use of interactive surgical systems and she had also worked on a number of projects evaluating NUI systems based on the first generation of Microsoft Kinect (Mentis *et al.*, 2012; O'Hara *et al.*, 2013). Dr. Mentis welcomed the idea for comparative evaluation of the Leap Motion and the Microsoft Kinect v2 sensor controllers in the context of their use for image interaction in surgery as a relevant research study (Appendix A). This contributed to the formulation of the following research question.

2.8.2 The question

How do the Microsoft Kinect and Leap Motion sensor devices perform and compare in terms of utility and usability in the context of their application for touchless image navigation and manipulation in sterile medical environments?

2.8.3 Research approach

The study assesses two commercially available motion sensor input devices, Microsoft Kinect for Xbox One and Leap Motion, integrated as part of the TedCas Medical Devices NUI commercial system. The devices are evaluated in terms of their utility, usability, speed, accuracy and general user acceptance. The study also aims to identify areas for design improvements and further evaluation.

For the purpose of answering the research question a mixed, qualitative and quantitative, study design has been selected. This is in keeping with a number of existing studies evaluating touchless gesture interface systems (Table 2). The study methods and materials are described in detail in Chapter 3 of the dissertation.

2.9 Utility and Usability

Nielsen (1994) defines acceptability as the overarching criterion for how well a system is satisfying the needs and requirements of its users and stakeholders. Within system acceptability, usefulness is described as the functional capability of the system to achieve a desired objective. Usefulness can be further broken down into utility and usability. Utility is the system quality of being able to do what is needed while usability concerns all aspects involved in the interaction with the user and has multiple components (Figure 26). Shackel (2009) explains further that the acceptance of a system depends on it being sufficiently useful, usable and likeable relative to its cost.

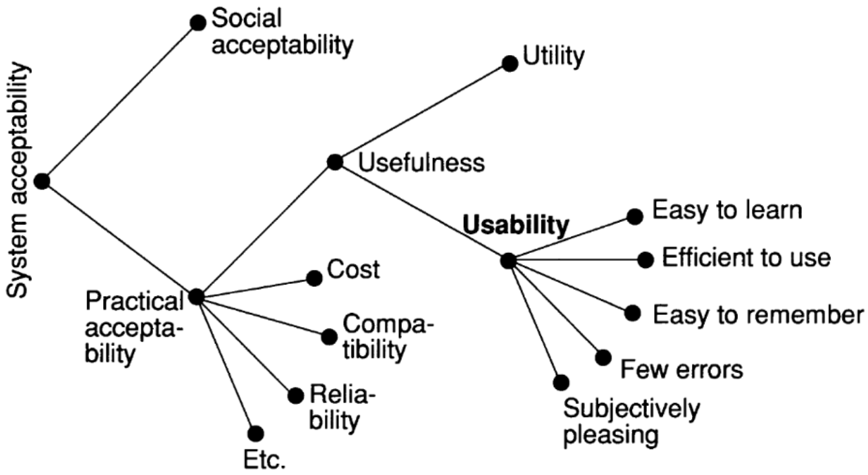


Figure 26 Model of the elements of system acceptability

There are a number of methods for evaluation of 3D user interfaces. Bowman *et al.* (2004) define the following methods which can be used in various combinations for system evaluation at each stage of the system development lifecycle:

a. Cognitive Walkthrough – a structured, task based, natural language method.
b. Heuristic Evaluation – informal, expert evaluation method.
c. Formative Evaluation – an empirical evaluation method.
d. Summative Evaluation – a method for evaluation and statistical comparison of two or more User Interfaces.
e. Questionnaires – subjective data evaluation method.
f. Interviews and Demos – a qualitative method.

Further methods for general technology acceptance (Davis, 1989) and system usability evaluation (Blandford *et al.*, 2008) exist and are commonly utilised. Some of these, such as the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) have been applied and further adapted for use in the healthcare domain (Alexander and Staggers, 2009; BenMessaoud *et al.*, 2011). In addition, a number of standardised questionnaires have been developed and proven as valid usability measurement tools. These include the IBM Computer System Usability Questionnaire (CSUQ) and After-Scenario Questionnaire (ASQ) (Lewis, 1995), the Questionnaire for User Interaction Satisfaction (QUIS) (Harper and Norman, 1993), the USE questionnaire (Lund, 2001) and the Health Information Technology Usability Evaluation Scale (Yen *et al.*, 2010).

The System Usability Scale (SUS) was developed by John Brooke in the mid 1980's with the motivation to provide a "*quick and dirty*" way of assessing the subjective perception of usability (Brooke, 2013). The SUS is a ten items questionnaire with odd-numbered questions worded positively and even-numbered ones worded negatively in order to avoid acquiescence bias. Since then, analyses of SUS data sets from a multitude of studies have established that SUS is a reliable and valid psychometric assessment of the subjective usability of a system (Lewis and Sauro, 2009). Furthermore, Lewis and Sauro (2009) established that SUS comprises of two factors measuring usability and learnability although these two constructs were found to be correlated to a certain degree (Borsci *et al.*, 2009). Recently, Peres *et al.* (2013) confirmed that SUS is not only a reliable measure of perceived usability across varied sample sizes but it also exhibits correlation with objective usability task performance. This qualifies SUS for use for comparative system usability analysis. Bangor *et al.* (2009) demonstrated strong correlation of the SUS scores to an adjective rating scale and provided a categorical meaning to the SUS scores (Figure 27).

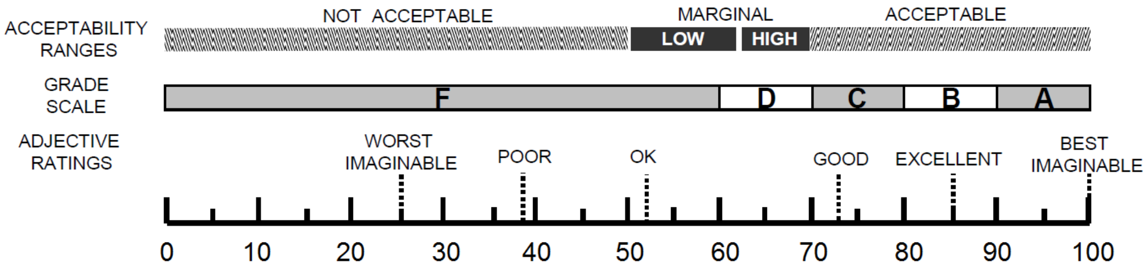


Figure 27 Comparison of the adjective ratings, acceptability scores, and school grading scales, in relation to the average SUS score (Bangor *et al.,* 2009)

2.10 Conclusion

Over the course of more than a century, computer interfaces have influenced and redefined how people use technology. The discipline of Human-computer Interactions provides a framework for understanding the complex relationships between human users and computer technology, and it is informing the design of useful and useable systems. Recent advances in COTS technology hold the promise of enabling natural, rich, multimodal human-computer interactions. NUI systems based on sensors like Microsoft Kinect have already been successfully implemented across a range of varied applications. More specifically, in the OR, systems for touchless biomedical image control have been demonstrated and used during live surgeries. A number of studies have evaluated the utility and usability of these systems but none using a formal, established method. The System Usability Scale is a short but effective measure of system usability which can provide a valid and reliable method for NUI system assessment. The recent release of the Leap Motion and Microsoft Kinect for Windows v2 motion sensors presents an opportunity to comparatively evaluate the two novel devices as interfaces of a NUI system for use in surgery.

Chapter 3 Research Design

3.1 Introduction

The following chapter outlines the research methods applied in the comparative performance evaluation of the Microsoft Kinect for Windows v2 and Leap Motion sensors as input devices of a NUI system for biomedical image control. The trial NUI system, its components and the process of iterative system design are specified. The study design aspects, namely the study participants, the study settings and the data collection and analysis are described. The approach for minimising bias and the ethical considerations are discussed.

3.2 Research Methods

A mixed methods study design was identified as the most appropriate approach to answering the research question (Collins and O'Cathain, 2009). The mixed methods design was also the most commonly applied research method in the reviewed evaluation studies of touchless, gesture interface medical systems (Table 2). The mixed methods, two-strand sequential design consists of the following components:

i. A quantitative assessment of the Microsoft Kinect for Windows v2, Leap Motion sensor and a computer mouse.

   The mean *time to measure* and *anatomical structure measurement* are the two most important task performance metrics (Bowman *et al.* 2004). The results from a pre-defined measurement task are recorded and compared in order to assess the speed and the accuracy of each of the input devices. The user task entails measuring the size of an anatomical structure (aorta diameter) and it is repeated 5 times using each of the three input devices.

ii. A descriptive field study mixing qualitative and quantitative components as part of single, semi-structured questionnaire.

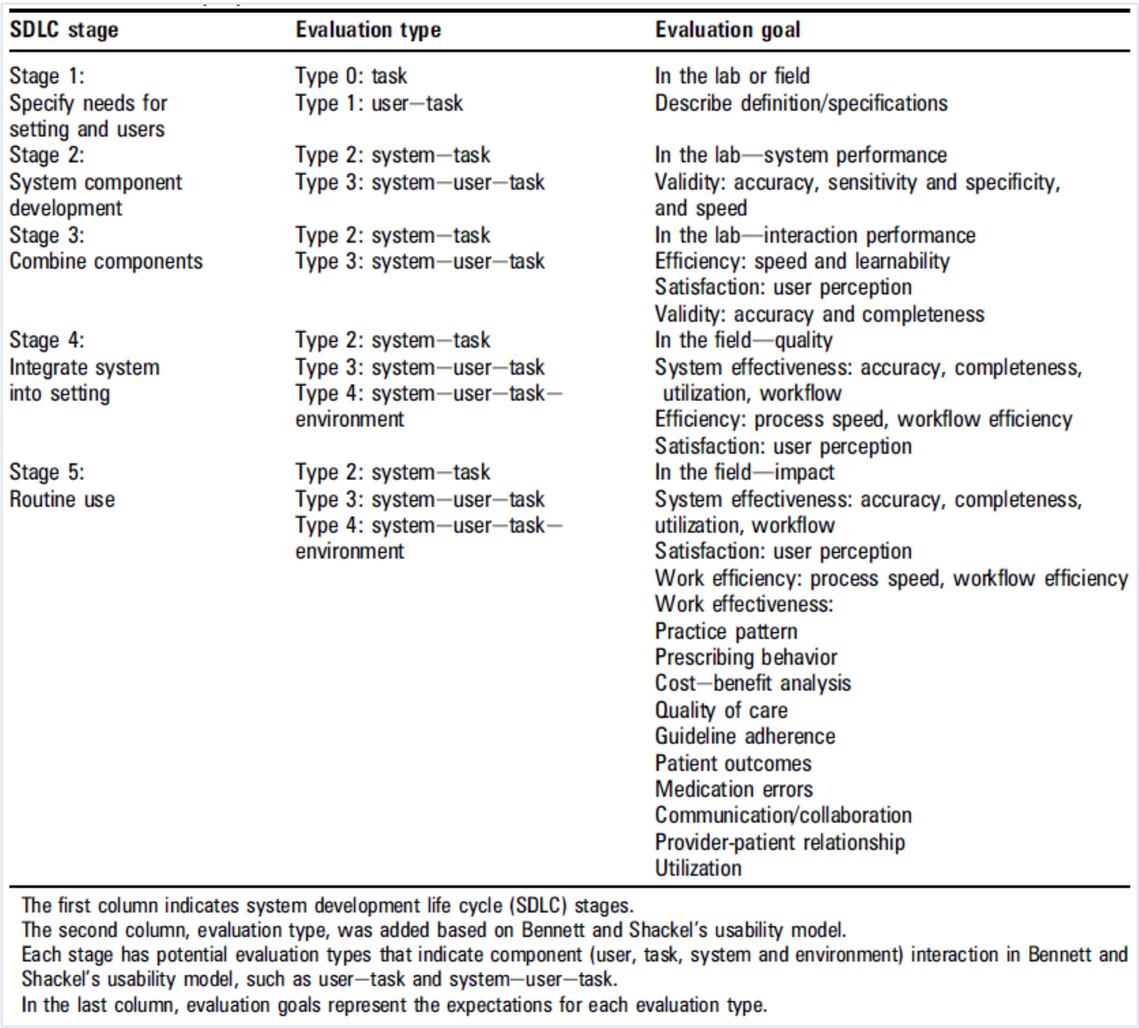
   The questionnaire incorporates a number of 5 and 3 point Likert scale questions as well as several open questions (Appendix E). It is administered at various stages during each individual user trial (section 3.8).

The decision to utilise a mixed approach for this study was pertinent to the chosen research question and it provides means of addressing all research objectives, as outlined below:

i. Do the Microsoft Kinect v2 and Leap Motion sensors facilitate accurate image manipulation and how do they compare to the traditional computer mouse in terms of their respective accuracy?
ii. How effective are the Microsoft Kinect v2 and Leap Motion sensors in terms of task completion time and how do they compare between each other and to the computer mouse?
iii. What is the perceived usability of the Microsoft Kinect v2 and Leap Motion sensors and how do they compare with each other?
iv. Are the Microsoft Kinect v2 and Leap Motion sensors useful in their application as touchless gesture interfaces for biomedical image manipulation in the OR?
v. To what extend the findings of Tan *et al.* (2013), who established that the majority (69%) of radiologists in an interventional radiology practice find Microsoft Kinect potentially useful, are applicable for the two new sensors?

The research trial was carried out in controlled, non-sterile setting at St. James's Hospital, Dublin (SJH), a large academic teaching hospital. According to Yen and Bakken (2011) this study is a Type 3 (user-task-system) evaluation at Stage 3 (combination of components) of the system development lifecycle (Table 3). The most appropriate methods for this type of study are objective measures of user interaction performance such as speed and accuracy and subjective measures of user perceived system utility and usability. Questionnaires are a convenient and effective method for measuring subjective perception metrics (Bowman *et al.* 2004). It is also the most commonly used method in Health Information Technology (HIT) usability studies at Stage 3 of the system development lifecycle (Yen and Bakken, 2011). Taking this into consideration, a semi-structured questionnaire was designed for the purpose of evaluating the utility and usability of the Microsoft Kinect v2 and Leap Motion sensor devices in the context of their application for gesture control of biomedical images.

Table 3 Usability specification and evaluation framework (Yen and Bakken, 2011)



SDLC stage	Evaluation type	Evaluation goal
Stage 1: Specify needs for setting and users	Type 0: task Type 1: user—task	In the lab or field Describe definition/specifications
Stage 2: System component development	Type 2: system—task Type 3: system—user—task	In the lab—system performance Validity: accuracy, sensitivity and specificity, and speed
Stage 3: Combine components	Type 2: system—task Type 3: system—user—task	In the lab—interaction performance Efficiency: speed and learnability Satisfaction: user perception Validity: accuracy and completeness
Stage 4: Integrate system into setting	Type 2: system—task Type 3: system—user—task Type 4: system—user—task—environment	In the field—quality System effectiveness: accuracy, completeness, utilization, workflow Efficiency: process speed, workflow efficiency Satisfaction: user perception
Stage 5: Routine use	Type 2: system—task Type 3: system—user—task Type 4: system—user—task—environment	In the field—impact System effectiveness: accuracy, completeness, utilization, workflow Satisfaction: user perception Work efficiency: process speed, workflow efficiency Work effectiveness: Practice pattern Prescribing behavior Cost—benefit analysis Quality of care Guideline adherence Patient outcomes Medication errors Communication/collaboration Provider-patient relationship Utilization

The first column indicates system development life cycle (SDLC) stages.
The second column, evaluation type, was added based on Bennett and Shackel's usability model.
Each stage has potential evaluation types that indicate component (user, task, system and environment) interaction in Bennett and Shackel's usability model, such as user—task and system—user—task.
In the last column, evaluation goals represent the expectations for each evaluation type.

3.3 Questionnaire Design

The subjective perception of the NUI system utility and usability for each of the two motion sensor controllers was measured using a semi-structured questionnaire (Appendix E). Initial questionnaire design guidelines were sought from and provided by Professor Mary Sharp from the School of Computer Science and Statistics. The very busy work schedule of the study participants (section 3.4) and the devised research protocol (section 3.8) were considered. Based on these inputs, the principal investigator identified the following key questionnaire design features:

i. Small number of questions for short completion time.
ii. Printed on paper for ease of administration at each individual step of the trial.
iii. Use of different font colours and picture cues for better legibility.

Usability was measured with the System Usability Scale (SUS). The ten items, 5 point Likert scale questionnaire met the requirement for using a quick, valid and reliable quantitative assessment method (Brooke, 2013). It comprises of the following items:

1. *I think that I would like to use this system frequently.*
2. *I found the system unnecessarily complex.*
3. *I thought the system was easy to use.*
4. *I think that I would need the support of a technical person to be able to use this system.*
5. *I found the various functions in this system were well integrated.*
6. *I thought there was too much inconsistency in this system.*
7. *I would imagine that most people would learn to use this system very quickly.*
8. *I found the system very cumbersome to use.*
9. *I felt very confident using the system.*
10. *I needed to learn a lot of things before I could get going with this system.*

The application of SUS for usability measurements in this study is an improvement to the reviewed evaluations of systems for gesture control of medical images (Table 2) and the majority of Stage 3 HIT usability studies (Yen and Bakken, 2011), none of which utilises a validated questionnaire.

The method from the study of Tan *et al.* (2013) was adopted for perceived system utility assessment. In their study, they used the following question:

"Do you feel that this system would be useful in an interventional radiology practice?"

This question was modified to reflect the wider range of clinical specialties in the population sample and to identify the specific sensor device. One additional question, using similar wording was added to allow for internal consistency assessment.

11. *Do you feel that a NUI system based on the Microsoft Kinect / Leap Motion controller would be useful in your practice?*
12. *Do you feel that a NUI system based on the Microsoft Kinect / Leap Motion controller will give you a greater degree of control in your practice?*

Three open-ended questions where included in the questionnaire. They formed the qualitative part of the study instrument and provided richer insight into the user acceptance of the NUI system.

Lastly, the demographic questions from the study of Tan *et al.* (2013) were adopted in order to allow for better comparison between the two studies. The level of training was modified to match the Irish medical career pathway, i.e. Non Consultant Hospital Doctor (NCHD), Specialist Registrar (SpR) and Consultant. In addition, the medical specialty was added as an additional demographic characteristic.

3.4 Sampling Design

For the quantitative part of the study assessing the system speed and accuracy, the principal investigator acquired a purposive sample by recruiting ten Specialist Registrars (SpR) in Diagnostic Radiology at St. James's University Hospital.

For the qualitative part of this study, the principal investigator recruited a statistically adequate population sample of forty medical doctors, resident in St. James's Hospital, from the following medical specialties:

- Diagnostic Radiology
- Interventional Radiology
- Cardiac Surgery
- Cardiothoracic Surgery
- ENT Surgery
- General Surgery
- Oral and Maxillofacial Surgery
- Orthopaedic Surgery
- Plastic Surgery
- Genitourinary Surgery (Urology)
- Vascular Surgery

The recruitment process included the following stages:

- Dr. Peter Hughes sent two emails to the SJH surgical mailing list outlining the study background and objectives and requesting volunteering participants.

- The principal investigator prepared a poster informing surgeons of the ongoing trial which was posted on the Radiology and Operating Theatre noticeboards as well as on the doors of the Operating Theatre changing rooms (Appendix G).
- The principal investigator prepared a short presentation outlining the study background and objectives and presented it at the SJH Grand Surgical Rounds meeting at the Trinity Centre, inviting surgeons to participate in the study.
- Dr. Peter Hughes and Dr. Nuala Healy assisted with the recruitment of Diagnostic Radiology SpRs and surgeons.
- Following an initial setback with the recruitment of participants for the study, while based in the Radiology library room, the principal investigator organised for the research trial location to be changed. As a result, the study equipment was moved to the SJH Operating Theatre Seminar Room (section 3.7). This allowed the principal investigator to approach surgeons directly, while they were in theatre, and invite them to take part in the study.

3.5 TedCas NUI Medical System

The NUI medical system used in the trial was provided by TedCas Medical Systems at no cost and solely for the purposes of this research. TedCas is a Spanish technology start-up company which develops systems for accessing and handling medical information *"using touch-free Natural User Interfaces based on optoelectronic devices"* (http://www.tedcas.com/). The complete, standalone system consisted of:

i. One TedSIGN system with an integrated Leap Motion controller. The TedSIGN system runs Windows 7 OS and includes a copy of the ClearCanvas Open Source diagnostic image review product. The TedSIGN system was connected to a 17" Dell E173FP LCD monitor (Figure 28).

ii. A laptop computer running Windows 8.1 OS. The computer had a copy of the TedCas TedGapp application integrated as part of the ClearCanvas Open Source diagnostic image review product. The Microsoft Kinect for Windows v2 controller was connected to the computer via an USB port. The computer was also connected to a 17" Dell E173FP LCD monitor.

Figure 28 TedCas TedSIGN system

For the purpose of the study, the Microsoft Kinect for Windows v2 was supplied with explicit permission from Microsoft (Appendix F), under their Kinect developer preview program (http://www.microsoft.com/en-us/kinectforwindowsdev/newdevkit.aspx).

In order to run the Kinect for Windows V2 sensor and Kinect enabled Windows applications, Microsoft recommended a machine with the following software and hardware configuration:

- Windows 8.1
- 4GB Memory (or more)
- i7 CPU running @ 2.5GHz (or higher)
- Built-in USB 3.0 port (Intel or Renesas chipset)
- DirectX 11 capable graphics adapter

The laptop computer was procured by the principal investigator specifically for this study had the following software and hardware configuration:

- Dell Inspiron 15
- Operating System: Windows 8.1 (64Bit) English
- Processor: 4th Generation Intel® Core™ i7-4500U (4M Cache, up to 3.0 GHz)
- Memory: 8GB3 Dual Channel DDR3L at 1600MHz
- GPU: NVIDIA® GeForce® GT 750M 2GB DDR5, Microsoft DirectX 11 compatible
- Built-in ports: (4) USB 3.0 incl. 1 with PowerShare

3.6 Iterative NUI System Design

Prior to commencing the research study, the TedCas system and software were repeatedly tested by the principal investigator and two clinicians. Dr. Peter Hughes and Dr. Nuala Healy, both Radiology SpRs at St. James's University hospital, tested the study system and provided valuable feedback (Appendix G). Based on this feedback, between November 2013 and March 2014 the TedCas system underwent four design iterations. This was in accordance with the user interface design best practices (Nielsen, 1993) and it ensured that the system functionality and performance are optimised prior to the commencement of the research trial.

