

DEVELOPMENT OF A TELEPRESENCE WHEELCHAIR USING ADVANCED WIRELESS VIDEO STREAMING

By

Van Kha Ly Ha

A thesis submitted to the Faculty of Engineering & Information Technology

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

at the University of Technology Sydney

Sydney, August 2017

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate

Van Kha Ly Ha

Sydney, August 2017

Acknowledgements

Foremost, I would like to take this opportunity to express my deepest gratitude and appreciation to my principal supervisor, Professor Hung Tan Nguyen, for his enthusiastic supervision, guidance, support and patience throughout the period of my doctoral research.

I would like to thank my co-supervisors, Dr. Nghia Nguyen and Dr. Rifai Chai, for all their help, especially for their valuable guidance and great support from the beginning of my research career at the University of Technology Sydney. I greatly appreciate Ms. Caroline Reed and Mr. John Hazelton for their great assistance in proofreading my papers and thesis.

I would also like to thank all of the staff and student members in the Centre for Health Technologies for their discussions, comments and advice during the helpful mixer CHT seminars, and staff of the University of Technology Sydney for their kind support.

I gratefully acknowledge the 911 VIED-UTS scholarship from the Vietnam Government; without this fund my overseas study dream would not come to reality.

Finally, I sincerely thank all of my friends and my family in Vietnam for their encouragement and strong support throughout my Ph.D. study.

Van Kha Ly Ha

Sydney, August 2017

TABLE OF CONTENTS

List of Figures	viii
List of Tables.	xvi
Abstract.....	xvii
Chapter 1 Introduction.....	1
1.1 Problem Statement	1
1.2 Objectives of the Thesis	4
1.3 Contributions of the Thesis.....	6
1.4 Structure of the Thesis.....	8
1.5 Publications	10
Chapter 2 Literature Review.....	11
2.1 Introduction.....	11
2.2 Intelligent Wheelchairs	12
2.3 Telepresence Systems	19
2.3.1 Telepresence Hardware System.....	19
2.3.2 Telepresence System Software.....	23

2.3.3	Telepresence System Applications.....	24
2.4	Advanced Communication Technologies	27
2.4.1	Wireless Technologies for Robot Control	27
2.4.2	Virtual Reality.....	30
2.4.3	360-Degree Video Communication	31
2.5	Discussion.....	33
Chapter 3	Real-Time Video Streaming for a Telepresence Wheelchair	36
3.1	Introduction.....	36
3.2	System Architecture.....	38
3.3	Wireless Video Streaming.....	41
3.3.1	Wireless Networking.....	41
3.3.2	Video Streaming over Wireless Networks.....	44
3.4	JPEG-Based Video Encoding and Quality Assessment.....	49
3.4.1	JPEG Coding.....	49
3.4.2	Video Quality Assessment	53
3.5	Experiments and Results.....	55
3.5.1	Experiment 1: Images Acquisition.....	55
3.5.2	Experiment 2: Images Streaming.....	59
3.5.3	Results.....	61

3.6	Discussion.....	71
-----	-----------------	----

Chapter 4 A Telepresence Wheelchair Based on Ubiquitous Platforms and Advanced Wireless Mobile Networks 73

4.1	Introduction.....	73
-----	-------------------	----

4.2	Streaming Speed Enhancement Based on Ubiquitous Platforms.....	76
-----	--	----

4.3	Advanced Wireless Mobile Networks	78
-----	---	----

4.4	Telepresence with Multiple Cameras.....	80
-----	---	----

4.5	Telepresence Wheelchair and Virtual Reality.....	85
-----	--	----

4.6	Experiments and Results.....	89
-----	------------------------------	----

4.6.1	Experiment 1: Real-time Video Streaming with Multi-Camera for a Telepresence Wheelchair	89
-------	--	----

4.6.2	Experiment 2: A Telepresence Wheelchair System Using Cellular Network Infrastructure in Outdoor Environments.....	94
-------	--	----

4.6.3	Experiment 3: Telepresence Wheelchair and Virtual Reality.....	99
-------	--	----

4.7	Discussion.....	108
-----	-----------------	-----

Chapter 5 An Advanced Telepresence Wheelchair Based on WebRTC and 360-degree Video Communication..... 110