3.7 The Trial System Setup

Permission was sought from and granted by Niall Sheehy, Clinical Director of Radiology at St. James's Hospital, to install the TedCas NUI study system in the Radiology library room in SJH Diagnostic Imaging Department.

Figure 29 shows the physical setup of the NUI system with Leap Motion interface. The TedSIGN box was placed on a desk, beside the LCD monitor.

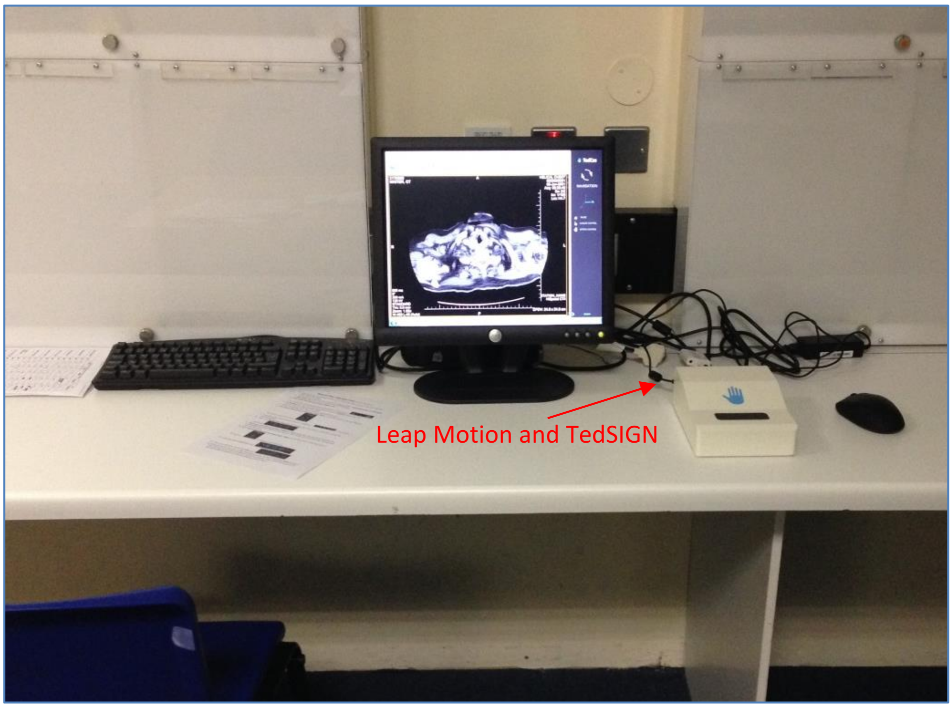


Figure 29 TedSIGN and Leap Motion

Figure 30 shows the setup of the Kinect v2 based system. The laptop computer was placed on a desk and the Kinect sensor was placed on a flat surface, directly in front of the LCD monitor and at a height of 145cm.

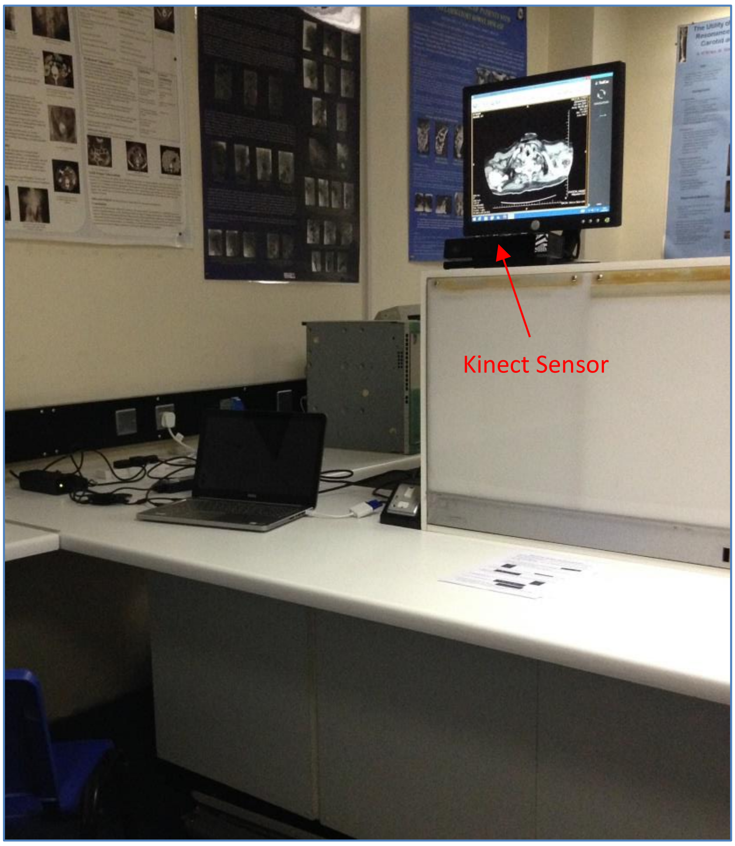


Figure 30 Microsoft Kinect v2 based NUI system setup

Seven days into the research trial it became clear that most surgeons are unlikely to take the time to come away from the Operating Theatre, into the Radiology library room, and participate in the study. With the assistance of Lucy Kielty, Clinical Informatics Manager at SJH and fellow student on the MSc in HI course, the principal investigator sought permission from Ms. Mary O'Brien, Theatre Manager and moved the trial system in the SJH Operating Theatre Seminar Room (Figure 31).

In the new setup, the Kinect sensor was placed at the same height of 145cm but this time it was attached to a photographic camera tripod. This change was important as it allowed tilting the *field of view* of the Kinect sensor.

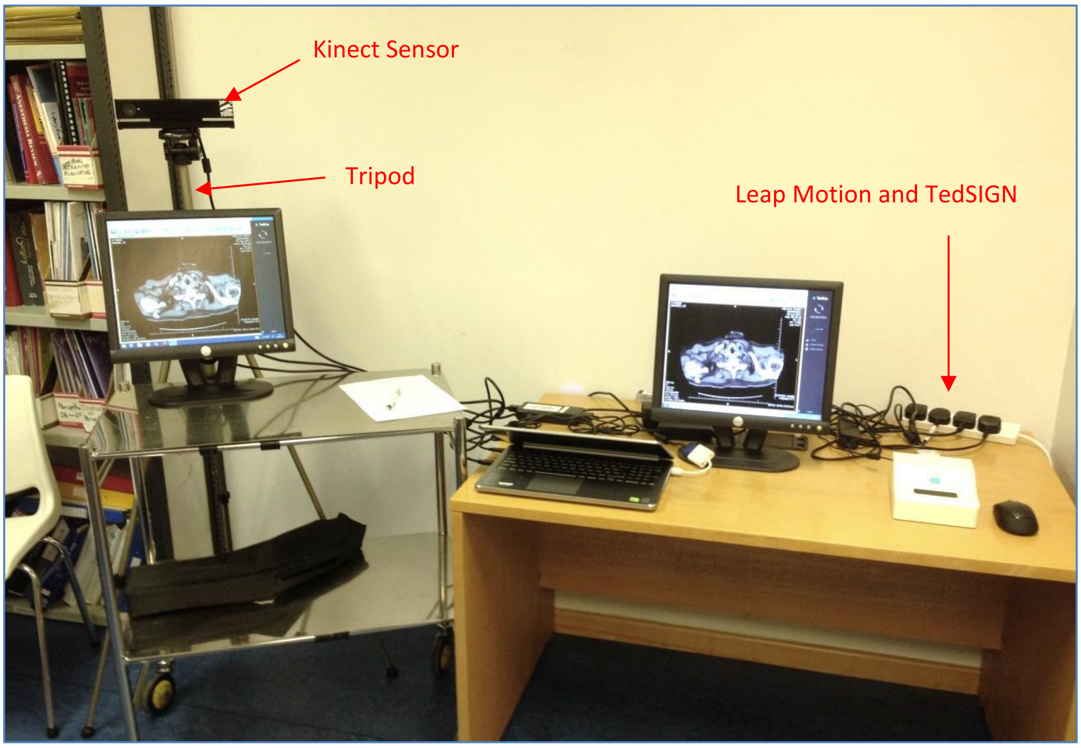


Figure 31 Setup in the SJH Operating Theatre seminar room

3.8 Research Protocol

In collaboration with TedCas, two short video tutorials were prepared – one for Leap Motion and one for Microsoft Kinect for Windows v2. The video clips have similar structure and they show the correct user position relative to the sensor device, the relevant control gestures and the available application options.

- The Leap Motion video tutorial is 2.57 minutes long and is available at: https://www.youtube.com/watch?v=WFPOtWY82gM
- The Kinect v2 video tutorial is 3.46 minutes long and is available at: https://www.youtube.com/watch?v=TP_ZKOVkN6k

Each study participant was required to trail both motion controllers. In order to minimise the potential similarity bias, the first device to be trialled was alternated between Leap Motion and Kinect v2. For each device, every participant followed a five step procedure:

1. Watched the video tutorial.
2. Completed the first two-question utility part of the study questionnaire.
3. Completed a predefined user task using the NUI system.

4. Completed the system usability test.
5. Completed the second two-question utility part of the study questionnaire.

The predefined NUI system user task consisted of the following:

1. Staring from slice #1 of the study Chest CT scan and scrolling to slice number 38.
2. Zooming and centring on the descending aorta.
3. Measuring the diameter of the descending aorta (Figure 32).

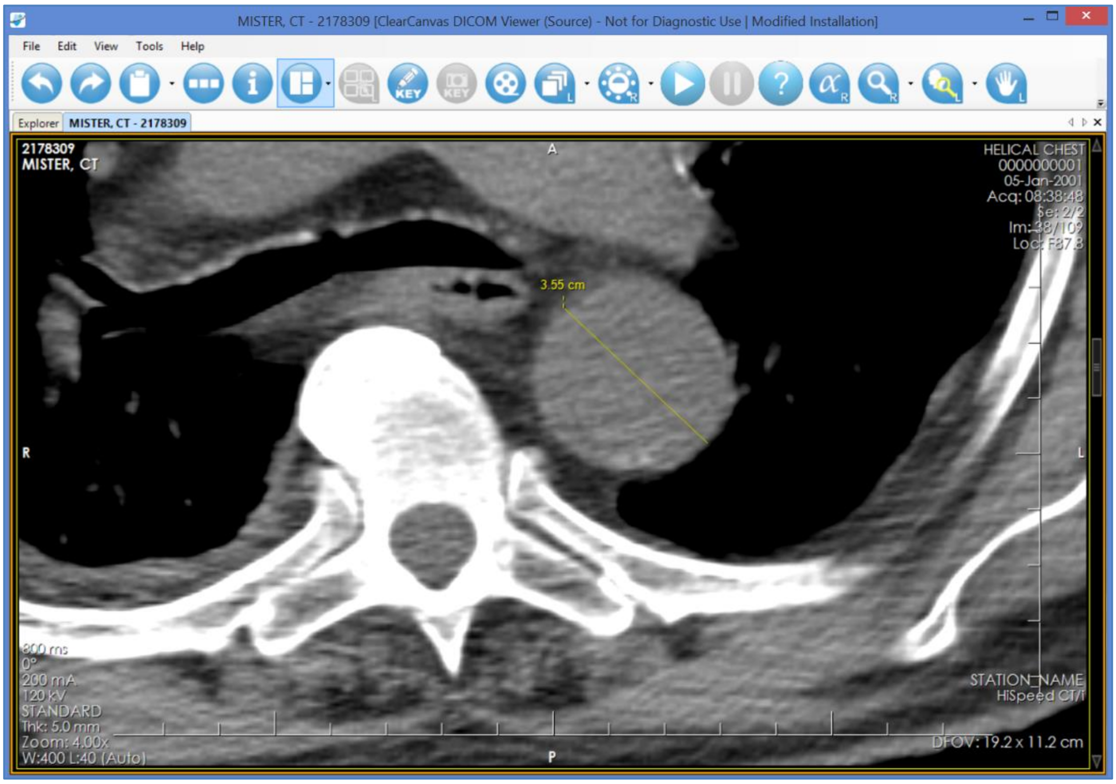


Figure 32 NUI system trial user task

Printed task instructions were provided for Leap Motion (Appendix I) and Microsoft Kinect v2 (Appendix J). In addition, the principal investigator was available to provide support to the participants on how to use the system, when required.

For the objective measurements of the system speed and accuracy, the ten Radiology SpRs participants were also asked to measure the diameter of the descending aorta five times with each of the three input devices: Leap Motion, Kinect v2 and PC mouse.

3.9 Data Collection and Analysis

Data for the study was collected between the 24th March 2014 and 9th April 2014.

The *time to measure* was measured by the principal investigator using a stopwatch Smartphone app. Together with the *anatomical structure measurement* values all results were recorded into a Microsoft Excel spreadsheet.

All participants filled in the study paper questionnaire. Their responses were transferred into Microsoft Excel spreadsheets and were then input into a Microsoft Access database for ease of query, aggregation and analysis. The SUS scores were calculated for each sensor device and converted to adjective school grading scales as described by Bangor *et al.* (2009).

The answers to the open-ended questions were copied into a Microsoft Excel spreadsheet and analysed for common themes and design recommendations.

The following tests were used for statistical analysis of the experimental data. Further information on these statistical tests is available in Appendix K.

i. Three-way Analysis of Variance (ANOVA) was used to compare the speed and accuracy of measurements of the three input devices: the Leap Motion, Microsoft Kinect v2 and a computer mouse. The null hypothesis is that all three devices have the same performance.
ii. In conjunction with the ANOVA test, the Tukey's HSD (honest significant difference) Test was used to compare each pair of input devices individually.
iii. The Wilcoxon Signed-Rank Test was used to compare the SUS ordinal scale usability measures for Kinect v2 and Leap Motion. This test was chosen because each study participant SUS scores for the two sensor devices are paired data since they belong to a single individual. The null hypothesis is that there is no difference in the usability of the Microsoft Kinect v2 and Leap Motion sensors.
iv. The Fisher’s Exact Test was used to examine the significance of association between the subject’s clinical specialty, age, level of training, prior familiarity with the sensors, prior gaming experience and computer literacy and their subjective perception of the usability and utility of each of the sensor devices.

v. Cronbach's Alpha was calculated from the responses to the two utility questions to establish their internal reliability (Bland and Altman, 1997).

IBM SPSS Statistics V19 was used to perform the statistical analysis.

3.10 Ethical Considerations

Research ethics approvals were obtained from St. James’s University Hospital and Trinity College Dublin (Appendix B). The principal investigator ensured full compliance with the Data Protection principles and legislation and no personally identifiable data was collected as part of this study. The principal investigator took any and all measures to ensure that as part of this research, the ethical principles of autonomy, beneficence, non-malfeasance, and justice are upheld:

- Beneficence and non-maleficence: The used medical imaging data is an example training set and it had been already anonymised.
- Autonomy: The principal investigator ensured that written, informed consent was obtained freely from all participants prior to the commencement of each user trial (Appendix D). All participants were given the option to withdraw from the study at any time and without any penalty.
- Integrity:
  - The following information was disclosed to the participants as a potentially competing interest: *Telefonica S.A. through its subsidiary Wayra, a start-up accelerator, owns a minority stake in TedCas Medical Systems. The principal investigator, Nikola Nestorov is employed by Telefonica Ireland, trading under the commercial brand* O_2 *and owned by Telefonica S.A.* (Appendix C).
  - There is no financial or other kind of benefit resulting from the above relationship. Furthermore, on the 24th June 2013, Three Ireland, a subsidiary of Hutchison Whampoa Limited, entered into agreement with Telefonica S.A. to acquire the Telefonica Ireland mobile phone operator. The sale of Telefonica Ireland was approved by the European Commission in June 2014.

3.11 Conclusion

This chapter described the mixed methods, two-strand sequential research design as well as the rationale for the chosen research methods and their components. The questionnaire design, the study participants and the research protocol were specified. The approach for data collection and analysis was detailed. The design of the TedCas trial NUI system, its individual components and the setup for the study in St. James's Hospital were described. Finally, the ethical considerations, including a presumed conflict of interest were discussed. The following chapter presents the results from the research trial and their analysis.

Chapter 4 Results and Data Analysis

4.1 Introduction

The objective of the research trial was to compare the Leap Motion and Microsoft Kinect for Windows v2 sensors in terms of their performance as input devices of a touchless system for medical image control. A research protocol was developed, implementing a mixed methods research design, in order to evaluate the utility and usability of the two motion controllers. This chapter presents the results from the analysis of the experimental data and outlines all relevant findings.

4.2 Participants Demographics

A total of 43 participants were recruited for the research trial. Forty participants provided valid responses. Data from three participants was not considered in the analysis, more specifically:

- One participant opted out of the study due to time constrains.
- One participant opted out of the study due to lack of interest compounded by time constrains.
- Data for one participant was discarded as he was not a medical doctor.

The age distribution for the study participants is shown in Figure 33. The majority (60%) were aged between 20 and 40 years with the remainder aged between 40 to 60 years. One of the study participants did not provide any age specific information (marked unknown).

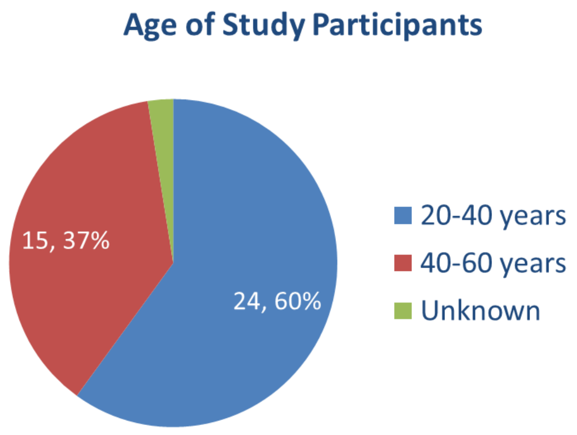


Figure 33 Age of participants

Diagnostic Radiologists comprised 30% (12) of the study participants. The remaining 70% (28) were Surgeons or Interventional Radiologists (IRs) (Table 4).

Table 4 Clinical specialty of participating users

Specialty	Number of participants	% of Total
Diagnostic Radiology	12	30.0%
Interventional Radiology	3	7.5%
Surgery, Cardiac	1	2.5%
Surgery, Cardiothoracic	1	2.5%
Surgery, ENT	1	2.5%
Surgery, General	5	12.5%
Surgery, Genitourinary	2	5.0%
Surgery, Oral and Maxillofacial	4	10.0%
Surgery, Orthopaedic	4	10.0%
Surgery, Plastic	3	7.5%
Surgery, Vascular	4	10.0%

With regard to level of professional training, 37.5% (15) of the study participants were hospital consultants, 42.5% (17) were SpRs and 20% (8) were NCHDs.

The majority of the study participants reported having good computer skills and limited gaming experience. More than four in five of all participants or 82.5% (33) were comfortable installing software and 77.5% (31) of them did not play any video games (Figure 34).

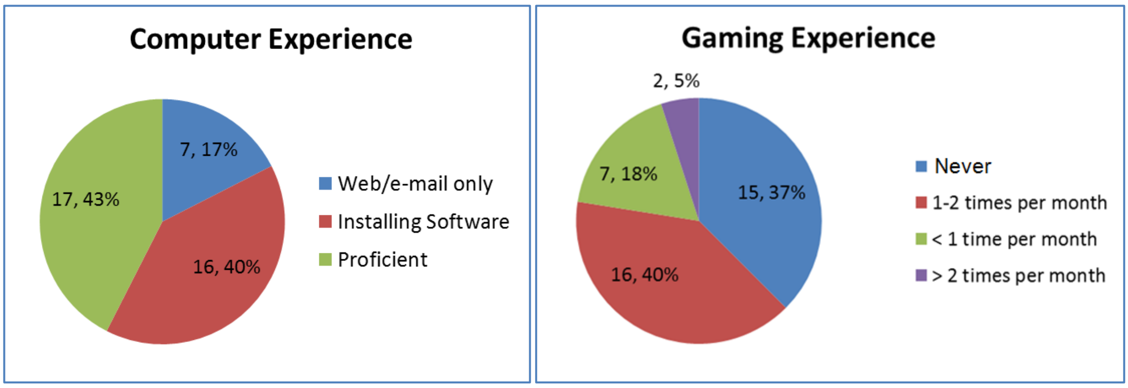


Figure 34 Computer and gaming experience

The NUI system and both sensor devices were a novelty for the clinicians participating in the study. None of them had any prior experience with Leap Motion while only 20% (8) had used Microsoft Kinect in the past.

4.3 Results from the Measurement Speed and Accuracy Tests

The *time to measure* and *anatomical structure measurement* (the descending aorta diameter) for the set measurement task were recorded for each of the 10 Diagnostic Radiology SpRs. A total of 50 pairs of measurements (*time to measure* and *anatomical structure measurement*) were taken for each of the three interface devices: Microsoft Kinect for Windows v2, Leap Motion and a Microsoft wireless computer mouse. In two instances study participants failed to complete the measurement task, once using Leap Motion and once using Microsoft Kinect. The two failed tasks were discarded from the experimental data (Appendix M). The *time to measure* was measured from the moment one measurement task was completed to the end of the following one, using a Smartphone stopwatch app. The exact *anatomical structure measurements* were recorded directly from the ClearCanvas DICOM Viewer application.

Figure 35 is a boxplot of the *time to measure* results; outliers are marked with ° and *.

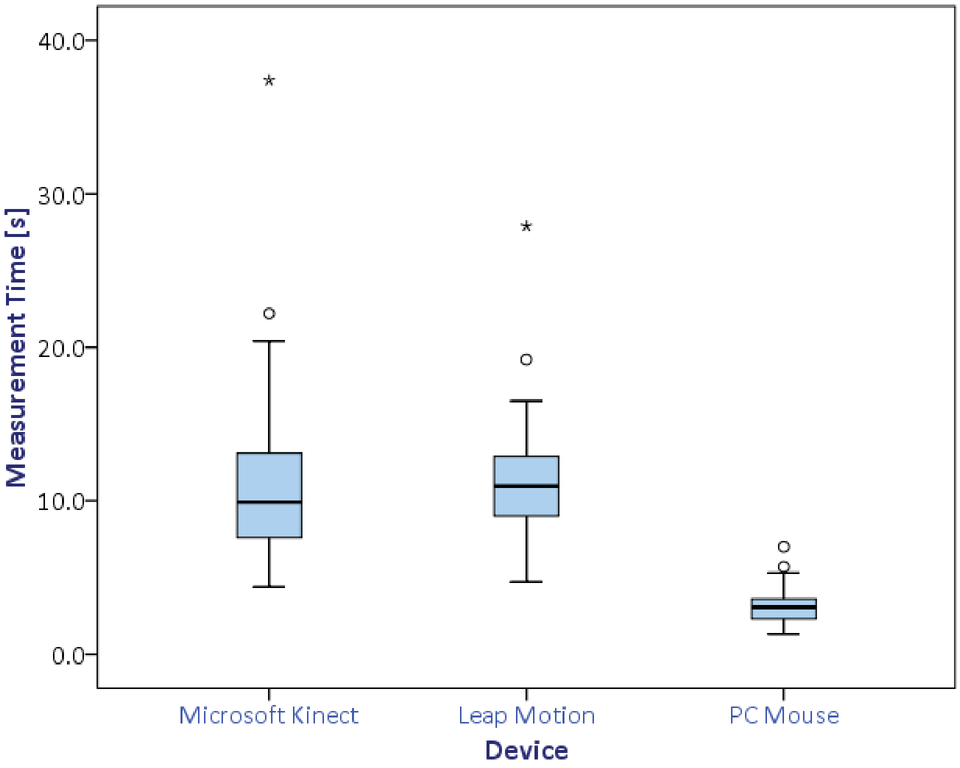


Figure 35 ***Time to measure*** **boxplot**

Figure 35 shows that the speed of measurement of the two motion controllers was comparable (the Microsoft Kinect average *time to measure* was 11.33s and the Leap Motion average *time to measure* was 11.25s) but considerably lower than the speed of measurement of the computer mouse (3.12s average *time to measure*). This was also confirmed by the Analysis of Variance (ANOVA) (Appendix K). The results from the statistical test (p = 0.00) rejected the null hypothesis that the three devices perform the same in terms of *time to measure* (Table 5). However, applying the ANOVA test to the Microsoft Kinect and Leap Motion data sets only, confirmed that the mean *time to measure* for both motion sensors was statistically equivalent (p = 0.93; Table 6).

Table 5 One-way ANOVA – *time to measure* by interface device

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2224.587	2	1112.293	69.846	**0.000**
Within Groups	2340.970	147	15.925		
Total	4565.557	149			

Table 6 One-way ANOVA – *time to measure* by motion sensor device

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.168	1	.168	.007	**0.932**
Within Groups	2275.910	98	23.224		
Total	2276.078	99			

The average *anatomical structure measurement* using the Microsoft Kinect sensor was 3.41cm and 3.48cm for the Leap Motion sensor respectively. The average descending aorta diameter, measured using the PC mouse, was 3.52cm. The boxplot on Figure 36 (outliers are marked with ° and *) shows that the accuracy of the Microsoft Kinect is the poorest, with the *anatomical structure measurement* data points spread over a larger range of values. In contrast, the Leap Motion data set, despite having a higher variance, had a mean of the *anatomical structure measurement* similar to that of the computer mouse.

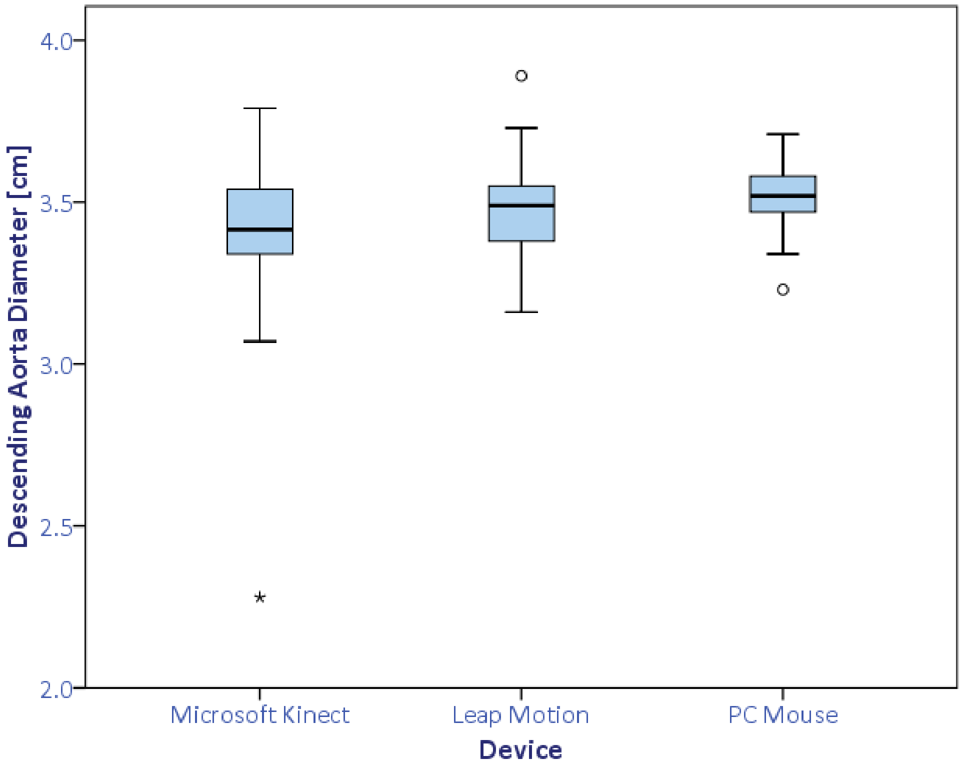


Figure 36 Accuracy of *anatomical structure measurement* boxplot

These findings were further confirmed by the ANOVA test. The results from the statistical test rejected the null hypothesis that all three devices perform the same in terms of *anatomical structure measurement* accuracy (p = 0.003; Table 7). The additional post-hoc analysis, using the Tukey HSD test (Appendix K), showed that the measurement accuracy of the Leap Motion controller was statistically comparable to that of the PC mouse (p = 0.415; Table 8)

Table 7 One-way ANOVA – *anatomical structure measurement*

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.327	2	.163	6.081	**0.003**
Within Groups	3.948	147	.027		
Total	4.275	149			

Table 8 Multiple Comparisons – *anatomical structure measurement*

Dependent Variable: *anatomical structure measurement*

						95% Confidence Interval	
	(I) Device	(J) Device	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	Kinect	Leap M.	-.07140	.03278	.078	-.1490	.0062
		PC mouse	-.11300*	.03278	.002	-.1906	-.0354
	Leap M.	Kinect	.07140	.03278	.078	-.0062	.1490
		PC mouse	-.04160	.03278	**0.415**	-.1192	.0360
	PC mouse	Kinect	.11300*	.03278	.002	.0354	.1906
		Leap M.	.04160	.03278	**0.415**	-.0360	.1192

*. The mean difference is significant at the 0.05 level.

4.4 Usability Analysis

The responses to the system usability scale (SUS) questions were analysed and the SUS scores were calculated as defined by Brooke (1996):

i. Subtracting one from the score for items 2,4,6,8 and 10
ii. Subtracting the score for items 1,3,5,7, and 9 from five
iii. Multiplying the sum of the so modified scores by 2.5

The resultant SUS score for each subject test response is a number between 0 and 100 (Brooke, 1996). Each score is then graded using the following rating scale (Figure 27):

i. A (Very Good) for SUS score greater than or equal to 80
ii. B (Good) for SUS score greater than or equal to 74 and less than 80
iii. C (Average) for SUS score greater than or equal to 68 and less than 74
iv. D (Pass) for SUS score greater than or equal to 51 and less than 68
v. F (Fail) for SUS score less than 51

System acceptability was rated as proposed by Bangor *et al.* (2009) (Figure 27):

i. *Not acceptable* for SUS score less than 50
ii. *Marginal-low* acceptability for SUS score between 50 and 62
iii. *Marginal-high* acceptability for SUS score between 62 and 70
iv. *Acceptable* for SUS score above 70

The distribution of all graded responses for Microsoft Kinect v2 and Leap Motion is presented in Figure 37.

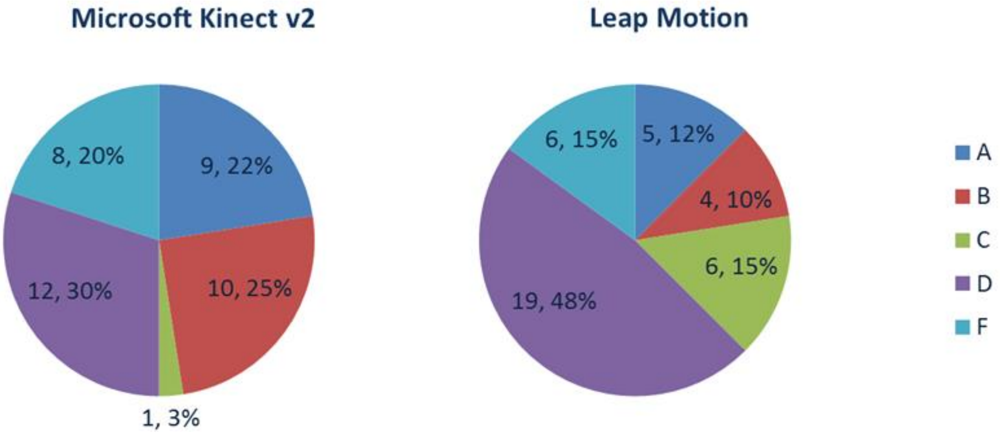


Figure 37 SUS ratings distribution per input device

With regard to system acceptability, Table 9 shows the acceptability rating for each of the sensor devices based on the acceptability ranges. Microsoft Kinect, when rated by Surgeons and Interventional Radiologists only, had an *acceptable* score of 71.7. This score corresponds to acceptability grade of C.

Table 9 System Acceptability based on the average SUS scores

Study Participants	Leap Motion	Microsoft Kinect
All participants	Marginal, High (63.4)	Marginal, High (66.1)
Surgeons and IRs	Marginal, High (63.8)	Acceptable (71.7)

The scatter plot of all participants' individual SUS scores is shown in Figure 38. On the graph, the distribution of data points (responses) is similar on both sides of the middle red line. This indicates that the number of responses favouring Leap Motion is similar to the number of responses favouring Microsoft Kinect v2 motion controller.

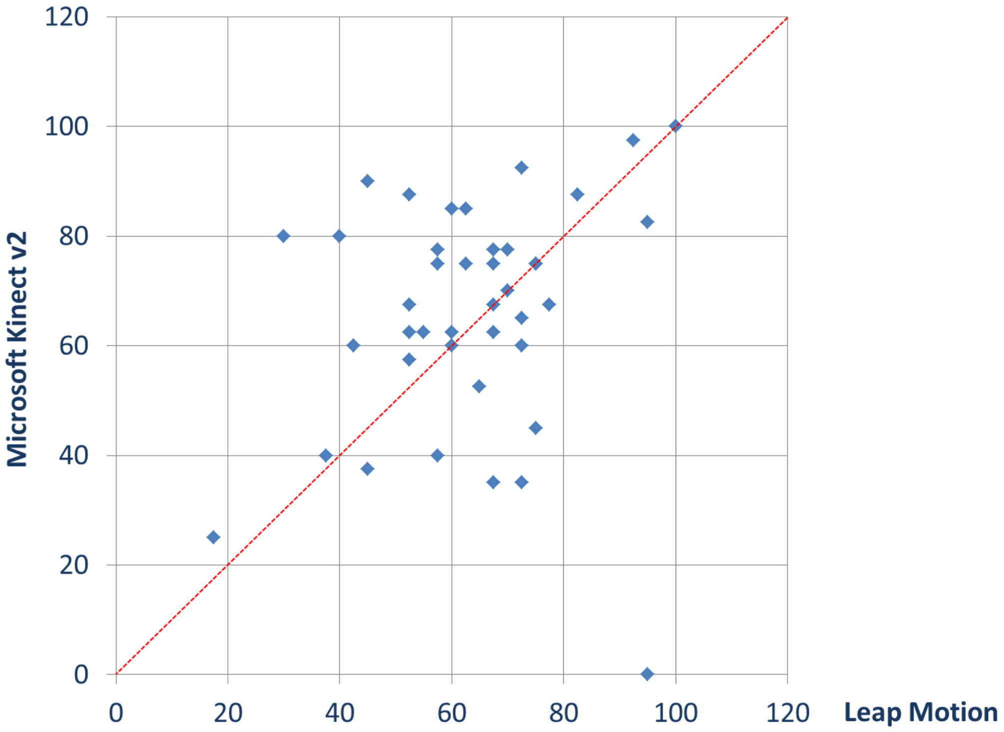
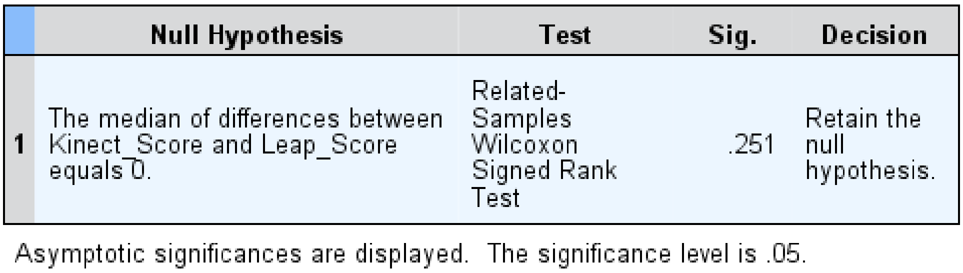


Figure 38 SUS rating scatter plot – all study participants

Further analysis of the SUS scores of all study participants using the Wilcoxon Signed-Rank Test for paired variables (i.e. each individual participant's Microsoft Kinect score and their respective Leap Motion score; Appendix K) determined that the usability of both motion sensors was statistically comparable (p = 0.251, Table 10).

Table 10 Differences between the sensor's SUS scores – all study participants



	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Kinect_Score and Leap_Score equals 0.	Related-Samples Wilcoxon Signed Rank Test	.251	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

When the responses of Diagnostic Radiologists were excluded, the analysis of perceived usability of the two motion sensors showed different results. In the scatter plot of participants' SUS scores there are more responses above the middle red line (Figure 39). This indicates that the Microsoft Kinect v2 controller has better performance with regard to perceived usability.

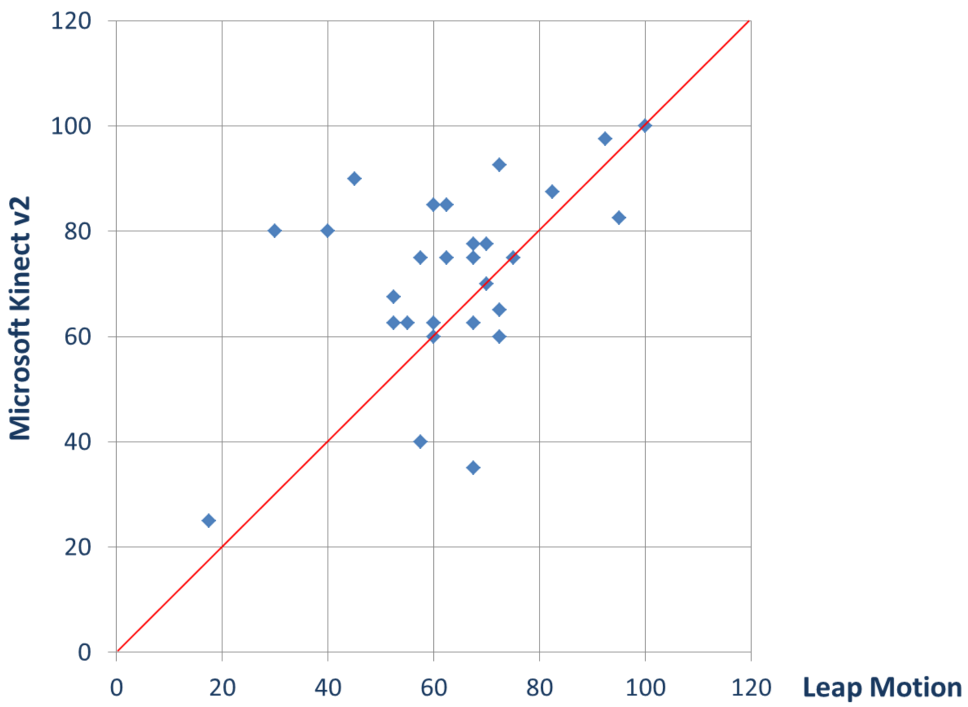
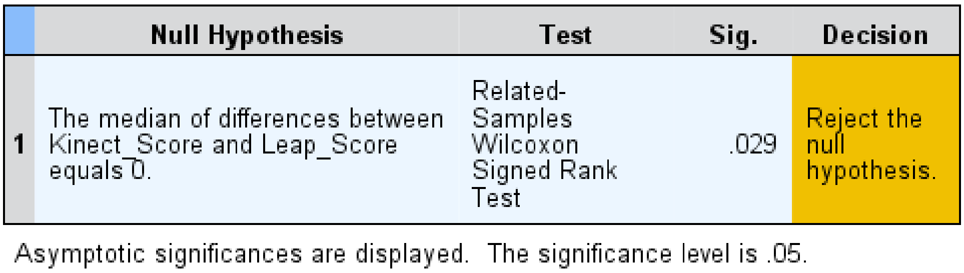


Figure 39 SUS rating scatter plot – Surgeons and IRs

The Wilcoxon Signed-Rank Test for paired variables (Appendix K) confirmed that with regard to perceived usability, the Microsoft Kinect v2 sensor performed better than the Leap Motion sensor (statistically significant p=0.029; Table 11).

Table 11 Differences between the sensor's SUS scores – Surgeons and IRs



	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between Kinect_Score and Leap_Score equals 0.	Related-Samples Wilcoxon Signed Rank Test	.029	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

The association between the study participants' prior experience with the Kinect sensor and their Microsoft Kinect SUS score was also examined. The results of the experimental data analysis, using the Fisher's Exact Test (Appendix K), showed that statistically there was no correlation between the participants' SUS scores and their prior familiarity with the Kinect sensor (p = 0.47; Table 12). The same analysis was not possible for the Leap Motion device as none of the participants had used the motion sensor prior to the NUI system research trial.

Table 12 Prior Kinect Use by Kinect_Rating Crosstabulation

			Kinect_Rating					Total
			A	B	C	D	F	
Kinect	1.0	Count	1	3	0	1	3	8
		% of Total	2.5%	7.5%	.0%	2.5%	7.5%	20.0%
	2.0	Count	8	7	1	11	5	32
		% of Total	20.0%	17.5%	2.5%	27.5%	12.5%	80.0%
Total		Count	9	10	1	12	8	40
		% of Total	22.5%	25.0%	2.5%	30.0%	20.0%	100.0%

Chi-Square Tests

	Value	df	Asymp. Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	3.872[a]	4	.424	.492
Likelihood Ratio	4.067	4	.397	.514
Fisher's Exact Test	3.930			**0.471**
N of Valid Cases	40			

a. 6 cells (60.0%) have expected count less than 5. The minimum expected count is .20.

Analysis of the association between the SUS score of the study participants and their age, level of training, prior gaming experience and self-reported computer literacy, using the Fisher's Exact Test showed no statistically significant relationships (Table 13).

Table 13 Significance levels of Fisher's Exact Test for usability analysis

	Age	Level of Training	Gaming Experience	Computer Literacy
Microsoft Kinect v2	p = 0.570	p = 0.709	p = 0.088	p = 0.199
Leap Motion	p = 0.311	p = 0.302	p = 0.202	p = 0.506

4.5 Utility Analysis

The utility of the NUI system and its respective interface devices, Microsoft Kinect v2 and Leap Motion, was assessed with a two-question survey, administered twice for each of the sensor devices.

- The participants were asked to answer the two utility questions after they had seen the video tutorials for each one of the two devices, prior to their use.

- After each participant had finished using the NUI system, they were asked to answer the two utility questions again.

The utility survey consisted of the following two questions:

Q1: Do you feel that a NUI system based on the Microsoft Kinect / Leap Motion controller would be useful in your practice?

Q2: Do you feel that a NUI system based on the Microsoft Kinect / Leap Motion controller will give you a greater degree of control in your practice?

The Cronbach's Alpha coefficient (Appendix K) was calculated for each of the four pairs of utility survey responses. The value of Alpha in all four cases was high – between 0.87 and 0.91 (Table 14). This indicated very good internal consistency of the survey instrument. Further examination of the variability using Factor Analysis determined that Question 1 accounted for most of the total variance (approximately 90% in all cases). Therefore it can be inferred that the two question utility test is one-dimensional and that the second question is redundant (Tavakol and Dennick, 2011).

Table 14 Utility survey – internal consistency analysis

	Before Try-out		**After Try-out**	
	Kinect (Q1, Q2)	Leap Motion (Q1, Q2)	Kinect (Q1, Q2)	Leap Motion (Q1, Q2)
Cronbach's Alpha	0.901	0.873	0.911	0.893
Factor analysis % of variance for Q1	91.07%	88.83%	91.80%	90.37%

The utility survey responses of the study participants after they had used the NUI system are summarised in Table 15. Half of the participants (20 of 40) rated the system with Microsoft Kinect v2 as potentially useful in their practice while only 38% (15 of 40) did so for the Leap Motion controller. These results demonstrate that Microsoft Kinect v2 was perceived as more useful input device than the Leap Motion.