5.1	Introduction.....	110
-----	-------------------	-----

5.2	Real-time Communication.....	112
-----	------------------------------	-----

5.2.1	Advanced Video Streaming over WebRTC	112
-------	--	-----

5.2.2	Prototype System Implementation and Deployment.....	117
5.3	Integration of Emerging Technologies for an Advanced Telepresence Wheelchair.....	120
5.3.1	Telepresence Wheelchair with 360-degree Vision.....	120
5.3.2	Remote Control Telepresence Wheelchair via WebRTC.....	128
5.4	QoE Estimation of Wireless Video Streaming Using Neural Networks.....	128
5.5	Experiments and Results.....	135
5.5.1	Experiment 1: Telepresence Wheelchair based on WebRTC.....	135
5.5.2	Experiment 2: An Advanced Telepresence Wheelchair with Wide Field View Using a Dual-Fisheye Camera	139
5.5.3	Experiment 3: QoE Estimation of Wireless Video Streaming Using Neural Networks.....	142
5.5.4	Experiment 4: Evaluation of Remote Control Telepresence Wheelchair over WebRTC and 360-degree Vision.....	146
5.6	Discussion.....	150
Chapter 6	Conclusion and Future Work	153
6.1	Conclusion	153
6.2	Future Work.....	158

Appendix A Power Wheelchair Components	159
Appendix B Software Code.....	164
Bibliography.....	214

List of Figures

2.1	The typical architecture of an intelligent wheelchair (Nguyen 2013).	13
2.2	Semi-autonomous wheelchair platform, Nagaoka University of Technology, Japan, (Katsura 2006).....	13
2.3	Smart wheelchair, University of Technology Sydney (Nguyen 2013).....	14
2.4	Intelligent wheelchair system (SAM), University of Technology Sydney, Australia, (Nguyen 2012).....	15
2.5	Intelligent wheelchair, Shanghai Jiao Tong University, China (Liu 2015).....	15
2.6	A computer vision based co-robot wheelchair, USA, (Li et al. 2016).....	16
2.7	EEG-based intelligent wheelchair, Korea University, Korea (Kim 2016).....	17
2.8	A BCI-based wheelchair, South China University of Technology, China, (Zhang 2016).....	18
2.9	Brain-machine interface (BMI) wheelchair, (Li 2017).....	18
2.10	MeBot platform of MIT Media Laboratory, (Adalgeirsson 2010).....	19
2.11	Principal components of Avatar robot system, (Martinez-Garcia 2012).....	20
2.12	Telepresence robot, the University of Tsukuba, Japan, (Hasegawa 2013).....	21
2.13	Telepresence Robot, Athabasca University, Canada, (Denojean 2014).....	21
2.14	Telepresence robot, Meijo University, Japan, (Hasegawa 2015).....	22
2.15	Remote patient monitoring telepresence robot, Canada, (Lepage 2016).....	22
2.16	Commercially-available telepresence robots,(Herring 2013)	24
2.17	The Giraff telepresence robot, (Gonzalez 2012).....	26
2.18	The network connection of the Beam telepresence robot, (Ackerman 2014)..	29

2.19	Oculus Rift, (Oculus 2016).....	30
2.20	The panoramic scene, National Chiao Tung University, Taiwan, (Huang 2014).	31
2.21	The panoramic stereo video, International Institute of Information Technology, India, (Aggarwal 2016).....	31
2.22	Driver Assistance System, the University of Texas, USA, (Pan 2016).....	32
3.1	The telepresence wheelchair system topology.....	38
3.2	The detail of the telepresence wheelchair hardware.....	39
3.3	The relation of the IEEE 802.11 standard to the OSI reference model.....	42
3.4	The bandwidth of the IEEE 802.11 standard.....	43
3.5	2.4 GHz band for Wi-Fi channels.....	43
3.6	5 GHz spectrum for Wi-Fi (Intel 2014).....	44
3.7	Video transmission over the wireless channel.....	45
3.8	Block diagram of the JPEG Encoding.....	51
3.9	Block diagram of the JPEG Decoding.....	51
3.10	Framework for video streaming over the wireless network.....	55
3.11	Video stream from Ladybug3.....	56
3.12	The configuration and side views of the Ladybug3 camera.....	57
3.13	Server and client topology.....	59
3.14	System performance test at the Centre for Health Technologies.....	61

3.15	Six images were taken from six camera units of Ladybug3.....	62
3.16	A JPEG panoramic frame generated after processing.....	62
3.17	Bitmap and JPEG file size comparison.....	62
3.18	Packet loss during transmission.....	63
3.19	The original image at the server.....	63
3.20	The histogram of the original image.....	64
3.21	The image received at the client.....	64
3.22	Histogram of the obtained images during the streaming process with MSE = 1.8651e+03 and PSNR = 15.4239 dB.....	64
3.23	An original panoramic image extracted from the wheelchair.....	65
3.24	The image obtained over wireless with errors.....	65
3.25	A sequence of six frames is extracted from the camera attached to the wheelchair.....	66
3.26	The image obtained at client side over wireless with our scheme.....	67
3.27	Images quality measured by mean squared error.....	67
3.28	PSNR measured received image quality.....	68
3.29	Wireless Network spectrums trace view.....	68
3.30	Streaming rates (Bytes/s) vs. Time (s).....	69
3.31	Client receives JPEG images from Server.....	70