Table 15 Responses to the usability questions after try-out (all participants)

Response	Kinect-Q1	Kinect-Q2	Leap Motion-Q1	Leap Motion-Q2
Yes	20	16	15	13
Maybe	15	18	19	19
No	5	6	6	8
Percentage "Yes"	**50%**	**40%**	**38%**	**33%**
Percentage "No"	13%	15%	15%	20%

The preference for the Microsoft Kinect v2 sensor was even more evident when the responses of the Diagnostic Radiologists were excluded from the results (Table 16). More than half of the Surgeons and Interventional Radiologists (54%, 15 of 28) found the Microsoft Kinect v2 based NUI system potentially useful. Two in five of them (39%, 11 of 28) perceived Leap Motion as having good utility.

Table 16 Responses to the usability questions after try-out (Surgeons and IRs)

Response	Kinect-Q1	Kinect-Q2	Leap Motion-Q1	Leap Motion-Q2
Yes	15	14	11	11
Maybe	10	11	14	12
No	3	3	3	5
Percentage "Yes"	**54%**	**50%**	**39%**	**39%**
Percentage "No"	11%	11%	11%	18%

The perceived utility responses (the answers to question Q1 after use of the system) were further examined with the Fisher’s Exact Test for any significant association between the participants’ prior experience with Microsoft Kinect and their Microsoft Kinect v2 utility scores (Appendix K). The results of the data analysis showed that statistically, there is no correlation between the utility score and the participants’ prior familiarity with the Microsoft Kinect sensor ($p = 0.404$). The same analysis was not applicable for Leap Motion as none of the participants had previously used the device.

Assessment with Fisher's Exact Test of the association between the study participants' age, level of training, prior gaming experience and self-reported computer literacy and their responses to the utility question (Q1, after try-out) found no statistically significant correlation except in the case of the participants' age and their view of the Leap Motion sensor utility (Table 17). Younger study participants found the Leap Motion interface more useful more often than older ones (p = 0.04; Table 17). There was even stronger association between the participants' age and the Leap Motion perceived utility when the responses of the Diagnostic Radiologists were excluded from the analysis (p = 0.023).

Table 17 Significance levels of Fisher's Exact Test for utility analysis, all participants

	Age	Level of Training	Gaming Experience	Computer Literacy
Microsoft Kinect v2	p = 0.43	p = 0.749	p = 0.122	p = 0.418
Leap Motion	p = 0.04	p = 0.513	p = 0.343	p = 0.318

4.6 Utility and Usability

The Fisher's Exact Test was used to examine the relationship between the two elements of system acceptability, its perceived utility and usability. The results are summarised in Table 18. The analysis established a statistically significant relationship between the two system properties, particularly when the responses of the Diagnostic Radiologists were excluded from the data set. Therefore, the system usability has a direct effect on the perception of system utility by Surgeons and Interventional Radiologists.

Table 18 Utility vs. usability: significance levels of Fisher's Exact Test

	All participants	Surgeons and Interventional Radiologists Only
Microsoft Kinect v2	p=0.022 (significant)	p=0.036 (significant)
Leap Motion	p=0.054 (non-significant)	p=0.025 (significant)

Before using the NUI system, all participants saw a video tutorial. Their view on the system utility was captured at this point by completing the two-question utility survey and once again after they had used the system. The comparison of user responses, before and after trialling the NUI system, showed that for 37.5% (14 of 50) of the participants there was deterioration in their perception of the Leap Motion utility. For Microsoft Kinect v2, deterioration was observed in 25% (10 of 40) of all cases. These results confirmed that weaknesses in the system usability negatively impact on the perception of utility.

4.7 Analysis of User Responses to the Unstructured Questions

The study questionnaire included three unstructured questions. These asked the study participants to provide their general comments on:

- Gesture control of medical images.
- The TedCas NUI system with Microsoft Kinect.
- The TedCas NUI system with Leap Motion.

Answers to the unstructured questions provided 23 of the study participants or 57.5%. These responses covered a broad spectrum of views about the utility and usability of the two systems. The general consensus, however, was that the systems can be useful. This is in line with the results from the utility analysis. The following four responses illustrate the variance of opinions:

> *“Not sure about the role in current practice.”*
>
> *“Limited usefulness to surgery, IR [Interventional Radiology]. Most image manipulation is performed prior to any intervention. If needed during a procedure, something has gone wrong.”*
>
> *“Excellent idea which would be extremely useful.”*
>
> *“Concept brilliant”*

The value of a system which allows for touchless medical image control within the sterile environment of the OR was clearly articulated: “*Good idea especially for CT guided procedures and IR. I see how it would be very useful in theatre also as I have scrubbed out as surgical SHO in order to look at images!”*

The TedCas NUI system generated most enthusiasm in Orthopaedic and Vascular surgeons. One of the Orthopaedic Consultants not only welcomed the idea but also offered to facilitate a clinical trial of the system during live surgery.

Opinions about the two sensors varied as well. The Microsoft Kinect sensor was often found tiresome to use (*"Arm got tired!!!"*, *"Tiring having to keep arm elevated"*) and less accurate for taking measurements (*"needs to be more accurate"*). It was, however, the one which more people saw better potential in due to its "*Bigger sensor field.*" Overall, albeit its present implementation limitations, the Microsoft Kinect was acknowledged to have *"potential if can be improved".*

Contrariwise, some people preferred the Leap Motion with some considering it a *"Very sleek interface."* Its better accuracy was acknowledged: *"Better than Kinect in terms of more reproducible measurements and less variability"* and some participants offered their explanation of why they think the sensor is more accurate: *"Closer to screen so easier to control detail, i.e. diameter of vessel* [sic]*"* and *"May require more time before timeout to measure structure on Kinect system."* The smaller *field of view* of the Leap motion sensor was found to be a disadvantage for use in the OR by a number of participants: *"Control panel width/range short. Have to stay too close to interface as a scrubbed surgeon."*

In summary, both sensors were found to have a degree of utility for use in the OR but their performance failed to always meet the clinicians' expectations. Further development is required in order to improve the NUI system performance and usability or in the words of one of the study participants:

> *"Good idea. Will obviously need work + tweaks [sic]."*

4.8 Conclusion

This chapter presented the results from the analysis of the study experimental data. The assessment of the speed and accuracy of measurement determined that both sensors performed similarly in terms of speed. The Leap Motion controller had better accuracy, comparable with the accuracy of a computer mouse. The Microsoft Kinect v2 sensor was shown to have better usability, based on the responses from Surgeons and

Interventional Radiologists, and better utility overall. The examination of the qualitative data found the Kinect sensor to a certain extent tiresome to use but with very good potential. The Leap Motion sensor was also acknowledged to have good potential for use in the OR but its limited *field of view* was highlighted as a disadvantage. A correlation was found between the participants' age and the Leap Motion perceived utility. Analysis of the internal consistency of the utility survey showed that both questions measure the same construct. There was also a link confirmed between the system usability and the perception of utility, with better perceived usability resulting in better perceived utility. The following chapter discusses these results and outlines areas for design focus and further work.

Chapter 5 Discussion

5.1 Introduction

The aim of the study was to evaluate and compare two COTS motion sensor devices in terms of their utility and usability as interfaces of a touchless medical image control system. Experimental data was collected in controlled, non-sterile setting. The results from the data analysis showed marginal to average acceptability of the two devices. Microsoft Kinect for Windows v2 was found to have better utility and usability while Leap Motion was established to be more accurate. The following section discusses the findings and draws recommendations for future system design and implementation improvements.

5.2 Factors Influencing the Accuracy of Operation

The measured anatomical structure was the descending aorta as shown on one of the transverse CT scan slices (Figure 32). It is not perfectly symmetrical and depending on the angle of measurement the diameter can vary up to ±5%. However, the large sample size (50 measurements per device) ensures that the potential measurement error is minimised. The analysis of the *anatomical structure measurement* data showed that the accuracy of the Leap Motion was better and comparable with the accuracy of a computer mouse. The poorer measurement accuracy of the Microsoft Kinect for Windows v2 can be attributed to several factors. These are the image display size, the system *field of view*, the gesture recognition algorithms and the gesture vocabulary.

5.2.1 Display size

The size of the two displays used in the NUI system user trial was 17 inch. This is an adequate display size when the user is sitting in front of or standing close to the monitor which was the actual setup in the case of Leap Motion. When the Microsoft Kinect sensor was used, the user had to be at a further distance away from the monitor (1.5-2m). This significantly reduces the intelligibility of the displayed biomedical image. The chosen level of zoom, which differed between users, can further compound this issue. Distance, image resolution, angle of viewing and image compression artefacts can all impact on the image quality (Bae *et al.*, 2009). The THX visual reproduction quality assurance system recommends a 50 inch class HDTV for viewing distance of 1.5 to 2.2m (THX Ltd., 2014).

5.2.2 Edge of field of view

During the initial phase of the study, the NUI system was setup in the Radiology library room in St. James's Hospital where the Microsoft Kinect for Windows v2 sensor was positioned on a flat-top unit (Figure 30). Unlike the Kinect for Windows v1 which has an integrated, programmable tilt motor, the second generation Kinect has a flat base. This resulted in an inability to vary the sensor *field of view* and had a negative impact on the measurement accuracy and the overall system operation. Participants who were shorter in stature were located at the edge of the sensor's *field of view* and as a result the tracking of their gestures was of poor quality. Manually adjusting the sensor inclination resolved this issue. Later on in the trial, the Microsoft Kinect v2 sensor was mounted on a camera tripod which allowed for finer tilt adjustments. This way the edge of *field of view* issue was avoided. In some cases, the same problem was observed with the Leap Motion controller when the user's hand was too far from the device. This is consistent with the findings of Guna *et al.* (2014) who observed that the Leap Motion sensor accuracy decreases sharply when the tracked objects move away from it. The TedCas system has a built in visual warning when the user's hand leaves the operational area of both sensors (a blue line appears on the screen). This procedure should be further enhanced to provide better user feedback, for example by displaying a quantitative measure of the loss of fidelity.

5.2.3 Image manipulation gestures

The choice of gestures can also impact on the accuracy of measurements. The control of the measurement command in the study system was implemented identically for the two sensors. Using a single hand, the NUI system user had to position the cursor at the start / end point of the anatomical structure and keep their hand stable for one second before the selection indicator appeared. It took another second to have the measurement point selected (the indicator completed full circle). For Microsoft Kinect v2 this time proved to be too short. In certain cases, the measurement command was completed prematurely, when the participant had slowed down their hand in order to select the end point accurately. Mouse-like, “click” type gestures, similar to the one described by Soutschek *et al*. (2008), were initially programmed and available for both sensors. During the iterative design stage, these gestures were disabled due to an observed issue with the position of the cursor being displaced by the discrete input or “*click*” (*close hand* for Kinect and *finger tap* for Leap Motion). This outcome has been previously described by Bowman *et al.* (2002) and named “*Heisenberg effect*”, after the quantum physics uncertainty principle. An alternative to the “*click*” type gesture is the use of both hands for certain operations. One example is the two hands gesture commands described by Tan *et al.* (2013). O’Hara *et al.* (2014a) recommend that the requirement to use both hands should be carefully assessed based on the constraints posed by the particular surgical procedure. Providing an option to choose from a larger predefined set of control gestures can enhance the system accuracy and utility and it will also cater for individual user preferences.

5.2.4 Motion smoothing

Hand tremor and general noise due to factors such as ambient lightning, position relative to the sensor device and rounding effects can impact on the precision and accuracy of gesture recognition. Both Leap Motion and Microsoft Kinect for Windows v2 have smoothing filter functions included as part of their software development tools. One area for further investigation is whether the application of different filtering algorithms such as the ones described by Mehran (2012) can improve the accuracy of the NUI system. Tan *et al.* (2013) have described a successful implementation of one such smoothing algorithm in their Kinect based intraoperative image control system in order to enable fine movements.

5.3 Factors Influencing the Speed of Operation

The *time to measure* was measured from the moment one measurement task was completed to the end of the following one, using a Smartphone stopwatch app. This method of measurement is not exact but provides good accuracy and it was chosen for its practicality. The Microsoft Kinect average *time to measure* was 11.33s and the Leap Motion average *time to measure* was 11.25s compared with an average *time to measure* of 3.12s for the computer mouse. Both motion sensor devices were markedly slower than the average *time to measure* of the computer mouse. This is partially due to the specific implementation of the measurement command with four seconds required for the selection of the start and end measurement points. In addition, the lack of prior experience with the NUI system also contributed to the longer average *time to measure*. This is confirmed by Jacob *et al.* (2013) in a study of a Kinect based system for touchless image navigation. They observed that after 10 trials the average task completion time was reduced significantly. Juhnke *et al.* (2013) further demonstrated that with sufficient practice, people using Kinect can perform better than those using a computer mouse at certain image manipulation tasks (e.g. adjusting the viewed tissue density). Ogura *et al.* (2014) reported similar results for Leap Motion stating that after 30 min of practice a set of abdominal angiographic images can be manipulated faster using the Leap Motion controller than using a standard PC mouse. Further analysis of the experimental data showed that the fastest average individual participant's *time to measure* for the Leap Motion sensor was 6.38s and 7.54s for Microsoft Kinect v2. These times are considerably lower than the overall average *time to measure* and therefore there is a substantial scope for improvement with more user practice.

5.4 Factors Influencing the System Usability in the OR

The average usability ratings of the two study systems were relatively poor with only Kinect achieving an *acceptable* score. Despite the weak score of the perceived usability, all participants were able to successfully complete the specified task. This is in line with the findings of Soutschek *et al.* (2008) and the subsequent NUI systems studies who report that proper handling of the system is relatively easy to attain. The usability analysis identified Kinect as the better performing device. This is despite the fact that users found the Microsoft Kinect physically tiresome and exerting bigger physical effort than the Leap Motion controller. Similar findings are reported in the studies of Francese *et al.* (2012) and Davidson (2012).

Gesture requirements pertinent to the system accuracy were discussed earlier in this Chapter. The gesture vocabulary of the evaluated NUI system was limited to a small set of commands, more specifically images set and scan slice scrolling, windowing, pan and zoom and the basic measurement commands. These command options are perceived to be the most commonly used and of most relevance within the OR practice. Strickland *et al.* (2013) have taken a similar approach in designing their system while O'Hara *et al.* (2014a) advise that the gesture vocabulary should be devised with due consideration for the clinical context of use and the strict constrains of intraoperative practices. The ability to control the NUI system state by being able to lock (engage) and unlock (disengage) the system is another important feature (Strickland *et al.,* 2013; Mauser and Burgert, 2014; O'Hara *et al.*, 2014a). This functionality was available in the Microsoft Kinect v2 variant of the TedCas NUI system but it was not implemented for the Leap Motion interface. This is something which should be addressed in future design iterations. In addition, it was noted by the principal investigator, the study collaborators and a few of the study participants that having functions which allow the user to reset the image view when using the zoom, pan and window commands can improve the system usability. This type of functions have been implemented by Ebert *et al.* (2012) and O'Hara *et al.* (2014b). Further on, using contextual information such as user head and torso orientation or delay between commands and command history can help improve the gesture recognition accuracy (Jacob *et al.*, 2012).

Implementing a speech recognition is another way to augment the gesture interface system, however recent studies caution the use of voice commands due to the background noise in the OR (O'Hara et al., 2014a) and the varying accents of the clinicians (Jacob *et al.*, 2012). In the case of the Microsoft Kinect sensor, which is equipped with a microphone array, using voice interactions for certain type of discrete commands such as *reset view* is appropriate and can be useful (O'Hara *et al.*, 2014b). This can also help reduce the physical effort associated with the Kinect interface.

5.5 System Utility Aspects

Perceived system utility was measured using a two-question survey. The first question was adapted from Tan *et al.* (2013). The second question asked the participants if the NUI system can enhance their control in their practice environment. The analysis of the data established that two-question utility test is one-dimensional and that the second question is redundant. Another way of interpreting this finding is that an essential quality of a useful system for touchless biomedical image control is its utility for providing the clinician with enhanced control in the clinical setting.

The study results showed that more than half (54%) of the participants, who were Surgeons or Interventional Radiologists, deemed the NUI system based on Microsoft Kinect v2 useful. These results, despite being positive, are not as good as the results reported by Tan *et al.* (2013). In their investigation, during a similar research trial involving 29 interventional radiologists, 69% of the participants found the Microsoft Kinect based *Touchless Radiology Imaging Control System (TRICS)* as potentially useful. In both studies, the age profile of the participants was similar. In this one, 62% were between 20-40 years of age compared to 66% in the study of Tan *et al.* (2013). In this research trial, however, a wider variety of clinical specialties were represented with Interventional Radiologists comprising only 7.5% of the population sample. The participants of this study were also with higher level of training (80% were specialists or in specialists training versus 62% in the reference study).

The analysis of the results indicated that the system usability has a direct effect on the perception of system utility by Surgeons and Interventional Radiologists. Poor usability translates into poor perception of utility. The poorer usability of the Leap Motion controller can partially explain the result that only less than two fifths (39%) of the participating Surgeons and Interventional Radiologists found the device categorically useful. Furthermore, the statistically significant association between the participants' age and the Leap Motion perceived utility can be attributed to the poorer usability of the Leap Motion sensor and the likelihood that younger doctors are more amenable to new technology. Another factor impacting the utility score is the closer proximity requirement of the Leap Motion sensor, which is seen as a potential drawback for its use during surgery.

5.6 Deployment Considerations

One of the most important aspects of the NUI system deployment is the physical arrangement of the system within the OR. The spatial location of the sensor device should be carefully planned based on analysis of the existing OR layout and the surgical procedures workflow so that line of sight is maintained between the clinician user and the motion sensor. The system display size and its position relative to the motion sensor are also important considerations. Ethnographic data from pilot deployments can inform prospective design changes and improve the NUI system usability. One example is the display monitor rearrangements reported by O'Hara *et al.* (2014b).

As part of this study, the requirements for system integration with a real-time imaging system such as the Interventional Radiology suite CT scanner were discussed with a General Electric (GE) engineer (Appendix N). The GE engineer confirmed that such integration will be difficult as access to CT imaging systems is restricted for reasons of safety and reliability. Therefore, the use of an intermediary device is necessary. One alternative, which was discussed at the time, is to convert the CT scanner real time video output into DICOM format and enable control of the CT imaging data via a separate DICOM viewer. Another solution, which TedCas currently provides, is to connect the NUI system to a standard USB port and to use as computer mouse and keyboard emulator. This is a much simpler option; however the installation of the NUI system in the OR can be complex and potentially costly.

Infrared interference is another deployment consideration. Halogen surgical ceiling lights are one of the IR emitting sources within the OR which can interfere with the Microsoft Kinect v2 and Leap Motion controllers and impair their motion sensing abilities (Strickland *et al.*, 2013; Mauser and Burgert, 2014).

5.7 Future Developments

A number of new COTS sensors are being currently developed and will be soon generally available. Some examples are the MYO gesture control armband, the Eye Tribe eye tracker and the FIN thumb ring motion sensor. These can also be used as NUI system input devices and the TedCas medical technology company have already begun work on integrating some of these sensors with their system (Llano, 2014). An important feature of a NUI system using multiple input devices will be the ability to fluidly switch between the different interfaces or to integrate their input data. Bigdelou *et al.* (2012) present framework architecture of a component system which integrates the Microsoft Kinect sensor input with the input of a system of four wireless orientation sensors. This type of NUI system can potentially address the issues of IR interference and no line of sight.

5.8 Conclusion

The NUI system usability can be enhanced by implementing design changes which improve its accuracy as well as the system gesture vocabulary. The Kinect sensor can benefit from the implementation of voice commands. The deployment of the NUI system in the OR should be carefully assessed and planned, particularly with respect to the sensors placement and the choice of display. Integrating the input from several COTS sensors can improve the system consistency and reliability.

Chapter 6 Conclusion and Future Work

6.1 Introduction

This study comparatively evaluates two new and recently released COTS motion sensors as interface devices of a pre-commercial NUI system for control of biomedical images. This chapter summarises the main findings from the mixed methods study and acknowledges its strengths and limitations. It provides an account of the general experiences from running the trial and offers recommendations for future research.

6.2 Adoption of NUI systems in the OR

The results from the study indicate that COTS sensor based NUI systems have the ability to enhance the practice of surgeons and interventional radiologists by enabling touchless control of biomedical images in sterile settings and providing enhanced control over the OR environment. The majority of the study participants recognised the potential of this type of system, particularly in the context of imaging intensive surgical procedures. Further on, the capability to navigate and manipulate imaging data while scrubbed can potentially strengthen the collaboration between the clinicians during surgery and augment their "*professional vision*" (O'Hara *et al.*, 2014b).

The system usability rating was determined to be *acceptable* with the Microsoft Kinect for Windows v2 sensor and it had *marginal* acceptability with the Leap Motion device. The Leap Motion sensor had better accuracy, comparable to that of a computer mouse. The study found that both sensors can be effectively used as human interface devices for touchless interactions. Microsoft Kinect, however, was established to have greater potential for use in the OR, notwithstanding its poorer accuracy. Further development is necessary to improve the gesture recognition performance. In order to successfully implement the NUI system, the interactions it enables and its gesture vocabulary should be designed specifically for the clinical context of use.

6.3 Strengths and Limitations of the Study

This study builds on previous research in this area and formalises the usability evaluation by employing the valid and reliable System Usability Scale (SUS). The performance of the two sensor devices is comparatively assessed after the completion of an iterative design phase involving two clinicians.

Considerable effort was made to recruit the participants randomly. Nevertheless, clinical doctors with general interest in technology might have been more inclined to take part in this study. This may have introduced participation bias. In addition, the fact that the quantitative and qualitative experimental data has been collected by the principal investigator may have introduced some measurement bias (Sica, 2006).

6.4 Recommendations for Future Research

The application of NUI systems in the Operating Room is an area with considerable scope for further research. Potential areas for future work include:

i. Establishing the optimal gesture vocabulary. An important part of such research is developing an understanding of individual surgical practices and their specific requirements. Based on some of the participants feedback received during this study, Orthopaedic and Vascular Surgery are two domains with potentially high probability of adoption where initial research can focus.
ii. The system performance can improve with training and practice. Of interest is to establish what amount or period of structured practice is required in order to achieve optimal user performance. This has also been previously identified as an area of research interest by Pajares *et al*. (2004).
iii. *In situ* evaluation of the impact of the NUI system on existing workflow and work practices in the OR. A specific area of interest is the impact on the existing spatial relationships between clinical staff in the OR, particularly when trying to avoid interference with the system.
iv. Research into potential workflow improvements and efficiencies. One example is a Randomised Controlled Clinical Trial to evaluate the system impact on time efficiency during Interventional Radiology procedures.
v. NUI system technology acceptance evaluation and research into the factors facilitating system adoption can benefit both system developers and hospital stakeholders by establishing what is necessary for a successful implementation.
vi. *In situ* evaluation the effect of the NUI system on professional collaboration.

6.5 Dissemination of Research Findings

The study results will be presented to and discussed with key members of St. James's Hospital Department of Radiology, Department of Medical Physics & Bioengineering as well as with all individual surgeons who have expressed interest in the results.

The findings of the study will be also shared with TedCas Medical Systems in order to provide design feedback and to highlight areas for NUI system improvement.

Finally, the research abstract has been submitted for consideration for presentation at the 100th Scientific Assembly and Annual Meeting of the Radiological Society of North America (RSNA) in Chicago, USA in December 2014.

6.6 Reflections on the Study

The initial research idea was to conduct a randomised controlled trial comparing the use of Microsoft Kinect and Leap Motion in live Interventional Radiology procedures. This proved to be an ambitious project which required additional time and financial resources. After the research approach was modified and the research question was formulated, an unanticipated amount of time and effort were spent during the iterative system design phase, as a number of changes were required in order to improve the software stability and system usability. Lastly, getting clinician time away from their busy practices to trial the system was, as expected, very challenging but at the same time rewarding as all participants fully engaged in the research trail and openly provided their feedback. Getting an insight into the way of thinking of practicing clinicians with considerable experience was very educational and an important aspect of the learning process for the principal investigator.

6.7 Conclusion

This study confirms that a Natural User Interface system for gesture control of biomedical images using the Microsoft Kinect for Windows v2 and Leap Motion COTS sensors is feasible and that it can benefit the practice of surgery by enabling touchless interactions with imaging data in sterile clinical environments. Further research and development is required to improve the system usability and to establish the design specifications, installation guidelines and user training requirements that can ensure successful deployment in varying clinical areas.

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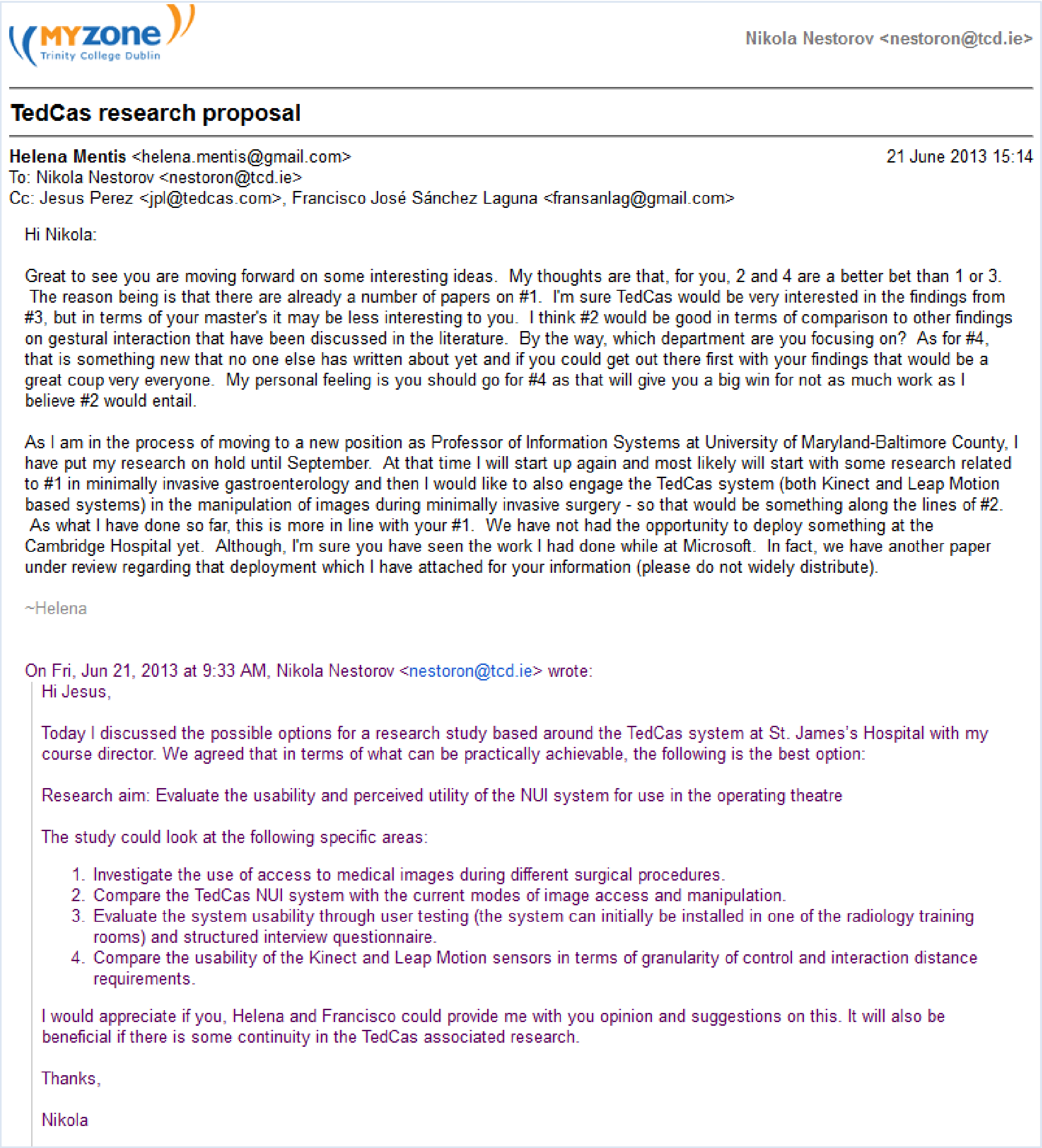
Appendix A. **Dr. Helena Mentis' Research Guidance**



Nikola Nestorov <nestoron@tcd.ie>

TedCas research proposal

Helena Mentis <helena.mentis@gmail.com>
21 June 2013 15:14
To: Nikola Nestorov <nestoron@tcd.ie>
Cc: Jesus Perez <jpl@tedcas.com>, Francisco José Sánchez Laguna <fransanlag@gmail.com>

Hi Nikola:

Great to see you are moving forward on some interesting ideas. My thoughts are that, for you, 2 and 4 are a better bet than 1 or 3. The reason being is that there are already a number of papers on #1. I'm sure TedCas would be very interested in the findings from #3, but in terms of your master's it may be less interesting to you. I think #2 would be good in terms of comparison to other findings on gestural interaction that have been discussed in the literature. By the way, which department are you focusing on? As for #4, that is something new that no one else has written about yet and if you could get out there first with your findings that would be a great coup very everyone. My personal feeling is you should go for #4 as that will give you a big win for not as much work as I believe #2 would entail.

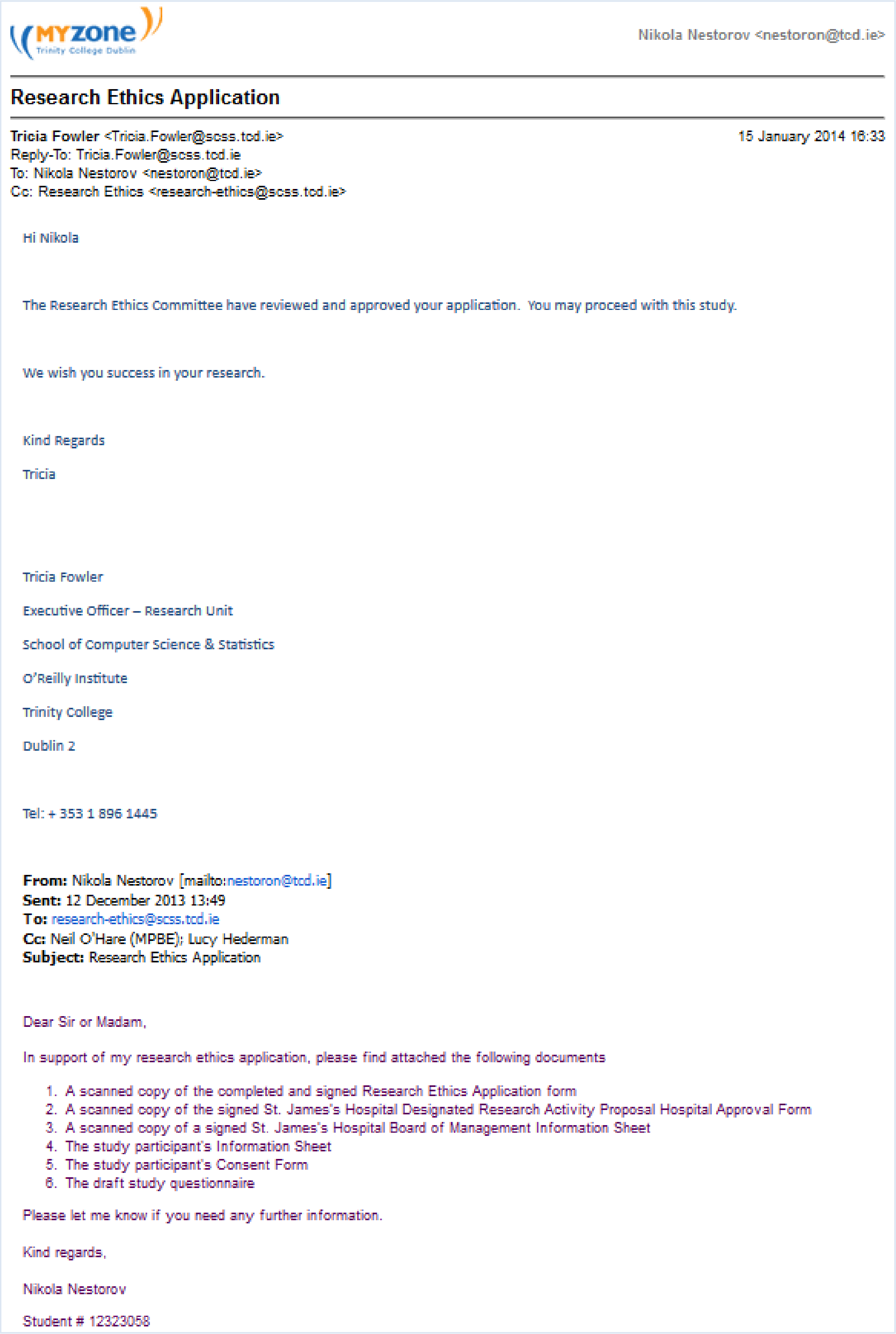
As I am in the process of moving to a new position as Professor of Information Systems at University of Maryland-Baltimore County, I have put my research on hold until September. At that time I will start up again and most likely will start with some research related to #1 in minimally invasive gastroenterology and then I would like to also engage the TedCas system (both Kinect and Leap Motion based systems) in the manipulation of images during minimally invasive surgery - so that would be something along the lines of #2. As what I have done so far, this is more in line with your #1. We have not had the opportunity to deploy something at the Cambridge Hospital yet. Although, I'm sure you have seen the work I had done while at Microsoft. In fact, we have another paper under review regarding that deployment which I have attached for your information (please do not widely distribute).

~Helena

On Fri, Jun 21, 2013 at 9:33 AM, Nikola Nestorov <nestoron@tcd.ie> wrote:

> Hi Jesus,
>
> Today I discussed the possible options for a research study based around the TedCas system at St. James's Hospital with my course director. We agreed that in terms of what can be practically achievable, the following is the best option:
>
> Research aim: Evaluate the usability and perceived utility of the NUI system for use in the operating theatre
>
> The study could look at the following specific areas:
>
> 1. Investigate the use of access to medical images during different surgical procedures.
> 2. Compare the TedCas NUI system with the current modes of image access and manipulation.
> 3. Evaluate the system usability through user testing (the system can initially be installed in one of the radiology training rooms) and structured interview questionnaire.
> 4. Compare the usability of the Kinect and Leap Motion sensors in terms of granularity of control and interaction distance requirements.
>
> I would appreciate if you, Helena and Francisco could provide me with you opinion and suggestions on this. It will also be beneficial if there is some continuity in the TedCas associated research.
>
> Thanks,
>
> Nikola

Appendix B. **Research Ethics Application Approval**



Nikola Nestorov <nestoron@tcd.ie>

Research Ethics Application

Tricia Fowler <Tricia.Fowler@scss.tcd.ie> 15 January 2014 16:33
Reply-To: Tricia.Fowler@scss.tcd.ie
To: Nikola Nestorov <nestoron@tcd.ie>
Cc: Research Ethics <research-ethics@scss.tcd.ie>

Hi Nikola

The Research Ethics Committee have reviewed and approved your application. You may proceed with this study.

We wish you success in your research.

Kind Regards

Tricia

Tricia Fowler

Executive Officer – Research Unit

School of Computer Science & Statistics

O'Reilly Institute

Trinity College

Dublin 2

Tel: + 353 1 896 1445

From: Nikola Nestorov [mailto:nestoron@tcd.ie]
Sent: 12 December 2013 13:49
To: research-ethics@scss.tcd.ie
Cc: Neil O'Hare (MPBE); Lucy Hederman
Subject: Research Ethics Application

Dear Sir or Madam,

In support of my research ethics application, please find attached the following documents

1. A scanned copy of the completed and signed Research Ethics Application form
2. A scanned copy of the signed St. James's Hospital Designated Research Activity Proposal Hospital Approval Form
3. A scanned copy of a signed St. James's Hospital Board of Management Information Sheet
4. The study participant's Information Sheet
5. The study participant's Consent Form
6. The draft study questionnaire

Please let me know if you need any further information.

Kind regards,

Nikola Nestorov

Student # 12323058

Appendix C. **Information Sheet for Participants**

INFORMATION SHEET FOR PARTICIPANTS

A study comparing the utility and usability of the Microsoft Kinect and Leap Motion sensor devices in the context of their application for gesture control of biomedical images

BACKGROUND OF RESEARCH:

The requirement to maintain asepsis along with the non-sterile nature of the traditional mouse and keyboard has resulted in complex arrangements between the scrubbed clinician and the non-scrubbed personnel for image interaction in the Operating Room (OR). The availability of touchless Natural User Interface image control systems based on advanced, low cost, commercially available sensors such as the Microsoft Kinect can enable the clinician to assume direct and dynamic control of the medical image navigation in the OR.

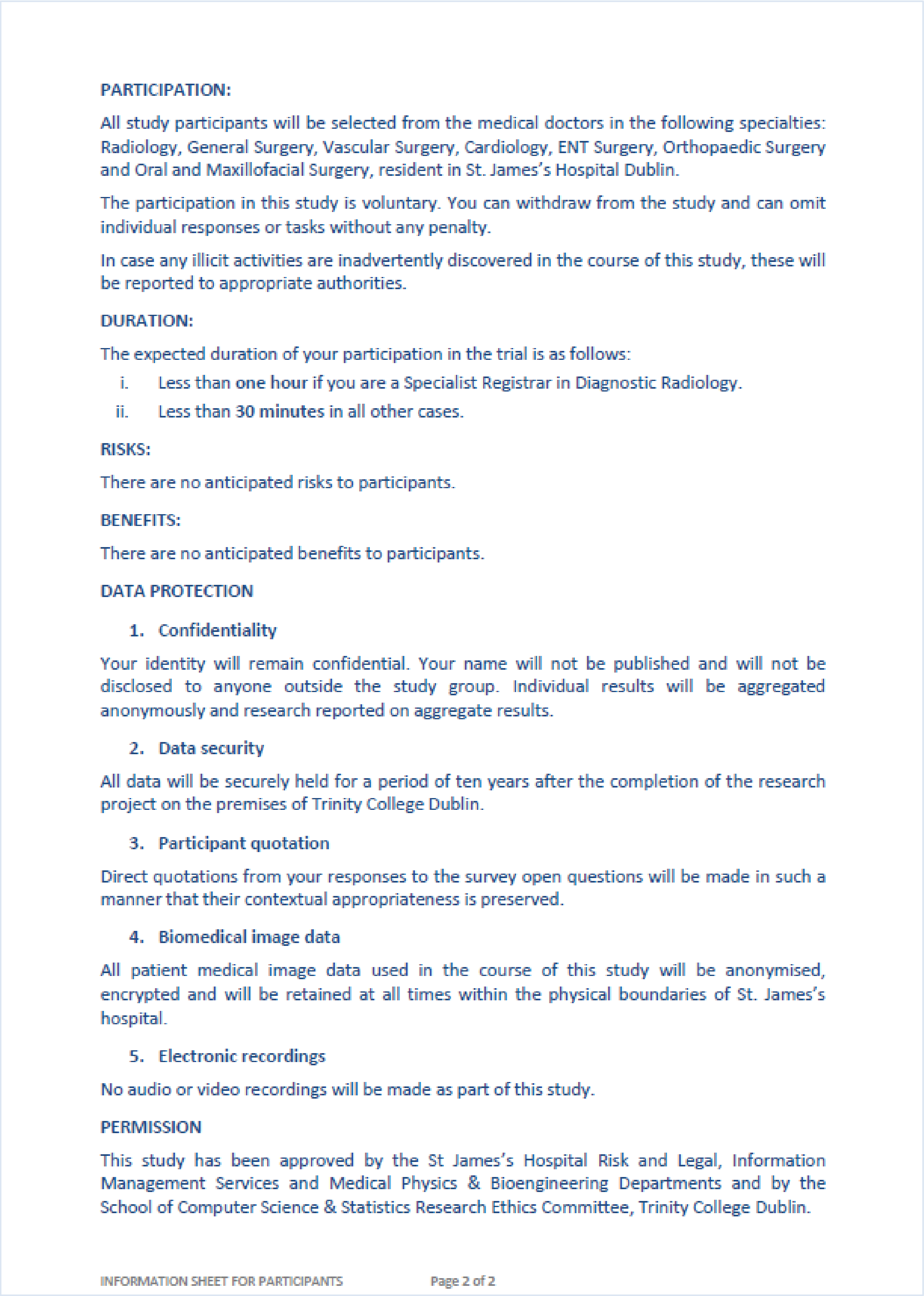
A number of recent studies have demonstrated the feasibility of use of touchless, gesture image control systems in the OR. The launch of the Leap Motion controller in July 2013 and the release of the new Microsoft Kinect One controller in November 2013 naturally raise the question of how these new 3D motion sensor devices compare in the context of their application for gesture control of biomedical images. Providing an answer to this question is the intention of this dissertation research project which is being undertaken in partial fulfilment of the requirements for the MSc in Health Informatics degree at Trinity College Dublin (https://www.scss.tcd.ie/postgraduate/health-informatics/).

PROCEDURES OF THIS STUDY:

1. You will be shown two short (approximately 2.5 min) video tutorials of the trial system, one showing how to use the Microsoft Kinect controller and one showing how to use the Leap Motion controller. The trial system is a commercial solution developed by TedCas Medical Systems (http://www.tedcas.com/en).
2. You will be asked to complete a number of predefined tasks using each of the controllers such as measuring the size of an anatomic feature. More specifically,
    a. If you are a Specialist Registrar (SpR) in Diagnostic Radiology there will be three sets of tasks. One set using a standard computer mouse and two sets using each of the two motion controllers. Task completion time will be measured. Completion of all tasks should take on average 40 to 45 minutes.
    b. In all other cases, there will be two sets of tasks, one using the Microsoft Kinect and one using the Leap Motion controller. Task completion time will not be measured. Completion of all tasks should take on average 15 to 20 minutes.
3. You will be asked to complete a paper questionnaire. The questionnaire will have two parts. Part one will be administered before the system use and part two after the completion of the predefined tasks. The questionnaire completion should take approximately 5 minutes.

CONFLICT OF INTEREST:

Telefonica S.A. through its subsidiary Wayra, a start-up accelerator, owns a minority stake in TedCas Medical Systems. The principal investigator, Nikola Nestorov is employed by Telefonica Ireland, trading under the commercial brand O2 and owned by Telefonica S.A.



PARTICIPATION:

All study participants will be selected from the medical doctors in the following specialties: Radiology, General Surgery, Vascular Surgery, Cardiology, ENT Surgery, Orthopaedic Surgery and Oral and Maxillofacial Surgery, resident in St. James's Hospital Dublin.

The participation in this study is voluntary. You can withdraw from the study and can omit individual responses or tasks without any penalty.

In case any illicit activities are inadvertently discovered in the course of this study, these will be reported to appropriate authorities.

DURATION:

The expected duration of your participation in the trial is as follows:

i. Less than **one hour** if you are a Specialist Registrar in Diagnostic Radiology.
ii. Less than **30 minutes** in all other cases.

RISKS:

There are no anticipated risks to participants.

BENEFITS:

There are no anticipated benefits to participants.

DATA PROTECTION

1. **Confidentiality**

Your identity will remain confidential. Your name will not be published and will not be disclosed to anyone outside the study group. Individual results will be aggregated anonymously and research reported on aggregate results.

2. **Data security**

All data will be securely held for a period of ten years after the completion of the research project on the premises of Trinity College Dublin.

3. **Participant quotation**

Direct quotations from your responses to the survey open questions will be made in such a manner that their contextual appropriateness is preserved.