4.1	A typical Skype architecture.....	76
4.2	A telepresence wheelchair based on Skype architecture.....	77
4.3	A simplified LTE cellular network architecture.....	78
4.4	The back and front view of the telepresence wheelchair.....	80
4.5	The diagram of a multi-video streaming based on Skype framework.....	81
4.6	The connections of the wheelchair control components.....	83
4.7	The front and the back view of the Oculus Rift and Gear VR.....	85
4.8	A remote user is wearing virtual reality device and control the wheelchair...	86
4.9	System experiments at the University of Technology Sydney.....	89
4.10	The average streaming rate of ten trials in the experiments.....	91
4.11	The average round-trip time of ten trials in the experiments.....	92
4.12	Multi-view video obtained from a telepresence wheelchair and the control interface at the remote site.....	93
4.13	(a) Wheelchair in an outdoor environment at Jones Street – Sydney. (b) A connection from a remote user in Vietnam to the wheelchair user in Sydney.....	95
4.14	Remote user controlled wheelchair from a long distance.....	96
4.15	The RSRP measurements from the wheelchair of experiments.....	96
4.16	Round trip time vs. jitter over a period of 4500 milliseconds of same country links (Australia – Australia).....	97
4.17	Round trip time vs. jitter over a period of 4500 milliseconds of different country connections (Vietnam – Australia).....	98

4.18	CPU usage of wheelchair computer and remote user's computer.....	98
4.19	The diagram of the telepresence wheelchair with virtual reality in wireless connections.....	99
4.20	A remote user was wearing Oculus Rift and controlling the wheelchair in outdoor environments.....	100
4.21	Participant (FS1) wore a virtual reality headset to observe the surrounding of the wheelchair and controlled the wheelchair to the desired locations from another room.....	101
4.22	Ten participants in the experiments.....	102
4.23	The signal strength of the wireless networks.....	103
4.24	A comparison of the latency of different connections.....	103
4.25	The measurement of PSNR of 1000 video frames.....	104
4.26	A remote user (MS2) was wearing Oculus Rift and controlling the wheelchair in indoor environments.....	105
4.27	The trajectories of the telepresence and joystick control wheelchair in the experiments.....	106
4.28	Time spent wheeling comparison between the manual control (Joystick) and remote control using telepresence (Tel).....	107
5.1	The MediaStream API component.....	113
5.2	WebRTC architecture (WebRTC 2017)	114
5.3	WebRTC Protocol Layer (Loreto & Romano 2012).....	115
5.4	WebRTC using STUN, TURN, and Signalling (WebRTC 2017)	115

5.5	The signal of A and B connections (Mozilla 2017)	116
5.6	The WebRTC based telepresence wheelchair design.....	117
5.7	A telepresence wheelchair equipped with a dual-fisheye camera.....	121
5.8	A 360-degree view telepresence using WebRTC architecture.....	121
5.9	An equirectangular projection.....	122
5.10	The block diagram of feature-based panoramic images stitching.....	123
5.11	Remote control telepresence wheelchair based on WebRTC.....	126
5.12	The connection of the control components.....	127
5.13	Neural Network.....	130
5.14	One layer of Neurons.....	130
5.15	Typical transfer functions.....	131
5.16	Multiple layers of Neural Networks.....	131
5.17	QoE Estimation model based on the Neural Network.....	132
5.18	Block diagram of QoE estimation based on Neural Network.....	133
5.19	The user interface and the video obtained by the remote user.....	136
5.20	Bandwidth and bitrate of the system.....	137
5.21	Round-trip time of telepresence based on WebRTC.....	137
5.22	Frame rate per second (fps) of WebRTC vs. Skype.....	138
5.23	System performance test at the Centre for Health Technologies.....	139
5.24	Dual-fisheye video without stitching processing.....	140

5.25	Spherical panoramic video obtained from a telepresence wheelchair and the control interface at the remote site.....	141
5.26	(a) The measurement of wireless network speed, (b) the average processing time per frame, (c) the frame rate and (d) the peak signal noise ratio of 10 experiments.....	141
5.27	The proposed neural network for QoE estimation.....	143
5.28	The performance progress over epochs.....	144
5.29	Regression plots for the training, validation, testing and all data.....	145
5.30	Estimated MOS based on ANN versus measured MOS.....	145
5.31	System performance test at the Centre for Health Technologies, UTS.....	146
5.32	Trajectory of the wheelchair when the remote user controlled the wheelchair with straight ahead directions.....	147
5.33	Test path setup with the figure eight curve.....	147
5.34	The full field of view obtained at the remote user.....	148
5.35	The full top-down view obtained at the remote user.....	148
5.36	The trajectory of the remote control telepresence wheelchair and the desired path.....	149
5.37	The telepresence wheelchair experiments in an outdoor environment.....	149
5.38	The trajectory of the remote control telepresence wheelchair in an outdoor environment at the campus of the University of Technology Sydney and the desired path.....	150