4. **Biomedical image data**

All patient medical image data used in the course of this study will be anonymised, encrypted and will be retained at all times within the physical boundaries of St. James's hospital.

5. **Electronic recordings**

No audio or video recordings will be made as part of this study.

PERMISSION

This study has been approved by the St James's Hospital Risk and Legal, Information Management Services and Medical Physics & Bioengineering Departments and by the School of Computer Science & Statistics Research Ethics Committee, Trinity College Dublin.

Appendix D. **Informed Consent Form**

INFORMED CONSENT FORM

A study comparing the utility and usability of the Microsoft Kinect and Leap Motion sensor devices in the context of their application for gesture control of biomedical images

BACKGROUND OF RESEARCH:

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1. You will be shown two short (approximately 2 min) video tutorials of the trial system, one showing how to use the Microsoft Kinect controller and one showing how to use the Leap Motion controller. The trial system is a commercial solution developed by TedCas Medical Systems (http://www.tedcas.com/en).
2. You will be asked to complete a number of predefined tasks using each of the controllers such as measuring the size of an anatomic feature. More specifically,
   a. If you are a Specialist Registrar (SpR) in Diagnostic Radiology there will be three sets of tasks. One set using a standard computer mouse and two sets using each of the two motion controllers. Task completion time will be measured. Completion of all tasks should take on average 40 to 45 minutes.
   b. In all other cases, there will be two sets of tasks, one using the Microsoft Kinect and one using the Leap Motion controller. Task completion time will not be measured. Completion of all tasks should take on average 15 to 20 minutes.
3. You will be asked to complete a paper questionnaire. The questionnaire will have two parts. Part one will be administered before the system use and part two after the completion of the predefined tasks. The questionnaire completion should take approximately 10 minutes.

PUBLICATION:

It is the intention of the research team to publish the results of this study in a peer reviewed journal such as the Radiological Society of North America, Inc (RSNA) RadioGraphics journal. Individual results will be aggregated anonymously and research reported on aggregate results.

DECLARATION:

- I am 18 years or older and am competent to provide consent.
- I have read, or had read to me, a document providing information about this research and this consent form. I have had the opportunity to ask questions and all my questions have been answered to my satisfaction and understand the description of the research that is being provided to me.
- I agree that my data is used for scientific purposes and I have no objection that my data is published in scientific publications in a way that does not reveal my identity.
- I understand that if I make illicit activities known, these will be reported to appropriate authorities.
- I understand that no electronic recordings will be made at any time, and that I may at any time, even subsequent to my participation have such recordings destroyed (except in situations such as above).
- I freely and voluntarily agree to be part of this research study, though without prejudice to my legal and ethical rights.
- I understand that I may refuse to answer any question and that I may withdraw at any time without penalty.
- I understand that my participation is fully anonymous and that no personal details about me will be recorded.
- I understand that if I or anyone in my family has a history of epilepsy then I am proceeding at my own risk.
- I have received a copy of this agreement.

PARTICIPANT'S NAME: ______________________

PARTICIPANT'S SIGNATURE: ______________________

Date: _______________

Statement of investigator's responsibility: I have explained the nature and purpose of this research study, the procedures to be undertaken and any risks that may be involved. I have offered to answer any questions and fully answered such questions. I believe that the participant understands my explanation and has freely given informed consent.

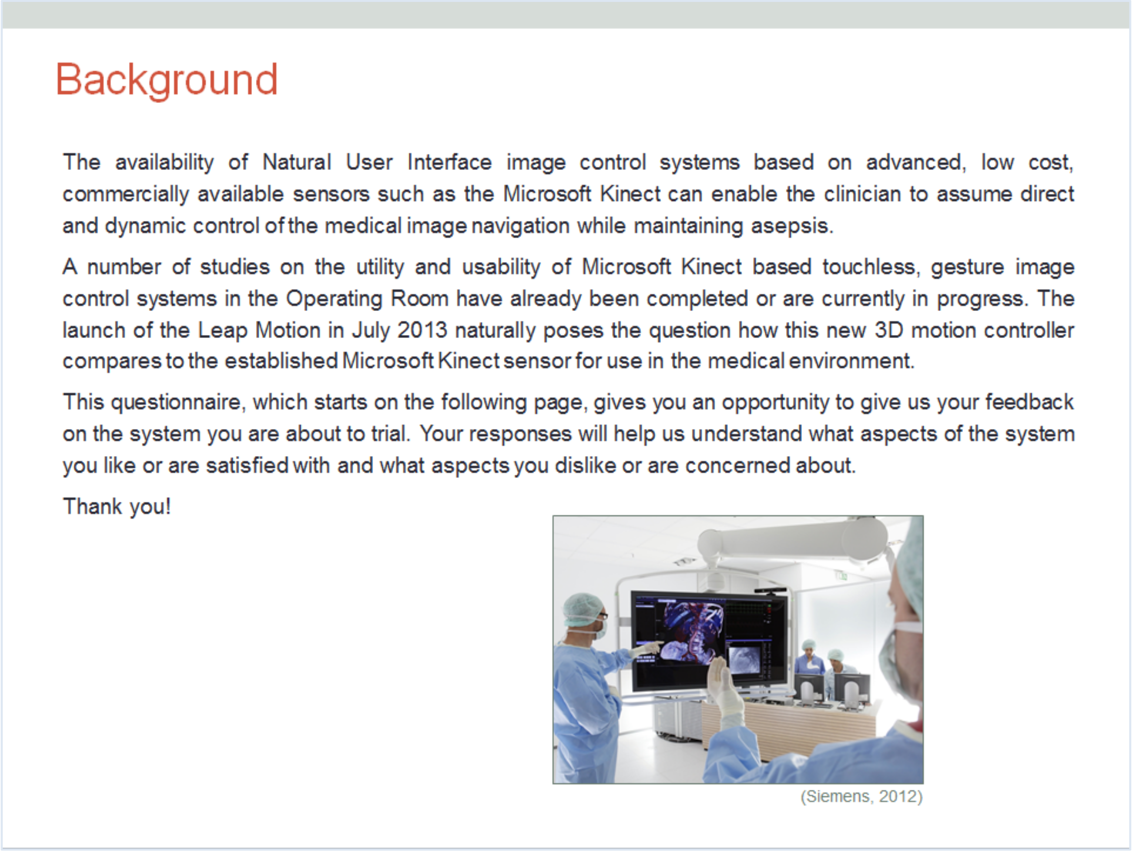
RESEARCHERS CONTACT DETAILS:

1. Nikola Nestorov, email: nestoron@tcd.ie, phone: +353 86 8145286
2. Dr. Peter Hughes, email: phughes@tcd.ie, phone: +353 87 7925039

INVESTIGATOR'S SIGNATURE: ______________________

Date: _______________

Appendix E. **Study Questionnaire**



Background

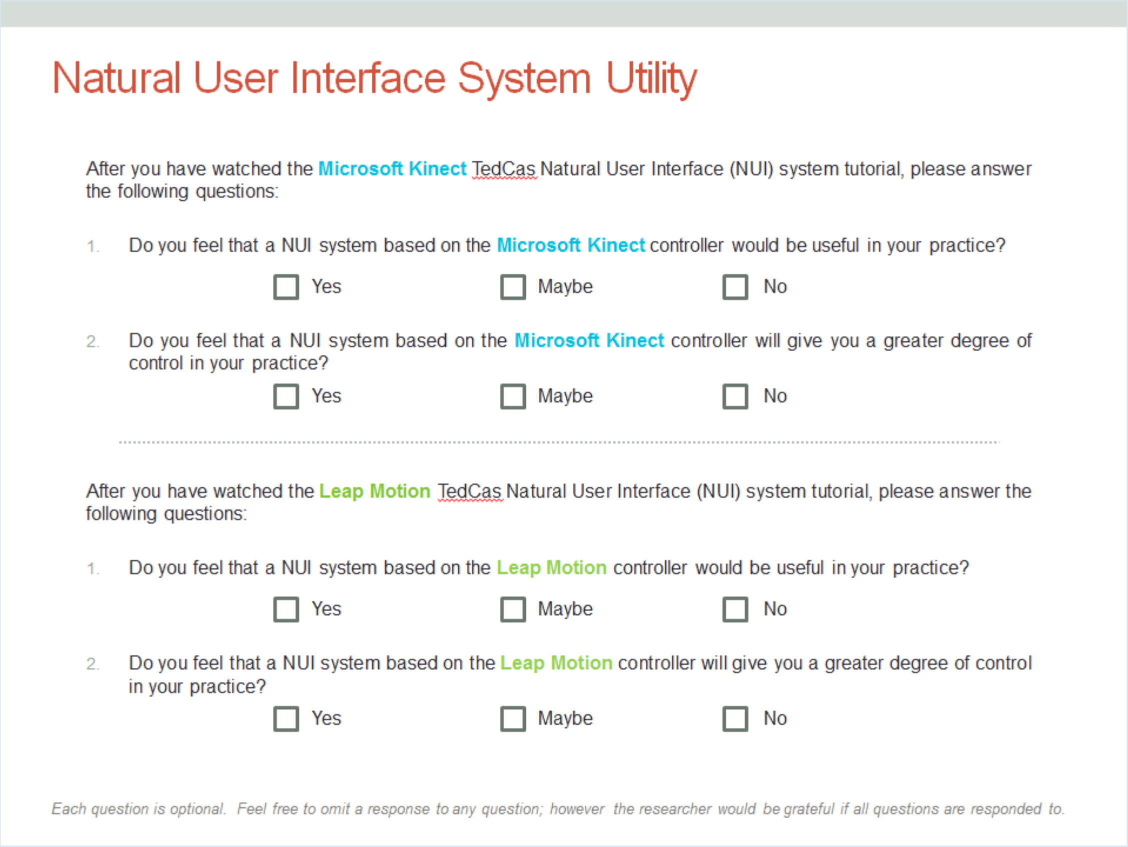
The availability of Natural User Interface image control systems based on advanced, low cost, commercially available sensors such as the Microsoft Kinect can enable the clinician to assume direct and dynamic control of the medical image navigation while maintaining asepsis.

A number of studies on the utility and usability of Microsoft Kinect based touchless, gesture image control systems in the Operating Room have already been completed or are currently in progress. The launch of the Leap Motion in July 2013 naturally poses the question how this new 3D motion controller compares to the established Microsoft Kinect sensor for use in the medical environment.

This questionnaire, which starts on the following page, gives you an opportunity to give us your feedback on the system you are about to trial. Your responses will help us understand what aspects of the system you like or are satisfied with and what aspects you dislike or are concerned about.

Thank you!

(Siemens, 2012)



Natural User Interface System Utility

After you have watched the **Microsoft Kinect** TedCas Natural User Interface (NUI) system tutorial, please answer the following questions:

1. Do you feel that a NUI system based on the **Microsoft Kinect** controller would be useful in your practice?

   ☐ Yes ☐ Maybe ☐ No

2. Do you feel that a NUI system based on the **Microsoft Kinect** controller will give you a greater degree of control in your practice?

   ☐ Yes ☐ Maybe ☐ No

……

After you have watched the **Leap Motion** TedCas Natural User Interface (NUI) system tutorial, please answer the following questions:

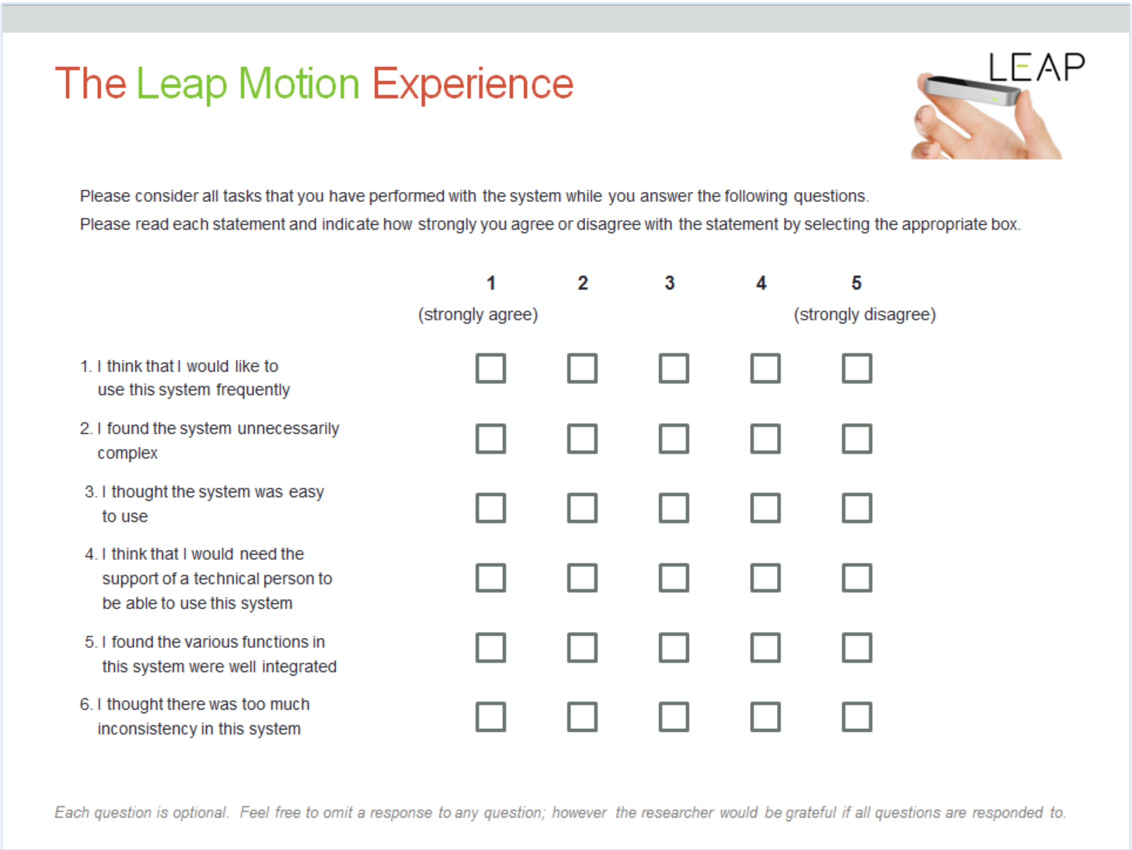
1. Do you feel that a NUI system based on the **Leap Motion** controller would be useful in your practice?

   ☐ Yes ☐ Maybe ☐ No

2. Do you feel that a NUI system based on the **Leap Motion** controller will give you a greater degree of control in your practice?

   ☐ Yes ☐ Maybe ☐ No

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.

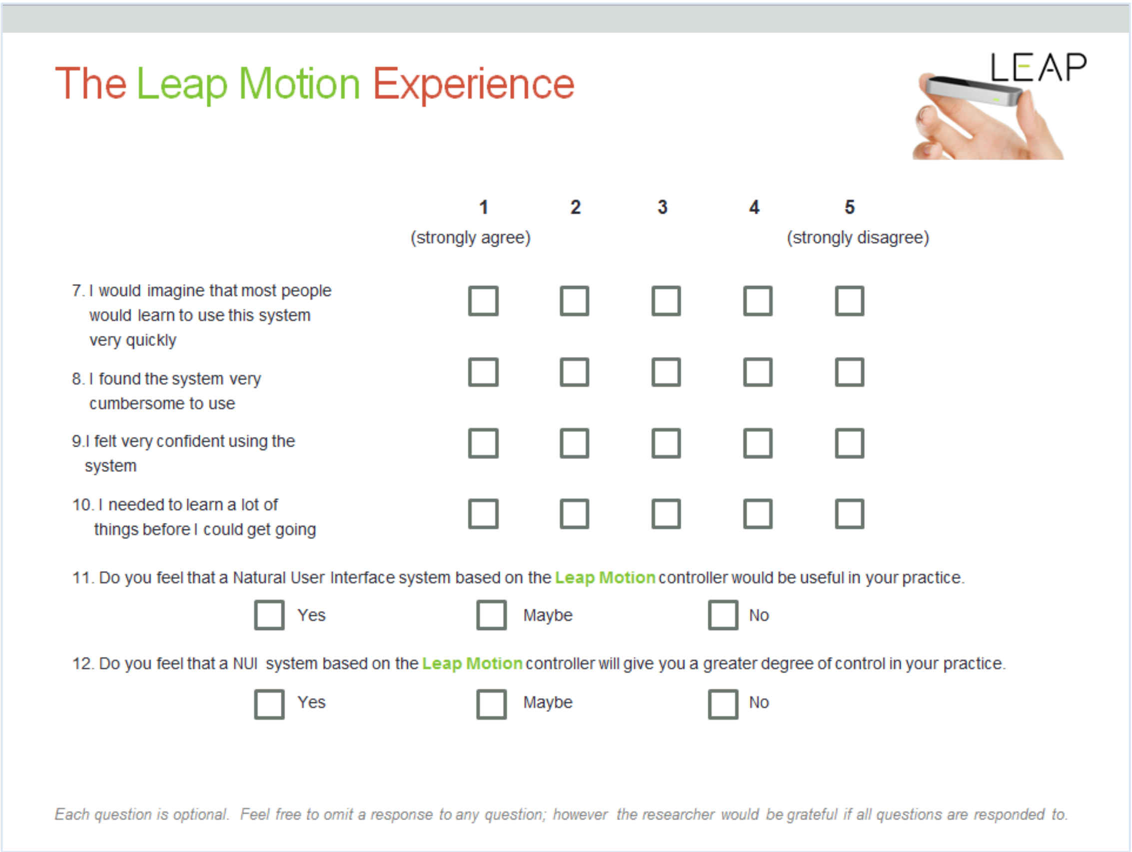


The Leap Motion Experience

Please consider all tasks that you have performed with the system while you answer the following questions.
Please read each statement and indicate how strongly you agree or disagree with the statement by selecting the appropriate box.

	1 (strongly agree)	2	3	4	5 (strongly disagree)
1. I think that I would like to use this system frequently	☐	☐	☐	☐	☐
2. I found the system unnecessarily complex	☐	☐	☐	☐	☐
3. I thought the system was easy to use	☐	☐	☐	☐	☐
4. I think that I would need the support of a technical person to be able to use this system	☐	☐	☐	☐	☐
5. I found the various functions in this system were well integrated	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in this system	☐	☐	☐	☐	☐

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.



The Leap Motion Experience

	1 (strongly agree)	2	3	4	5 (strongly disagree)
7. I would imagine that most people would learn to use this system very quickly	☐	☐	☐	☐	☐
8. I found the system very cumbersome to use	☐	☐	☐	☐	☐
9.I felt very confident using the system	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going	☐	☐	☐	☐	☐

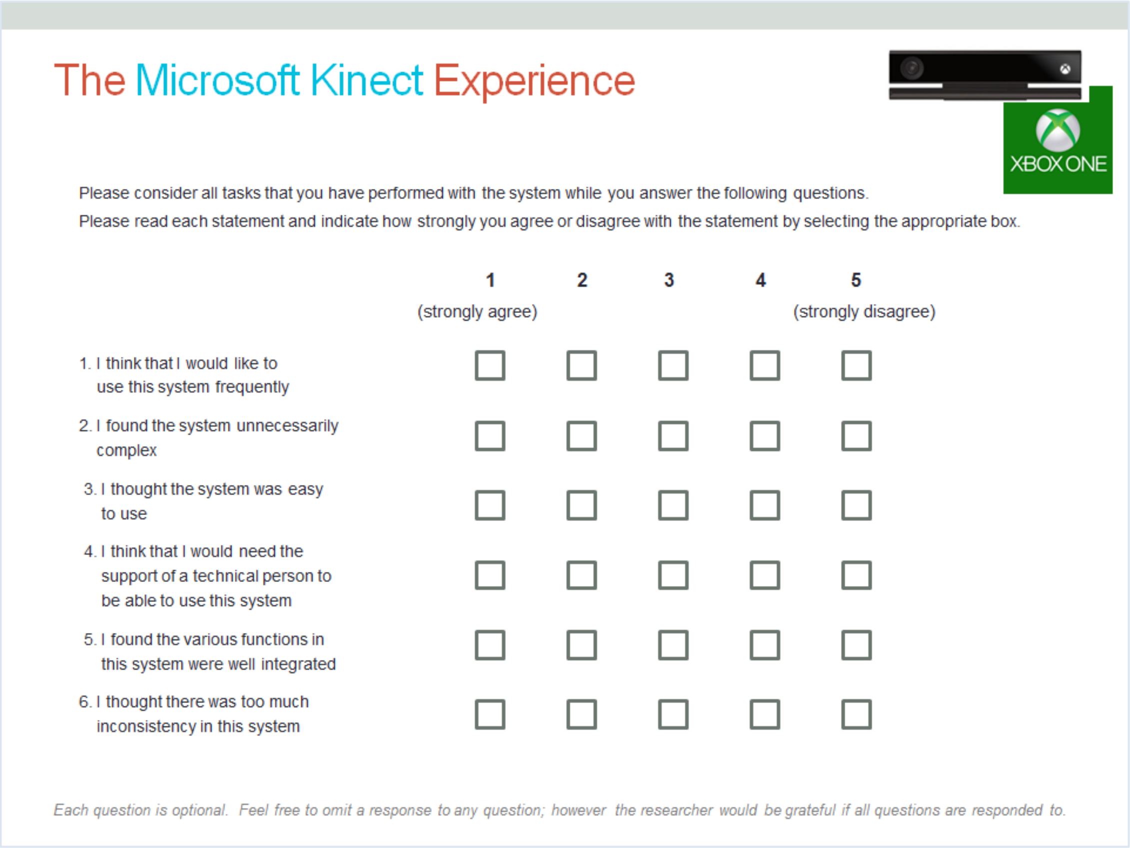
11. Do you feel that a Natural User Interface system based on the **Leap Motion** controller would be useful in your practice.

☐ Yes ☐ Maybe ☐ No

12. Do you feel that a NUI system based on the **Leap Motion** controller will give you a greater degree of control in your practice.

☐ Yes ☐ Maybe ☐ No

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.

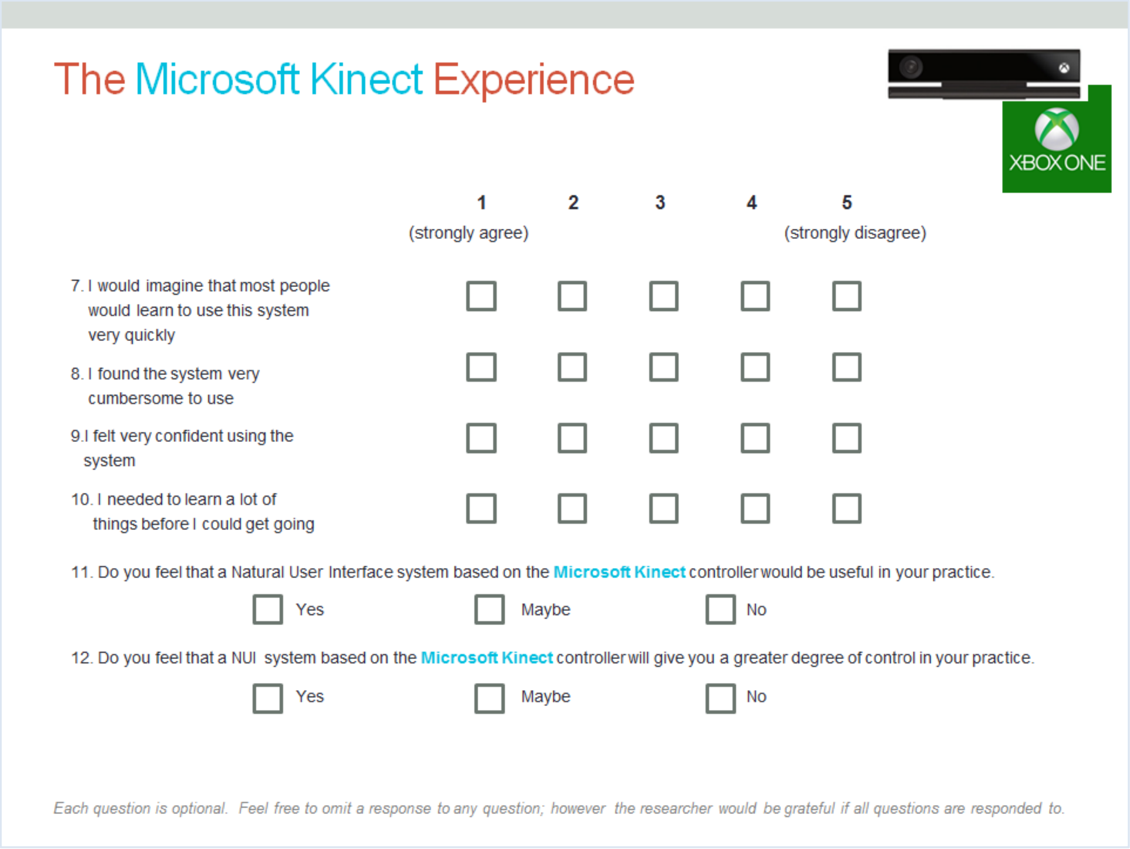


The Microsoft Kinect Experience

Please consider all tasks that you have performed with the system while you answer the following questions.
Please read each statement and indicate how strongly you agree or disagree with the statement by selecting the appropriate box.

	1 (strongly agree)	2	3	4	5 (strongly disagree)
1. I think that I would like to use this system frequently	☐	☐	☐	☐	☐
2. I found the system unnecessarily complex	☐	☐	☐	☐	☐
3. I thought the system was easy to use	☐	☐	☐	☐	☐
4. I think that I would need the support of a technical person to be able to use this system	☐	☐	☐	☐	☐
5. I found the various functions in this system were well integrated	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in this system	☐	☐	☐	☐	☐

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.



The Microsoft Kinect Experience

	1 (strongly agree)	2	3	4	5 (strongly disagree)
7. I would imagine that most people would learn to use this system very quickly	☐	☐	☐	☐	☐
8. I found the system very cumbersome to use	☐	☐	☐	☐	☐
9.I felt very confident using the system	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going	☐	☐	☐	☐	☐

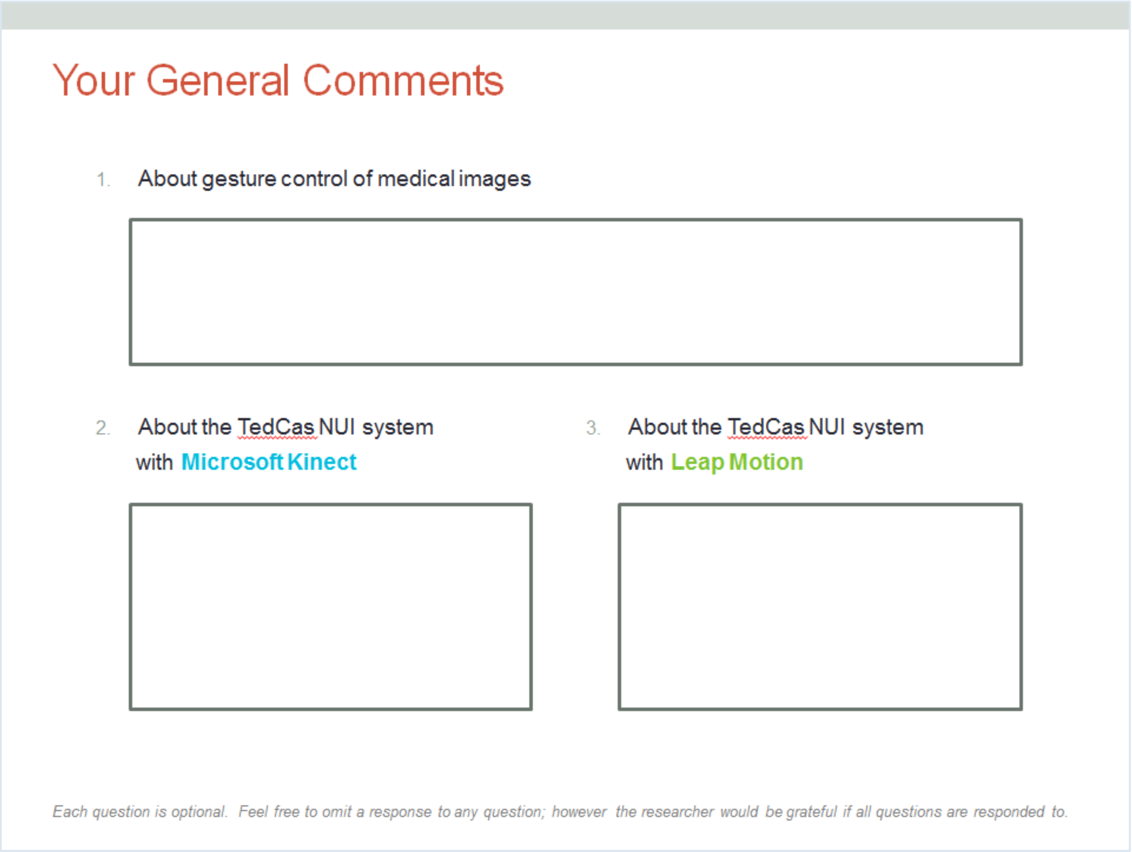
11. Do you feel that a Natural User Interface system based on the **Microsoft Kinect** controller would be useful in your practice.

☐ Yes ☐ Maybe ☐ No

12. Do you feel that a NUI system based on the **Microsoft Kinect** controller will give you a greater degree of control in your practice.

☐ Yes ☐ Maybe ☐ No

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.



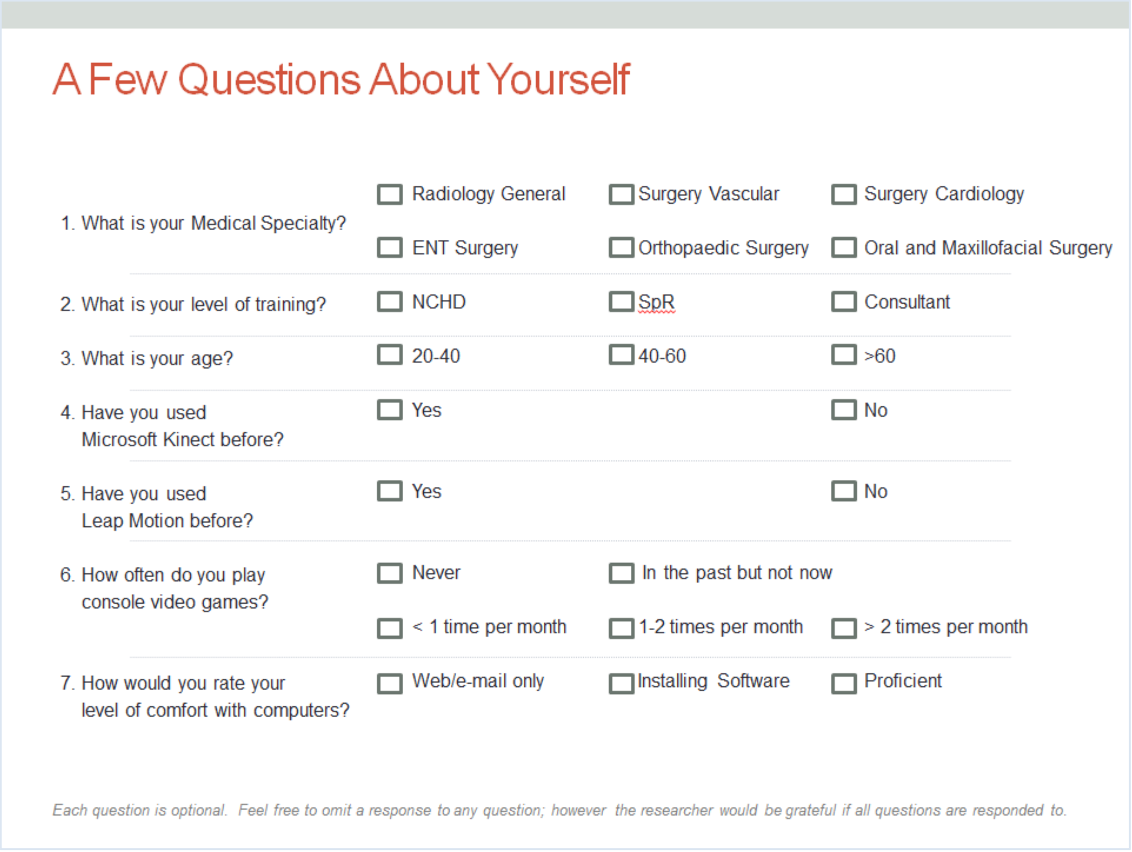
Your General Comments

1. About gesture control of medical images

2. About the TedCas NUI system with **Microsoft Kinect**

3. About the TedCas NUI system with **Leap Motion**

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.

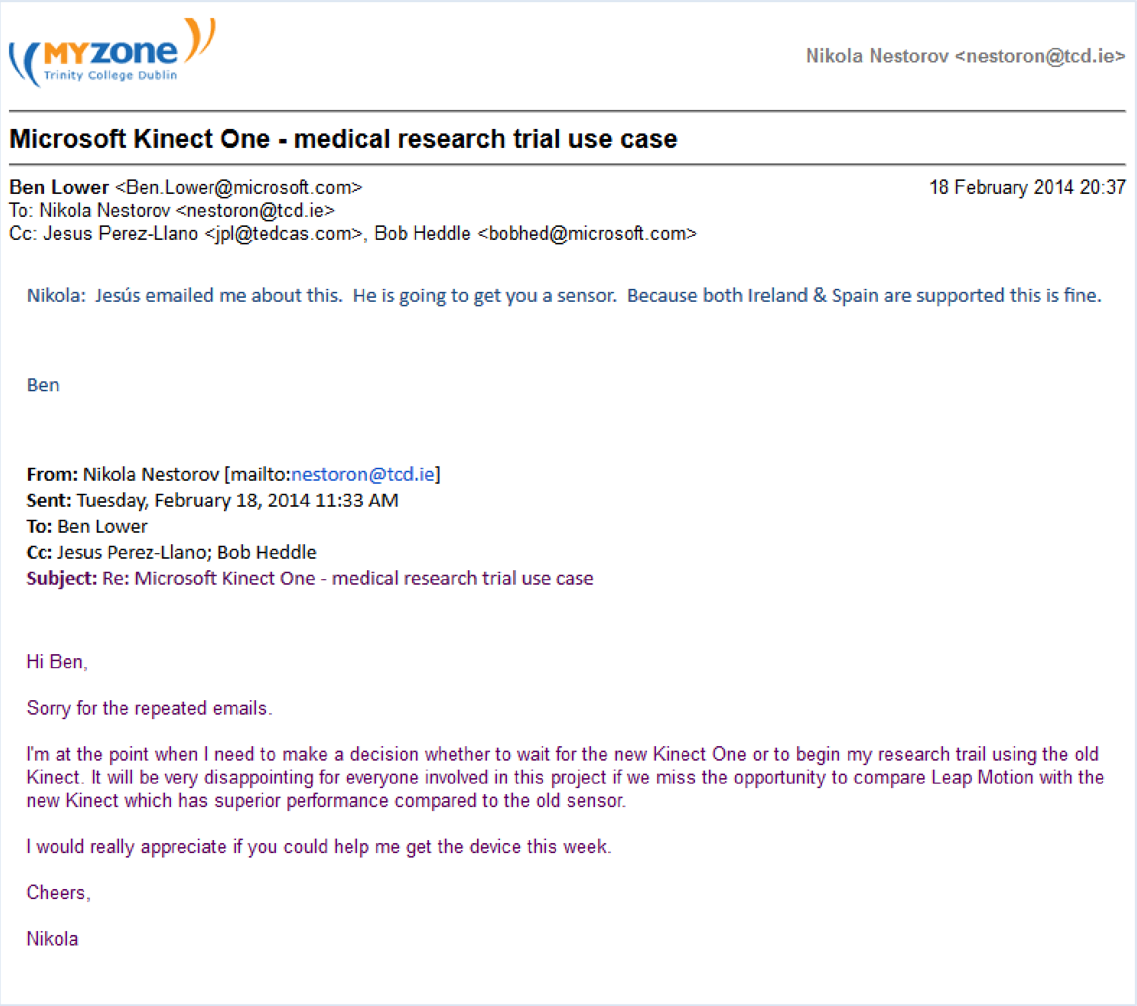


A Few Questions About Yourself

1. What is your Medical Specialty?	☐ Radiology General	☐ Surgery Vascular	☐ Surgery Cardiology
	☐ ENT Surgery	☐ Orthopaedic Surgery	☐ Oral and Maxillofacial Surgery
2. What is your level of training?	☐ NCHD	☐ SpR	☐ Consultant
3. What is your age?	☐ 20-40	☐ 40-60	☐ >60
4. Have you used Microsoft Kinect before?	☐ Yes		☐ No
5. Have you used Leap Motion before?	☐ Yes		☐ No
6. How often do you play console video games?	☐ Never	☐ In the past but not now	
	☐ < 1 time per month	☐ 1-2 times per month	☐ > 2 times per month
7. How would you rate your level of comfort with computers?	☐ Web/e-mail only	☐ Installing Software	☐ Proficient

Each question is optional. Feel free to omit a response to any question; however the researcher would be grateful if all questions are responded to.

Appendix F. Permission to Use the Developer Version of Kinect for Windows v2



Nikola Nestorov <nestoron@tcd.ie>

Microsoft Kinect One - medical research trial use case

Ben Lower <Ben.Lower@microsoft.com> 18 February 2014 20:37
To: Nikola Nestorov <nestoron@tcd.ie>
Cc: Jesus Perez-Llano <jpl@tedcas.com>, Bob Heddle <bobhed@microsoft.com>

Nikola: Jesús emailed me about this. He is going to get you a sensor. Because both Ireland & Spain are supported this is fine.

Ben

From: Nikola Nestorov [mailto:nestoron@tcd.ie]
Sent: Tuesday, February 18, 2014 11:33 AM
To: Ben Lower
Cc: Jesus Perez-Llano; Bob Heddle
Subject: Re: Microsoft Kinect One - medical research trial use case

Hi Ben,

Sorry for the repeated emails.

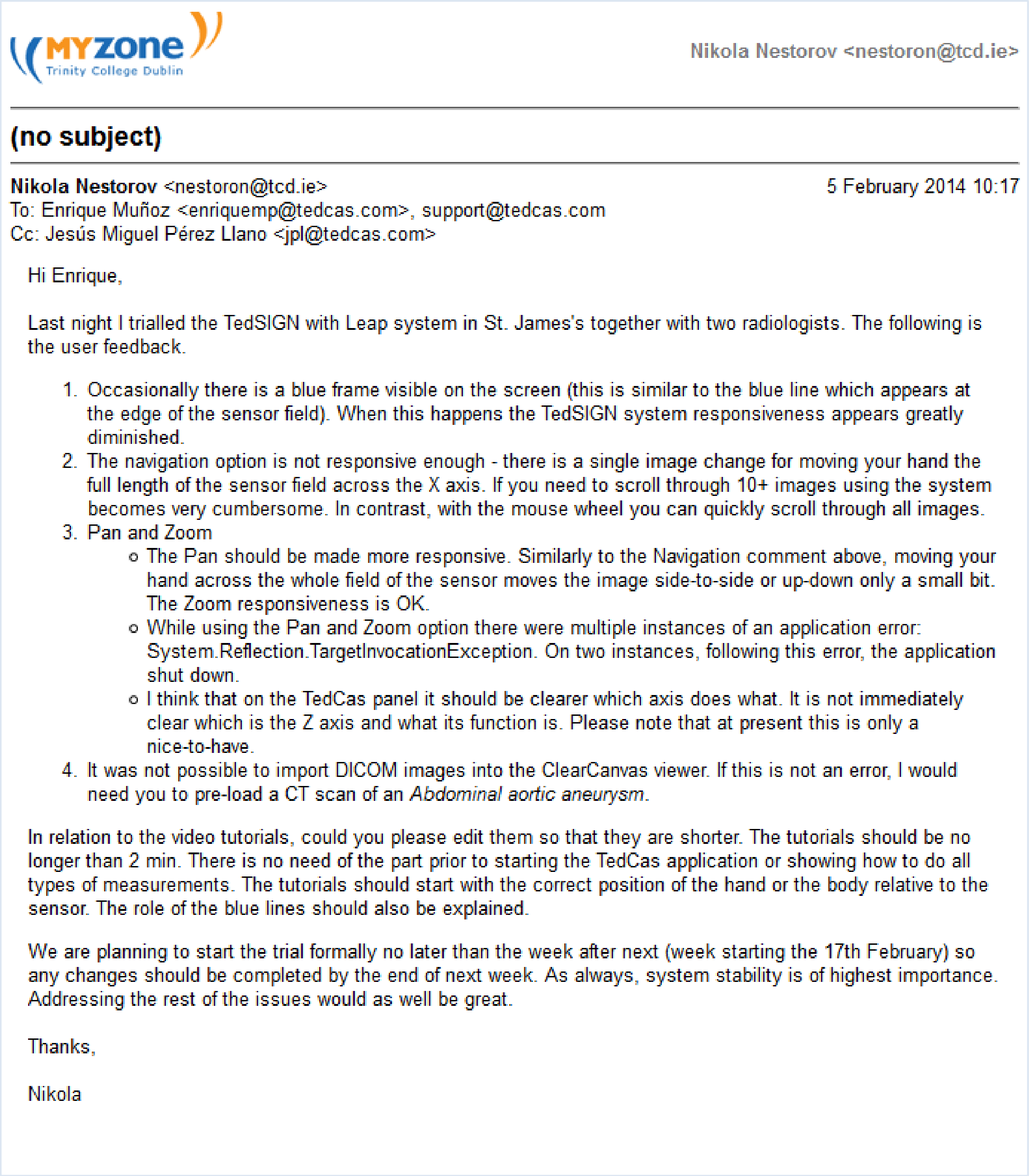
I'm at the point when I need to make a decision whether to wait for the new Kinect One or to begin my research trail using the old Kinect. It will be very disappointing for everyone involved in this project if we miss the opportunity to compare Leap Motion with the new Kinect which has superior performance compared to the old sensor.

I would really appreciate if you could help me get the device this week.

Cheers,

Nikola

Appendix G. **Example of TedCas System Performance Feedback**



Nikola Nestorov <nestoron@tcd.ie>

(no subject)

Nikola Nestorov <nestoron@tcd.ie> 5 February 2014 10:17
To: Enrique Muñoz <enriquemp@tedcas.com>, support@tedcas.com
Cc: Jesús Miguel Pérez Llano <jpl@tedcas.com>

Hi Enrique,

Last night I trialled the TedSIGN with Leap system in St. James's together with two radiologists. The following is the user feedback.

1. Occasionally there is a blue frame visible on the screen (this is similar to the blue line which appears at the edge of the sensor field). When this happens the TedSIGN system responsiveness appears greatly diminished.
2. The navigation option is not responsive enough - there is a single image change for moving your hand the full length of the sensor field across the X axis. If you need to scroll through 10+ images using the system becomes very cumbersome. In contrast, with the mouse wheel you can quickly scroll through all images.
3. Pan and Zoom
    - The Pan should be made more responsive. Similarly to the Navigation comment above, moving your hand across the whole field of the sensor moves the image side-to-side or up-down only a small bit. The Zoom responsiveness is OK.
    - While using the Pan and Zoom option there were multiple instances of an application error: System.Reflection.TargetInvocationException. On two instances, following this error, the application shut down.
    - I think that on the TedCas panel it should be clearer which axis does what. It is not immediately clear which is the Z axis and what its function is. Please note that at present this is only a nice-to-have.
4. It was not possible to import DICOM images into the ClearCanvas viewer. If this is not an error, I would need you to pre-load a CT scan of an *Abdominal aortic aneurysm*.