A.1	Wheelchair gear-motors	159
A.2	DX System	159
A.3	Keypad of the wheelchair	160
A.4	Battery charging	160
A.5	Signal Label Application Diagram and pin out	161
A.6	NI USB-6008/6009 Block Diagram.	163
A.7	NI USB-6008/6009 Analog Input Circuitry.	163

List of Tables

3.1	TASO Picture Rating.....	53
3.2	CCIR Five-Grate Scale	53
3.3	Camera Specifications.....	57
3.4	Network settings for experiments.....	60
3.5	Average PSNR Results for Various Distances.....	69
4.1	The Test Positions of the Experiments.....	90
4.2	Command buttons available during experiments.....	91
4.3	The average accuracy of command tasks.....	93
4.4	Details of the computers used for implementation.....	94
4.5	Performance of the System with Ten Participants.....	106
5.1	ITU 5-Point Quality Scale Measurement of MOS.....	133
5.2	Mapping the PSNR, SSIM to the MOS.....	134
5.3	The average performance results of the 30-trials.....	136
A.1	NI USB-6008 and NI USB-6009 Comparison	161
A.2	Signal Descriptions	162

Abstract

In recent years, assistive technologies, especially intelligent wheelchairs have played a crucial role in supporting the elderly and people with disabilities. Current smart wheelchairs are usually controlled by individuals sitting in the wheelchairs. There has been limited research undertaken on the ability to control the mobility of wheelchairs while people are not inside the wheelchairs. Along with intelligent wheelchairs, telepresence robots have been developed for various applications. However, there has been limited work in developing telepresence systems based on wheelchair platforms for assistive technologies. Thus, an effective integration of telepresence functions into a wheelchair would create an innovative health care support solution.

This thesis aims at developing a telepresence wheelchair using an assistive technology which is capable of providing two-way video communication and interaction. The telepresence wheelchair developed in this thesis can support independent mobility of the wheelchair users, especially in the scenarios where people with disabilities might use the telepresence function to move the remote wheelchair towards their positions without the help of caregivers. In addition, the system can allow users to look at the environment surrounding the wheelchair and to control the wheelchair to move around different places to communicate and meet other people. Thus, the designed system would be significantly meaningful and helpful for individuals with mobility impairment. However, designing and developing such an Internet-enabled telepresence wheelchair remain significant technical challenges in terms of implementing in real-time, providing remote control, and realizing a wide field of view.

The key contribution of this thesis is to develop a unique telepresence wheelchair system that provides high-quality video communication with a full field of view and efficient remote control over the wireless Internet in real-time. The current telepresence systems which are coping with one view direction at one time are not flexible and are cumbersome while operating in the reverse direction. To address these issues, this thesis investigates the advanced technologies to develop a telepresence wheelchair with 360-degree vision. To develop a complete telepresence wheelchair, this thesis has exploited technological

advancement in image processing, wireless communication networks, and healthcare systems. There are three core tasks to be considered: Firstly, to investigate the data communication techniques to stream the views surrounding the wheelchair wirelessly from the unknown environment to the remote users to find the appropriate protocol for the real-time application. Secondly, to develop real-time communication and remote interaction with depth information for immersive experiences in telepresence. Thirdly, to implement the 360-degree field of view for a telepresence wheelchair and to develop an independent application based on emerging technologies.

Accordingly, in the first stage, the Internet protocol for transmitting video based on client-server topology over a wireless network has been developed and implemented as the first attempt. The experimental results with the video transmission based on client-server topology over a wireless network showed that the proposed method successfully streamed the *panoramic images* with the average peak signal to noise ratio (PSNR) of 39.19 dB.

In the second stage, the real-time video streaming based on the cross-platform, namely Skype framework has been explored for *multiple-video transmission* to improve the system performance. The experimental results also showed that the streaming rate was between 25 and 30 frames per second (fps) and the round-trip time varies from 3 to 271 milliseconds. In addition, the wheelchair can successfully navigate by remote control at different distances with the average accuracy of 97.72 %.

In the final stage, this thesis has performed the development and implementation of *360-degree video streaming* and remote controlling based on *advanced real time communication*. The experimental results showed that the round-trip time significantly decreased and fluctuated from 3 to 20 ms. Moreover, the proposed system is able to stream *a full field of view video* surrounding the wheelchair smoothly in real-time with the average frame rate of 25.83 fps, and the average PSNR of 29.06 dB.

The experimental results demonstrated that the proposed telepresence wheelchair is able to stream *a full field of view video* surrounding the wheelchair effectively and smoothly in real-time. Furthermore, the results showed the designed telepresence wheelchair could be controlled remotely via the wireless Internet with high accuracy.