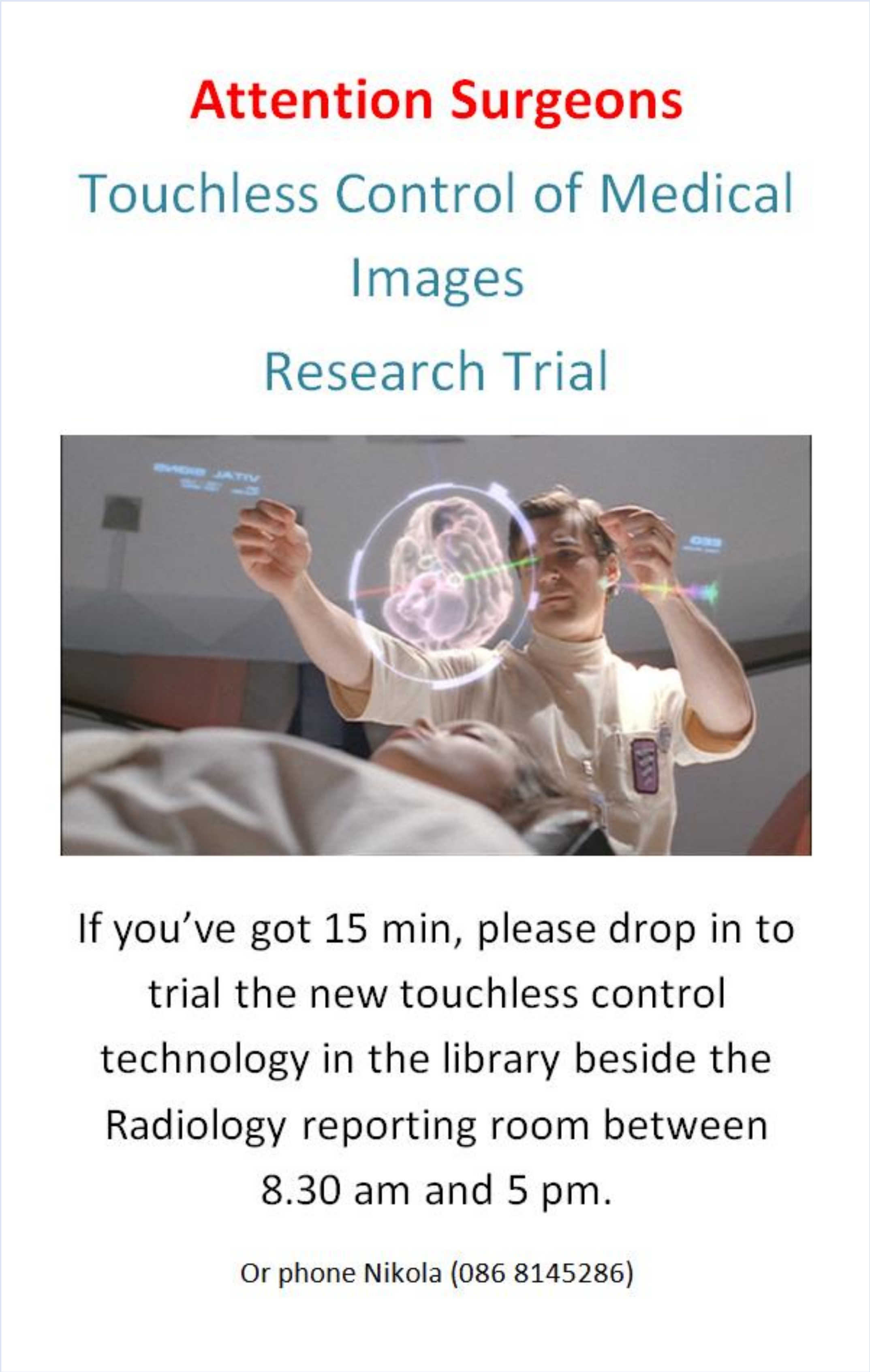
In relation to the video tutorials, could you please edit them so that they are shorter. The tutorials should be no longer than 2 min. There is no need of the part prior to starting the TedCas application or showing how to do all types of measurements. The tutorials should start with the correct position of the hand or the body relative to the sensor. The role of the blue lines should also be explained.

We are planning to start the trial formally no later than the week after next (week starting the 17th February) so any changes should be completed by the end of next week. As always, system stability is of highest importance. Addressing the rest of the issues would as well be great.

Thanks,

Nikola

Appendix H. **Poster Used to Recruit Study Participants in SJH**



Attention Surgeons

Touchless Control of Medical Images

Research Trial

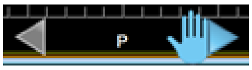
If you’ve got 15 min, please drop in to trial the new touchless control technology in the library beside the Radiology reporting room between 8.30 am and 5 pm.

Or phone Nikola (086 8145286)

Appendix I. **Task Instructions – Leap Motion**

Natural User Interface Trial: Leap Motion

1. You are at the top (image 1/109) of a CT Chest. The slice number is shown in the top right above the image.
2. By holing your hand over the Leap Motion sensor, with a **closed hand and an extended index finger** you can move the cursor around the screen.
3. **Open your hand & spread your fingers** wide.

   You will see the following appear at the bottom of the screen: 

4. By **moving** your hand over the right hand arrow and **holding** it there you can continuously scroll through the images.
5. SCROLL to IMAGE 38 (at the pulmonary artery bifurcation)
6. With **closed hand and an extended index finger,** move the cursor to the top right of the screen over this button: 

7. Hold the cursor until a blue circle has completed –  – and a menu bar will appear.
8. Select the ZOOM AND PAN tool (by holding the cursor over it until a blue circle has completed) 
9. **Open your hand & spread your fingers to zoom in** (by moving the hand towards you) and **centre** the descending thoracic aorta in the middle of your screen (by moving your hand up and left).
10. With **closed hand and an extended index finger**, move the cursor to the top right of the screen –  – to bring up the menu bar.

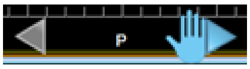
11. Select the MEASUREMENT tool: 
12. From the submenu, select the LINE tool: 
13. Measure the AP diameter of the descending aorta. To start measuring **hold** the cursor over the desired location and allow a circle to complete, then move the cursor to the desired location opposite and hold to allow a circle to form.

Appendix J. **Task Instructions – Microsoft Kinect**

Natural User Interface Trial: Microsoft Kinect

1. **Hold Up** your right hand (or left if your left handed) until you see your image turn blue - you are now in control!
2. You are at the top (image 1/109) of a CT Chest. The slice number is shown in the top right above the image.
3. By moving your **open hand** in front of the **Microsoft Kinect** sensor you can move the cursor around the screen.
4. **Make a fist.**

   You will see the following appear at the bottom of the screen:

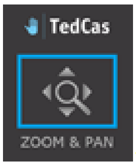
5. By **moving** your hand over the right hand arrow and **holding** it there you can continuously scroll through the images.
6. SCROLL to IMAGE 38 (at the pulmonary artery bifurcation)
7. 7. With your **hand open**, move the cursor to the top right of the screen over this button:

8. Hold the cursor until a blue circle has completed – – and a menu bar will appear.

   
9. Select the ZOOM AND PAN tool (by holding the cursor over it until a blue circle has completed)

   
10. **Make a fist** to **zoom in** (by moving the hand towards you) and **centre** the descending thoracic aorta in the middle of your screen (by moving your hand up and left).
11. With **open hand**, move the cursor to the top right of the screen – – to bring up the menu bar.

12. Select the MEASUREMENT tool:

    
13. From the submenu, select the LINE tool:

    
14. Measure the AP diameter of the descending aorta. To start measuring **hold** the cursor over the desired location and allow a circle to complete, then move the cursor to the desired location opposite and hold to allow a circle to form.

Appendix K. **Statistical Tests Used for the Data Analysis**

Test	Function	Purpose for the Study	Null Hypothesis
One-way Analysis Of Variance (ANOVA)	To compare the means of a number of samples drawn from experiments based on single factor.	Used to compare the means of the *time to measure* and anatomical feature measurements for the Microsoft Kinect, Leap Motion and computer Mouse interface devices.	The samples in the three groups of measurements are drawn from populations with the same mean values, i.e. the interface devices have equivalent performance.
Tukey's HSD (honest significant difference) or Range Test	A multiple comparisons test used to identify means that are significantly different from each other.	Used to compare each pair of input devices individually.	The samples in the three groups of measurements are drawn from populations with the same mean values, i.e. the interface devices have equivalent performance.
Wilcoxon Signed-Rank Test	A nonparametric test used instead of the t-test when the data sets are dependent or paired (same user) and their values not normally distributed.	Used to compare the SUS ordinal scale usability measures for Kinect v2 and Leap Motion.	There is no difference in the usability of the Microsoft Kinect v2 and Leap Motion sensors.
Fisher's Exact Test (two-sided)	A test of independence for contingency tables with a small number of samples in some of the cells (less than 5).	Used to examine the significance of association between the subjects' clinical specialty, age, level of training, prior familiarity with the sensors, gaming experience and computer literacy and their perception of the usability and utility of each of the sensor devices.	There is no relationship between the user's specific demographics and the resultant utility and usability rating
Cronbach's Alpha	A coefficient used to measure the internal consistency or correlation between the items of a survey or test.	To compare the inter-correlation between the two usability questions.	N/A. A higher value of Alpha indicates higher internal consistency

Appendix L. **Qualitative Data – Open Questions Responses**

Please note that some participants have opted not to answer the open questions.

#	General	Kinect	Leap	Coding
R1	Kinect was much more sensitive in all aspects of scrolling or measuring			Kinect inconsistent
R2	Very good idea but needs to be more consistent and needs to have a function equivalent to clicking on a mouse button. Resting your hand still to select something is the same as resting the mouse over something and not using the button.	Better than Leap in terms of space to control from - not holding your hand over a box.	Better than Kinect in terms of more reproducible measurements and less variability	Kinect better but Leap more accurate. Clicking gesture option welcomed.
R4	Both were inconsistent in registering commands but potentially useful in interventional radiology with user practice and familiarity			Useful but both inconsistent
R5	Good idea especially for CT guided procedures and IR. I see how it would be very useful in theatre also as I have scrubbed out as surgical SHO in order to look at images!	I found this difficult to use. It wouldn't pick up my fist easily. Also it was jerky. I liked the idea of this one more but I preferred the other system after using them both.	This was definitely the system I found easier to use. I feel I had more control with it.	Leap better
R6		Tiring having to keep arm elevated	More useful	Kinect tiring. Leap better
R7	Good idea. Will obviously need work + tweaks.	Tiring keeping arm up. Could be problematic in real life if someone was standing beside / behind you.	Much more likely to work in real life	Kinect tiring. Leap better
R8	Not ideal for day to day diagnostic radiology but very good for interventional cases.	Easy to learn, more fluid than the Leap Motion system.	I found it difficult to keep my finger perfectly still so that made it harder to use.	Kinect better

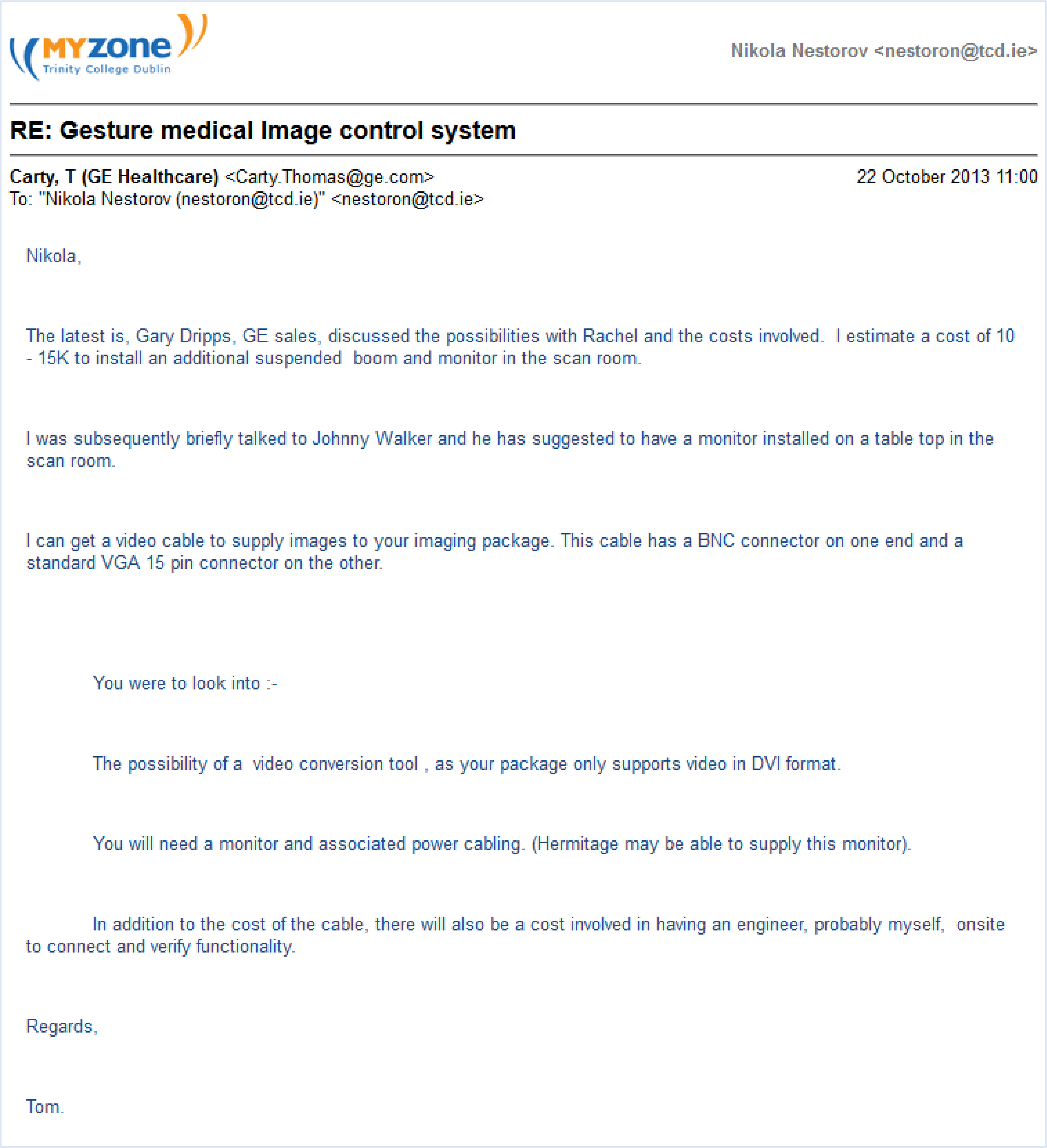
#	General	Kinect	Leap	Coding
R10		Less responsive, difficulty detecting hand. Bigger sensor filed.	Sensor filed limited in size but seemed very responsive.	Leap better but the sensor field is limitation
A1	Great idea, will be useful.	Excellent	Excellent	
A3	Can see it would be useful in niche theatre settings. Not of value to me as non interventional radiologist.	Difficult to use. Have to stand too far from sensor. Tiring + difficult to hold arm steady.	Easy to use. Quick learning curve.	Kinect tiring. Leap better
A5	Very inconsistent. I don't think it is usable in current form. It would be too frustrating for the user.	Might be difficult for a tired user.	Very difficult to know when you are outside the control area.	Both inconsistent
A6	Potentially very useful			Both useful
A8	Limited usefulness to surgery, IR. Most image manipulation is performed prior to any intervention. If needed during a procedure, something has gone wrong.	Feels labour intensive and will tire pretty quickly	Better option. Very sleek interface.	Kinect tiring. Leap better
A10	Would be very useful in operating theatre. Would complete Cerner imaging system rather than replacing.	Measuring tool, hard to use		Leap better
A11	Great tool.	Needs a little refinement.	Easy to use.	Leap better
A12	Both systems are great but need to be less sensitive or it needs more training for the personnel who will use it.	It's a brilliant system which is very useful in theatre and intervention rooms.		Kinect better
A16	Both systems are very similar. I would think that using each system for a while would give you a better idea of which you prefer.			Both systems similar
A17			Closer to screen so easier to control detail, i.e. diameter of vessel.	Leap better as closer to screen

#	General	Kinect	Leap	Coding
A18	Concept brilliant			Both useful
A19	Very good - Kinect	Very good. Large range area. Easy to use.	Control panel width/range short. Have to stay too close to interface as a scrubbed surgeon.	Kinect better
A20	Clear, easy to understand. ?any improvement on mouse though and need for Kinect to stand a downside			Kinect tiring
A21	Not sure about the role in current practice.			Not useful, both
A23	Good idea.	Good.	Little bit more difficult	Kinect better
A24	Yes, would be of definite value for complex surgery	I found this system easier to use.	I found this system less easy to use, more restricted spatially.	Kinect better
A25		May require more time before timeout to measure structure on Kinect system	Increase field of view / action	Kinect better but can be improved
A26	Excellent idea which would be extremely useful.	Slightly more difficult to the measurements.	I prefer this system controls, although the smaller area of operation is a little bit of a disadvantage.	Leap better but the sensor field is limitation
A29	I would expect them to be increasingly used in clinical practise.	Worked more for me.	Not as usable (? I have a shaky hand!).	Both useful. Kinect better
A31		Arm got tired!!! Good but inconsistent; needs to be more accurate. HUGE potential if can be improved.	Impractical for theatre (sterility, etc.)	Kinect better but tiring

Appendix M. **Measurement Task Experimental Data**

User	Device	T1	T2	T3	T4	T5	M1	M2	M3	M4	M5	Comment
R1	Leap Motion	6.9	12.9	7.7	10.8	11.5	3.38	3.31	3.16	3.4	3.54	
R1	Kinect	7.5	9.6	7.6	8.2	9.5	2.28	3.35	3.47	3.54	3.64	
R1	Mouse	4.1	2.1	1.6	2.3	2.4	3.62	3.62	3.59	3.52	3.47	
R2	Leap Motion	5.8	16.5	10.3	15	11.3	3.59	3.45	3.49	3.53	3.69	
R2	Kinect	9.9	5.9	13.7	11.6	7.9	3.34	3.24	3.07	3.13	3.48	
R2	Mouse	1.6	2.3	3.1	2.5	3	3.39	3.23	3.51	3.57	3.54	
R3	Leap Motion	9.3	7.9	10.4	19.2	11.3	3.58	3.25	3.48	3.73	3.32	1 failed
R3	Kinect	10.3	9.9	37.4	14.1	9.6	3.67	3.47	3.39	3.67	3.38	
R3	Mouse	1.3	3.4	3.1	3.6	3.3	3.4	3.5	3.58	3.64	3.71	
R4	Leap Motion	10.3	9.7	15.6	14.9	12.1	3.52	3.56	3.33	3.55	3.54	
R4	Kinect	9.3	11.5	11.3	10.9	8.8	3.11	3.35	3.61	3.35	3.45	
R4	Mouse	3.5	3.4	3.5	2.4	3.3	3.65	3.56	3.49	3.43	3.52	
R5	Leap Motion	5.6	14.3	15.5	8.9	7.6	3.47	3.28	3.27	3.34	3.49	
R5	Kinect	18	11.8	11.2	8	12.6	3.79	3.22	3.12	3.39	3.76	
R5	Mouse	2.5	3.2	3.2	3.9	5.7	3.34	3.5	3.53	3.54	3.52	
R6	Leap Motion	9	4.7	5.6	6.5	6.1	3.72	3.55	3.51	3.89	3.24	
R6	Kinect	7	13.1	20.4	12.6	16.2	3.6	3.46	3.34	3.54	3.59	
R6	Mouse	1.7	2.6	2.3	2.6	2.1	3.47	3.47	3.57	3.58	3.63	
R7	Leap Motion	7.8	9.7	12.7	14.7	10.5	3.51	3.45	3.5	3.49	3.63	
R7	Kinect	11.3	7.2	7.3	7.4	13.4	3.51	3.51	3.52	3.26	3.41	1 failed
R7	Mouse	7	3.5	5	4.6	5.3	3.5	3.54	3.55	3.63	3.63	
R8	Leap Motion	12.5	12.8	10.4	13.9	9.2	3.45	3.65	3.36	3.54	3.55	
R8	Kinect	7.5	15.1	12.3	4.4	5	3.3	3.22	3.56	3.51	3.58	
R8	Mouse	2.1	1.9	2.3	2.1	2	3.52	3.43	3.45	3.4	3.42	
R9	Leap Motion	10.1	12.4	11.2	13.1	12.4	3.6	3.36	3.35	3.4	3.49	
R9	Kinect	18.1	14.8	22.2	20.3	7.1	3.36	3.4	3.38	3.62	3.52	
R9	Mouse	3.6	4.1	2.9	3.3	4.3	3.52	3.49	3.44	3.69	3.66	
R10	Leap Motion	13.6	11.1	12.7	10.5	27.9	3.59	3.53	3.44	3.49	3.48	
R10	Kinect	6	6.2	8.3	9	8.2	3.35	3.47	3.41	3.34	3.42	
R10	Mouse	2.9	2.5	3.6	2.2	5.2	3.4	3.46	3.56	3.57	3.55	

Appendix N. **GE feedback on CT Scanner integration options**



Nikola Nestorov <nestoron@tcd.ie>

RE: Gesture medical Image control system

Carty, T (GE Healthcare) <Carty.Thomas@ge.com>
To: "Nikola Nestorov (nestoron@tcd.ie)" <nestoron@tcd.ie>

22 October 2013 11:00

Nikola,

The latest is, Gary Dripps, GE sales, discussed the possibilities with Rachel and the costs involved. I estimate a cost of 10 - 15K to install an additional suspended boom and monitor in the scan room.

I was subsequently briefly talked to Johnny Walker and he has suggested to have a monitor installed on a table top in the scan room.

I can get a video cable to supply images to your imaging package. This cable has a BNC connector on one end and a standard VGA 15 pin connector on the other.

You were to look into :-

The possibility of a video conversion tool , as your package only supports video in DVI format.

You will need a monitor and associated power cabling. (Hermitage may be able to supply this monitor).

In addition to the cost of the cable, there will also be a cost involved in having an engineer, probably myself, onsite to connect and verify functionality.

Regards,

Tom.